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Climate change threatens the most biodiverse regions of Mexico

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AUTHOR CONTRIBUTIONS

MER: design of the research; performance of the research; data analysis, collection, and interpretation; writing the manuscript

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

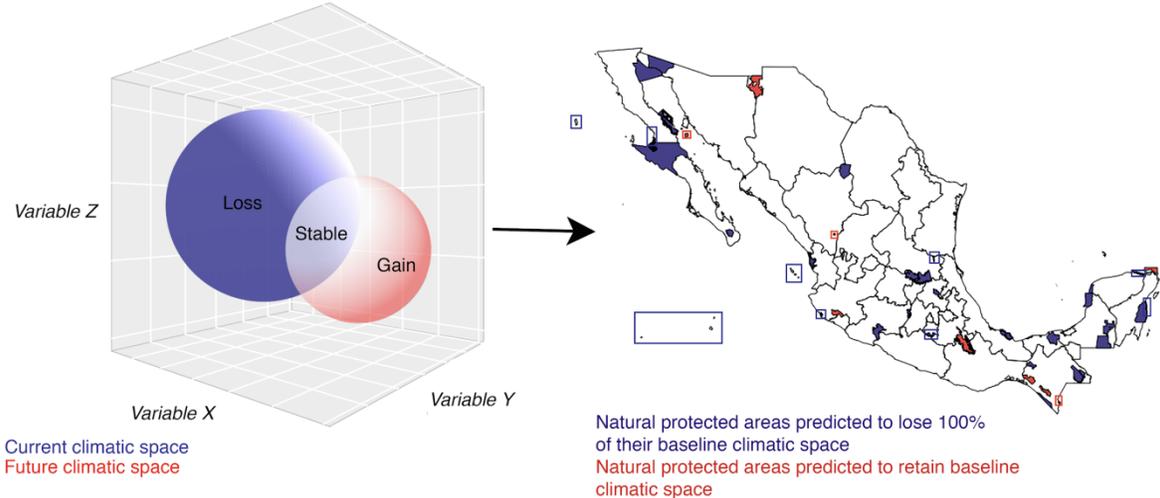
JM: performance of the research; expertise advice on methods; editing the manuscript

ACM: design of the research; expertise advice on methods; editing the manuscript

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

Climate change threatens the most biodiverse regions of Mexico

GRAPHICAL ABSTRACT



1 **ABSTRACT**

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

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

25 **HIGHLIGHTS**

- 26 • Across 40 protected areas, temperature is predicted to increase ~3°C by
27 2050
- 28 • 31 protected areas are predicted to lose 100% of their baseline climatic
29 space
- 30 • 17 protected areas may lose climate variability (homogenization),
31 decreasing species' niches
- 32 • The effect of non-analogue conditions on species and ecosystems is largely
33 unknown
- 34 • We propose a vulnerability index to categorise natural protected areas

35 **INTRODUCTION**

36 Rapid modern climate change is already altering species distributions and
37 reorganising the composition of many ecosystems (Lenoir and Svenning 2015).
38 These changes have important direct and indirect consequences on ecosystem
39 functioning, human health, and climatic feedbacks (Bonebrake et al. 2018; Pecl et
40 al. 2017; Scheffers et al. 2016). Thus, projected increases in temperature, shifts in
41 precipitation patterns, and the increasing occurrence of extreme weather events
42 jeopardize the persistence of ecosystems and the species they support (Field et al.
43 2014).

44 Effective conservation and management practices depend strongly on our
45 ability to predict the impacts of climate change on natural and human-managed
46 ecosystems (Mawdsley et al. 2009). However, predicting the impacts of climate
47 change is particularly challenging, due to the complexities of climatic processes
48 and uncertainty about the rate and magnitude of changes (Baumgartner et al.
49 2018; Beaumont et al. 2019; Fatichi et al. 2016; Grierson et al. 2011; Loarie et al.
50 2009; Ohlemüller 2011). As changes in climate intensify, assessments of the
51 extent to which the available climatic space may change are particularly important
52 in order to identify species most threatened by changing climate (Guisan et al.
53 2014).

54 During past abrupt climatic changes, populations persisted in areas with
55 relatively stable climate, referred to as refugia (or microrefugia). These areas
56 apparently retained local environmental conditions suitable for species persistence,
57 amidst regionally unsuitable conditions (Correa-Metrio et al. 2014; Médail and
58 Diadema 2009; Tzedakis et al. 2002). Thus, refugia are recognised as important

59 areas fostering endemic biodiversity (Harrison and Noss 2017). Although the
60 concept of refugia has been more commonly applied to historical periods during
61 the Quaternary, the idea that some areas may act as potential refugia (or
62 microrefugia) under contemporary and future anthropogenic climate change is now
63 widely accepted by the scientific community (Hannah et al. 2014; Keppel et al.
64 2012; Keppel and Wardell-Johnson 2015). Hence, maintaining a functional network
65 of protected areas that retain a sufficient proportion of their existing climatic space
66 into the future will limit biodiversity losses associated with rapid climate change,
67 promote the delivery of ecosystem services, provide livelihoods, and sustain local
68 communities (Ervin 2003; IUCN 2005).

69 Mexico is a megadiverse country harbouring almost 10% of the world's
70 biodiversity (Challenger 1998; Mittermeier et al. 1998; Sarukhán Kermez and Dirzo
71 1992). Currently, the Mexican natural protected areas (NPAs), administered by the
72 National Commission of Natural Protected Areas (Comisión Nacional de Áreas
73 Naturales Protegidas; CONANP), cover more than 25.3 million hectares (Vargas
74 Márquez et al. 2011). Such a large network has the potential to provide refugial
75 capacity (sensu Keppel and Wardell-Johnson 2015) for ecosystems and adjacent
76 areas, facilitating the maintenance of populations, water quality, nutrient cycling,
77 and ecological flows (DeFries et al. 2010). These NPAs provide habitat for species
78 considered endemic, threatened, or endangered (Batisse 1982; Ishwaran et al.
79 2008). Because of the significance of these NPAs, we highlight the importance of
80 understanding the exposure of these ecosystems and the species they harbour to
81 risks associated with future climate change. This understanding is essential for
82 developing and designing effective management and conservation programs (Cash

83 and Moser 2000). Such a task, in turn, requires the use of approaches and tools
84 that can be applied to species, taxonomic groups, and regions to propose and
85 design a climate-ready protected area network (Graham et al. 2019). One such
86 approach is an assessment of the climatic space that is currently available and
87 how this may be altered by modern rapid climate change.

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

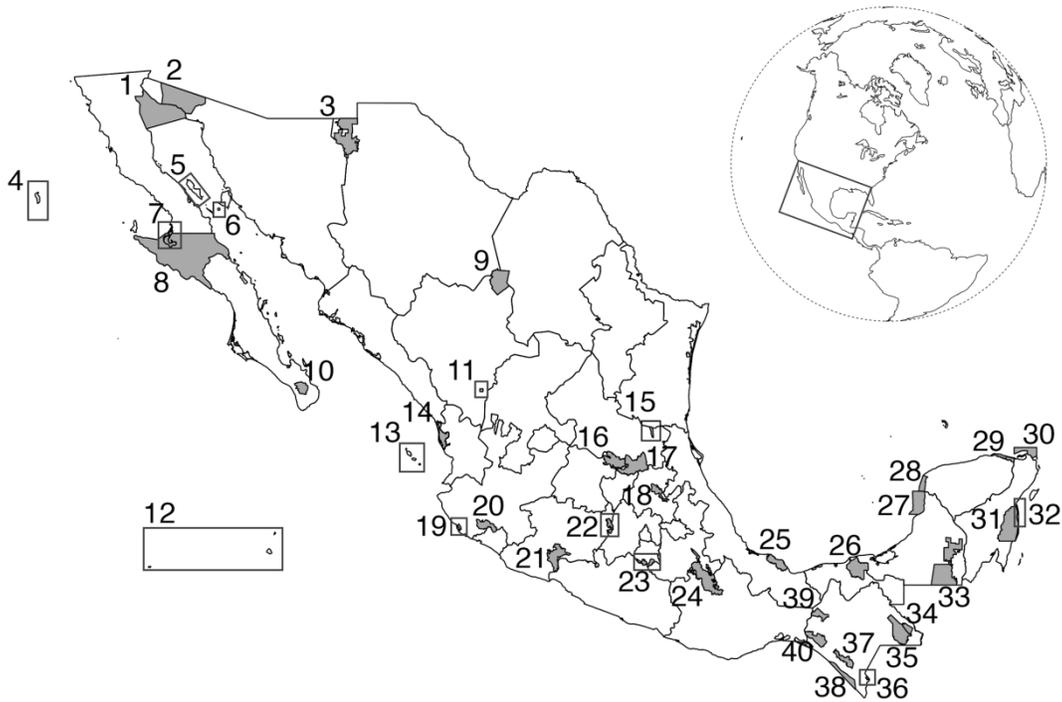
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95 **METHODS**

96 *Natural protected areas (NPAs)*

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

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



111
 112 **Figure 1.** Location of the 40 protected areas of Mexico: 1) Alto Golfo de California y delta
 113 del río Colorado; 2) El Pinacate y Gran Desierto de Altar; 3) Janos; 4) Isla Guadalupe; 5)
 114 Bahía de los Angeles, canales de Ballenas y de Salsipuedes; 6) Isla San Pedro Mártir; 7)
 115 Complejo lagunar Ojo de Liebre; 8) El Vizcaíno; 9) Mapimí; 10) Sierra de la Laguna; 11)
 116 La Michilía; 12) Archipelago de Revillagigedo; 13) Islas Marias; 14) Marismas
 117 Nacionales; 15) Sierra del Abra-Tanchipa; 16) Sierra Gorda de Guanajuato; 17) Sierra
 118 Gorda; 18) Barranca de Metztitlán; 19) Chamela-Cuixmala; 20) Sierra de Manantlán; 21)
 119 Zicuirán Infiernillo; 22) Mariposa Monarca; 23) Sierra de Huautla; 24) Tehuacán-Cuicatlán;
 120 25) Los Tuxtlas; 26) Pantanos de Centla; 27) Los Petenes; 28) Ría Celestún; 29) Ría

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

124

125 *Climate data*

126 For both the baseline and future climate data across the 40 NPAs, we downloaded
127 the set of 19 bioclimatic variables at a spatial resolution of 30 arc-seconds (~1 km
128 at the equator) from WorldClim (Version 1.4) (<http://www.worldclim.org/>). Data
129 were projected to the INEGI Lambert Conformal Conic equal area projection
130 (EPSG:6362) with 1 × 1 km resolution. Baseline data represent climate conditions
131 during the period 1960-1990. For future climate data, we downloaded projections
132 of four Global Climate Models (GCMs) recommended for Mexico (Cavazos et al.
133 2013; Fernández Eguiarte et al. 2015): (1) MPI-ESM-LR (Germany); (2) GFDL-
134 CM3 (USA); (3) HADGEM2-ED (United Kingdom); and (4) CNRM (France). For
135 these four GCMs, we used the Representative Concentration Pathway (RCP) 8.5,
136 which projects emissions to continue to rise throughout the 21st century
137 (Meinshausen et al. 2011). Following the precautionary principle of risk
138 assessment, we chose a high-emission scenario in order to investigate the
139 maximum change that can be expected for climate and to maximize the impact of
140 CO₂ concentration change and CO₂-related climate change on vegetation (Yu and
141 Wang 2014). Additionally, this scenario is often used to assess risks and possible
142 costs associated with climate change (Riahi et al. 2011). We selected data for
143 2050 (average for 2041-2060), aiming to explore a future scenario that matches
144 the short-term timeframe of current management and conservation practices.

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

147 We evaluated correlations among the 19 bioclimatic variables using
148 Pearson's product-moment correlation (Legendre and Legendre 2012) (**Appendix**
149 **1**). Out of the highly correlated pairs ($|r| > 0.7$), we selected one of the covariates
150 based on biological relevance. We retained a subset of nine uncorrelated
151 bioclimatic variables. We then performed a principal component analysis (PCA) on
152 baseline data and based on the magnitude and direction of the vectors (i.e.
153 bioclimatic variables) in relation to main principal components (i.e. first two PC
154 axes) and biological relevance, we selected a final set of five bioclimatic variables
155 to perform our subsequent analyses: (1) Max Temperature of the Warmest Month
156 (BIO5; *MTWM*); (2) Min Temperature of the Coldest Month (BIO6; *MTCM*); (3)
157 Temperature Annual Range (BIO7; *TAN*); (4) Annual Precipitation (BIO12; *AP*);
158 and (5) Precipitation Seasonality (BIO15; *PS*). This additional reduction in the
159 number of variables was necessary to reduce computational demand associated
160 with calculating hypervolumes (see details below).

161 Maximum and minimum temperature (*MTWM*, *MTCM*) are useful to examine
162 how species distributions are affected by warm and cold temperature anomalies
163 throughout the year. The temperature annual range (*TAN*) is useful when
164 examining whether species' distributions are affected by ranges of extreme
165 temperature conditions (O'Donnell and Ignizio 2012). Evidence suggests that
166 increases in temperature might affect species' ranges, ecological interactions, and
167 even survival of populations (Allen et al. 2010; Field et al. 2014; Thomas et al.
168 2004; Walther et al. 2002). Annual precipitation (*AP*) affects ecosystems

169 differentially and plays a key role in determining species' distributions (Moles et al.
170 2014; O'Donnell and Ignizio 2012; Weltzin et al. 2003). The predicted changes in
171 precipitation patterns and total rainfall represent a risk to both species and
172 ecosystems (Anderegg et al. 2015; Field et al. 2014). Precipitation seasonality (*PS*)
173 is a measure of the variation in precipitation throughout the year, with higher values
174 indicating higher variability (O'Donnell and Ignizio 2012), and may be important for
175 species dependent on seasonal patterns of rainfall. The values of these five
176 variables were extracted for each NPA using a 1 × 1 km grid, yielding baseline and
177 future scenarios comprising the average of future projections from the four GCMs.
178 Baseline and future scenarios for each NPA were characterized in terms of the
179 mean, standard deviation, and range of the five variables across all grid cells
180 occurring within a given NPA. The magnitude of climate change in the NPAs was
181 then assessed by estimating the absolute difference between baseline and future
182 values (mean, standard deviation, and range) of each variable.

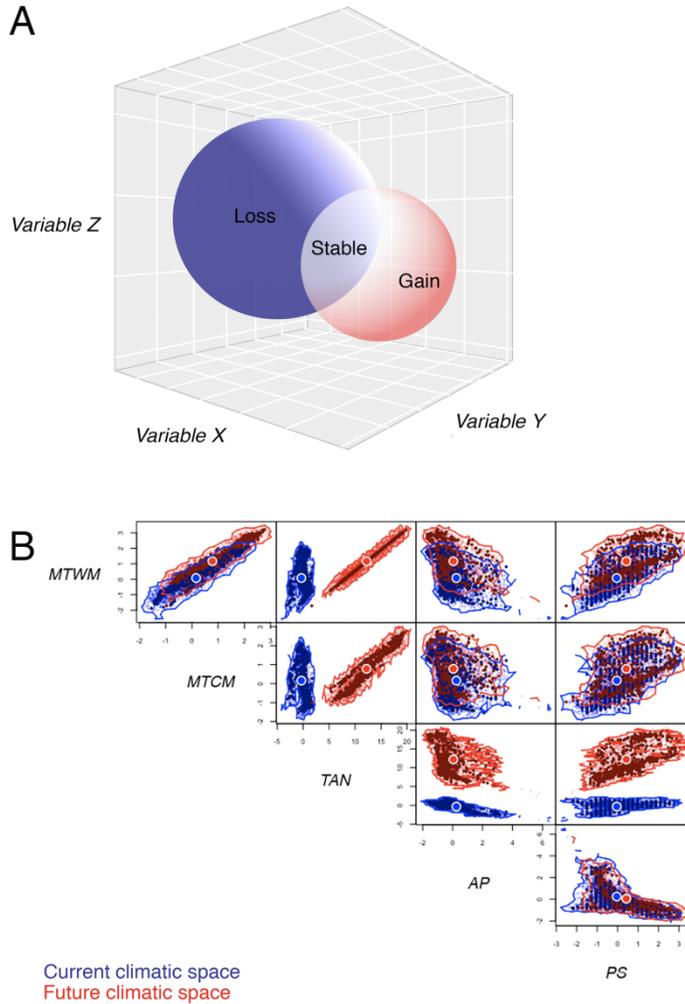
183

184 *Climatic space*

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

193 To quantify the climatic space, we used the package *hypervolume* (version
194 2.0.11) (Blonder and Harris 2018) in R (version 3.4.4) (R Core Team 2018). Default
195 settings were used to estimate hypervolumes with the Gaussian kernel density
196 estimate method and the Silverman estimator for bandwidth selection. Specifically,
197 we used the function `<hypervolume_overlap_statistics>` to compare baseline and
198 future climatic space. This function provides a set of metrics: (1) unique fraction 1
199 (volume of the unique component of the baseline climatic space divided by the total
200 volume of the baseline climatic space); and (2) unique fraction 2 (volume of the
201 unique component of the future climatic space divided by the total volume of the
202 future climatic space) (Blonder and Harris 2018).

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



210

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

221 we assessed the shift from baseline (blue) to future (red) climatic space for the protected
222 area of Tehuacan-Cuicatlan, Puebla-Oaxaca. For this protected area, the predicted
223 percentages of stable climate, climate loss and climate gain are ~44%, ~55.7% and
224 ~56.6%, respectively. Axes are given in units of standard deviations (SDs) of baseline
225 values.

226

227 *Vulnerability of natural protected areas to climate change*

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

238

$$239 \quad V_i = (V_{CSL} + V_{TA} + V_{SR}) / 3 \quad (1)$$

240

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

244

245
$$V_{\text{CSL}} = (\text{CSL}_i / \text{CSL}_{\text{MAX}}) \quad (2)$$

246

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

249

250
$$V_{\text{TA}} = 1 - (\text{TA}_i / \text{TA}_{\text{MAX}}) \quad (3)$$

251

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

255

256
$$V_{\text{SR}} = (\text{SR}_i / \text{SR}_{\text{MAX}}) \quad (4)$$

257

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

262

263 *Species richness and composition of natural protected areas*

264 To assess species richness (SR) and composition at each NPA, we queried the
265 Global Biodiversity Information Facility (January 2019; GBIF, <http://www.gbif.org>),
266 identifying all species of vascular plants (Tracheophyte), fungi, and animals
267 (amphibians, arthropods, birds, mammals, and reptiles) recorded in each NPA.
268 Occurrence records were downloaded for all of Mexico and then subsetted to

269 retain only records georeferenced within each NPA. We further restricted records
270 to those with an observational basis reported as “human observation”,
271 “observation”, “specimen”, “living specimen”, “literature occurrence”, or “material
272 sample”.

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

284

285 **RESULTS**

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

287 Across all NPAs, average conditions for all temperature variables (*MTWM*, *MTCM*,
288 *TAN*) are predicted to increase by 2050, with the exception of a decrease in *TAN* at
289 Sierra de la Laguna. On average (\pm SD), *MTWM* is predicted to increase by $2.8 \pm$
290 0.5°C , with *MTCM* and *TAN* predicted to be $2.1 \pm 0.2^\circ\text{C}$ and $0.7 \pm 0.4^\circ\text{C}$ warmer
291 relative to baseline climatic averages (1960-1990), respectively. In contrast, annual
292 precipitation (*AP*) is predicted to decrease in 30 NPAs, by 34.4 ± 32 mm. Only ten

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

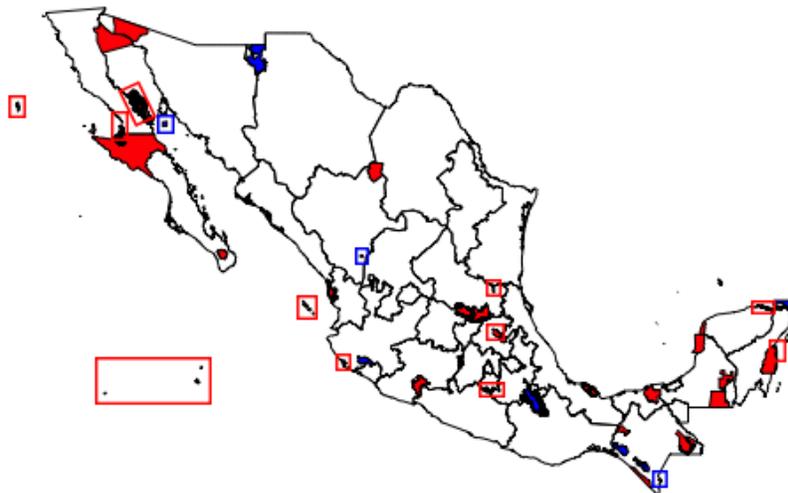
296 For baseline and future conditions, the highest values of *MTWM*, *MTCM*,
297 *TAN*, *AP*, and *PS* were found in the Alto Golfo de California, La Encrucijada
298 (Chiapas), Janos (Chihuahua), Montes Azules (Chiapas), and Sierra de la Laguna
299 (Baja California Sur), respectively (**Appendix 2**).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

306

307 *Climatic space*

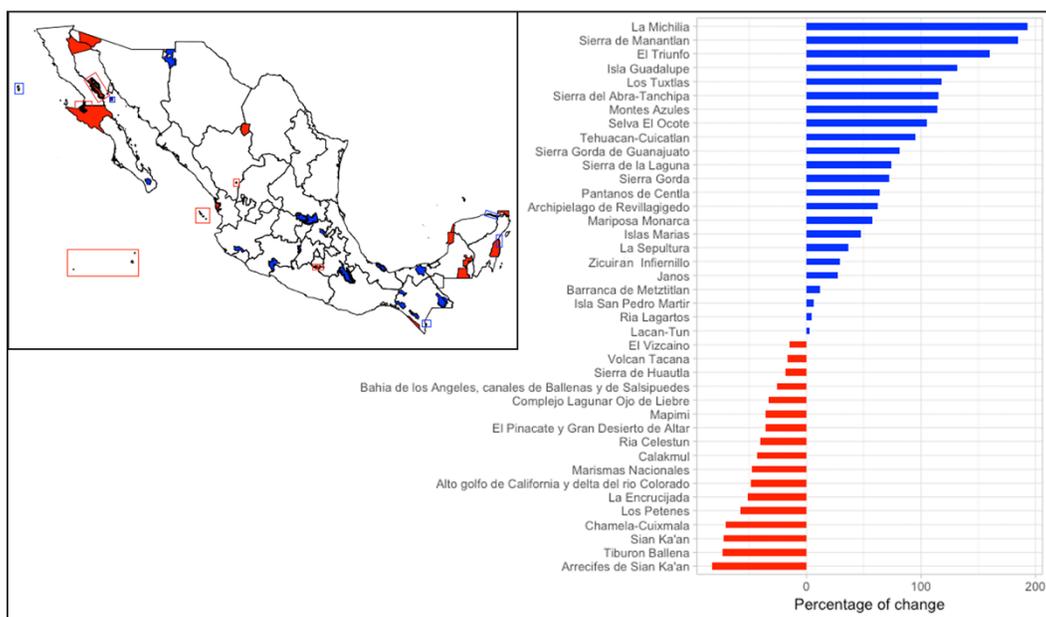
308 Across all 40 NPAs, the volume of climatic space averaged $89.7 (\pm 107.7)$ and
309 $120.3 (\pm 137.5)$ for the baseline and future time period, respectively, representing
310 greater variability under future conditions relative to baseline. For both time
311 periods, Volcan Tacana (Chiapas) had the broadest climatic space. The narrowest
312 climatic space was found in Calakmul (Campeche) and Sian Ka'an for baseline and
313 future time periods, respectively. Thirty-one NPAs (78%) were predicted to have no
314 stable climate (i.e. no intersection between the baseline and future climatic space).
315 Hence, these areas are projected to contain completely novel climates by 2050.

316 For the remaining nine NPAs, the proportion of the current climatic space
317 remaining stable reached, on average, 48%, ranging from 1% in Janos to 86% in
318 La Michilía. Across these NPAs, the average loss of baseline climatic space was
319 55.7% ($\pm 26.7\%$), whereas 54.5% ($\pm 32.5\%$) of future climatic space was novel.
320 The greatest loss of current and gain of novel climatic space were found in Janos
321 (98.8% and 99.01%, respectively), whereas the lowest loss and gain of climatic
322 space were found in La Michilia (13.9%) and Tiburon Ballena (4.5%), respectively
323 (**Figure 3; Appendix 3**).



324
325 **Figure 3.** Protected areas in red are predicted to have no stable climate (i.e. no
326 intersection between the baseline and future climatic space), hence the whole climatic
327 space by 2050 will be novel. Protected areas in blue are predicted to retain some of their
328 baseline climatic space as well as gain novel climatic space by 2050. See **Appendix 3** for
329 details on changes in climatic space and **Figure 1** for names of protected areas.
330

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



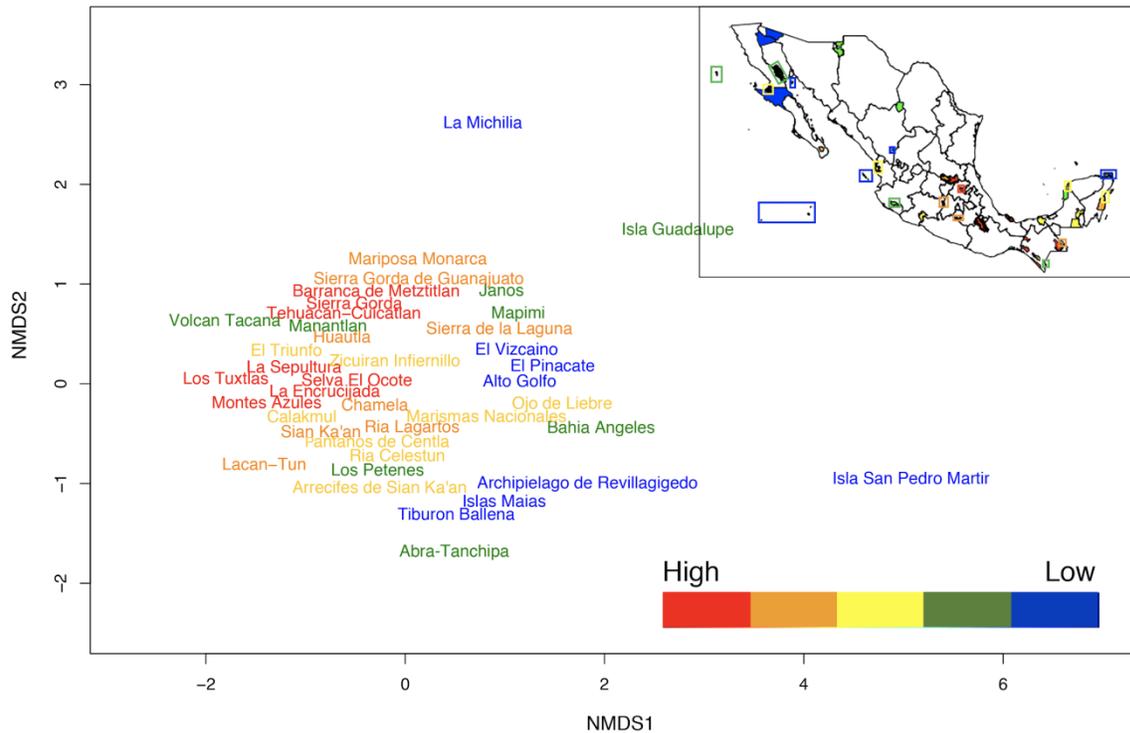
340
 341 **Figure 4.** Percentage of decreases (red) and increases (blue) to the overall volume of
 342 climatic space between baseline (1960-1990) and future (2050, average for 2041-2060)
 343 conditions within 40 protected areas, and their location in Mexico (inset map). An increase
 344 in volume represents a gain in climate variability, while a decrease indicates a more
 345 homogenous future climate. For names of protected areas, see **Figure 1**.

346

347 *Vulnerability of natural protected areas to climate change*

348 The average size of the 40 NPAs spans 3127.11 km² (\pm 4260.7 km²), with the
349 largest being El Vizcaino (24,930.9 km²) while the smallest is Volcan Tacana (63.8
350 km²). The number of species for which there are GBIF records varied across
351 NPAs, with an average of 2147 species (\pm 1740 species), a maximum of 7524
352 species recorded in Tehuacan-Cuicatlan (Oaxaca, Puebla) and a minimum of 98
353 species recorded in Isla San Pedro Martir (Sonora) (**Appendix 4**). The mean
354 vulnerability (*V*) was 0.69 (\pm 0.11), with a maximum (high vulnerability) of 0.91 at
355 Los Tuxtlas (Veracruz; 1551.22 km² and 5945 species), and a minimum (low
356 vulnerability) of 0.38 at Tiburon Ballena (1459.9 km² and 334 species) (**Appendix**
357 **3**).

358 Species composition also varied across NPAs (**Figure 5**), with La Michilia (*V*
359 = 0.40, ranked 39), Isla Guadalupe (Baja California; *V*= 0.62, ranked 32), Isla San
360 Pedro el Martir (*V*= 0.48, ranked 37), and Sierra Abra Tanchipa (San Luis Potosí;
361 *V*= 0.67, ranked 27) having a relatively different composition of species compared
362 to the other NPAs. The set of NPAs identified to have higher vulnerability (in red
363 and orange in **Figure 5**) clustered broadly in two geographical groups: (1)
364 mountainous regions of central Mexico (except Sierra de la Laguna) with a more
365 temperate climate and (2) south-east of Mexico in Chiapas and Veracruz (except
366 for Chamela) where the climate is more tropical.



367

368 **Figure 5.** Non-metric multidimensional scaling (NMDS) plot for the ordination of the

369 species composition of 40 protected areas and their location in Mexico (inset map).

370 Colours are indicative of vulnerability ranked from high (red) to low (blue). For names of

371 protected areas, see **Figure 1**.

372

373 **DISCUSSION**

374 *Climate change in natural protected areas of Mexico*

375 The predicted increases in temperature, and changes in both total precipitation and

376 precipitation seasonality, will likely affect species' ranges, interactions, and even

377 survival (Allen et al. 2010; Anderegg et al. 2015; Field et al. 2014; Thomas et al.

378 2004; Walther et al. 2002). Within Mexico, temperature is predicted to become

379 warmer across all 40 NPAs by 2050, with larger increases (up to 3.75°C in *MTWM*

380 and 2.5°C in *MTCM*) predicted to occur in arid regions that already experience high
381 temperatures (e.g. Janos, Mapimí [Chihuahua, Coahuila, Durango], El Pinacate,
382 and Tehuacán-Cuicatlán). Although the species within these NPAs are adapted to
383 high temperatures, further increases in *MTWM* and *MTCM* might represent an
384 additional stress, particularly to those species that are near their upper thermal
385 limits (McCain and Colwell 2011).

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

401 Decreases in precipitation are predicted in 30 NPAs, while for nine other
402 NPAs, only minor increases in precipitation are likely to occur (i.e. <22 mm per
403 year). The largest decreases in annual rainfall are predicted among NPAs where

404 baseline precipitation is already high (>1000 mm per year). Additionally, 34 of the
405 40 NPAs studied here are predicted to experience changes in *PS*. An increase in
406 *PS* indicates higher variability of precipitation (O'Donnell and Ignizio 2012),
407 implying increased duration and severity of soil water stress (Knapp et al. 2008).
408 This scenario poses a considerable risk for Sierra de la Laguna, which has the
409 highest *PS* among the studied areas, and is predicted to experience the largest
410 increases in the same variable by 2050. This NPA provides habitat to at least 1943
411 species. Of these, 86 are endemic plants, including *Arbutus peninsularis*
412 (Ericaceae), *Opuntia lagunae* (Cactaceae), and the vulnerable *Pinus cembroides*
413 ssp. *lagunae* (Arriaga et al. 2000; Farjon 2013). Importantly, some *Pinus* species
414 are highly vulnerable to changes in precipitation and have low drought tolerance
415 (Esperón-Rodríguez and Barradas 2015b).

416

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

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

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

433 Along with the threat represented by rising sea levels for islands and coastal
434 NPAs (Mimura 1999; Nicholls and Cazenave 2010), the loss of current climate
435 space is a major concern for the ecosystems they harbor. Except for Isla San
436 Pedro Mártir (stable climate of ~56.7%), the other NPAs on islands (Archipelago de
437 Revillagigedo, Isla Guadalupe, and Islas Marias [Nayarit]) are predicted to lose all
438 their baseline climatic space. Islands are highly vulnerable systems as they are
439 geographically confined and, similar to mountaintops, their associated species
440 have limited space to track changes in climate (Mimura et al. 2007). For Isla
441 Guadalupe, for example, the loss of the current climatic space may affect at least
442 461 species, including 82 plants and nine bird species endemic to the island. This
443 island is one of the main refugia of marine mammals, such as the northern
444 elephant seal (*Mirounga angustirostris*) and the Guadalupe fur seal (*Arctocephalus*
445 *townsendi*) (Arriaga et al. 2000; Gallo-Reynoso 1994).

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

452 Ballena) predicted to lose all their baseline climatic space and also experience
453 substantial decreases in the overall volume of climatic space (**Figure 3**). A
454 decrease in the volume of climatic space within an NPA represents a loss of
455 climatic variability (i.e. climatic conditions will become spatially more homogenous),
456 and hence a decreasing array of niches that are available, potentially diminishing
457 the refugial capacity of the area. Arrecifes de Sian Ka'an is predicted to suffer from
458 the greatest decrease in climatic volume (~82%), in addition to vulnerability to sea
459 level rise, invasive alien species, and growing pressure from tourism (Brenner
460 2010; CONABIO 1995).

461

462 *Vulnerability of natural protected areas to climate change*

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

469 Although our index ranks NPAs in terms of their vulnerability, we note that
470 this is a relative index that can only be used to prioritize management and
471 conservation actions within the network of the 40 NPAs assessed here. A low
472 vulnerability score does not mean that an NPA is not vulnerable to climate change
473 per se. Furthermore, some NPAs, such as Isla San Pedro Martir and La Michilia,
474 have relatively low vulnerability rankings ($V = 0.48$, ranked 37 of 40 and $V = 0.40$,
475 ranked 39 of 40; respectively); however, these NPAs harbor a very unique

476 composition of species (**Figure 5**) and are predicted to retain baseline climatic
477 conditions in 2050. These characteristics make these NPAs important potential
478 climate refugia and conservation actions are required to secure the persistence of
479 species and ecosystems in those NPAs.

480

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

482 A series of caveats are associated with our methodology. First, our assessment of
483 the climatic space did not consider other environmental factors that can mitigate or
484 exacerbate the effects of climate change, such as soil type and topography, or the
485 presence/absence of water bodies; furthermore, our approach does not consider
486 the potential feedback mechanisms between climate and biota (e.g. the role of
487 vegetation in modulating temperature). Second, the climate data we used here are
488 based on coarse-grained spatial interpolations from weather stations that are
489 shielded from direct solar radiation and thus fail to account for the microclimate
490 experienced by organisms living in their natural habitats (Lenoir et al. 2017). For
491 instance, our analyses cannot explicitly consider locations where microclimatic
492 conditions are more benign (e.g. protected slopes or areas with high canopy
493 cover). Third, A key source of uncertainty arises from the use of alternative, yet
494 plausible, climate scenarios. By selecting four different GCMs, we aimed to
495 account for the variation among different models in terms of projected temperature
496 and precipitation trends. The selected GCMs have been applied throughout the
497 territory of Mexico and are recommended for impacts assessments (Cavazos et al.
498 2013; Fernández Eguiarte et al. 2015). Nevertheless, we acknowledge that
499 different climate scenarios can produce different results, which might affect

500 conservation and management actions (Beaumont et al. 2019; Baumgartner et al.
501 2018; Graham et al. 2019). Further, by selecting the scenario RCP8.5 with the
502 highest radiative forcing and CO₂ emissions, our predictions might overestimate
503 the losses of climatic space, in contrast to using a more conservative scenario,
504 such as RCP6.0 (Raftery et al. 2017). Given that our aim is to assess risks, this
505 approach is consistent with the precautionary principle.

506 Another limitation of our approach is that we did not consider the effects of
507 elevated CO₂ on photosynthesis and transpiration. The combined effects of the
508 CO₂ fertilization effect and climate change can increase plant biomass (Zhu et al.
509 2016) and affect the performance and functioning of plant species with cascading
510 effects over the biota at each NPA. In NPAs where precipitation is predicted to
511 decrease and temperature to increase, plant phenology may accelerate, reducing
512 dry matter accumulation and altering ecosystem performance (Cao et al. 2010).
513 However, under drought conditions, CO₂ fertilization may not counteract the effects
514 of reduced water availability (Temme et al. 2019).

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

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

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

540

541 *Future recommendations*

542 Our index can be used to categorise NPAs in terms of their bioregional
543 vulnerability, their capacity to act as potential climatic refugia until 2050 (i.e. retain
544 stable baseline climate), and the number of species that they harbour. **This vital
545 information can be used in prioritization frameworks which explicitly consider the
546 benefits, costs, and feasibility of targeted conservation actions (Brown et al. 2015).
547 While some vulnerable species within NPAs likely require immediate conservation**

548 interventions to mitigate direct impacts, such as the world's most endangered
549 marine mammal, the vaquita (*Phocoena sinus*) in Alto Golfo de California y Delta
550 del río Colorado (SEMARNAT 2017) whose primary threat is fishing, many other
551 species can benefit from climate-mitigating actions taken in and around NPAs.
552 Prioritizing what actions occur when and where to deliver the largest benefits to the
553 existing NPA network will be a critical next step.

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

568 In extreme cases where NPAs and additional area-based management (e.g.
569 the establishment of buffer zones and corridors) fail to provide or retain suitable
570 conditions, thereby jeopardizing species survival, species translocation or assisted
571 migration may be necessary (Hoegh-Guldberg et al. 2008). While managed

572 relocation of species remains a contentious issue, there are quantitative
573 frameworks that could be explored for species with limited dispersal capacities
574 which are found in the more vulnerable NPAs (McDonald-Madden et. al 2011) Yet,
575 consideration must be given to minimise potential risks of invasion in the
576 introduced area when translocating species. Further, the species and locations that
577 will benefit most from translocation have yet to be explored for Mexico's
578 biodiversity.

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

592

593 **CONCLUSION**

594 The capacity of Mexico's 40 UNESCO World Network of Biosphere Reserves to
595 function as long-term refugia for biodiversity is likely to decline as the magnitude of

596 climate change increases. By the mid-century, 31 NPAs, which together provide
597 habitat to at least 22,866 species, are predicted to lose all their baseline climatic
598 space, shifting to novel climates. The extent to which these conditions will be within
599 the tolerance of species and ecosystems is currently unknown.

600

601 **SUPPLEMENTARY MATERIAL DESCRIPTION**

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

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

606 **Appendix 3.** Changes in climate spaces comparing baseline (averages between
607 1960 and 1990) and future (2050 [average for 2041-2060]; average of four global
608 circulation models) conditions across the 40 NPAs.

609 **Appendix 4.** Number of species and records of each taxonomic group across the
610 40 NPAs.

611

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616

617 **DECLARATION OF INTERESTS**

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

619

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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

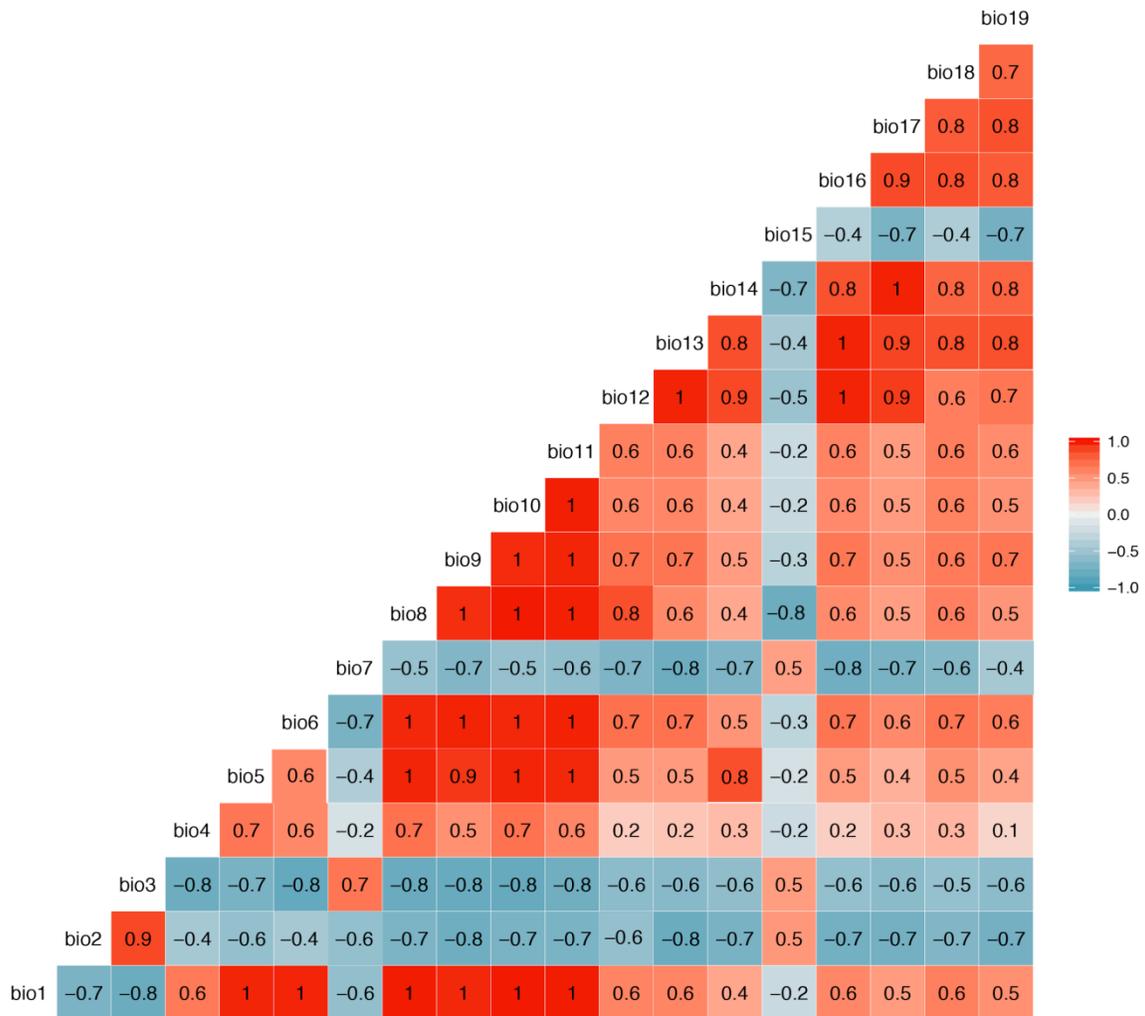


Figure A1. Pearson correlation of 19 bioclimatic variables (data from WorldClim (<http://www.worldclim.org/>)). Bioclimatic variables are coded as follows:

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
<i>MTWM</i>	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)

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

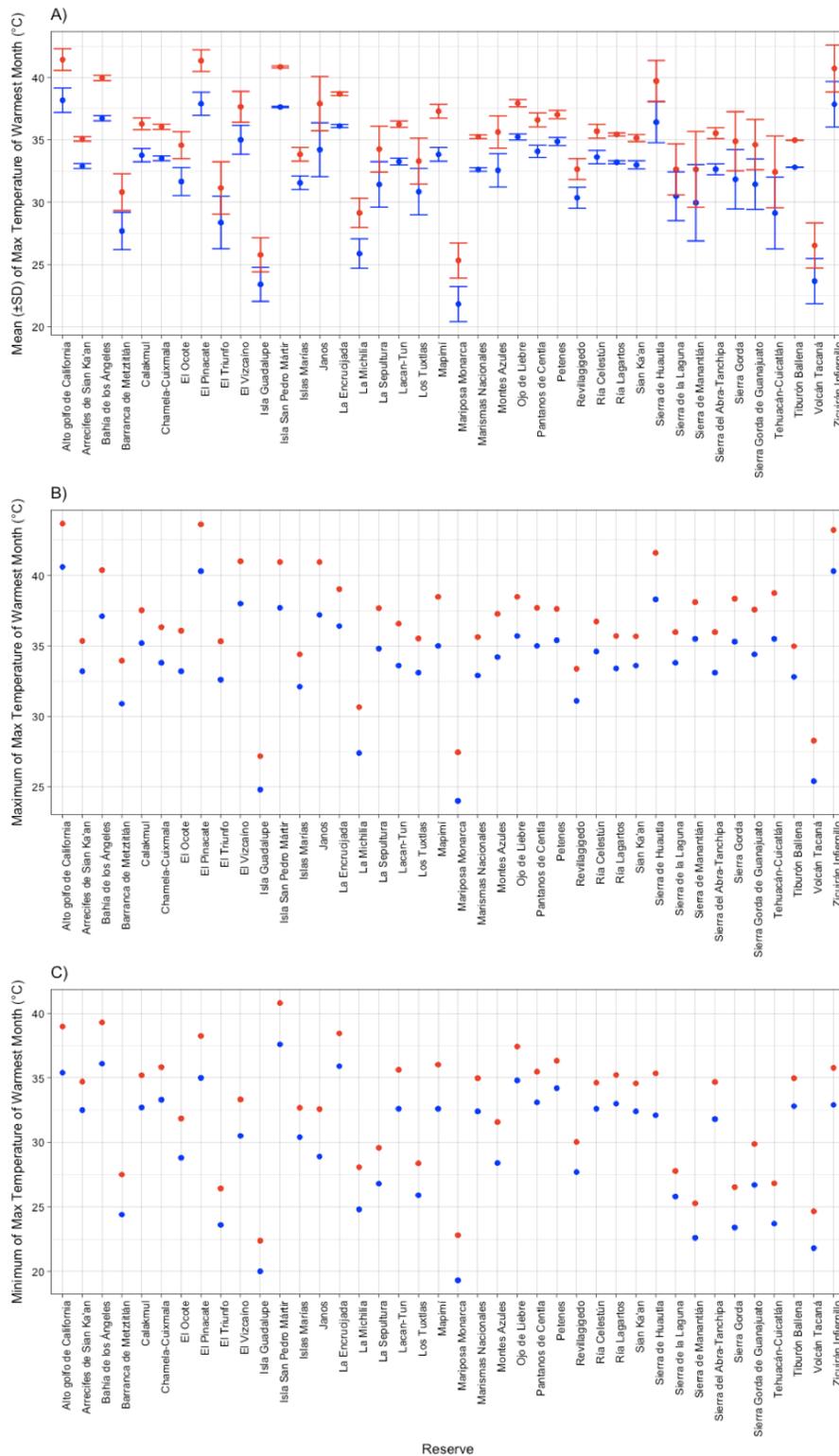


Figure A2.1. Changes in mean and standard deviation (A), maximum (B) and minimum (C) values of Max Temperature of Warmest Month (*MTWM*) comparing two time periods (blue: baseline, 1960-1990; red: future, 2050 [average for 2041-2060]) for 40 protected areas of Mexico.

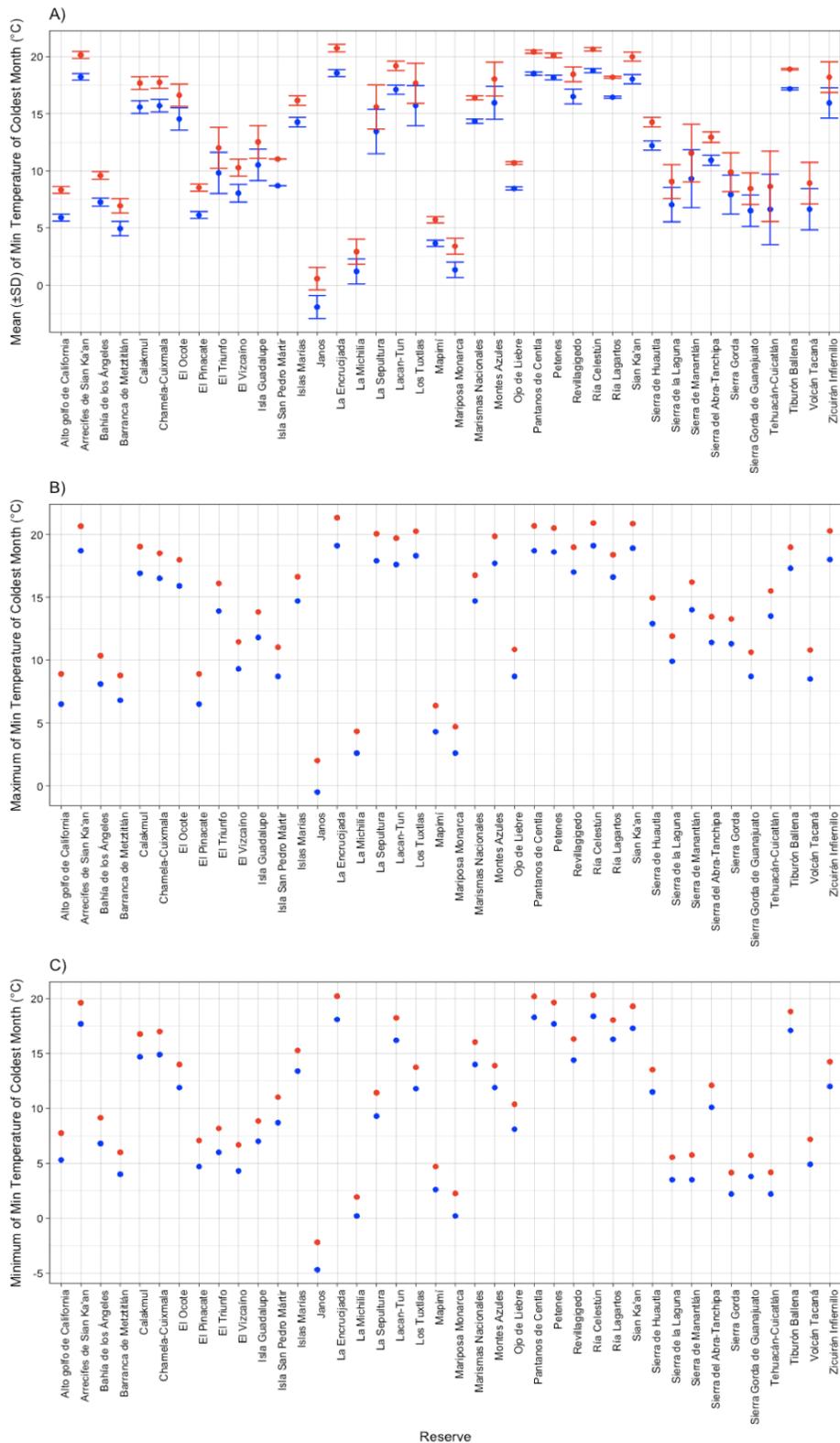


Figure A2.2. Changes in mean and standard deviation (A), maximum (B) and minimum (C) values of Min Temperature of Coldest Month (*MTCM*) comparing two time periods (blue: baseline, 1960-1990; red: future, 2050 [average for 2041-2060]) for 40 protected areas of Mexico.

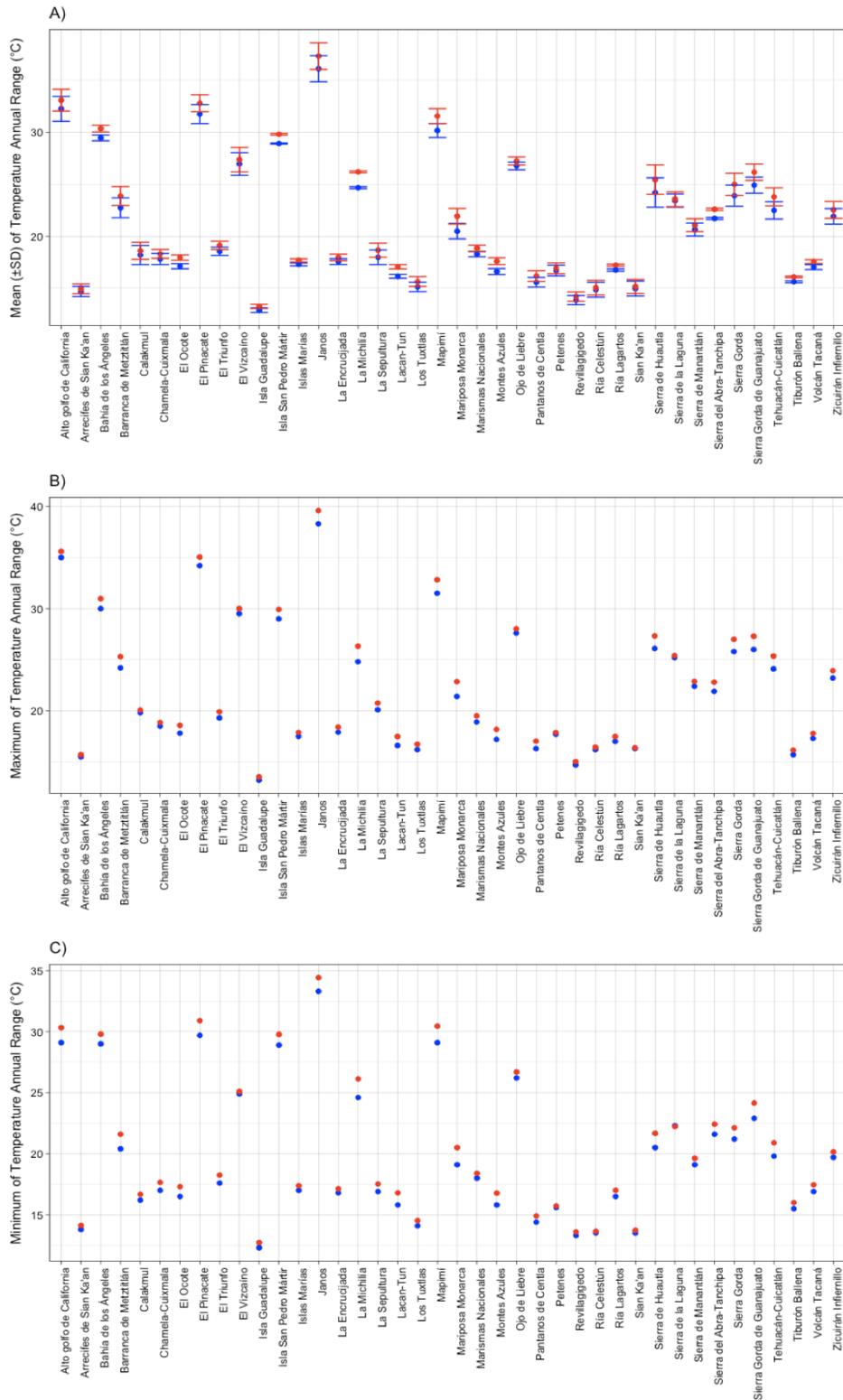


Figure A2.3. Changes in mean and standard deviation (A), maximum (B) and minimum (C) values of Temperature Annual Range (*TAN*) comparing two time periods (blue: baseline, 1960-1990; red: future, 2050 [average for 2041-2060]) for 40 protected areas of Mexico.

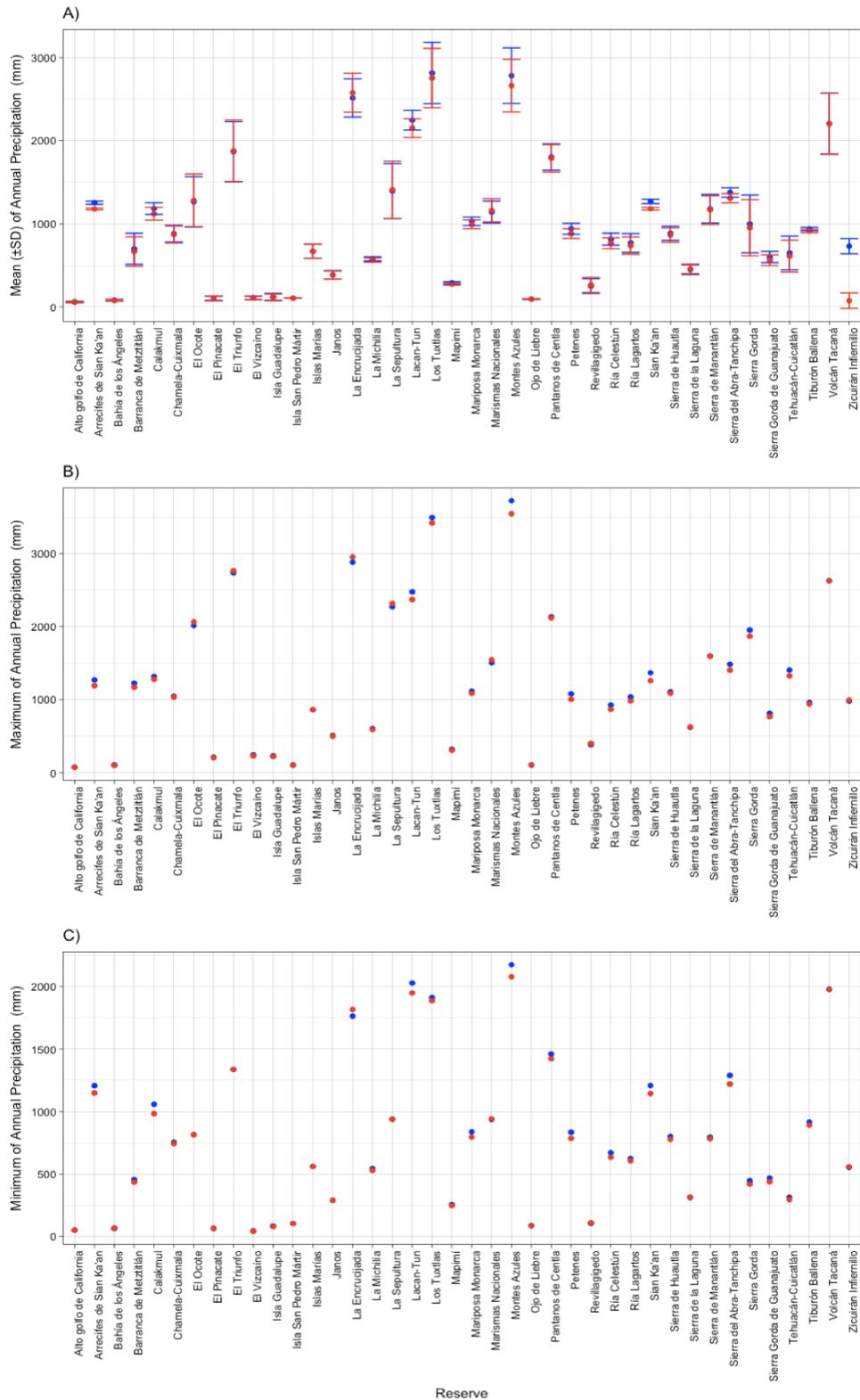


Figure A2.4. Changes in mean and standard deviation (A), maximum (B) and minimum (C) values of Annual Precipitation (AP) comparing two time periods (blue: baseline, 1960-1990; red: future, 2050 [average for 2041-2060]) for 40 protected areas of Mexico.

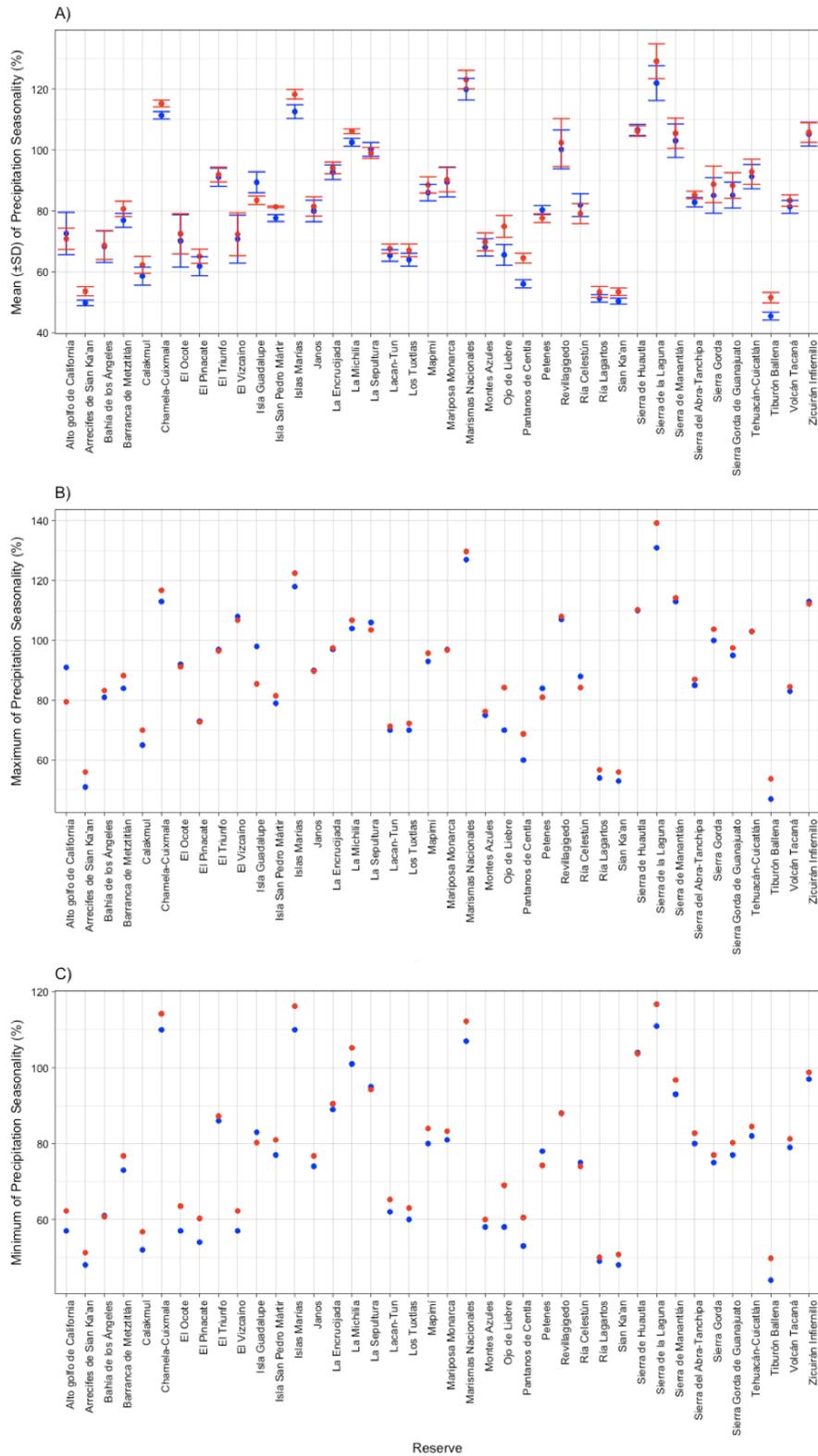


Figure A2.5. Changes in mean and standard deviation (A), maximum (B) and minimum (C) values of Precipitation Seasonality (*PS*) comparing two time periods (blue: baseline, 1960-1990; red: future, 2050 [average for 2041-2060]) for 40 protected areas of Mexico.

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 Golfo 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 (km²)	Species	V	Rank
Archipiélago 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
Bahía de los Angeles, canales de Ballenas y de Salsipuedes	108.2	80.4	0	100	100	3879.6	1256	0.67	28
Barranca de Metztitlán	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 (km²)	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 (km²)	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
Tiburón Ballena	51.0	13.8	85.2	14.80	4.49	1459.9	334	0.38	40
Volcán Tacaná	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 \pm 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

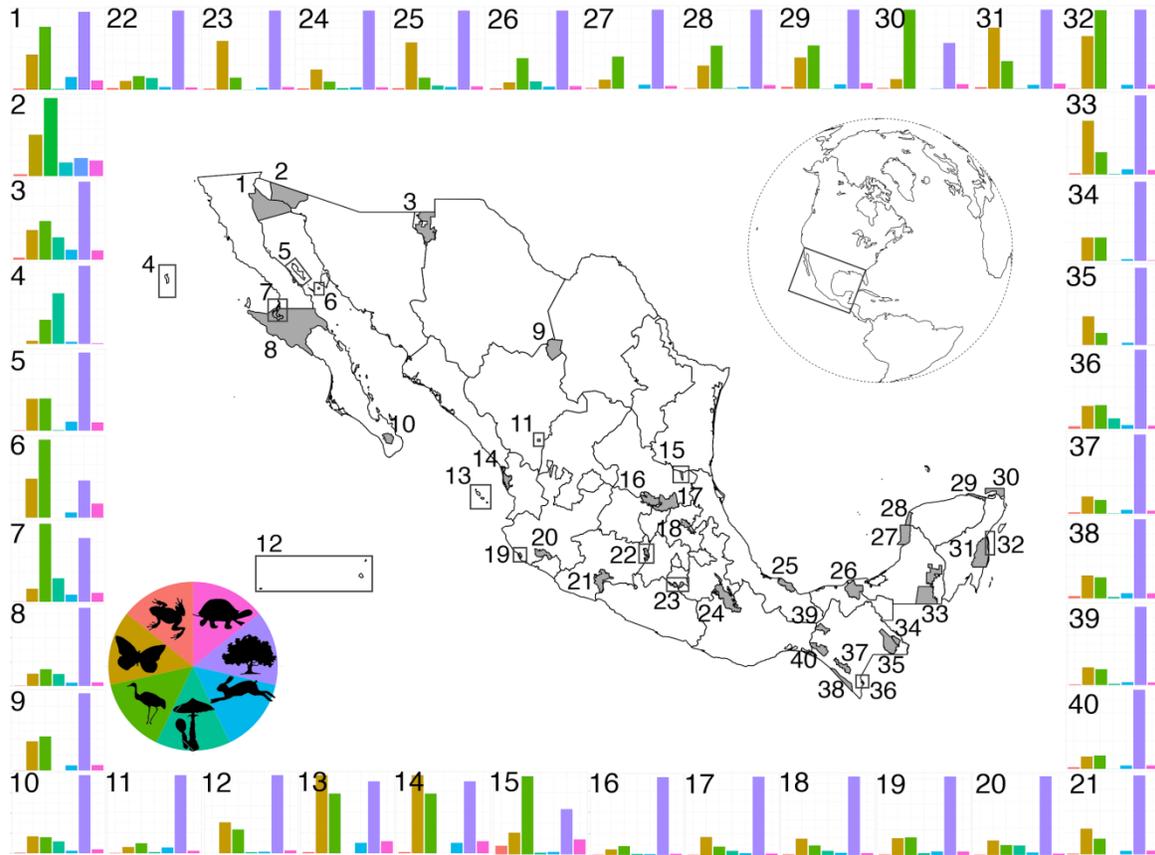


Figure A4. Location of the 40 protected areas of Mexico and histograms indicating the number of species recorded of seven major taxonomic groups within three kingdoms: 1) vascular plants (Tracheophytes); 2) fungi; and 3) animals (amphibians, arthropods, birds, mammals, and reptiles) (see details on **Table 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) Bahía 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) Archipiélago 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 (Tehuacán-Cuicatlán)	0 (Archipiélago de Revillagigedo, Isla Guadalupe, Isla San Pedro Mártir)
Arthropoda	383	403	1867 (Los Tuxtlas)	9 (Isla Guadalupe)
Aves	298	131	530 (Tehuacán-Cuicatlán)	44 (Isla San Pedro Mártir)
Mammalia	59	44	162 (Tehuacán-Cuicatlán)	1 (Tiburón Ballena)
Reptilia	56	38	161 (Tehuacán-Cuicatlán)	2 (Isla Guadalupe)
Fungi	64	89	366 (Sierra de Manantlán)	0 (Arrecifes de Sian Ka'an, Isla San Pedro Mártir, Islas Marías, Mapimí, Marismas Nacionales, los Petenes, Tiburón Ballena, Zicuirán Infiernillo)
Tracheophyte	1267	1168	5161 (Tehuacán-Cuicatlán)	21 (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 Metztlán	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 El Vizcaíno										
Reserva de la Biosfera Janos	Chihuahua	1427	15,744	16	223	290	75	70	168	585
Reserva de la Biósfera La Encrucijad a	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 ElOcate										
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