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

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

Results. The most important environmental variables in the model were the range of mean daytime temperature and the marine primary productivity in the summer. Under the future climate change scenarios, the spatial distribution of the pelican is predicted to slightly change. The severe scenario predicts that the habitable surface will be 4.51% higher than that of the current distribution.

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

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

Keywords: Conservation, MaxEnt, South America.

Introduction

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

The Peruvian pelican *Pelecanus thagus* (hereafter pelican) is a seabird endemic to the Humboldt Current Large Marine Ecosystem (HCLME) of South America. The pelican's home range lies on the Pacific coast from southern Ecuador, through Peru down to southern Chile (BirdLife International, 2018). However, its reproductive distribution is more limited, ranging from Santa Clara Island (3°S) in southern Ecuador, to Mocha Island (38°S) in central Chile (Housse, 1945; Vinueza, Sornoza & Yañez, 2015). At the global level, the pelican is classified as near threatened (BirdLife International, 2018). In Peru, this species is considered endangered (MINAGRI, 2018). In Chile and Ecuador there is no classification concerning its conservation status, even though the Chilean coastline comprises more

Comentado [GL-J1]: Please specify that this is mostly valid for South Americcan seabirds, and mostly for seabirds inhabiting the Humboldt Current System.

Comentado [GL-J2]: Please adds some relevants references, e.g.:
Jenouvrier, S., Holland, M., Stroeve, J., Serreze, M., Barbraud, C., Weimerskirch, H., & Caswell, H. (2014). Projected continent-wide declines of the emperor penguin under climate change. *Nature Climate Change*, *4*(8), 715.

Cristofari, R., Liu, X., Bonadonna, F., Cherel, Y., Pistorius, P., Le Maho, Y., ... & Trucchi, E. (2018). Climate-driven range shifts of the king penguin in a fragmented ecosystem. *Nature Climate Change*, *8*(3), 245.

Comentado [GL-J3]: Please clarify that this "geographical breding range" it is not continus along the coast, but is very localized in certain coastal islands than 50% of pelican's habitat range (Cursach et al., 2018). Between 2010 and 2015 the abundance of pelicans in Chile decreased significantly on the central coast (Cursach et al., 2018). Currently, this area encompasses the main reproductive population; thus, evaluating its conservation status in Chilean waters is urgent (Cursach et al., 2018).

Predicting the response of the biodiversity to climate change has developed into an active field of research (Bellard et al., 2012). Therefore, projections of species distribution models play an important role in alerting scientists and decision makers to assess the potential future risks of climate change (Pereira et al., 2010; Parmesan et al., 2011). The current study aims to generate a model of the potential geographic distribution of the pelican, to identify the environmental factors that affect its current distribution, and to predict its future distribution range under two climate change scenarios (moderate and severe). Our hypothesis was that the spatial distribution of the pelican will decrease and that the main cause of this will be climate change.

Comentado [GL-J4]: This is more a suggestion for the discussion that an introductory remarks. Here you have to argue why the Peruvian pelican is a suitable species for this study.

Comentado [GL-J5]: I think you have adds more recent references. This one is from 6 years ago, and although is still valid there are new studies on this issue that could help you to reinforce your study.

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Materials & Methods

Species records

Pelican occurrence data were compiled from four main sources: the Neotropical Waterbird Census (https://lac.wetlands.org/), eBird (https://ebird.org/), the Global Biodiversity Information Facility (https://www.gbif.org/), and the literature (Cursach et al., 2018). The geo-coordinates for each data point were referenced from the information in the literature or through the use of coordinates in Google Earth. We excluded duplicate or unclear locations and verified the accuracy of the data. We found a total of 4,818 georeferenced data points referring to pelican sightings, encompassing its entire geographic distribution from 1967 to 2015 (Fig. 1). Although the pelican sightings were registered between 1967 and 2015, approximately 97% of them occurred between 2000 and 2015. Of these records, a subsampling was performed at a distance of 15 km (cell size), obtaining a total of 264 records, with which the modeling was performed.

Comentado [GL-J8]: Please specify what kinds of points are these: reproductive colony, resting place, coves, etc. And also date would be also fine.

Comentado [GL-J9]: Please give details; how did you subsampling the entire data base?

Environmental variables

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

To evaluate the effects of the different climate change scenarios on the spatial distribution of pelicans, we did not include the oceanographic variables. This was because there are no projections related to oceanographic climate change. The future climate scenarios corresponded to those proposed by the Intergovernmental Panel on Climate Change (IPCC, 2014). These scenarios were obtained from the ecoClimate website (http://ecoclimate.org/), which contains climate models available for different temporal intervals. To do this, we used the model developed by the Community Climate System Model version 4 of the National Center for Atmospheric Research (Gent et al., 2011). This is due to the good results for the South-East Pacific (Larson, Pegion & Kirtman, 2018; Zheng et al., 2018).

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

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 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. Both AUC values were relatively similar, so the model used is appropriate for predicting the presence of the species. $AUC_{evaluation}$ 0.98 indicates that the pelican has a wide geographic distribution 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 1. These areas are mainly distributed from northern Peru to central Chile (Figure 1).

Importance of environmental variables

Among the six climatic variables and eight oceanographic variables, the mean daytime temperature range (Bio2) and the summer marine primary productivity, contributed the most to the current and potential distribution of the pelican (Table 2). These two factors explained 78.47% of the modeled distribution. The mean daytime temperature responded to the probability of the presence of the pelican, with a high probability of finding the species in areas where the mean daytime temperature ranges between 6 and 8°C. In turn, the summer marine primary productivity also influenced the probability of the presence of the pelican, with a greater probability of finding the species during the summer season in areas with high primary productivity.

Comentado [GL-J10]: Yes, it is expected for seabirds in general, but these locations are reproductive colonies? If those zones correspond to colonies, then a possible question would be how will these conditions change in scenarios of climate change?

The other factors such as, spring marine primary productivity, isothermality, and seasonality in temperature, contributed 9.24%, 3.23%, and 1.74%, respectively, to the modeled distribution. Therefore, thermal and primary productivity conditions are more important than other variables for mapping pelican distribution (Table 2).

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

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

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

Discussion

The potential geographic distribution of the pelican currently attains an approximate area of 466,836 km^2, distributed latitudinally from southern Ecuador (2°13′09″S) to the Taitao Peninsula in southern Chile (46°59′07″S). The mean daytime temperature range and marine primary productivity explain the current potential distribution of the pelican, which is an endemic species closely associated with the oceanographic barriers of the Humboldt Current Ecosystem (Jeyasingham et al., 2013; Kennedy et al., 2013). In South America, the Humboldt Current encompasses the greater part of the Pacific coast. Despite the wide latitudinal gradient, the marine–coastal area exhibits a mean daytime temperature range between 4°C and 8°C. This is consistent with the highest probability of occurrence of the pelican (https://climatologia.meteochile.gob.cl/application/). In turn, marine productivity is the main predictor of biodiversity and especially of the presence of top predators such as seabirds (Wakefield, Phillips & Matthiopoulus, 2009). In the case of the pelican, there is an overlap between areas with high summer marine primary productivity and areas with nesting colonies (Simeone et al., 2003).

Comentado [GL-J11]: Yes, but unfortunately in your study you do not analyze this aspect. Here you have the opportunity to present a comprehensive analysis of the location of the colonies and the conditions they must have for nesting. There are sites on the Chilean coast that seem appropriate for pelicans to nest, but for some reason they do not and move to other places. This study could shed light on the conditions that pelicans require to install their colonies, which would help to better understand the effects of climate change

Under the future climate change scenarios, the spatial distribution of the pelican is predicted to slightly change. The severe scenario predicts that the habitable surface will be 4.51% higher than that of the current distribution. This increase in habitable area is explained by the climatic conditions in southern Chile, and those climatic conditions will likely be similar to the current conditions of the central coast of Chile (Falvey & Garreaud, 2009; Garreaud, 2011). Over the last decade, an increase in pelican abundance has been reported along the coast of southern Chile, with observations of large flocks following schools of pelagic fishes in the inner sea (Imberti, 2005; Häusserman, Forsterra & Plotnek, 2012; Cursach, Rau & Vilugrón, 2016; Cursach et al., 2018). In this area, there has even been one report of an unsuccessful attempt to nest (Cursach, Rau & Vilugrón, 2016). The occurrence of competitive interactions with other seabirds has also been observed with endemic species from Patagonia (Cursach, Rau & Vilugrón, 2016). In southern Chile, a group of pelicans was observed displacing nesting pairs of Imperial shag (*Phalacrocorax atriceps*), causing the abandonment of the nest (Cursach, Rau & Vilugrón, 2016). Therefore, projecting the population increase of pelicans toward southern Chile requires a better understanding of the potential ecological interactions they may encounter.

Comentado [GL-J12]: Or 'high sea'???

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The present study is one of only a few evaluations of the potential effects of climate change on seabirds on the Pacific coast of South America. To evaluate the different scenarios caused by climate change on the spatial distribution of the pelican, we did not include oceanographic variables. Therefore, further studies are required to assess the effects of climate change on seabird populations. In addition, it is important to recognize that the species spatial distribution models have methodological constraints, including operating based on climatic variables without integrating ecological interactions (Soberón, Osorio-Olvera & Peterson, 2017). In the case of the pelican, ecological interactions associated with the development of fishing activities and El Niño events (i.e., ENSO) can affect pelican population dynamics (Cursach et al., 2018). Fishing activities, particularly discards and bycatch, constitute a significant source of food for a range of different seabirds, leading to changes at the demographic level and affecting the movement patterns of birds at the regional scale (i.e., 10–250 km) (Votier et al., 2004; Bartumeus et al., 2010). The pelican is a recognized consumer of fishing discard and organic waste from fishing, and follows fishing fleets in search of food (Duffy, 1983b; Weichler et al., 2004; Cursach et al., 2018). Therefore, the increased fishing and aquaculture activities in southern Chile over recent years (IFOP, 1997; Torres & Valderrama, 2008; Niklitschek et al., 2013), could also cause the increase in pelican populations across its austral range of distribution. Moreover, the pelican is greatly affected by El Niño because the irruption of warm waters from the equator toward the south displaces their prey (pelagic fish) toward higher latitudes and depths, resulting in a shortage of food and mass migration (mostly to the south) (Tovar & Cabrera, 1985; Jahncke, 1998). Forecasts indicate that both the occurrence and intensity of El Niño along the coast of Chile will increase (Garreaud, 2011). In addition, the co-occurrence of fishing exploitation and El Niño generates synergistic effects that may push the pelican to critical levels of abundance (Duffy, 1983b; Tovar et al., 1987). Therefore, future modeling analyses should include information related to fishing, aquaculture, and El Niño occurrence.

In conclusion, the current potential geographic distribution of the pelican is influenced to a large extent by thermal conditions and primary productivity. Under the future climate change scenarios, the spatial distribution of the pelican is predicted to slightly change. Under the severe scenario, a slight increase in pelican spatial distribution is predicted. This increase in habitable area is explained by the climatic conditions in southern Chile, and those climatic conditions will likely be similar to the current conditions of the central coast of Chile. We predict that the coasts of southern Chile will constitute an important refuge for the conservation of the Peruvian pelican under future climate change scenarios. It is necessary that future investigations evaluate in detail the ecological interactions of the pelican and its population increase in southern Chile, considering the different dimensions of the local socio-ecological system.

Acknowledgements

To the University of Los Lagos for financing the costs of this publication. To Dr. Cristián Hernandez and Dr. Matthew Lee for their revisions to the manuscript.

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