Predicting the potential distribution of the endemic seabird *Pelecanus thagus* in the Humboldt Current Large Marine Ecosystem under different climate change scenarios

Jaime A. Cursach[1], A. Arriagada[2], Jaime R. Rau[3], Jaime Ojeda[4,5,6], Gustavo Bizama[7] and Anderson Becerra[8]

[1]Programa de Doctorado en Ciencias mención Manejo y Conservación de Recursos Naturales, Universidad de Los Lagos, Puerto Montt, Chile. *jcurval@gmail.com

[2]Litoral Austral Ltda., Puerto Montt, Chile.

[3]Laboratorio de Ecología, Departamento de Ciencias Biológicas & Biodiversidad, Universidad de Los Lagos, Casilla 933, Osorno, Chile.

[4]Laboratorio de Ecosistemas Marinos Antárticos y Subantárticos (LEMAS), Universidad de Magallanes, Punta Arenas, Chile.

[5]School of Environmental Studies, University of Victoria, Victoria, British Colombia, Canada.

[6]Instituto de Ecología y Biodiversidad (IEB), Santiago, Chile.

[7]Facultad de Ciencias, Universidad de Chile, Santiago, Chile.

[8]Programa de Master en Ciencias y Tecnología Espacial, Escuela de Ingeniería, Universidad del País Vasco, Bilbao, España.

Corresponding Author: Jaime A. Cursach, Programa de Doctorado en Ciencias, Escuela de Postgrado, Universidad de Los Lagos, Puerto Montt, Chile. *jcurval@gmail.com

ABSTRACT

Background. The effects of global climate change on species inhabiting marine ecosystems are of growing concern, especially for endemic species that are sensitive due to restricted distribution. One method employed for determining the effects of climate change on the distribution of these organisms is species distribution modeling.

Methods. We generated a model to evaluate the potential geographic distribution and breeding distribution of the Peruvian pelican (*Pelecanus thagus*). Based on maximum entropy modeling (MaxEnt), we identified the environmental factors that currently affect its geographic distribution and breeding. Then we predicted its future distribution range under two climate change scenarios: moderate (rcp 2.6) and severe (rcp 8.5).

33 **Results.** The mean daytime temperature range and marine primary productivity explain the
34 current potential distribution and breeding of the pelican. Under the future climate change
35 scenarios, the spatial distribution of the pelican is predicted to slightly change. While, the
36 breeding distribution of the pelican can be benefited in the moderate scenario, but is predicted to
37 decrease (near −20 %) in the severe scenario.

38 **Discussion.** The current potential geographic distribution of the pelican is influenced to a large
39 extent by thermal conditions and primary productivity. Under the moderate scenario, a slight
40 increase in pelican breeding distribution is predicted. This increase in habitable area is explained
41 by the climatic conditions in southern Chile, and those climatic conditions will likely be similar
42 to the current conditions of the central coast of Chile. We predict that the coasts of southern
43 Chile will constitute an important refuge for the conservation of the Peruvian pelican under
44 future climate change scenarios.

45 **Subjects:** Biogeography, Conservation Biology, Marine Biology, Natural Resource Management

46 **Keywords:** Conservation, MaxEnt, South America.

47

48 Introduction

49 Climate change is of increasing concern for seabirds because it negatively affects their
50 conservation status and has become the third most important threat after exotic invasive species
51 and incidental capture (Croxall et al., 2012). In turn, a great proportion of seabirds (e.g., of the
52 Humboldt Current System) feed in a relatively narrow range of trophic levels, mainly on larger
53 zooplankton, small pelagic fish, or squid (Quillfeldt & Masello, 2013). Most of the prey species
54 consumed by seabirds are strongly affected by climate-induced changes on the productivity of
55 phytoplankton, generating changes in both the abundance and fecundity of herbivorous
56 zooplankton (small copepods and euphausiids). Consequently, carnivorous zooplankton and
57 pelagic fish or squid are also affected (Crawford et al., 2008a, Crawford et al., 2008b; Wynn et
58 al., 2007; Luczak et al., 2011). The dynamics of small pelagic fish have been studied intensively
59 in the marine upwelling ecosystems such the Humboldt and Benguela currents, where the
60 collapse of small populations of pelagic fish is often followed by severe decreases in the
61 populations of seabirds (Crawford & Jahncke, 1999; Crawford et al., 2008a). Seabirds face
62 multiple imminent threats (overfishing and incidental death, pollution, introduced species,
63 habitat destruction, and human disturbance) that may seem more urgent than gradual climate
64 change and its associated climate phenomena (Croxall et al., 2012; Quillfeldt & Masello, 2013).
65 However, some of these threats are locally restricted, whereas the climate phenomena have the
66 potential to alter an entire region and increase the cumulative pressures that affect many seabirds,
67 especially endemic species (Quillfeldt & Masello, 2013; Jenouvrier et al., 2014).

68 The Peruvian pelican *Pelecanus thagus* (hereafter pelican) is a seabird endemic to the Humboldt
69 Current Large Marine Ecosystem (HCLME) of South America. The pelican's home range lies on

70   the Pacific coast from southern Ecuador, through Peru down to southern Chile (BirdLife
71   International, 2018). However, it breeding distribution is not continuous along the coast, but is
72   very localized in certain coastal islands from Santa Clara Island (3°S) in southern Ecuador, to
73   Mocha Island (38°S) in central Chile (Housse, 1945; Vinueza, Sornoza & Yañez, 2015). At the
74   global level, the pelican is classified as near threatened (BirdLife International, 2018). In Peru,
75   this species is considered endangered (MINAGRI, 2018). In Chile and Ecuador there is no
76   classification concerning its conservation status, even though the Chilean coastline comprises
77   more than 50% of pelican's habitat range (Cursach et al., 2018). Between 2010 and 2015 the
78   abundance of pelicans in Chile decreased significantly on the central coast, area encompasses the
79   main breeding population (Cursach et al., 2018).

80   Predicting the response of biodiversity to climate change has developed into an active field of
81   research (Bellard et al., 2012; Molinos et al., 2015; Pecl et al., 2017). Therefore, projections of
82   species distribution models play an important role in alerting scientists and decision makers to
83   assess the potential future risks of climate change (Pereira et al., 2010; Parmesan et al., 2011).
84   Climate change may alter the suitability of habitat and contraction of the distribution range of
85   several groups of marine and terrestrial organisms, including Southern Ocean seabirds (Marzloff
86   et al., 2016; Krüger et al., 2017). The current study aims to generate models of the potential
87   geographic distribution and breeding of the pelican, to identify the environmental factors that
88   affect its current distribution, and to predict its future distribution range under two climate
89   change scenarios (moderate and severe). Our hypothesis was that the spatial distribution and
90   breeding distribution of the pelican will decrease and that the main cause of this will be climate
91   change.

92

Materials & Methods

Species records

95   Pelican nesting and occurrence data were compiled from four main sources: the Neotropical
96   Waterbird Census (https://lac.wetlands.org/), eBird (https://ebird.org/), the Global Biodiversity
97   Information Facility (https://www.gbif.org/), and the literature. The geo-coordinates for each
98   data point were referenced from the information in the literature or through the use of
99   coordinates in Google Earth. We excluded duplicate or unclear locations and verified the
100   accuracy of the data. We found a total of 4,818 georeferenced data points referring to pelican
101   sightings (in resting place, nesting sites, coves, beaches, etc.), encompassing its entire geographic
102   distribution from 2000 to 2015. Of these records, a subsampling was performed at a distance of
103   15 km (cell size), obtaining a total of 264 records, with which the modeling was performed. This
104   subsampling were conducted in R, version 3.0.2 (R Development Core Team 2013). The
105   breeding distribution of the pelican was modeling with information for 34 nesting sites (Vinueza
106   et al., 2015; Zavalaga et al., 2015; Cursach et al., 2018).

107

Environmental variables

109 The environmental variables used to characterize the current distribution (and breeding) of the
110 pelican were selected based on climate and oceanography. The climate variables used in this
111 study were downloaded from the EcoClimate database http://www.ecoclimate.org) (Lima-
112 Ribeiro et al., 2015). These variables were represented by maximum, minimum, and mean values
113 of monthly, quarterly, and annual temperatures, and the precipitation values recorded between
114 1950 and 2000. These parameters provided a combination of means, extremes, and seasonal
115 differences in variables known to influence the distribution of species (Root et al., 2003). With
116 the species distribution modeling toolbox extension implemented in ArcGIS, all bioclimate
117 variables that showed a correlation higher than 0.7 were eliminated (Brown, 2014). Finally, six
118 climate variables were selected: annual mean temperature, mean daytime temperature range,
119 isothermality, seasonality in temperature, annual precipitation, seasonality in precipitation. The
120 oceanographic variables used were sea surface temperature (SST) and marine net primary
121 productivity (mg C m^{-2} day^{-1}), as they are considered the main descriptors of the spatial
122 distribution of seabirds (Quillfeldt et al., 2015; Ingenloff, 2017). These variables were obtained
123 from the National Oceanic and Atmospheric Administration (NOAA,
124 http://www.ngdc.noaa.gov/). For the analyses, we used mean values per climate season for a
125 period of nine years (2004 to 2013), totaling eight oceanographic variables. All environmental
126 variables used in this study were interpolated by the kriging method, with a uniform resolution of
127 0.5º x 0.5º using the QGIS 3.2.0 software (Lima-Ribeiro et al., 2015; Varela, Lima & Terribile,
128 2015).

129 To evaluate the effects of the different climate change scenarios on the spatial distribution of
130 pelicans, we did not include the oceanographic variables. The future climate scenarios
131 corresponded to those proposed by the Intergovernmental Panel on Climate Change (IPCC,
132 2014). These scenarios were obtained from the ecoClimate website (http://ecoclimate.org/),
133 which contains climate models available for different temporal intervals. To do this, we used the
134 model developed by the Community Climate System Model version 4 of the National Center for
135 Atmospheric Research (Gent et al., 2011). This is due to the good results for the South-East
136 Pacific (Larson, Pegion & Kirtman, 2018; Zheng et al., 2018).

137 The projections for the six preselected variables and the projected minimum and maximum
138 trajectories of the concentrations of greenhouse gases were obtained. That is 2.6 and 8.5 rcp
139 (representative concentration pathways), respectively. These values indicate increases in the heat
140 absorbed by the planet Earth due to the concentration of greenhouse gases up to 2010, in each
141 trajectory and expressed in watts per square meter. Thus, 2.6 rcp is the moderate projection for
142 the scenario with the least climate change; whereas, 8.5 rcp is a more pessimistic projection and
143 represents a severe scenario with the greatest climate change (Taylor, Stouffer & Meehl, 2012).

144

Modeling of the potential geographic distribution

The MaxEnt software (MaxEnt version 3.3.3k, http://www.cs.princeton.edu/~schapire/maxent/) has been frequently used for species distribution models under current and future climate scenarios (Phillips & Dudík, 2008). We used MaxEnt to model the geographic distribution of the pelican, including under two previously described climate change scenarios (Elith et al., 2006; Taylor, Stouffer & Meehl, 2012). The model was elaborated by MaxEnt auto-features (5,000 iterations). Logistic output was used for all analyses. The quality of the model was evaluated using the area under the curve (AUC) and the continuous Boyce index (Hirzel et al., 2006). AUC values can vary from 0 to 1, where a value greater than 0.9 is considered an indicator of "good" discrimination skills (Peterson et al., 2011). Values of the Boyce index vary between −1 and 1, where positive values indicate a model with predictions that are consistent with the distribution of observed presences in the evaluation dataset (Boyce, 2002). Both analyses were conducted in R using the "biomod2" package (R Development Core Team 2013).

For each distribution model, a 30-fold cross-validation was used, with a data proportion of 25% for training and 75% for evaluation. The most important environmental variables were identified by estimating the relative contribution (%) to the model (Phillips, Anderson & Schapire, 2006). Jackknife test was used to evaluate the importance of the environmental variables for predictive modeling (Almalki et al. 2015).

Results

Model yield for potential distribution

The model of presence with the best fit showed a gain of 3.04 and a Boyce Index of 0.99. Also, an $AUC_{training}$ of 0.98 and an $AUC_{evaluation}$ of 0.98 and a standard deviation of 0.004. While, the modeling of breeding distribution showed a gain of 2.24 and a Boyce Index of 0.98, with an $AUC_{training}$ of 0.98 and an $AUC_{evaluation}$ of 0.98 and a standard deviation of 0.003. The AUC values were relatively similar, so the models used are appropriate for predicting the presence and breeding distribution of the species. $AUC_{evaluation}$ 0.98 indicates that the pelican has a wide geographic distribution and breeding in relation to the area corresponding to the environmental data. The model predicts that the potential geographic distribution of the pelican reaches an approximate surface area of 466,836 km^2, latitudinally distributed from southern Ecuador (2°13′09″S) to southern Chile (46°59′07″S). Over this extensive marine–coastal surface, the probability of occurrence for this species varied between a 0.16 (minimum) and 0.84 (maximum) (Table 1). Areas with the highest probabilities of occurrence for the pelican are represented with intense red colors in Figure 1A and Figure 2A. These areas are mainly distributed from northern Peru to central Chile.

181 **Importance of environmental variables**

182 Among the six climatic variables and eight oceanographic variables, the mean daytime
183 temperature range (Bio2) and the summer marine primary productivity, contributed the most to
184 the current and potential distribution of the pelican (Table 2). These two factors explained
185 78.47% of the modeled distribution. The mean daytime temperature responded to the probability
186 of the presence of the pelican, with a high probability of finding the species in areas where the
187 mean daytime temperature ranges between 6 and 8°C. In turn, the summer marine primary
188 productivity also influenced the probability of the presence of the pelican, with a greater
189 probability of finding the species during the summer season in areas with high primary
190 productivity. The other factors such as, spring marine primary productivity, isothermality, and
191 seasonality in temperature, contributed 9.24%, 3.23%, and 1.74%, respectively, to the modeled
192 distribution. Therefore, thermal and primary productivity conditions are more important than
193 other variables for mapping pelican distribution (Table 2).

194 The modeling of breeding distribution showed that the mean daytime temperature range
195 contributed with 91.5% to the model, while the summer marine primary productivity contributed
196 with 8.5%.

197

198 **Potential geographic distribution of the pelican as a function of climate change**

199 Based on the six climatic variables selected in the study, the model predicts that the projected
200 pelican distribution currently attains an area of 596,753 km^2 (Table 3). This area is larger than
201 that initially projected (466,836 km^2), where the oceanographic variables were integrated.
202 Regarding the projections of climate change for 2100, under the moderate scenario of 2.6 rcp a
203 slight decrease (−0.68%) in pelican spatial distribution is predicted (Table 3). Under the severe
204 scenario of 8.5 rcp, a slight increase (4.51%) in pelican spatial distribution is predicted (Table 3).

205 The projected habitable surface area under climate change of 2.6 rcp does not presents a major
206 change with respect to the current geographic distribution of the pelican (Table 3). Under the
207 severe scenario, the model predicts that the pelican habitable surface will vary depending on
208 geographic area (Fig. 1). For example, in northern Chile its habitable surface would decrease,
209 whereas in central and southern Chile it would increase over time (Fig. 2). The projected
210 habitable surface area and the probabilities of occurrence for the pelican are spatially
211 schematized in Figure 2.

212 For the case of the modeling of breeding distribution, an area of 435,640 km^2 is projected (Table
213 4). Regarding the projections of climate change for 2100, under the moderate scenario of 2.6 rcp
214 an increase (8.77%) in pelican breeding distribution is predicted (Table 4). Under the severe
215 scenario of 8.5 rcp, a decrease (−19.30%) in pelican breeding distribution is predicted (Table 4).
216 Under the severe scenario, the model predicts a decrease of occurrence probability of nesting
217 sites of the pelican in northern Ecuador and north-central Chile (Fig. 2).

218

Discussion

220 The potential geographic distribution of the pelican currently attains an approximate area of
221 466,836 km^2, distributed latitudinally from southern Ecuador (2°13′09″S) to the Taitao Peninsula
222 in southern Chile (46°59′07″S). While, the potential breeding distribution of the pelican currently
223 attains an approximate area of 435,640 km^2. The mean daytime temperature range and marine
224 primary productivity explain the current potential distribution and breeding of the pelican, which
225 is an endemic species closely associated with the oceanographic barriers of the Humboldt
226 Current Ecosystem (Jeyasingham et al., 2013; Kennedy et al., 2013). In South America, the
227 Humboldt Current encompasses the greater part of the Pacific coast. Despite the wide latitudinal
228 gradient, the marine–coastal area exhibits a mean daytime temperature range between 4°C and
229 8°C. This is consistent with the highest probability of occurrence of the pelican
230 (https://climatologia.meteochile.gob.cl/application/). In turn, marine productivity is the main
231 predictor of biodiversity and especially of the presence of top predators such as seabirds
232 (Wakefield, Phillips & Matthiopoulus, 2009). In the case of the pelican, there is an overlap
233 between areas with high summer marine primary productivity and areas with nesting sites.

234 Under the future climate change scenarios, the spatial distribution of the pelican is predicted to
235 slightly change. The pelican's breeding distribution might be facilitated by the moderate
236 scenario, increasing near 9 %. However, under the severe scenario, the prediction decreased to
237 near −20 %. This trend is similar to other studies described for seabirds, whose breeding
238 distribution will be reduced by climate change (Jenouvrier et al., 2014; Krüger et al., 2017). This
239 increase in habitable area is explained by the climatic conditions in southern Chile, and those
240 climatic conditions will likely be similar to the current conditions of the central coast of Chile
241 (Falvey & Garreaud, 2009; Garreaud, 2011). Over the last decade, an increase in pelican
242 abundance has been reported along the coast of southern Chile, with observations of large flocks
243 following schools of pelagic fishes in the inner sea (Imberti, 2005; Häusserman, Forsterra &
244 Plotnek, 2012; Cursach, Rau & Vilugrón, 2016; Cursach et al., 2018). In this area, there has even
245 been one report of an unsuccessful attempt to nest (Cursach, Rau & Vilugrón, 2016). The
246 occurrence of competitive interactions with other seabirds has also been observed with endemic
247 species from Patagonia (Cursach, Rau & Vilugrón, 2016). In southern Chile, a group of pelicans
248 was observed displacing nesting pairs of Imperial shag (*Phalacrocorax atriceps*), causing the
249 abandonment of the nest (Cursach, Rau & Vilugrón, 2016).

250 The present study is one of only a few evaluations of the potential effects of climate change on
251 seabirds on the Pacific coast of South America. To evaluate the different scenarios caused by
252 climate change on the spatial distribution of the pelican, we did not include oceanographic
253 variables. This is because the climatic variable "Mean daytime temperature range" was what
254 largely explained the potential spatial distribution and breeding of the pelican. However, further
255 studies are required to assess the effects of climate change on seabird populations, including

256 oceanographic variables. In addition, it is important to recognize that the species spatial
257 distribution models have methodological constraints, including operating based on climatic
258 variables without integrating ecological interactions (Soberón, Osorio-Olvera & Peterson, 2017).
259 The co-occurrence of fishing exploitation and El Niño events generates synergistic ecological
260 effects that may push the pelican to critical levels of abundance (Passuni et al., 2016; Barbraud et
261 al., 2018). In addition, the human disturbances on nesting sites are a key factor in the pelican
262 population dynamics (Coker, 1919; Figueroa & Stucchi, 2012). Future modeling analyses should
263 include field data about fishing, aquaculture, ENSO events, and human disturbances in nesting
264 sites of the pelican.

265 In conclusion, the current potential geographic distribution of the pelican is influenced to a large
266 extent by thermal conditions and primary productivity. Under the future climate change
267 scenarios, the spatial distribution of the pelican is predicted to slightly change. While the range
268 of breeding distribution of the pelican will be decrease by main cause of climate change. Under a
269 moderate scenario, we predict that the coasts of southern Chile will constitute an important
270 refuge for the conservation of the pelican. It is necessary that future investigations evaluate in
271 detail the ecological interactions of the pelican and its population increase in southern Chile,
272 considering the different dimensions of the local socio-ecological system.

273

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278

References

280 **Almalki M, M Alrashidi, M O'Connell, M Shobrak, T Szekely. 2015.** Modelling the
281 distribution of wetland birds on the Red Sea coast in the Kingdom of Saudi Arabia. Applied
282 Ecology and Environmental Research 13: 67−84 DOI 10.15666/aeer/1301_067084.

283 **Barbraud C, Bertrand A, Bouchón M, Chaigneau A, Delord K, Demarcq H, Gimenez O,**
284 **Gutiérrez-Torero M, Gutiérrez D, Oliveros-Ramos R, Passuni G, Tremblay Y, Bertrand S.**
285 **2018.** Density dependence, prey accessibility and prey depletion by fisheries drive Peruvian
286 seabird population dynamics. *Ecography* **41**: 1092−1102 DOI 10.1111/ecog.02485.

287 **Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F. 2012.** Impacts of climate
288 change on the future of biodiversity. *Ecology letters* **15**: 365−377 DOI 10.1111/j.1461-
289 0248.2011.01736.x

290 **BirdLife International. 2018.** Species factsheet: Pelecanus thagus. *Available at*
291 *http://www.birdlife.org.*

292 **Boyce MS. 2002.** Relating populations to habitats using resource selection functions. *Ecological*
293 *Modelling* **157**: 281–300 DOI 10.1016/S0169-5347(99)01593-1.

294 **Brown JL. 2014.** SDMtoolbox: A Python-Based GIS Toolkit for Landscape Genetic,
295 Biogeographic and Species Distribution Model Analyses. *Methods in Ecology and Evolution* **5**:
296 694–700 DOI 10.1111/2041-210X.12200.

297 **Castillo AG, Alò D, González BA, Samaniego H. 2018.** Change of niche in guanaco (*Lama*
298 *guanicoe*): the effects of climate change on habitat suitability and lineage conservatism in Chile.
299 *PeerJ* **6**: e4907 DOI 10.7717/peerj.4907.

300 **Coker RE. 1919.** Habits and economic relations of the guano birds of Peru. *Proceedings U.S.*
301 *National Museum* 56: 449–529.

302 **Crawford RJM, Jahncke J. 1999.** Comparison of trends in abundance of guano-producing
303 seabirds in Peru and southern Africa. *South African Journal of Marine Science* **21**: 145−156 DOI
304 10.2989/025776199784126006.

305 **Crawford RJM, Sabarros PS, Fairweather T, Underhill LG, Wolfaardt AC. 2008a.**
306 Implications for seabirds of a longterm change in the distribution of sardine: A South African
307 experience. *African Journal of Marine Science* **30**: 177−184.

308 **Crawford RJM, Tree AJ, Whittington PA, Visagie J, Upfold L, Roxburg KJ, Martin AP,**
309 **Dyer BM. 2008b**. Recent distributional changes of seabirds in South Africa: Is climate having an
310 impact?. *African Journal of Marine Science* **30**: 189−193 DOI 10.2989/AJMS.2008.30.1.20.470.

311 **Croxall JP, Butchart SHM, Lascelles B, Stattersfield AJ, Sullivan B, Symes A, Taylor P.**
312 **2012.** Seabird conservation status, threats and priority actions: A global assessment. *Bird*
313 *Conservation International* **22**: 1−34 DOI 10.1017/S0959270912000020.

314 **Cursach JA, Rau JR, Vilugrón J. 2016.** Presence of the Peruvian pelican (*Pelecanus thagus*) in
315 seabird colonies of Chilean Patagonia. *Marine Ornithology* **44**: 27−30.

316 **Cursach JA, Rau JR, Gelcich S, Rodríguez-Maulén J. 2018.** Situación poblacional del
317 Pelícano Peruano (*Pelecanus thagus*) en Chile: prospección inicial. *Ornitología Neotropical* **29**:
318 77−89.

319 **Elith J, Graham CH, Anderson RP, Dudk M, Ferrier S, Guisan A, Hijmans RJ,**
320 **Huettmann F, Leathwick JR, Lehmann A, Li J, Lohmann LG, Loiselle BA, Manion G,**
321 **Moritz C, Nakamura M, Nakazawa Y, Overton JM, Peterson AT, Phillips SJ, Richardson**
322 **K, Scachetti-Pereira, Ricardo S, Schapire RE, Soberon J, Williams S, Wisz MS,**
323 **Zimmermann NE. 2006.** Novel methods improve prediction of species' distributions from
324 occurrence data. *Ecography* **29**: 129−151. DOI 10.1111/j.2006.0906-7590.04596.x.

325 **Falvey M, Garreaud RD. 2009.** Regional cooling in a warming world: Recent temperature
326 trends in the southeast Pacific and along the west coast of subtropical South America (1979-
327 2006). *Journal of Geophysical Research* **114**: D04102 DOI 10.1029/2008JD10519.

328 **Figueroa J, Stucchi M. 2012.** Isla Foca (Perú): Registros de reproducción más septentrionales
329 del pelícano (*Pelecanus thagus*) y del pilpilén negro (*Haematopus ater*). *Boletín Chileno de*
330 *Ornitología* 18: 35−43.

331 **Garreaud R. 2011.** Cambio climático: bases físicas e impactos en Chile. Revista Tierra Adentro
332 - INIA **93**: 13−19.

333 **Gent PR, Danabasoglu G, Donner LJ, Holland MM, Hunke EC, Jayne SR, Lawrence DW,**
334 **Neale RB, Rasch PJ, Vertenstein M, Worley PH. 2011.** The community climate system model
335 version 4. *Journal of Climate* **24**: 4973−4991 DOI 10.1175/2011JCLI4083.1.

336 **Häussermann V, Forsterra G, Plotnek E. 2012.** Sightings of marine mammals and birds in the
337 Comau Fjord, Northern Patagonia, between 2003 and mid 2012 (Mammalia; Aves). *Spixiana* **35**:
338 247−262.

339 **Hirzel AH, Le Lay G, Helfer V, Randin C, Guisan A. 2006.** Evaluating the ability of habitat
340 suitability models to predict species presences. *Ecological Modelling* **199**: 142–152 DOI
341 10.1016/j.ecolmodel.2006.05.017.

342 **Housse R. 1945.** *Las aves de Chile en su clasificación moderna, su vida y costumbres*. Santiago:
343 Ediciones de la Universidad de Chile.

344 **Imberti S. 2005.** Distribución otoñal de aves marinas y terrestres en los canales Chilenos. *Anales*
345 *del Instituto de la Patagonia* **33**: 21−30.

346 **Ingenloff K. 2017**. Biologically informed ecological niche models for an example pelagic,
347 highly mobile species. *European Journal of Ecology* 3: 55−75 DOI 10.1515/eje-2017-0006.

348 **Intergovernamental Panel of Climate Change. 2014.** *Climate Change 2014: Impacts,*
349 *Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Cambridge: Contribution of
350 Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate
351 Change. Cambridge and New York: Cambridge University Press.

352 **Jenouvrier S, Holland M, Stroeve J, Serreze M, Barbraud C, Weimerskirch H, Caswell H.**
353 **2014.** Projected continent-wide declines of the emperor penguin under climate change. *Nature*
354 *Climate Change* **4**: 715−718 DOI 10.1038/NCLIMATE2280.

355 **Jeyasingham WS, Taylor SA, Zavalaga CB, Simeone A, Friesen VL. 2013.** Specialization to
356 cold-water upwellings may facilitate gene flow in seabirds: new evidence from the Peruvian
357 pelican *Pelecanus thagus* (Pelecaniformes: Pelecanidae). *Journal of Avian Biology* **44**: 297−304.

358 **Kennedy M, Taylor SA, Nádvorník P, Spencer HG. 2013.** The phylogenetic relationships of
359 the extant pelicans inferred from DNA sequence data. *Molecular Phylogenetics and Evolution*
360 **66**: 215−222 DOI 10.1016/j.ympev.2012.09.034.

361 **Krüger L, Ramos JA, Xavier JC, Gremillet D, González-Solís J, Petry MV, Phillips RA,**
362 **Wanless RM, Paiva VH. 2018.** Projected distributions of Southern Ocean albatrosses, petrels
363 and fisheries as a consequence of climatic change. *Ecography* 41: 195−208 DOI
364 10.1111/ecog.02590.

365 **Larson SM, Pegion KV, Kirtman BP. 2018**. The South Pacific Meridional Mode as a thermally
366 driven source of ENSO amplitude modulation and uncertainty. *Journal of Climate* **31**:
367 5127−5145 DOI 10.1175/JCLI-D-17-0722.1.

368 **Lima-Ribeiro MS, Varela S, González-Hernández J, Oliveira G, Diniz-Filho JA, Terribile
369 LC. 2015.** ecoClimate: a database of climate data from multiple models for past, present, and
370 future for macroecologists and biogeographers. *Biodiversity Informatics* **10**: 1−21 DOI
371 10.17161/bi.v10i0.4955.

372 **Luczak C, Beaugrand G, Jafré M & Lenoir S. 2011.** Climate change impact on Balearic
373 shearwater through a trophic cascade. *Biology Letters* **7**: 702−705 DOI 10.1098/rsbl.2011.0225.

374 **Marzloff MP, Melbourne-Thomas J, Hamon KG, Hoshino E, Jennings S, Van Putten IE,
375 Pecl GT. 2016.** Modelling marine community responses to climate-driven species redistribution
376 to guide monitoring and adaptive ecosystem-based management. *Global Change Biology* 22:
377 2462−2474 DOI: 10.1111/gcb.13285.

378 **Molinos JG, Halpern BS, Schoeman DS, Brown CJ, Kiessling W, Moore PJ, Pandolfi JM,
379 Poloczanska ES, Richardson AJ & Burrows MT. 2015.** Climate velocity and the future global
380 redistribution of marine biodiversity. *Nature Climate Change* **6**: 83-88 DOI:
381 10.1038/NCLIMATE2769.

382 **MINAGRI. 2014.** *Decreto Supremo que aprueba la actualización de la lista de clasificación y
383 categorización de las especies amenazadas de fauna silvestre legalmente protegidas (D.S. N°
384 004−2014).* Lima: Ministerio de Agricultura y Riego, Gobierno del Perú.

385 **Montecino V, Pizarro G. 2006.** Productividad primaria, biomasa y tamaño del fitoplancton en
386 canales y fiordos australes: patrones primavera-verano. In: Silva N, Palma S, eds. *Avances en el
387 conocimiento oceanográfico de las aguas interiores chilenas, Puerto Montt a cabo de Hornos.*
388 Valparaíso: Comité Oceanográfico Nacional, 93−97.

389 **Parmesan C, Duarte CM, Poloczanska E, Richardson AJ, Singer MC. 2011.** Overstretching
390 attribution. *Nature Climate Change* **1**: 2−4 DOI 10.1038/nclimate1056.

391 **Passuni G, Barbraud C, Chaigneau A, Demarcq H, Ledesma J, Bertrand A, Castillo R,
392 Perea A, Mori J, Viblanc V, Torres-Maita J, Bertrand S. 2016.** Seasonality in marine
393 ecosystems: Peruvian seabirds, anchovy, and oceanographic conditions. *Ecology* **97**: 182−193
394 DOI 10.1890/14-1134.1.

395 **Pecl GT, Araujo MB, Bell J, Blanchard J, Bonebrake TC, Chen I, Clark TD, Colwell RK,
396 Danielsen F, Evengard B, Falconi L, Ferrier S, Frusher S, García RA, Griffis RB, Hobday
397 AJ, Janion-Scheepers C, Jarzyna MA, Jennings S, Lenoir J, Linnetved HI, Martin VY,
398 McCormack PC, McDonald J, Mitchell NJ, Mustonen T, Pandolfi JM, Pettorelli N, Popova
399 E, Sharon A. Robinson SA, Scheffers BR, Shaw JD, Sorte CJ, Strugnell JM, Sunday JM,
400 Tuanmu M, Vergés A, Villanueva C, Wernberg T, Wapstra E, Williams SE. 2017**.
401 Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being.
402 *Science* **355** DOI: 10.1126/science.aai9214.

403 **Peterson AT, Soberón J, Pearson RG, Anderson RP, Martinez-Meyer E, Nakamura M,**
404 **Araujo MB. 2011.** *Ecological niches and geographic distributions*. Princeton: Princeton
405 University Press.

406 **Pereira HM, Leadley PW, Proenca V, Alkemade R, Scharlemann JPW, Fernandez-**
407 **Manjarres JF, Araujo MB, Balvanera P, Biggs R, Cheung WWL, Chini L, Cooper HD,**
408 **Gilman EL, Guenette S, Hurtt GC, Huntington HP, Mace GM, Oberdorff T, Revenga C,**
409 **Rodrigues P, Scholes RJ, Sumaila UR, Walpole M. 2010.** Scenarios for Global Biodiversity in
410 the 21st Century. *Science* 330: 1496–1501 DOI 10.1126/science.1196624.

411 **Phillips SJ, Anderson RP, Schapire RE. 2006.** Maximum entropy modeling of species
412 geographic distributions. *Ecological Modelling* 190: 231–259 DOI
413 10.1016/j.ecolmodel.2005.03.026.

414 **Phillips S, Dudík M. 2008.** Modeling of species distributions with Maxent: New extensions and
415 a comprehensive evaluation. *Ecography* **31**: 161–175 DOI 10.1111/j.0906-7590.2008.5203.x.

416 **Quillfeldt P, Masello JF. 2013.** Impacts of climate variation and potential effects of climate
417 change on South American seabirds – a review. *Marine Biology Research* **9**: 337−357 DOI
418 10.1080/17451000.2012.756982.

419 **Quillfeldt P, Cherel Y, Delord K, Weimerkirch H. 2015.** Cool, cold or colder? Spatial
420 segregation of prions and blue petrels is explained by differences in preferred sea surface
421 temperatures. *Biology letters* **11**: 20141090 DOI 10.1098/rsbl.2014.1090

422 **R Development Core Team. 2013.** R: a language and environment for statistical computing.
423 Vienna: R Foundation for Statistical Computing. Available at http://www.Rproject.org.

424 **Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA. 2003.** Fingerprints of
425 global warming on wild animals and plants. *Nature* **421**: 57−60 DOI 10.1038/nature01333.

426 **Soberón J, Osorio-Olvera L, Peterson T. 2017.** Diferencias conceptuales entre modelación de
427 nichos y modelación de áreas de distribución. *Revista Mexicana de Biodiversidad* **88**: 437−441
428 DOI 10.1016/j.rmb.2017.03.011.

429 **Taylor KE, Stouffer RJ, Meehl GA. 2012.** An overview of CMIP5 and the experiment design.
430 *Bulletin of the American Meteorological Society* **93**: 485−498 DOI 10.1175/BAMS-D-11-
431 00094.1.

432 **Varela S, Lima-Ribeiro MS, Terribile LC. 2015.** A short guide to the climate variables of the
433 last glacial maximum for biogeographers. *PLOS ONE* **10**: e0129037

434 **Vinueza GS, Sornoza, F, Yáñez-Muñoz MH. 2015.** Primer registro de anidación del pelícano
435 peruano *Pelecanus thagus* (Pelecaniformes: Pelecanidae) en Ecuador. *Avances en Ciencias e*
436 *Ingenierías* **7**: B4−B6.

437 **Wakefield ED, Phillips RA, Matthiopoulos J. 2009.** Quantifying habitat use and preferences of
438 pelagic seabirds using individual movement data: a review. *Marine Ecology Progress Series*
439 **391**: 165−182 DOI 10.3354/meps08203.

440   **Wynn RB, Josey SA, Martin AP, Johns DG, Yésou P. 2007.** Climate-driven range expansion
441   of a critically endangered top predator in northeast Atlantic waters. *Biology Letters* **3**: 529−532
442   DOI 10.3354/meps08203.

443   **Zavalaga CB. 2015.** *Índices para el inicio y cierre de las campañas de extracción de guano en*
444   *la RNSIIPG (Especial atención a los aspectos reproductivos de las tres especies de aves*
445   *guaneras y considerando como caso de estudio a la Isla Guañape Sur)*. Lima: Informe técnico
446   Proyecto GEF Humboldt–UNDP.

447   **Zheng J, Wang F, Alexander MA, Wang M. 2018.** Impact of South Pacific Subtropical Dipole
448   Mode on the Equatorial Pacific. *Journal of Climate* **31**: 2197−2216 DOI 10.1175/JCLI-D-17-
449   0256.1.

Probability of occurrence ranges

Probability of occurrence ranges of the Peruvian Pelican (*Pelecanus thagus*) expressed in surface area.

1   **Table 1:**

2   **Probability of occurrence ranges of the Peruvian Pelican (*Pelecanus thagus*) expressed in**
3   **surface area.**

Potential geographic distribution		Potential reproductive distribution	
Probability of occurrence	Projected surface (km²)	Probability of occurrence	Projected surface (km²)
0.16–0.25	174,841	0.1–0.2	103,148
0.25–0.33	82,153	0.2–0.3	49,407
0.33–0.42	40,498	0.3–0.4	63,245
0.42–0.50	59,119	0.4–0.5	31,296
0.50–0.59	43,793	0.5–0.6	28,232
0.59–0.67	36,910	0.6–0.7	110,200
0.67–0.76	18,950	0.7–0.8	88,326
0.76–0.84	10,572	0.8–0.9	0
Total	**466,836**	**Total**	**473,854**

Environmental variables to the current potential distribution

Contribution of environmental variables to the current potential distribution model of the Peruvian pelican (*Pelecanus thagus*)

Table 2:

Contribution of environmental variables to the current potential distribution model of the Peruvian pelican (*Pelecanus thagus*).

Variable	Contribution to the model (%)	Importance in permutation (%)
Mean daytime temperature range	46.03	12.28
Summer marine Primary productivity	32.44	1.26
Spring marine Primary productivity	9.24	41.20
Isothermality	3.23	0.02
Seasonality in temperature	1.74	0.61
Sea surface temperature in winter	1.47	0.90
Sea surface temperature in spring	1.20	0.44
Sea surface temperature in summer	1.12	20.21
Seasonality of precipitation	1.10	11.54
Mean annual temperature	1.02	2.68
Annual precipitation	0.83	1.10
Fall marine Primary productivity	0.41	3.35
Sea surface temperature in fall	0.11	4.34
Winter marine Primary productivity	0	0

Probability of occurrence ranges of the Peruvian pelican

Probability of occurrence ranges of the Peruvian pelican (*Pelecanus thagus*) expressed in surface area, and those projected to 2100 under two climate change scenarios

1 **Table 3:**

2 **Probability of occurrence ranges of the Peruvian pelican (*Pelecanus thagus*) expressed in**
3 **surface area, and those projected to 2100 under two climate change scenarios.**

Probability of occurrence	Projected surface (km²)	2.6 rcp scenario		8.5 rcp scenario	
		km²	Delta (km²)	km²	Delta (km²)
0.089–0.17	111,147	115,583	4,436	160,747	49,600
0.17–0.26	109,380	92,394	−16,986	99,147	−10,233
0.26–0.35	80,529	77,101	−3,428	63,727	−16,802
0.35–0.44	58,849	62,374	3,525	53,352	−5,497
0.44–0.53	92,290	79,882	−12,408	62,344	−29,946
0.53–0.62	50,623	55,252	4,629	71,301	20,678
0.62–0.71	44,424	47,008	2,584	36,534	−7,890
0.71–0.80	32,837	35,903	3,066	55,481	22,644
0.80–0.89	16,674	27,161	10,487	21,059	4,385
TOTAL	**596,753**	**592,657**	**−4,096**	**623,692**	**26,939**

Probability of occurrence ranges of nesting sites

Probability of occurrence ranges of nesting sites of the Peruvian pelican (*Pelecanus thagus*) expressed in surface area, and those projected to 2100 under two climate change scenarios

1 **Table 4:**

2 **Probability of occurrence ranges of nesting sites of the Peruvian pelican (*Pelecanus thagus*)**
3 **expressed in surface area, and those projected to 2100 under two climate change scenarios.**

Probability of occurrence	Projected surface (km²)	2.6 rcp scenario		8.5 rcp scenario	
		km²	Delta (km²)	km²	Delta (km²)
0.1–0.2	75,037	103,148	28,111	88,676	13639
0.2–0.3	61,766	49,407	−12,359	37,961	−23805
0.3–0.4	51,566	63,245	11,679	55,694	4128
0.4–0.5	28,432	31,296	2,864	41,435	13003
0.5–0.6	61,167	28,232	−32,935	30,496	−30671
0.6–0.7	102,422	110,200	7,778	86,676	−15746
0.7–0.8	55,250	88,326	33,076	10,622	−44628
TOTAL	**435,640**	**473,854**	**38,214**	**351560**	**−84080**

Figure 1

Models of potential geographic distribution of the Peruvian pelican

Models of potential geographic distribution of the Peruvian pelican (*P. thagus*) based on climatic variables and projected for 2010 according to two climate change scenarios. Where, A= projection of current geographic distribution; B= projection at 2.6 rcp; C= projection at 8.5 rcp. The arrows show relative change to the current distribution
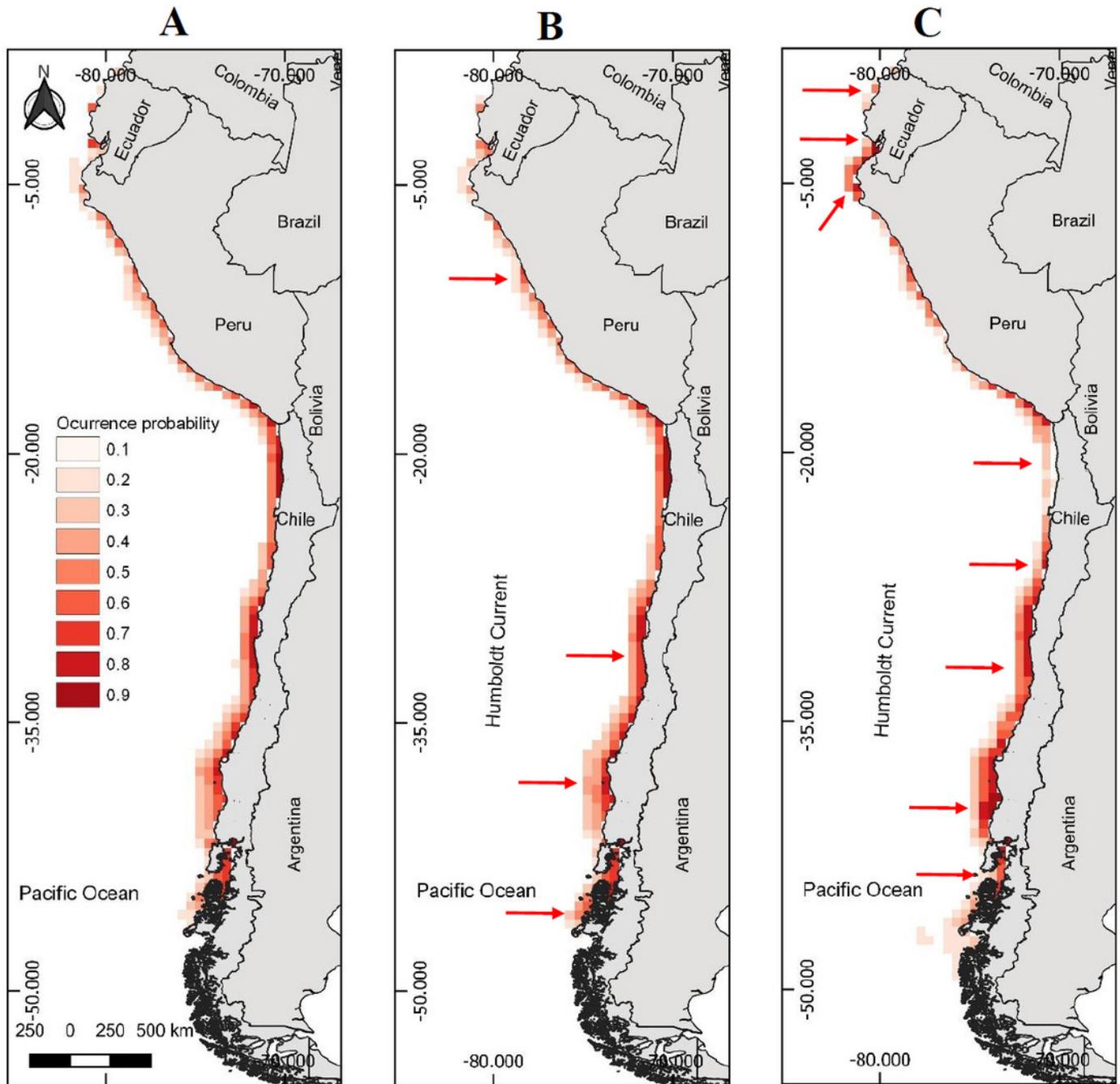
Figure 2

Models of potential reproductive distribution of the Peruvian pelican

Models of potential reproductive distribution of the Peruvian pelican (*P. thagus*) based on climatic variables and projected for 2010 according to two climate change scenarios. Where, A= projection of current reproductive distribution; B= projection at 2.6 rcp; C= projection at 8.5 rcp. The arrows show relative change to the current distribution

A

B

C

Occurrence probability

0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9