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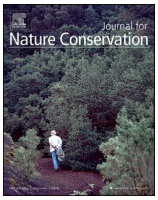

Potential biodiversity map of bird species (Passeriformes): Analyses of ecological niche, environmental characterization and identification of priority conservation areas in southern Patagonia

Yamina Micaela Rosas [a,*], Pablo L. Peri [b], Julieta Benítez [c], María Vanessa Lencinas [c], Natalia Politi [d], Guillermo Martínez Pastur [c]

[a] *Department of Geosciences and Natural Resource Management, University of Copenhagen, Rolighedsvej 23, 1958 Frederiksberg, Denmark*
[b] *Instituto Nacional de Tecnología Agropecuaria (INTA), Universidad Nacional de la Patagonia Austral (UNPA), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), CC 332 (9400) Río Gallegos, Santa Cruz, Argentina*
[c] *Laboratorio de Recursos Agroforestales, Centro Austral de Investigaciones Científicas (CADIC), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Houssay 200 (9410) Ushuaia, Tierra del Fuego, Argentina*
[d] *Instituto de Ecoregiones Andinas (INECOA), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Juan Bautista Alberdi 47 (Y4600DTA), Jujuy, Argentina*

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ABSTRACT

Different methodologies try to identify priority conservation areas (PCA) to improve habitat conservation and decrease human pressures over bird species at coarse-scale. Map of potential biodiversity (PB) can identify PCA (high PB values) at different scale levels by considering ecological requirements and distributions through potential habitat suitability (PHS) models. The aim was to elaborate a map of PB of bird species based on PHS models to spatially identify PCA in Santa Cruz, Argentina. Moreover, we want to analysis species' ecology requirements, and evaluate PB values and spatially identify PCA through two scale levels. We computed 47 models using Environmental Niche Factor Analysis (ENFA) on Biomapper software. Each model was visualized and combined to get a unique map of PB. We analyzed ecological requirements by specialization and marginality and PHS maps. Moreover, considering natural environments (regional level) and forest types' cover (forest landscape level), we evaluated PB values using ANOVAs and identified PCA under different human pressures, using human footprint (HPF) map. Bird species related to *Nothofagus* forests were most specialist and exhibited a narrower potential distribution than grassland species. At regional level, Magellanic grass steppes displayed the highest PB values, where most of the PCA had high HPF values. At forest landscape level, ecotone *N. antarctica* forests had the highest PB values, where PCA with low HFP values were outside current protected networking. We conclude that combining PHS models and the map of PB allowed us to improve bird distribution studies and to assist biodiversity conservation strategies under human pressures.

1. Introduction

The Passeriformes order has the highest richness among avian lineages, representing >60% of land bird species (Oliveros et al., 2019). In general, bird species richness decreases progressively when latitude increases, where the lowest richness is located between 47° and 57°S (Willig et al., 2003). Climate, vegetation types and biotic constraints influence in the global geographical patterns of bird richness (Kissling et al., 2009), where temperature and precipitation are good predictors for bird species distribution along elevation gradients (Boucher-Lalonde et al., 2014). However, vegetation structure determines the complexity of the environment, where most complex habitats support higher bird species richness (Martínez Pastur et al., 2015). Thus, habitat structure is essential, since it provide food resources, nesting and feeding places (Erdős et al., 2018).

According to FAO and UNEP (2020) forests provide habitats for almost 75% of bird species, representing most of the hotspots of biodiversity around the world. Moreover, forest mountain landscapes contain

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* Corresponding author.
E-mail addresses: ymro@ign.ku.dk (Y. Micaela Rosas), peri.pablo@inta.gob.ar (P.L. Peri), j.benitez@conicet.gov.ar (J. Benítez), vlencinas@cadic.gov.ar (M. Vanessa Lencinas), natipoliti@fca.unju.edu.ar (N. Politi), gpastur@conicet.gov.ar (G. Martínez Pastur).

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high bird specialist endemic species, due to rapid changes of environmental conditions across small spatial distance (Fjeldså et al., 2012). Transitional areas (ecotones) provides suitable habitat for more generalist organisms (Erdős et al., 2018), and usually had higher bird species richness than adjacent forest-steppe areas (Gonçalves et al., 2017). Despite the complex habitat structure of shrub-lands and steppes in arid ecosystems and the different bird species related to these ecosystems, they have been received much less attention as hotspot (Belder et al., 2022). In fact, shrub layer provides crucial habitat for a number of bird species, mainly as nesting areas (Kusch et al., 2016; Belder et al., 2022).

Mostly protected areas (e.g., National Parks) around the world were created to protect emblematic big mammals, umbrella species or unique landscapes more than bird species (Virkkala et al., 2013; Watson et al., 2016; Shrestha et al., 2021). In this sense, different initiatives around the world have been undertaken to identify priority conservation areas (PCA[1]) of birds. Most of these areas are related to threatened and range-restricted specific species (e.g., Important Bird Areas identified by BirdLife International) or migratory species on some wetlands across migratory routes (e.g., Ramsar sites established by UNESCO). These strategies use expert knowledge on species distribution and density maps, while spatial distribution models had been used on a large scale to analyze climatic change influence (Gahbauer et al., 2022) and the effectiveness of the current protected areas networking (de Carvalho et al., 2017).

Spatial distribution models (e.g., Environmental Niche Factor Analysis-ENFA[2], Generalized Linear Models-GLM) describe the relationship between the occurrence of individual species and environmental variables by defining potential distribution maps (Hirzel et al., 2002). Biomapper software (Hirzel et al., 2002, 2004, 2006) provides potential habitat suitability (PHS[3]) models based on the niche ecology concept (Hirzel & Le Lay, 2008). In addition, ENFA provides two indexes related to ecological requirements: the global marginality, which is defined as the species' mean compared to the mean of all sites, where high values indicate that the species tend to live in narrow conditions throughout the study area; and the global specialization, which is defined as the species' variance compared to the global variance of all sites, where high values indicate specialist species tending to live in a very narrow range of environmental conditions (Hirzel et al., 2002). This software uses ENFA, biogeographical information, and only presence data, being a powerful tool for areas with few available species data (Rosas et al. (2017). Spatial distribution models has been used to improve the understanding about ecological requirement of species and to create distribution maps at large scales by using several species (Orme et al., 2005; Kissling et al., 2009; Nagy, 2020). Moreover, combining several maps of PHS it is possible to get a unique map of potential biodiversity (PB[4]) to spatially support conservation strategies (Rosas et al., 2018). Despite the power of theses methodologies, it is necessary to take into consideration how species distribution patterns are affected by human pressures (Polaina et al., 2019; Shrestha et al., 2021; Yang et al., 2021). One of the main threat of biodiversity are human impacts that greatly modified natural ecosystems, reducing its complexity and resources availability (e.g., feeding and nesting) (Lencinas et al., 2009; Kusch et al., 2016; Yang et al., 2021). As humans continue to transform and ecologically degrade many natural ecosystems many bird species' distribution patterns have been affected (Shrestha et al., 2021; Yang et al., 2021).

Patagonia hosts a unique variety of bird species, presenting 138 land bird species, whereas Passeriformes order is the most abundant and is closely related to different natural environments, from forests, grass steppes to wetlands, and different altitude gradients from high mountains to seashores (Narosky & Yzurieta, 2010). Many species are residents of specific ecosystems, while others show different migratory patterns (e.g., partial or full migratory). In this area, the extreme climatic conditions determine lower bird species richness than in the northern hemisphere at similar latitudes and ecosystems (Vuilleumier, 1985). While 41% of Patagonia's forest birds exhibited a high level of endemism, restricted distribution (e.g., *Nothofagus* forests) and a strong association with specific habitat requirements (Vuilleumier, 1985; Altamirano et al., 2017), southern steppes is one of the nine areas with endemic bird species in Argentina (Di Giacomo et al., 2005). In fact, most of the protected area are located in *Nothofagus* forests (Fasioli & Díaz, 2011). However, Vuilleumier (1985) showed that southern Patagonia forested areas are poorer in number of genera and species than non-forested areas. Despite southern Patagonia is classified as a recently-used compared to other areas in the world and it is not considered in a global biodiversity conservation priority (Polaina et al., 2019). Recent studies showed high human footprint (HFP[5]) values in specific vegetation types (e.g., shrub-lands, *N. antarctica* forest types) with a lack of protected areas (Rosas et al., 2021). Furthermore, different studies reveal how human pressures affect the richness and density of bird species in forests (Lencinas et al., 2005, 2009; Benitez, 2021; Tadey, 2021) and shrub-lands stand level (Kusch et al., 2016).

The main objective was to elaborate a map of potential biodiversity of bird based on potential habitat suitability of the most important bird species in Santa Cruz province to evaluate priority conservation areas. In this context, first we aim to determine how specie's ecological requirements change according to potential habitat suitability maps. Second, by considering different scales (regional and forest landscape level), we aim to: (i) analyze spatial patterns of the map of potential biodiversity; (ii) evaluate how potential biodiversity values change; and (iii) spatially identify PCA (high PB values) of birds under different intensities human pressures.

2. Materials and methods

2.1. Study area

The study area is the whole Santa Cruz province located in southern Patagonia, Argentina (46°00́ to 52°30́ S, 66°00́ to 73°00́ W) (Fig. 1A). Mean annual rainfall ranges from 1681 to 136 mm/yr from west to east, while temperature varies from −8.6 at top of the Andes Mountain to 13.5 °C in the northeast coast (annual mean temperature). Different natural environments are present in the province: (i) *Nothofagus* forests and (ii) Sub-Andean grasslands both located in the west, (iii) Magellanic grass steppes and (iv) Shrub-lands in the south, while the (v) Central plateau is sited in the north (Fig. 1B). Magellanic grass steppes includes humid and dry steppes, while the Central plateau includes central plateau, shrub-steppe San Jorge Gulf, and mountains and plateau areas (thin dark line, Fig. 1B) (Oliva et al., 2004). The current protected areas network (Fig. 1C) has 4 national parks, that represent only 4.1% of the provincial surface, and these are mainly located in the west. Protected areas were complemented with 29 provincial reserves (2.7% of the provincial surface) that mainly protect steppes and seashores (Fasioli & Díaz, 2011). *Nothofagus* forests are distributed from 46° to 52° S, and are subdivided into *N. pumilio* forests (dominate most of the *Notohofagus* distribution), mixed evergreen forests (located near the large lakes in the center of the mountain range), and *N. antarctica* forests (prevail in the southwest of the province) (Veblen et al., 1996) (Fig. 1D).

Fig. 1.

2.2. Bird species

We used 5,512 presence points (geographic location) of native bird species belonging to the Ornithological Collection of Santa Cruz

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[1] Priority conservation areas.

[2] Environmental Niche Factor Analysis.

[3] Potential habitat suitability.

[4] Potential biodiversity.

[5] Human footprint.

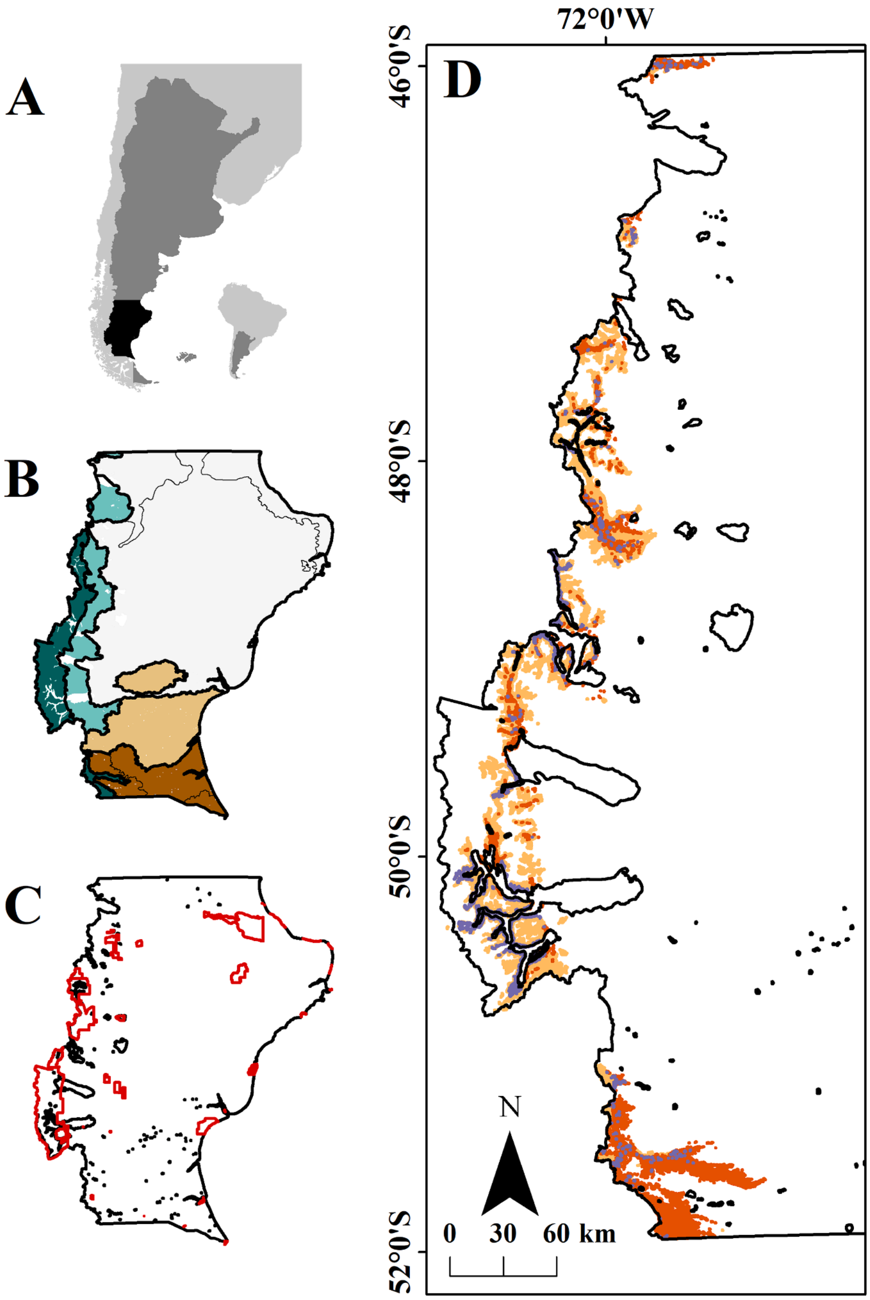

Fig. 1. Characterization of the study area: (A) location of Argentina (dark grey) and Santa Cruz province (black); (B) natural environments (dark aquamarine = *Nothofagus* forests, light aquamarine = Sub-Andean grasslands, brown = Magellanic grass steppes (humid and dry), light brown = Shrub-lands, light grey = Central plateau (central plateau, shrub-steppe San Jorge Gulf, and mountains and plateaus) (Oliva et al., 2004); (C) protected areas (red lines) including National Parks and Provincial Reserves; and (D) *Nothofagus* forests (light orange = *N. pumilio*, purple = mixed evergreen, dark orange = *N. antarctica*). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

province (Darrieu et al., 2009) and to the International Repository of Bird species (https://ebird.org/), is one of the biggest citizen-science projects collecting bird observation records (Amano et al., 2016) (Appendix A). Each geographic location represents a unique presence point of the considered species, however, some locations shared different species' presences. For the selection of the species, we considered the different natural environments including the sub-classifications of Magellanic grass steppes and Central plateau. We selected the most common native bird species, which have the highest overall presence in the province. For this we identified the 15 species with highest percentage of presence in each environment. The percentage of presence points was calculated as the ratio between each species' presence point for each environment and the total in the province. We selected 47 bird species of Passeriformes order to model spatially explicit PHS (Appendix B). The species belong to two suborders: (i) Tyranni Suborder included 26 species, where most of them (n = 23) belong to two families (Furnariidae and Tyrannidae), while other two species are included in Rhinocryptidae and only one in Cotingidae family; (ii) Passeri Suborder involved 21 species, where 14 species belong to three families (Thraupidae, Hirundinidae and Icteridae), while other seven species belong to five different families (Emberizidae, Fringillidae, Mimidae, Motacillidae and Turdidae). The selected species are native of the study area, where most of them are native resident/breeding (n = 45), spending the entire year in their breeding grounds or visiting regularly during the breeding season and breed, while *Geositta* antarctica is native breeding and non-breeding, while *Hirundo rustica* is native non-breeding, these two species visit different areas of the study area during breeding and non-breeding season.

2.3. *Potential habitat suitability maps*

The 47 PHS map was built using Biomapper 4.0 software (Hirzel et al., 2004) based on the ENFA (Hirzel et al., 2002) and exploring 41 potential explanatory variables (climatic, topographic and landscape variables) (Appendix C). ENFA compares the distribution of the eco-geographical variables for a presence data set consisting of locations where the species has been detected with the predictor distribution of the study area (Hirzel et al., 2001). In addition, ENFA calculated the global marginality (from 0 to 1) and the global tolerance or specialization (tolerance-1) (from 0 to infinite) and used cross-validation to compare the model results with random modeling (Hirzel et al., 2006) using the Boyce index (B[6]), the continuous Boyce index (B cont), the proportion of validation points (P[7]) (Boyce et al., 2002; Hirzel et al., 2006), the absolute validation index (AVI[8]), and the contrast validation index (CVI[9]) (Hirzel & Arlettaz, 2003; Hirzel et al., 2004). We used a distance of geometric-mean algorithm to perform each PHS, which provides a good generalization of the niche model (Hirzel & Arlettaz, 2003). Explanatory variables were rasterized at 90 × 90 m resolution using the nearest resampling technique on ArcMap 10.0 software (ESRI, 2011), moreover we evaluated their autocorrelation using Pearsońs correlation index. The resulting PHS maps had scores that varied from 0 (minimum) to 100 (maximum habitat suitability). For further details about validation process significances, climatic, topographic, and landscape variables, see Rosas et al. (2017, 2018).

We visualized the PHS maps for each species into a GIS project, then we combined them with a mask based on NDVI (normalized difference vegetation index) <0.05 to detect bare soil, ice fields and water bodies (Lillesand & Kiefer, 2000). The 47 PHS maps (one for each bird species) were combined (average values for each pixel) to obtain the map of PB of bird species of Santa Cruz province. This map had scores that varied from 1% to 70% (average values of PHS for all the studied species), and it was re-scaled by a lineal method from 1% to 100%.

2.4. Map of potential biodiversity

Considering two spatial scales (regional and forest landscape level) and hexagonal binning processes, we visualized spatial patterns of the map of PB, evaluated how PB values change through the different natural environments and forest types' cover and spatially identify PCAs considering the highest PB values and the human footprint.

Hexagonal binning processes is a spatial methodology that have the advantage of combining pixel values (e.g. average values for each pixel) into polygonal regions to capture spatial patterns and effectively represent complex data sets (Battersby et al., 2017). The hexagonal binning processes consisted on create two spatial matrix by dividing the study area into hexagonal areas considering the before two mentioned scale levels, which have different surfaces: (A) At the regional level, we considered the different natural environments using 117 hexagons of 250,000 ha each and (B) at the forest landscape level, we considered different forest types' cover using 408 hexagons of 5,000 ha each (Oliva et al., 2004; CIEFAP-MAyDS, 2016). The forest types' cover consists of two classes: (i) hexagons with forest cover between 1 and 50%, which include grasslands associated with forest types and (ii) hexagons with forest cover >50%, which include only forest types. Forests we identified as pure (*N. antarctica* or *N. pumilio*) forests and mixed (*N. antarctica* with *N. pumilio* or *N. pumilio* with mixed evergreen) forests. For further details about the forest landscape matrix, see Rosas et al. (2019). Then, using those spatial matrices we calculated the average values of PB into each hexagon using "zonal statistics" of ArcGIS software. Zonal statistics calculates the average of all cells in the value raster that belong to the same zona as the output cell. To visualize spatial patterns, each average hexagon of the map of PB were classified according to low, medium and high values considering an equal number of hexagons. Moreover, to evaluate PB values changes at regional and forest landscape level, the average of PB values were compared through one-way ANOVAs and Tukey post-hoc test. Then, to identify PCAs of birds we crossed the hexagonal map of PB, only considering the highest values with the hexagonal map of human footprint (HFP) (Rosas et al., 2021), which was classified according to high HFP (HFP > 0.3) and low values (HFP < 0.3). PCAs of birds were classified as hotspot of conservation (high PB and low HFP values) or threatened areas (high PB and high HFP values).

3. Results

3.1. Potential habitat suitability maps

The species with the greatest number of presence points in Santa Cruz province were *Z. capensis* (n = 583) and *L. rufa* (n = 456), while *E. albiceps chilensis* (n = 20) and *M. bonariensis* (n = 20) showed the smallest number of presence points (Appendix D). Among the 15 selected species in *Nothofagus* forests, *P. albogularis* exhibited the first position and the highest percentage of presence points (91%), following for *P. tarnii* (90% of presence points), while *E. albiceps chilensis* showed the last position and the lowest percentage of presence points (30%). The main species in sub-Andean grasslands was *P. unicolor* (46% of presence points), while *G. rufipennis* (22% of presence points) was the last one in this ranking. Magellanic grass steppes (humid and dry) share most of the selected species with similar ranking positions, for example, *A. anthoides* was first (36% of presence points) in humid and second (37% of presence points) in dry Magellanic grass steppe, while *H. rustica* (38% of presence points in dry and 17% in humid Magellanic grass steppes) exhibited the opposite ranking position. Moreover, *Upucerthia dumetaria* (15% of presence points) was the number fifteen in the ranking of dry and fourteen in humid Magellanic grass steppe (10% of presence points). The species with the first position was *E. phoenicurus* (15% of presence points) in shrub-lands and second in central plateau (40% of presence points) and shrub-steppe San Jorge Gulf (15% of presence points). Finally, *A. micropterus* was the first one (51% of presence points) in the central plateau, while *P. elegans* was the number one in the ranking of shrub-steppe San Jorge Gulf (26% of presence points) and mountains and plateaus (34% of presence points).

Seven ecogeographical variables better fitted PHS maps, where only four variables had high values (>0.80) based on Pearsońs correlation index (Appendix E). The correlation index varied between 0.03 and 0.96, where the lowest values was detected for minimum temperature of the coldest month (MINCM[10]) and the distance to rivers (DR[11]). The highest correlation indexes were represented by annual mean temperature (AMT[12]), global potential evapotranspiration (EVTP[13]) and MINCM and elevation (ELE[14]).

The outputs of the 47 PHS models explained 100% of the information in the first four axes (Appendix F). The score matrix of environmental variables showed that NDVI had the highest coefficient value in the first axis for most of the models, where climatic and topographic variables showed high coefficient values in the following axes (Appendix G). In addition, cross-validation showed the following fitting. These validation values (i) Boyce index varied between 0.02 and 0.92, (ii) P varied between 0.08 and 0.64, (iii) Bcont varied between −0.26 and 0.77, (iv) AVI varied between 0.38 and 0.62, and (v) CVI varied between 0.10 and 0.57. Some models' accuracy did not outperform a random model (CVI close to cero) indicating that those species can be more generalist, while other model accuracies were different from a random model (CVI close to 0.50) indicating that those species are more specialist. The best cross-validation statistics were obtained for *A. spinicauda*, which showed the

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[6] Continuous Boyce index.
[7] Proportion of validation points.
[8] Absolute validation index.
[9] Contrast validation index.
[10] Minimum temperature of the coldest month.
[11] Distance to rivers.
[12] Annual mean temperature.
[13] Global potential evapotranspiration.
[14] Elevation.

highest Boyce index value (B = 0.92) indicating that this model had the best fit to the distribution data and displayed a high CVI value (CVI = 0.53) indicating that it is a specialist specie (Appendix H).

Species PHS maps displayed differences in the spatial distribution (Appendix I) and the habitat requirements related to the marginality and specialization values (Fig. 2). Among the 47 PHS maps, eleven species showed higher PHS values in western areas of the province (Appendix I A, F, M, Y, AD, AE, AH, AI, AK, AL, AT) where most of the species exhibited higher marginality (1.72 to 2.45) and specialization (4.74 to 7.10) values, while only one specie (*S. auriventris*) had the lowest specialization and marginality values of this group. The other 36 species showed medium to low marginality and specialization values, however PHS values are higher in different geographical zones of the province. Fifteen species exhibited higher PHS values in the south (Appendix I C, E, G, L, AC, AM, AN, AO, AP, AQ and AR), where four of them also include western areas (Appendix H J, K, R, AF). Most of these species showed medium marginality values (1.66 to 1.00) and low to medium specialization values (1.39 to 4.47), while only two species (*P. gayi* and *S. lebruni*) showed the lowest specialization and marginality values of this group. In the east of the province, five species displayed higher values of PHS with low marginality (from 0.80 to 0.91) and low to medium specialization (from 1.61 to 4.28) values. In the north, only two species had high PHS values (Appendix I AA and AF) with similar marginality (*P. fruticeti* = 0.87 and *P. elegans* = 0.76), but different specialization (2.25 and 5.05, respectively) values. Finally, fourteen species showed high values of PHS in sectors of the province (Appendix I B, D, H, I, N, P, Q, R, V, Z, AA, AJ, AS, AU) and displayed low to medium marginality (1.12 to 0.80) and specialization (2.17 to 4.56) values.

3.2. *Map of potential biodiversity*

The map of PB showed an increased from north to south and from west to east (Fig. 3). At regional level (Fig. 4A), the hexagonal map showed high values (55–83%) in some specific hexagons in the west and central north part of the province, while the biggest areas were located in the south and east of the province. While most of the medium values (48–55%) occurred in the north and in few small areas located near the big lakes Argentino and Viedma in the west (50°0ó S and 72°0ó W), low PB values (29–48%) were found in the west of the province, near mountains, ice fields and around the Rio Chico basin in the central area. At forest landscape level, hexagons distribution and PB values showed differences across *Nothofagus* forest distribution (Fig. 4B and C). First, hexagons with forest cover between 1% and 50% exhibited a more continuous distribution, while hexagons with forest cover >50% were sited in small and disperse groups. Second, PB values decreased from east to west when forest cover between 1 and 50% were considered, showing most of the hexagons with high values (41–74%) outside protected areas, while medium (33–41%) and low (14–33%) values were inside of them (Fig. 4B). On the other side, PB values decreased from south to north when forest cover >50% where analyzed, where high values (36–50%) were located in the southernmost part of the province in *N. antarctica* forest outside protected areas, medium values (32–36%) in the central and north and low values (7–32%) near to the biggest lakes.

Figs. 3 and 4.

ANOVAs showed that PB values significantly changed across the different spatial scale analyzed (Table 1 and 2). At regional level, Magellanic grass steppes exhibited the highest values (71.7), while shrub-lands showed high to medium values (60.8). Medium PB values (51.5 and 45.7) were associated to Central plateau and Sub-Andean grasslands, while the lowest values (33.7) occurred in *Nothofagus* forest environment (Table 1). At forest landscape level, ANOVAs showed that hexagons with forest cover between 1% and 50% had the highest values (36.1). However, *N. Antarctica* forest type displayed the highest PB values in both percentages of forest cover (from 1 to 50% and >50%), following for hexagons where *N. antarctica* and *N. pumilio* were associated, while *N. pumilio* and mixed evergreen forests showed the lowest PB values (Table 2).

3.3. *Priority conservation areas of birds*

Different PCA of birds were spatially identified at regional level (Fig. 5A). Most of the hotspot of conservation (high PB and low HFP values) were located mainly in the west and central-north of the province. Among this hexagons, only one was located inside a protected area (Monte León National Park). Because most of the protected areas are located in western areas, threatened areas (high PB and HFP values) were in the south and east parts of the province, where one hexagon was under protection (Meseta Espinosa and El Cordón Provincial Reserve). At forest landscape level, hotspot of conservation were located in several areas from north to south in the easiest part of *Nothofagus* forests distribution in the external border of protected areas, when hexagons with forest cover between 1 and 50% were considered (Fig. 5B). Moreover, only few hotspot of conservation were inside two national parks (Los

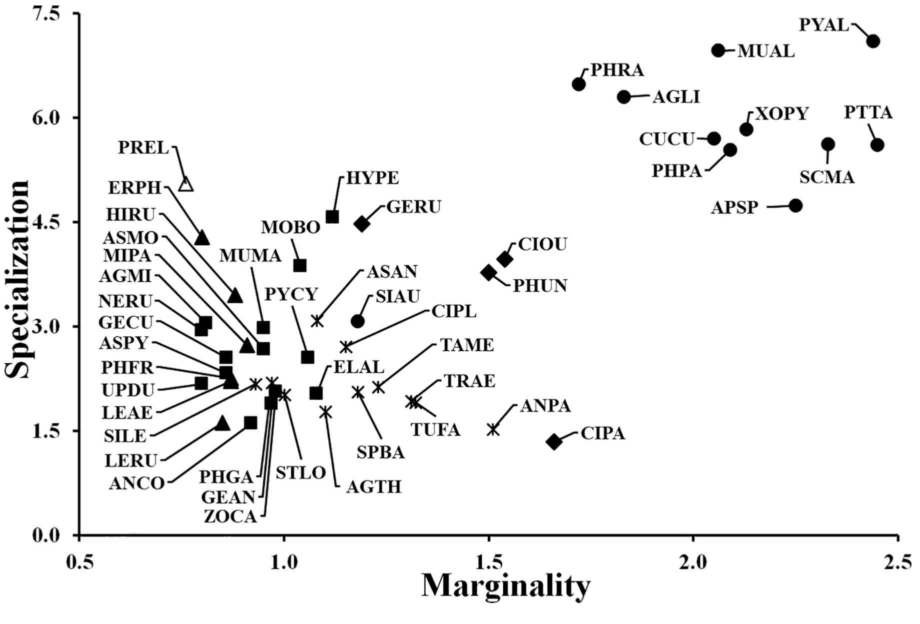

Fig. 2. Specialization (species' variance compared to the global variance of all the study area) vs. marginality (species' mean compared to the mean of all the study area) of the studied bird species (n = 47) in Santa Cruz province, classified according to the geographical zone where potential habitat suitability values are higher (Appendix 6) (circle = west, diamond = west and south, star = south, full triangle = east, empty triangle = north, and square = around all the province). Codes for bird species are presented in Appendix A.

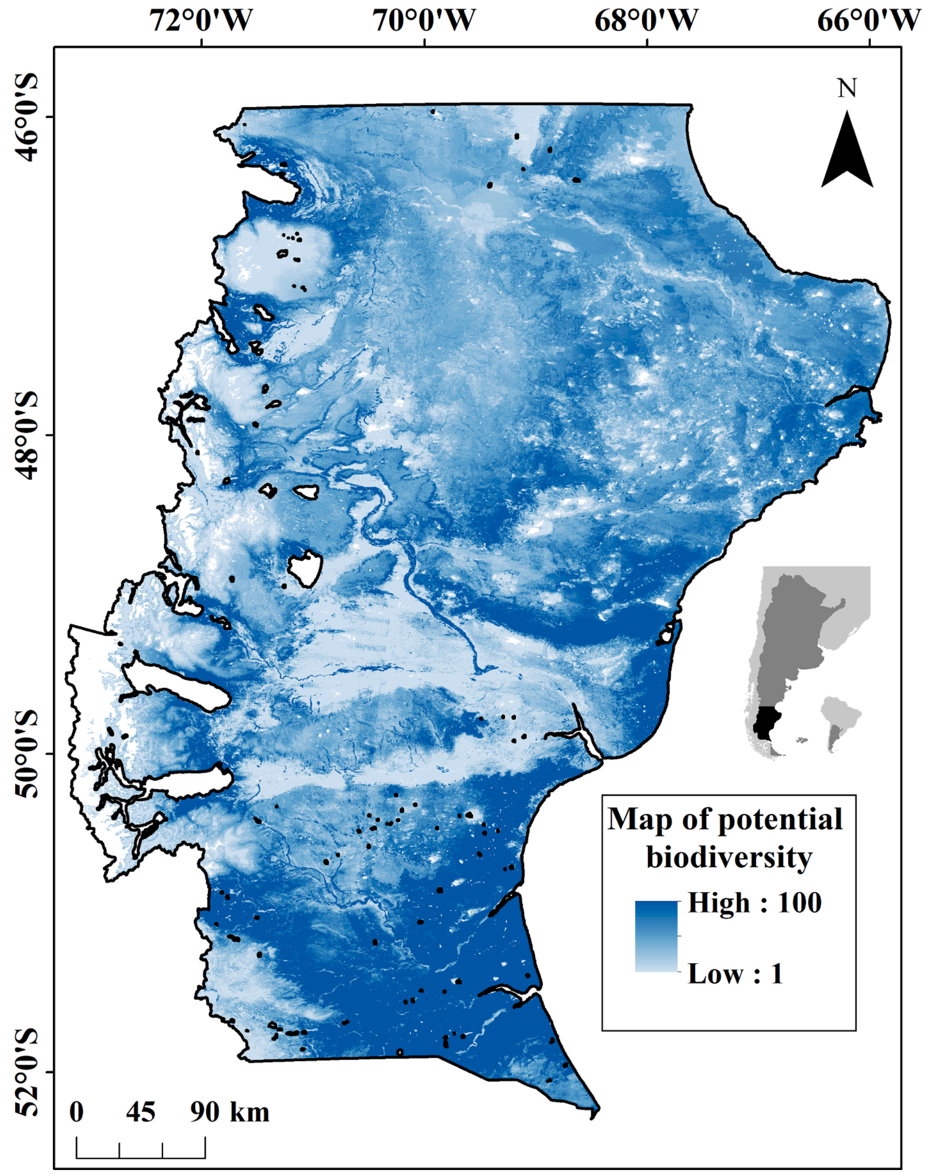

Fig. 3. Maps of potential biodiversity of bird species of Santa Cruz province.

Glaciares and Perito Moreno National Park), while threatened areas occurred in specific zones next to some hotspot of conservation, for example "San Martin" lake (49°06′43″ S; 72°20′50″ W) in the north and near to "Rio Turbio" city (51°32′10″ S; 72°20′16″ W) in the south. On the other side, when hexagons with only forest cover >50% where analyzed (Fig. 5C), most of the hotspot of conservation and threatened areas were identified in the southwest part of the province outside protected areas, where *N. antarctica* forests prevail.

Fig. 5.

4. Discussion

4.1. Potential habitat suitability maps

Our study presented the most common Passerine land bird species, belonging to the best-represented families of Santa Cruz province (Darrieu et al., 2009), where Furnariidae and Tyrannidae families showed the most restricted distribution area related to all South America (Nagy et al., 2020). Ecological factors determined distribution variation of bird species, where climate, topographic and vegetation structure appears to be the most important variables at macro geographic scale (Kissling et al., 2009; Boucher-Lalonde et al., 2014). In this sense, PHS models (Hirzel and Le Lay, 2008) allowed to relate ecological requirements with species distribution, using presence points and environmental variables. For example, Radeloff et al., (2019) found a positive relation between NDVI (indicator of vegetation cover and primary productivity) and habitat suitability, where high values indicates more resource availability for birds. Our results showed that NDVI was the most important variable in the modelling, where PHS values of all models increased with this variable. However climatic and topographic variables played a crucial role in limiting species distributions in southern Patagonian extreme environments (Vuilleumier, 1985).

The fitted PHS models with high values in a narrow strip at the Andes Mountain were associated with an increase in annual precipitation and a decrease in annual temperature values and elevation. In these areas, the restricted environmental ranges play a crucial role in the high endemism of these bird species and their strong relationship with different forest types (Fjeldså et al., 2012), which is supported for the high marginality and specialization values. Among them, *A. spinicauda*, *P. albogularis* and *P. tarnii* are considered forest specialists, while *C. curaeus* and *X. pyrope* use forests only occasionally (Martínez Pastur et al., 2015) or in specific seasons (Lencinas et al., 2005). Moreover, *S. magellanicus* and

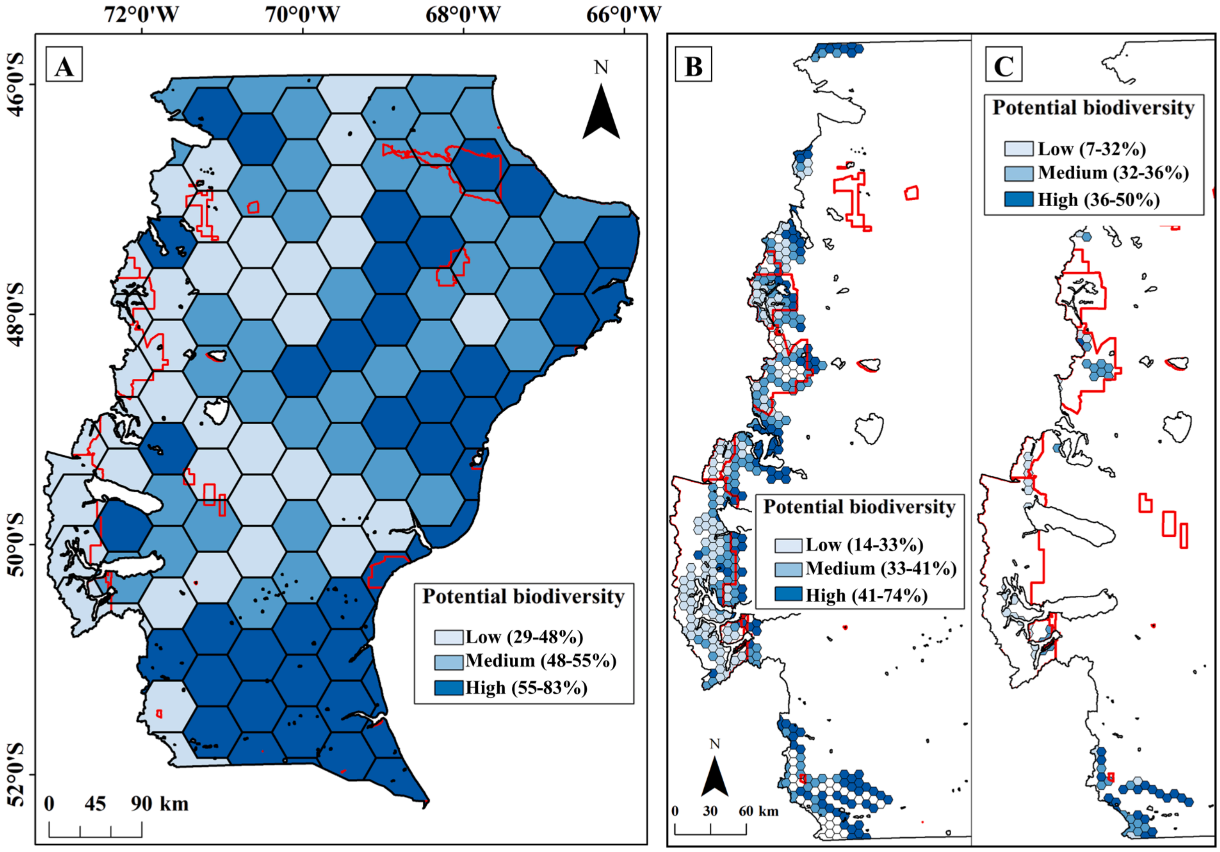

Fig. 4. Hexagonal maps of potential biodiversity of bird species in Santa Cruz province, considering hexagons of 250,000 ha at regional level (A); and hexagons of 5,000 ha at forest landscape level, where coloured hexagons presented forest cover 1–50% (B), and forest cover >50% (C). Hexagons were classified according to low, medium and high (light to dark blue colour) potential biodiversity values considering an equal number of hexagons observed in the landscape for each category. Current protected areas are indicated in red lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
ANOVA analysing potential biodiversity (PB) of bird species at 250,000 ha hexagons, considering the different natural environments of Santa Cruz province (Argentina).

Natural environments	PB
Nothofagus forests	33.7 a
Sub-Andean grasslands	45.7b
Central plateau	51.5b
Shrub-lands	60.8c
Magellanic grass steppes	71.7 d
F(p)	29.06 (<0.001)

F = Fisher test, (p) = probability. Different letters showed significant differences using Tukey test at $p < 0.05$.

Table 2
ANOVA analysing potential biodiversity (PB) of bird species at 5,000 ha hexagons in Santa Cruz province (Argentina), considering different forest types' cover: grasslands and forests types (hexagons with forest cover 1–50%) and forest types (hexagons with forest cover > 50%), where: G = grasslands, NA = *N. antarctica* forests, NP = *N. pumilio* forests, and MIX = mixed evergreen forests.

Category	Treatments	PB
Forested landscape	Forest cover 1–50%	36.1b
	Forest cover >50%	31.5 a
	F(p)	14.17 (<0.001)
Grasslands and forests types (Forest cover 1–50%)	G + NP-MIX	28.0 a
	G + NP	33.6b
	G + NA-NP	39.5c
	G + NA	49.1 d
	F(p)	87.35 (<0.001)
Forest types (Forest cover > 50%)	NP-MIX	19.7 a
	NP	23.9 a
	NA-NP	31.2b
	NA	37.5c
	F(p)	20.09 (<0.001)

F = Fisher test, (p) = probability. Different letters showed differences by Tukey test at $p < 0.05$.

P. patagonicus are more related to mixed deciduous-evergreen or mixed deciduous forests (Martínez Pastur et al., 2015), while *X. pyrope* is a forest-edge species related to monocot cover (Martínez Pastur et al. 2015; Benitez, 2021). Finally, *S. auriventris* that habits in open shrubby and grassy areas on Andean slopes (Ridgely & Tudor, 1989) had the lowest marginality and specialization values of the group, where high PHS values were linked to areas with low precipitation and high temperatures.

PHS models with high values in southern steppes of the province were related with low temperature values. These species displayed medium marginality and specialization values and habits a wide range of environmental conditions in the province. Most of these species are permanent residents, while *T. meyeni* is a migratory species, which uses open areas to nest and/or feeding (Llambías et al., 2018). Among

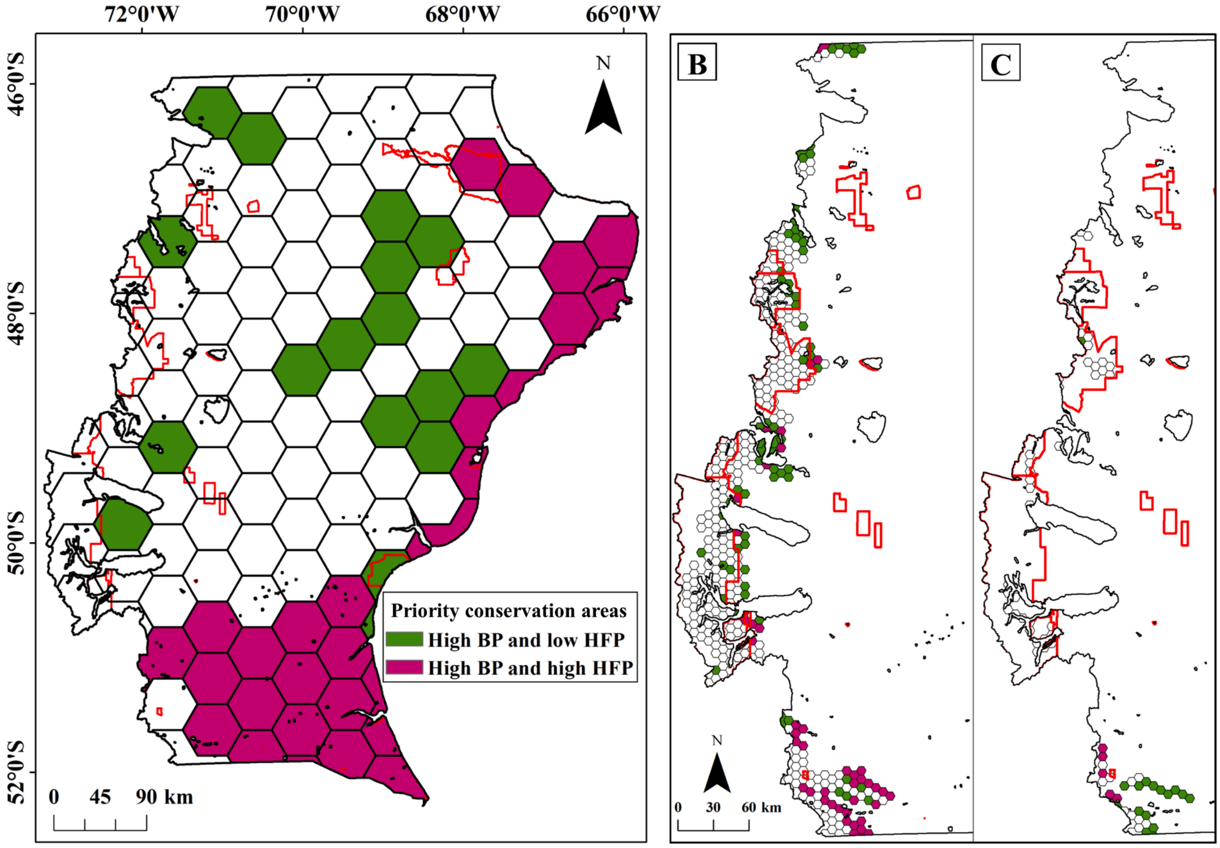

Fig. 5. Hexagonal maps of priority conservation areas of birds in Santa Cruz province, considering hexagons of 250,000 ha (A); and hexagons of 5,000 ha for the different forest landscapes level, where coloured hexagons presented forest cover between 1 and 50% (B), and those with forest cover >50% (C). Hexagons had high PB values following Fig. 3 and were classified according to low potential human footprint values (HFP < 0.3) in green and high HFP values in pink. Current protected areas are indicated in red lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

permanent residents, *A. parulus* showed the highest marginality value, exposing the need of big vegetation parches for prey searching, while *A. anthoides* exhibited the highest specialization value of this group, revealing their extreme sensitive to shrub-lands changes and being identified as indicators of shrub-lands quality (Kusch et al., 2016). Moreover, some PHS models had high values in the west-south of the province related to high precipitation associated to *Nothofagus* forests and low temperature associated with southern steppes. These species use lacustrine environments (*C. patagonicus*) or high-altitude rocky sites (*C. oustaleti* and *G. rufipennis*) with an altitudinal migrations, moving to the costs in winter (Vielma & Medrano 2015).

Contrarily, PHS models with high values in the east part of the province were related to high temperature and low elevation environments. The low but large range of specialization, could be associated to the extensive range of environmental conditions where species habit. *E. phoenicurus* and *H. rustica* showed the highest specialization values. *H. rustica* had the largest habitat range, which breeds across North America and winters in Central and South America (Brown & Brown, 2019). In contrast, *M. patagonicus* showed medium values which only moves from south to northern areas within Argentina (Capllonch, 2018), and L. *rufa* that exhibited the lowest values with a narrowest range by using only Patagonia as a breeding area. The resident, *L. aegithaloides* showed medium specialization value related to the use of a large nesting areas in the shrub-steppe ecosystems in Patagonia (Matus & Jaramillo, 2008; Tadey, 2021). Furthermore, *P. fruticeti,* and *P. elegans* showed higher PHS values in the extreme northeast associated with an increase in temperature values and medium elevations, both species with an extremely large native resident area from Peru or Bolivia to Patagonia. However, the distribution of *P. fruticeti* occurred in all our study area with the lowest specialization value (2.25), while *P. elegans* was determined in a small zone in the extreme north of Santa Cruz (Narosky & Yzurieta, 2010).

Finally, PHS models with high values around most of the province showed low to medium specialization and marginality values. These species have a large range of elevation (from sea level to 4600 m a.s.l.) and latitudinal distributions from Mexico to Argentina, occupying a wide variety of environments and habitats (Narosky & Yzurieta, 2010). For example, the lowest specialization values of *A. correndera*, could be linked with the use of wetlands in Chile and Argentina in an extensive elevation distribution (0 to 2800 m.a.l.s.), while the high specialization value of *H. perspicillatus* with the recent arrival and expanding in our study area (Matus & Jaramillo, 2008). Moreover, *P. cyanoleuca*¸ *N. rufiventris* and *M. maculirostris,* which have a larger native breeding areas around Argentina showed medium specialization values.

4.2. Map of potential biodiversity

In this southernmost latitude of southern hemisphere (46° to 52°S), bird species richness is low (Willig et al., 2003). However, our study showed that PB changed through the different natural environments and at different spatial scales. At regional level, the lowest PB values displayed in *Nothofagus* forests were coincident with Vuilleumier (1985), who found more bird richness in non-forested than forested areas in south Patagonia compare to north Patagonia. Moreover, the map of PB allowed us to spatially identify high PB values, highlighting the importance of southern steppes and specific areas in north, which are consider one of the nine endemism bird areas of Argentina (Di Giacomo et al., 2005). Several steppe bird species with highly restricted distribution, e.g., *E. phoenicurus*, *G. antarctica* and *N. rufiventris* habits these environments (Di Giacomo et al., 2005). However, only few protected areas are present in these zones (e.g., Meseta Espinosa and El Cordón Provincial Reserve). Despite the poorer potential biodiversity importance of *Nothofagus* forest environment at regional scale, our study highlights the importance of *N. antarctica* ecotone forest areas when a more fine scale was considered. These more complex habitats offer more diversity of food and refuge availability by increasing richness of range-limited species (Martínez Pastur et al., 2015; Gonçalves et al., 2017). Instead a high conservation value, ecotones areas have low conservation strategies attention around the world (Erdős et al., 2018). In fact, in our study this areas are located in the external border of protected areas or in extreme remote areas. These results emphases the importance of different scale analyses to improve biodiversity analysis, highlighting the different forest landscapes and forest types where bird species had the highest specialization and marginality values in the province strongly associated with different forest types (Benitez, 2021; Altamirano et al., 2017; Martínez Pastur et al., 2015; Lencinas et al., 2005).

4.3. Priority conservation areas of birds

The main objective of protected areas (e.g., national parks or reserves) is to preserve biodiversity (Virkkala et al., 2013, Shrestha et al., 2021), however our results showed that only some hotspots of conservation are under current protection (one national park at regional level and two at forest landscape level). In fact, despite most of the *Nothofagus* forest environments are under protection (Fasioli & Díaz, 2011) with highly endemic and restricted habitat bird species, most of the conservation hotspots were located outside protected areas, such as ecotone areas where *N. antartica* prevail. Different studies had shown the low effectiveness of traditional protected areas because these are not located in areas with high biodiversity values (Virkkala et al., 2013; Watson et al., 2016; de Carvalho et al., 2017). Moreover, most of the protected areas are designed to protect threatened or umbrella mammals, which are partially effective in protecting birds or reptiles (Shrestha et al., 2021). At regional level, hotspots of conservation outside protected areas were coincident with low human pressures (e.g., low grazing intensity in central north of the province) or associated with ecotourism activities (e.g., birdwatching) in western environments (Rosas et al., 2021). High grazing by livestock is the most common human pressures in threatened areas identified in this study. This pressure increase degradation, habitat loss and negatively affect the richness and abundance of birds (Kusch et al., 2016; Belder et al., 2022). In this sense, the importance to protect birds promoted the expansion of not common conservation areas (de Carvalho et al., 2017), including relevant areas in Argentina (e.g., Ramsar sites, Important Bird Areas). Instead several Important Bird Areas are in private lands improving the conservation of species under human pressures (Di Giacomo et al., 2005), only few sites included the most threated areas associated to *N. antarctica* forests in the southernmost part of the province.

Because most of the PCA of birds were outside protected areas, it is relevant to inform and motivate landowners to implement "bird-friendly" practices, this is crucial in Magellanic grass steppes and shrublands areas, where grazing is the main economic activity (Peri, Ladd, et al., 2016). For example, rotational grazing with long-term rest in grasslands areas improves composition and structure of vegetation to support more bird biodiversity (Sliwinski et al., 2019). In fact, new ecological systems, such as silvopastoral systems in *N. antarctica* forests had been applied in several private lands through the application of forest sustainable management (Peri, Bahamonde, et al., 2016). This strategy increased the richness and diversity of flora and birds, however the conservation of managed forest structures change bird composition, incorporating species from surrounding areas (Benitez, 2021). While, another strategy for bird conservation, is the inclusion in private areas of new economic activities related to birdwatching in the segment of ecotourism (Sekercioglu, 2002). This study showed that combined PB maps with others studies (e.g., human footprint map) it is possible improve conservation studies and assist biodiversity conservation strategies.

5. Conclusions

PHS models allowed us to increase our knowledge about autoecology, potential distribution and environmental requirements (marginality and specialization) of bird species in southern Patagonia. Our study showed how species related to *Nothofagus* forest environment presented the highest marginality and specialization values and narrower potential habitat distribution compared with grassland bird species. However, some grassland species showed high restricted habitats that need to be considered for conservation. The development of a map of PB using the most common species permitted us to identify areas with the highest PB values at different landscape levels, highlighting Magellanic grass steppes and shrub-lands at regional level and ecotone *N. antarctica* forest areas at forest landscape level. Moreover, combining high PB values with two level of human pressures (HFP map) we could spatially located PCA of birds to assist birds' conservation strategies. Hotspot of conservation were in northern and western environments, while south steppes and east coast displayed most of the threatened areas. Additionally, at forest landscape level *Nothofagus* forest environment showed several hotspot of conservation in ecotone areas near to protected areas borders, while threatened areas were grouped in the southernmost part of *Nothofagus* forest distribution. This study showed that to improve bird conservation strategies it is necessary to include the most common bird species of different environments, consider different scale analysis to highpoint specialist and generalist species. Moreover, including external variables, as human footprint map, allowed us to improve the identification of PCA of bird species under human pressures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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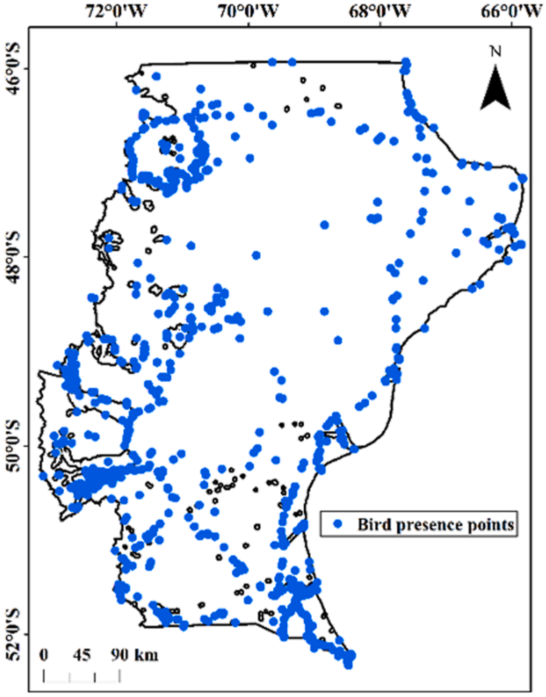
Appendix A. Brid presence data points.



Appendix B. Taxonomy, code, general distribution and red list category of native bird species based on Narosky and Yzurieta (2005) and IUCN (2023), selected for the modelling of potential habitat suitability of Santa Cruz province. NR = native resident/breeding, NB = native breeding, NNB = native no breeding and LC = least concern.

N	Species	ACRON	Suborder	Family	Distribution	IUCN Red List Category
1	*Agriornis lividus*	AGLI	Tyranni	Tyrannidae	NR	LC
2	*Agriornis micropterus*	AGMI	Tyranni	Tyrannidae	NR	LC
3	*Agelaius thilius*	AGTH	Passeri	Icteridae	NR	LC
4	*Anthus correndera*	ANCO	Passeri	Motacillidae	NR	LC
5	*Anairetes parulus*	ANPA	Tyranni	Tyrannidae	NR	LC
6	*Aphrastura spinicauda*	APSP	Tyranni	Furnariidae	NR	LC
7	*Asthenes anthoides*	ASAN	Tyranni	Furnariidae	NR	LC
8	*Asthenes modesta*	ASMO	Tyranni	Furnariidae	NR	LC
9	*Asthenes pyrrholeuca*	ASPY	Tyranni	Furnariidae	NR	LC
10	*Cinclodes oustaleti*	CIOU	Tyranni	Furnariidae	NR	LC
11	*Cinclodes patagonicus*	CIPA	Tyranni	Furnariidae	NR	LC
12	*Cistothorus platensis*	CIPL	Passeri	Troglodytidae	NR	LC
13	*Curaeus curaeus*	CUCU	Passeri	Icteridae	NR	LC
14	*Elaenia albiceps chilensis*	ELAL	Tyranni	Tyrannidae	NB	LC
15	*Eremobius phoenicurus*	ERPH	Tyranni	Furnariidae	NR	LC
16	*Geositta antarctica*	GEAN	Tyranni	Furnariidae	NB-NNB	LC
17	*Geositta cunicularia*	GECU	Tyranni	Furnariidae	NR	LC
18	*Geositta rufipennis*	GERU	Tyranni	Furnariidae	NR	LC
19	*Hirundo rustica*	HIRU	Passeri	Hirundinidae	NNB	LC
20	*Hymenops perspicillatus*	HYPE	Tyranni	Tyrannidae	NR	LC
21	*Leptasthenura aegithaloides*	LEAE	Tyranni	Furnariidae	NR	LC
22	*Lessonia rufa*	LERU	Tyranni	Tyrannidae	NB	LC
23	*Mimus patagonicus*	MIPA	Passeri	Mimidae	NR	LC
24	*Molothrus bonariensis*	MOBO	Passeri	Icteridae	NR	LC
25	*Muscisaxicola albilora*	MUAL	Tyranni	Tyrannidae	NB	LC
26	*Muscisaxicola maculirostris*	MUMA	Tyranni	Tyrannidae	NB	LC
27	*Neoxolmis rufiventris*	NERU	Tyranni	Tyrannidae	NB	LC
28	*Phrygilus fruticeti*	PHFR	Passeri	Thraupidae	NR	LC
29	*Phrygilus gayi*	PHGA	Passeri	Thraupidae	NR	LC
30	*Phrygilus patagonicus*	PHPA	Passeri	Thraupidae	NR	LC
31	*Phytotoma rara*	PHRA	Tyranni	Cotingidae	NB	LC
32	*Phrygilus unicolor*	PHUN	Passeri	Thraupidae	NR	LC
33	*Progne elegans*	PREL	Passeri	Hirundinidae	NB	LC
34	*Pteroptochos tarnii*	PTTA	Tyranni	Rhinocryptidae	NR	LC

(*continued on next page*)

(*continued*)

N	Species	ACRON	Suborder	Family	Distribution	IUCN Red List Category
35	*Pygarrhichas albogularis*	PYAL	Tyranni	Furnariidae	NR	LC
36	*Pygochelidon cyanoleuca*	PYCY	Passeri	Hirundinidae	NB	LC
37	*Scytalopus magellanicus*	SCMA	Tyranni	Rhinocryptidae	NR	LC
38	*Sicalis auriventris*	SIAU	Passeri	Thraupidae	NR	LC
39	*Sicalis lebruni*	SILE	Passeri	Thraupidae	NR	LC
40	*Spinus barbatus*	SPBA	Passeri	Fringillidae	NR	LC
41	*Sturnella loyca*	STLO	Passeri	Icteridae	NR	LC
42	*Tachycineta meyeni*	TAME	Passeri	Hirundinidae	NB	LC
43	*Troglodytes aedon*	TRAE	Passeri	Troglodytidae	NR	LC
44	*Turdus falcklandii*	TUFA	Passeri	Turdidae	NR	LC
45	*Upucerthia dumetaria*	UPDU	Tyranni	Furnariidae	NR	LC
46	*Xolmis pyrope*	XOPY	Tyranni	Tyrannidae	NR	LC
47	*Zonotrichia capensis*	ZOCA	Passeri	Emberizidae	NR	LC

Appendix C. Explanatory variables used in modelling of habitat suitability of birds.

Category	Description	Code	Unit	Data source
Climate	annual mean temperature	AMT	°C	WorldClim(1)
	mean diurnal range	MDR	°C	WorldClim(1)
	isothermality	ISO	%	WorldClim(1)
	temperature seasonality	TS	°C	WorldClim(1)
	max temperature of warmest month	MAXWM	°C	WorldClim(1)
	min temperature of coldest month	MINCM	°C	WorldClim(1)
	temperature annual range	TAR	°C	WorldClim(1)
	mean temperature of wettest quarter	MTWEQ	°C	WorldClim(1)
	mean temperature of driest quarter	MTDQ	°C	WorldClim(1)
	mean temperature of warmest quarter	MTWAQ	°C	WorldClim(1)
	mean temperature of coldest quarter	MTCQ	°C	WorldClim(1)
	annual precipitation	AP	$mm.yr^{-1}$	WorldClim(1)
	precipitation of wettest month	PWEM	$mm.yr^{-1}$	WorldClim(1)
	precipitation of driest month	PDM	$mm.yr^{-1}$	WorldClim(1)
	precipitation seasonality	PS	%	WorldClim(1)
	precipitation of wettest quarter	PWEQ	$mm.yr^{-1}$	WorldClim(1)
	precipitation of driest quarter	PDQ	$mm.yr^{-1}$	WorldClim(1)
	precipitation of warmest quarter	PWAQ	$mm.yr^{-1}$	WorldClim(1)
	precipitation of coldest quarter	PCQ	$mm.yr^{-1}$	WorldClim(1)
	global potential evapo-transpiration	EVTP	$mm.yr^{-1}$	CSI (2)
	global aridity index	GAI		CSI (2)
Topography	elevation	ELE	m.a.s.l.	DEM(3)
	slope	SLO	degree	DEM(3)
	aspect cosine	ASPC	cosine	DEM(3)
	aspect sine	ASPS	sine	DEM(3)
	distance to locality	DL	km	SIT Santa Cruz(4)
	distance to lakes	DLK	km	SIT Santa Cruz(4)
	distance to rivers	DR	km	SIT Santa Cruz(4)
	distance to routs	DRO	km	SIT Santa Cruz(4)
Landscape	forest edge density	ED	$m.ha^{-1}$	Forest map 4/ Fragstats(5)
	total core area	TCA	ha	Forest map 4/ Fragstats(5)
	large parch index	LPI	%	Forest map 4/ Fragstats(5)
	normalized difference vegetation index	NDVI		MODIS(6)
	net primary productivity	NPP	$gr\ C.m^2.yr^{-1}$	MODIS(7)
	desertification	DES	degree	CENPAT(8)
	total forests	TF	occurrence	Forest map4
	total mixed forests	TMF	occurrence	Forest map4
	total *Nothofagus pumilio*	TNP	occurrence	Forest map4
	total *Nothofagus antarctica*	TNA	occurrence	Forest map4
	total *Nothofagus betuloides*	TNB	occurrence	Forest map4

(1) Hijmans et al. (2005), (2) Consortium for Spatial Information (CSI) (Zomer et al., 2008), (3) Farr et al. (2007), (4) SIT-Santa Cruz (https://www.sitsantacruz.gob.ar), (5) McGarigal et al. (2012), (6) ORNL DAAC (2018), (7) Zhao and Running (2010), (8) Del Valle et al. (1998).

Appendix D. Number of species' presence points in each natural environments and total in Santa Cruz province, percentage of presence points (species' presence point for each natural environment / total) between brackets and followed by the rank (1 to 15) in black for the 15 most dominant species of each natural environments (NF = *Nothofagus* forests, SAG = sub-Andean grasslands, HMGS = humid Magellanic grass steppe, DMGS = dry Magellanic grass steppe, SL = shrub-lands, CP = central plateau, SSJG = shrub-steppe San Jorge Gulf, MP = mountains and plateaus). Codes for bird species are presented in Appendix 1.

ACRON	NF	SAG	Magellanic grass steppes		SL	Central plateau			Total
			HMGS	DMGS		CP	SSJG	MP	
AGLI	24(53%)**10**	13(29%)**8**	0(0%)	0(0%)	0(0%)	6(13%)	0(0%)	2(4%)	45
AGMI	5(11%)	9(20%)	0(0%)	0(0%)	0(0%)	23(51%)**1**	3(7%)**10**	5(11%)**7**	45
AGTH	6(10%)	22(37%)**5**	2(3%)	1(2%)	3(5%)	18(30%)**15**	0(0%)	8(13%)**3**	60
ANCO	12(7%)	34(19%)	29(16%)**4**	56(31%)**3**	11(6%)	21(12%)	4(2%)	4(8%)**9**	182
ANPA	26(41%)**14**	10(16%)	7(11%)**10**	3(5%)	3(5%)	13(21%)	0(0%)	1(2%)	63
APSP	80(81%)**4**	12(12%)	3(3%)	0(0%)	1(1%)	3(3%)	0(0%)	0(0%)	99
ASAN	10(11%)	9(10%)	32(36%)**1**	33(37%)**2**	2(2%)	3(3%)	0(0%)	1(1%)	90
ASMO	6(14%)	10(23%)**13**	3(7%)	4(9%)	2(5%)	17(39%)**4**	0(0%)	2(5%)	44
ASPY	8(12%)	14(21%)	1(2%)	5(8%)	6(9%)**5**	23(35%)**10**	6(9%)**4**	3(5%)	66
CIOU	11(42%)**13**	7(27%)**11**	3(12%)**9**	2(8%)	0(0%)	3(12%)	0(0%)	0(0%)	26
CIPA	31(53%)**9**	11(19%)	5(9%)	1(2%)	1(2%)	6(10%)	0(0%)	4(5%)	58
CIPL	8(21%)	11(28%)**9**	3(8%)	4(10%)	3(8%)**10**	9(23%)	0(0%)	1(3%)	39
CUCU	37(66%)**8**	15(27%)**12**	3(5%)	0(0%)	0(0%)	1(2%)	0(0%)	0(0%)	56
ELAL	6(30%)**15**	4(20%)	2(10%)**12**	0(0%)	2(10%)**4**	5(25%)	0(0%)	1(5%)	20
ERPH	1(1%)	6(8%)	3(4%)	7(10%)	11(15%)**1**	29(40%)**2**	11(15%)**2**	4(6%)**14**	72
GEAN	4(6%)	22(34%)**7**	4(6%)	9(14%)	2(3%)	21(32%)**12**	0(0%)	3(5%)	65
GECU	13(7%)	24(13%)	31(16%)**3**	46(24%)**6**	16(8%)**7**	41(22%)	15(8%)**6**	4(2%)	190
GERU	9(28%)	7(22%)**15**	0(0%)	0(0%)	0(0%)	12(38%)**6**	0(0%)	4(13%)**5**	32
HIRU	3(6%)	5(11%)	8(17%)**2**	18(38%)**1**	4(9%)**6**	8(17%)	1(2%)	0(0%)	47
HYPE	9(12%)	32(44%)**2**	0(0%)	0(0%)	0(0%)	23(32%)**14**	0(0%)	9(12%)**6**	73
LEAE	9(11%)	11(13%)	8(10%)	11(13%)	5(6%)	30(36%)**9**	6(7%)9	4(5%)	84
LERU	39(9%)	81(18%)	56(12%)**8**	108(24%)**7**	33(7%)**14**	92(20%)	29(6%)**11**	18(4%)	456
MIPA	11(7%)	33(21%)	2(1%)	8(5%)	18(11%)**2**	62(39%)**3**	12(8%)**7**	12(8%)**12**	158
MOBO	3(15%)	8(40%)**3**	0(0%)	0(0%)	0(0%)	5(25%)	0(0%)	4(20%)**2**	20
MUAL	23(74%)**6**	5(16%)	0(0%)	0(0%)	1(3%)	1(3%)	0(0%)	1(3%)	31
MUMC	4(11%)	13(34%)**6**	2(5%)	2(5%)	1(3%)	13(34%)**11**	0(0%)	3(8%)**10**	38
NERU	8(7%)	18(15%)	16(13%)**7**	18(15%)	13(11%)**3**	39(32%)**13**	10(8%)**5**	1(1%)	123
PHFR	10(9%)	16(15%)	4(4%)	6(5%)	8(7%)**13**	41(37%)**7**	14(13%)**3**	11(10%)**8**	110
PHGA	40(14%)	46(17%)	37(13%)**6**	47(17%)**11**	21(8%)**11**	67(24%)	6(2%)	13(5%)	277
PHPA	43(69%)**7**	12(19%)	0(0%)	0(0%)	3(5%)	3(5%)	0(0%)	1(2%)	62
PHRA	29(50%)**11**	16(28%)**10**	0(0%)	0(0%)	0(0%)	13(22%)	0(0%)	0(0%)	58
PHUN	11(46%)**12**	11(46%)**1**	0(0%)	0(0%)	0(0%)	2(8%)	0(0%)	0(0%)	24
PREL	0(0%)	2(45)	0(0%)	0(0%)	0(0%)	17(36%)**8**	12(26%)**1**	16(34%)**1**	47
PTTA	19(90%)**2**	2(10%)	0(0%)	0(0%)	0(0%)	0(0%)	0(0%)	0(0%)	21
PYAL	40(91%)**1**	4(9%)	0(0%)	0(0%)	0(0%)	0(0%)	0(0%)	0(0%)	44
PYCY	21(13%)	35(22%)**14**	13(8%)	25(16%)**14**	11(7%)**15**	24(15%)	8(5%)**14**	29(13%))**4**	157
SCMA	27(87%)**3**	4(13%)	0(0%)	0(0%)	0(0%)	0(0%)	0(0%)	0(0%)	31
SIAU	3(13%)	9(38%)**4**	1(4%)	0(0%)	1(4%)	9(38%)**5**	0(0%)	1(4%)	24
SILE	11(11%)	8(8%)	15(15%)**5**	30(29%)**4**	8(8%)**9**	22(21%)	5(5%)**15**	4(4%)	103
SPBA	55(23%)	36(15%)	12(5%)	44(18%)**9**	9(4%)	58(24%)	11(5%)	14(6)**13**	239
STLO	53(15%)	62(17%)	24(7%)	90(25%)**5**	29(8%)**8**	71(19%)	19(5%)**13**	17(5%)	365
TAME	64(28%)	50(22%)	14(6%)	40(17%)**10**	12(5%)	29(13%)	3(1%)	18(8%)**11**	230
TRAE	88(29%)	48(16%)	30(10%)**13**	50(17%)**12**	14(5%)	47(16%)	9(3%)	14(5%)	300
TUFA	80(28%)	54(19%)	30(11%)**11**	47(17%)**13**	13(5%)	42(15%)	3(1%)	15(5%)**15**	284
UPDU	14(7%)	37(19%)	19(10%)**14**	29(15%)**15**	14(7%)**12**	55(29%)	14(7%)**8**	9(5%)	191
XOPY	64(80%)**5**	11(14%)	3(4%)	0(0%)	1(1%)	0(0%)	0(0%)	0(0%)	80
ZOCA	87(15%)	92(16%)	56(10%)**15**	117(20%)**8**	33(6%)	140(24%)	31(5%)**12**	27(5%)	583
Total	1,165	1,001	481	681	315	1,168	232	289	5,512

Appendix E. Correlation indices among the variables included in the modelling of the habitat suitability maps of the different bird species. Significant correlation values (>0.80) were identified with one asterisk.

Variables	MINCM	AP	EVTP	ELE	DR	NDVI
AMT	−0.25	0.43	0.96*	0.32	0.61	0.58
MINCM		−0.59	−0.49	−0.85*	0.03	−0.55
AP			0.56	0.69	0.22	0.51
EVTP				0.53	0.55	0.67
ELE					0.09	0.45
DR						0.19

AMT = annual mean temperature (°C), MINCM = minimum temperature of the coldest month (°C), AP = annual precipitation (mm.year^{-1}), EVTP = global potential evapo-transpiration (mm.year^{-1}), ELE = elevation (m.a.s.l.), DR = distance to rivers (km), NDVI = normalized difference vegetation index.

Appendix F. Model outputs for each potential suitability habitat of birds, eigenvalues and explained information between brackets for the first four axes. Codes for bird species are presented in Appendix 1.

ACRON	Axis 1	Axis 2	Axis 3	Axis 4	Total explained information
AGLI	188.35(0.95)	5.10(0.03)	2.78(0.01)	1.50(0.01)	(1.00)
AGMI	34.82(0.94)	1.05(0.03)	0.55(0.02)	0.45(0.01)	(1.00)
AGTH	9.14(0.58)	3.38(0.21)	1.76(0.11)	0.92(0.06)	(0.96)
ANCO	5.33(0.54)	2.48(0.24)	1.35(0.13)	0.84(0.08)	(1.00)
ANPA	4.42(0.38)	3.92(0.34)	1.84(0.16)	1.04(0.10)	(0.97)
APSP	19.18(0.17)	88.26(0.78)	3.51(0.03)	1.13(0.01)	(1.00)
ASAN	30.93(0.65)	13.28(0.28)	1.94(0.04)	0.90(0.02)	(1.00)
ASMO	30.81(0.86)	2.48(0.07)	1.35(0.04)	0.72(0.02)	(1.00)
ASPY	18.74(0.87)	1.34(0.06)	0.81(0.04)	0.62(0.03)	(1.00)
CIOU	8.97(0.11)	66.81(0.85)	1.81(0.02)	0.84(0.01)	(1.00)
CIPA	2.30(0.26)	3.85(0.43)	1.56(0.17)	0.88(0.10)	(0.96)
CIPL	28.69(0.78)	4.45(0.12)	2.49(0.07)	0.65(0.02)	(1.00)
CUCU	39.82(0.25)	116.90(0.72)	3.81(0.02)	1.12(0.01)	(1.00)
ELAL	14.47(0.88)	1.15(0.07)	0.57(0.04)	0.26(0.02)	(1.00)
ERPH	83.08(0.91)	6.03(0.07)	1.64(0.01)	0.47(0.01)	(1.00)
GEAN	10.59(0.60)	5.04(0.28)	1.42(0.08)	0.49(0.03)	(1.00)
GECU	28.36(0.87)	1.67(0.05)	1.29(0.04)	0.76(0.02)	(1.00)
GERU	93.46(0.94)	4.20(0.04)	1.57(0.02)	0.44(0.00)	(1.00)
HIRU	45.83(0.77)	8.96(0.15)	2.92(0.05)	1.57(0.03)	(1.00)
HYPE	78.70(0.94)	3.11(0.04)	1.00(0.01)	0.53(0.01)	(1.00)
LEAE	15.81(0.81)	2.05(0.11)	0.88(0.05)	0.81(0.04)	(1.00)
LERU	6.25(0.60)	2.23(0.21)	1.22(0.12)	0.72(0.07)	(1.00)
MIPA	33.06(0.89)	2.32(0.06)	0.86(0.02)	0.74(0.02)	(1.00)
MOBO	56.64(0.95)	1.92(0.03)	0.62(0.01)	0.38(0.01)	(1.00)
MUAL	193.50(0.95)	6.74(0.03)	1.59(0.01)	1.11(0.01)	(1.00)
MUMC	36.17(0.82)	4.33(0.10)	2.63(0.06)	0.65(0.02)	(1.00)
NERU	39.26(0.91)	1.53(0.04)	1.24(0.03)	0.74(0.02)	(1.00)
PHFR	22.14(0.88)	1.69(0.07)	0.77(0.03)	0.51(0.02)	(1.00)
PHGA	15.72(0.82)	1.82(0.10)	0.97(0.05)	0.66(0.03)	(1.00)
PHPA	39.92(0.26)	109.73(0.71)	2.69(0.02)	1.16(0.01)	(1.00)
PHRA	202.94(0.96)	3.32(0.02)	2.00(0.01)	1.41(0.01)	(1.00)
PHUN	50.85(0.89)	4.06(0.07)	1.66(0.03)	0.35(0.01)	(1.00)
PREL	90.12(0.71)	31.54(0.25)	3.52(0.03)	1.53(0.01)	(1.00)
PTTA	43.50(0.28)	107.95(0.69)	4.91(0.03)	0.94(0.01)	(1.00)
PYAL	27.97(0.11)	218.55(0.87)	4.16(0.02)	0.93(0.00)	(1.00)
PYCY	22.41(0.87)	1.75(0.07)	1.14(0.04)	0.61(0.02)	(1.00)
SCMA	38.23(0.24)	114.47(0.73)	3.46(0.02)	1.33(0.01)	(1.00)
SIAU	29.85(0.79)	5.06(0.13)	2.73(0.07)	0.21(0.01)	(1.00)
SILE	14.70(0.78)	2.49(0.13)	0.99(0.05)	0.71(0.04)	(1.00)
SPBA	13.07(0.77)	2.51(0.15)	0.88(0.05)	0.55(0.03)	(1.00)
STLO	12.09(0.74)	2.48(0.15)	1.03(0.06)	0.68(0.04)	(1.00)
TAME	14.08(0.77)	2.58(0.14)	1.10(0.06)	0.45(0.03)	(1.00)
TRAE	10.64(0.72)	2.64(0.18)	1.07(0.07)	0.49(0.03)	(1.00)
TUFA	9.70(0.67)	3.12(0.21)	1.25(0.09)	0.49(0.03)	(1.00)
UPDU	19.36(0.82)	1.69(0.07)	1.35(0.06)	0.64(0.03)	(0.98)
XOPY	64.11(0.38)	100.65(0.59)	4.19(0.03)	1.02(0.01)	(1.00)
ZOCA	13.60(0.80)	1.76(0.10)	0.91(0.05)	0.64(0.04)	(1.00)

Appendix G. Model outputs for each potential suitability habitat of birds, score matrix with eigenvectors showing in black the highest coefficient (in absolute value) of each axis for the ecogeographical variables used in each modelling.

ACRON	Variable	Axis 1	Axis 2	Axis 3	Axis 4	ACRON	Variable	Axis 1	Axis 2	Axis 3	Axis 4
AGLI	AMT	0.18	**−0.87**	−0.06	0.31	CIPA	AMT	0.14	**−0.90**	0.25	0.16
	AP	**0.62**	0.14	0.03	0.15		AP	**0.59**	0.02	0.29	0.12
	MINCM	−0.06	−0.04	**−0.84**	−0.42		MINCM	−0.11	−0.22	**0.86**	−0.64
	ELE	0.09	−0.44	−0.53	**−0.83**		ELE	0.09	−0.35	−0.32	**−0.73**
	NDVI	**0.75**	0.15	−0.02	−0.13		NDVI	**0.78**	0.16	−0.11	−0.12
AGMI	AMT	0.51	0.11	**−0.80**	−0.16	CIPL	AMT	0.33	**−0.57**	0.51	−0.18
	AP	0.44	**−0.58**	−0.04	**0.71**		AP	**0.45**	−0.34	−0.21	−0.36
	ELE	0.32	−0.57	0.09	**−0.68**		MINCM	−0.16	**−0.57**	0.36	**0.61**
	NDVI	**0.67**	0.58	0.59	−0.03		ELE	0.01	0.38	**0.75**	0.57
AGTH	AMT	0.37	0.27	**0.71**	0.22		NDVI	**0.82**	0.30	−0.03	0.38
	AP	**0.40**	0.17	0.03	0.13	CUCU	AMT	0.14	−0.41	−0.56	**0.76**
	MINCM	−0.13	0.23	0.43	**−0.69**		AP	**0.57**	−0.01	0.15	−0.03
	ELE	0.04	**−0.91**	0.47	−0.64		ELE	0.05	−0.16	**−0.58**	−0.46
	NDVI	**0.83**	−0.13	−0.29	−0.23		NDVI	**0.80**	−0.05	0.11	−0.14
ANCO	AMT	0.33	**−0.76**	**0.78**	−0.10		DR	−0.12	**−0.90**	0.57	−0.44
	AP	0.34	−0.23	−0.55	**−0.71**	ELAL	AMT	0.26	**−0.93**	−0.17	0.04
	ELE	−0.06	−0.50	−0.27	**0.60**		AP	0.61	0.16	−0.55	**−0.67**

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(*continued*)

ACRON	Variable	Axis 1	Axis 2	Axis 3	Axis 4	ACRON	Variable	Axis 1	Axis 2	Axis 3	Axis 4
	NDVI	**0.88**	0.35	−0.10	0.35		ELE	0.27	−0.18	**0.78**	−0.27
ANPA	AMT	0.20	−0.38	**0.83**	−0.10		NDVI	**0.70**	0.27	0.24	0.69
	AP	**0.54**	0.23	0.20	−0.14	ERPH	AMT	**0.58**	−0.38	0.46	**0.70**
	MINCM	−0.07	−0.06	0.12	**0.72**		AP	0.26	**0.83**	0.46	−0.01
	ELE	0.04	**−0.89**	−0.41	0.66		ELE	−0.05	0.12	**−0.36**	0.18
	NDVI	**0.81**	−0.01	−0.31	0.15		EVTP	0.53	0.29	**−0.67**	−0.69
APSP	AMT	0.11	0.41	**−0.68**	0.64		NDVI	**0.57**	−0.25	−0.09	−0.06
	AP	**0.66**	0.02	0.19	0.04	GEAN	AMT	0.21	**−0.62**	0.37	−0.26
	ELE	0.10	0.18	−0.35	**−0.70**		AP	0.29	−0.07	**−0.90**	−0.14
	NDVI	**0.73**	0.03	0.08	−0.08		MINCM	−0.55	−0.60	−0.18	**0.67**
	DR	−0.11	**0.90**	0.61	−0.30		ELE	0.45	−0.50	−0.04	**0.60**
ASAN	AMT	0.26	**−0.87**	0.40	0.08		NDVI	**0.61**	0.08	0.16	0.31
	AP	0.39	0.10	0.21	**−0.87**	GECU	AMT	0.38	**0.67**	0.54	−0.14
	MINCM	−0.07	−0.22	**0.77**	0.01		AP	0.38	0.10	**−0.70**	**−0.72**
	ELE	−0.15	**−0.42**	−0.40	0.25		MINCM	−0.22	0.26	**0.41**	−0.19
	NDVI	**0.87**	0.13	−0.21	0.41		ELE	0.00	**0.63**	0.15	0.55
ASMO	AMT	0.32	**−0.48**	−0.11	0.35		NDVI	**0.82**	−0.29	0.18	0.35
	AP	0.37	0.19	**0.77**	0.12	GERU	AMT	0.25	−0.13	**0.68**	−0.05
	MINCM	−0.33	**−0.64**	0.27	**−0.65**		AP	**0.54**	0.07	0.04	−0.51
	ELE	0.26	−0.57	0.43	**−0.60**		MINCM	−0.31	**−0.74**	−0.48	0.35
	NDVI	**0.76**	0.02	−0.36	−0.29		ELE	0.37	**−0.66**	−0.50	−0.23
ASPY	AMT	0.47	−0.21	−0.20	**−0.84**		NDVI	**0.64**	0.02	−0.25	**0.75**
	AP	0.41	−0.58	**0.75**	0.00	HIRU	AMT	0.42	0.56	**0.77**	**−0.70**
	ELE	0.08	**−0.62**	−0.60	0.24		AP	0.33	−0.38	**−0.50**	−0.21
	NDVI	**0.78**	0.49	−0.21	0.48		ELE	−0.23	**−0.43**	0.32	−0.01
CIOU	AMT	0.18	0.45	**−0.73**	0.54		EVTP	0.41	**−0.59**	−0.23	0.67
	AP	**0.57**	0.00	0.13	0.15		NDVI	**0.71**	0.05	0.01	0.12
	ELE	0.12	0.14	−0.25	**−0.78**						
	NDVI	**0.78**	0.05	0.23	−0.16						
	DR	−0.15	**0.88**	0.58	−0.22						

ACRON	**Variable**	**Axis 1**	**Axis 2**	**Axis 3**	**Axis 4**	**ACRON**	**Variable**	**Axis 1**	**Axis 2**	**Axis 3**	**Axis 4**
HYPE	AMT	0.42	0.06	**0.87**	−0.28	PHPA	AMT	0.13	−0.46	−0.50	**−0.76**
	AP	0.40	−0.04	0.10	**0.88**		AP	**0.65**	−0.04	0.21	0.01
	MINCM	−0.08	**−0.99**	0.03	0.30		ELE	0.12	−0.15	**−0.65**	0.44
	NDVI	**0.81**	−0.11	−0.49	−0.27		NDVI	**0.73**	0.00	0.09	0.13
LEAE	AMT	0.48	0.17	0.27	**−0.79**		DR	−0.12	**−0.88**	0.53	0.47
	AP	0.44	−0.34	**−0.89**	−0.14	PHRA	AMT	0.17	**0.55**	0.15	0.51
	ELE	−0.03	**0.92**	0.14	0.12		AP	**0.65**	−0.14	0.05	0.14
	NDVI	**0.76**	0.12	0.35	0.58		MINCM	−0.13	0.41	**−0.79**	−0.12
LERU	AMT	0.38	−0.59	**0.69**	−0.35		ELE	0.16	**0.71**	−0.59	**−0.84**
	AP	0.42	−0.18	**−0.72**	**−0.59**		NDVI	**0.72**	−0.09	−0.09	−0.09
	ELE	−0.04	**−0.71**	0.05	0.55	PHUN	AMT	0.22	**−0.87**	0.46	−0.05
	NDVI	**0.83**	0.33	0.04	0.48		AP	0.58	0.15	0.29	**0.81**
MIPA	AMT	0.47	0.40	0.00	**−0.81**		ELE	0.13	−0.42	**−0.81**	−0.10
	AP	0.37	−0.19	**−0.83**	0.01		NDVI	**0.77**	0.20	−0.21	−0.58
	ELE	0.02	**−0.63**	0.43	−0.10	PREL	AMT	**0.81**	0.23	−0.17	−0.54
	EVTP	0.43	**−0.60**	0.20	0.54		AP	0.17	**−0.94**	−0.18	0.28
	NDVI	**0.68**	0.23	0.31	0.22		MINCM	0.18	−0.08	**0.58**	0.54
MOBO	AMT	0.47	−0.10	**0.88**	0.04		ELE	0.11	−0.25	**0.78**	−0.05
	AP	0.46	0.38	−0.19	**0.85**		NDVI	0.52	0.03	−0.04	**0.58**
	ELE	0.14	**−0.92**	−0.04	−0.17	PTTA	AMT	0.10	0.36	**0.68**	−0.61
	NDVI	**0.74**	0.01	−0.43	−0.51		AP	**0.66**	0.04	−0.24	−0.22
MUAL	AMT	0.13	−0.41	**−0.65**	0.66		ELE	0.17	0.14	0.38	**0.67**
	AP	**0.70**	−0.03	0.26	0.10		NDVI	**0.72**	0.01	−0.04	0.17
	ELE	0.14	−0.17	−0.42	**−0.64**		DR	−0.10	**0.92**	−0.58	0.32
	NDVI	**0.68**	−0.02	0.06	−0.17	PYAL	AMT	0.09	0.39	**−0.70**	0.60
	DR	−0.13	**−0.89**	0.58	−0.34		AP	**0.67**	0.02	0.17	0.06
MUMA	AMT	0.33	−0.47	**0.51**	0.27		ELE	0.16	0.19	−0.33	**−0.75**
	AP	0.33	−0.23	**−0.79**	0.18		NDVI	**0.71**	0.02	0.09	−0.01
	MINCM	−0.37	**−0.65**	0.21	−0.62		DR	−0.11	**0.90**	0.61	−0.28
	ELE	0.25	−0.53	−0.09	**−0.66**	PYCY	AMT	0.34	0.57	**−0.81**	0.56
	NDVI	**0.76**	0.16	0.25	−0.28		AP	**0.41**	−0.13	−0.02	0.32
NERU	AMT	0.43	−0.30	**−0.48**	−0.31		EVTP	0.34	**−0.80**	0.57	**−0.76**
	AP	0.37	**0.84**	0.06	−0.48		NDVI	**0.78**	0.17	0.11	−0.08
	MINCM	−0.27	−0.28	**−0.50**	0.11	SCMA	AMT	0.10	−0.51	**−0.67**	0.60
	ELE	0.10	−0.19	**−0.70**	**0.73**		AP	**0.70**	0.01	0.17	0.23
	NDVI	**0.77**	−0.31	0.15	0.35		ELE	0.13	−0.25	−0.31	**−0.67**
PHFR	AMT	0.51	−0.07	−0.09	**0.75**		NDVI	**0.69**	−0.02	0.09	−0.24
	AP	0.39	0.58	**−0.74**	0.04		DR	−0.11	**−0.82**	0.64	−0.29
	ELE	0.07	**0.65**	0.49	−0.13	SIAU	AMT	0.08	**0.93**	−0.17	0.21
	EVTP	**0.45**	0.13	0.43	0.02		AP	0.34	−0.36	**−0.85**	−0.49
	NDVI	**0.62**	−0.47	0.18	−0.64		ELE	**0.67**	0.03	−0.03	**0.69**
PHGA	AMT	0.34	**−0.83**	0.61	0.11		NDVI	**0.65**	0.04	0.50	−0.48
	AP	0.47	−0.15	−0.14	**−0.80**	SILE	AMT	0.37	0.66	**0.74**	0.09
	ELE	0.08	−0.29	**−0.78**	0.46		AP	0.42	−0.18	0.08	**−0.87**

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ACRON	Variable	Axis 1	Axis 2	Axis 3	Axis 4	ACRON	Variable	Axis 1	Axis 2	Axis 3	Axis 4
	NDVI	**0.81**	0.46	−0.09	0.37		ELE	−0.06	**0.72**	−0.53	0.26
							NDVI	**0.83**	−0.15	−0.40	0.42

ACRON	Variable	Axis 1	Axis 2	Axis 3	Axis 4
SPBA	AMT	0.31	−0.57	**0.78**	−0.10
	AP	0.49	0.07	0.08	**0.84**
	ELE	0.03	**−0.79**	−0.52	−0.29
	NDVI	**0.82**	0.20	−0.33	−0.46
STLO	AMT	0.36	0.64	**0.83**	−0.02
	AP	0.46	−0.02	−0.19	**−0.79**
	ELE	−0.02	**0.73**	−0.45	0.39
	NDVI	**0.81**	−0.26	−0.27	0.47
TAME	AMT	0.27	**−0.73**	**−0.75**	0.02
	AP	0.51	0.08	0.07	**0.80**
	ELE	0.03	**−0.64**	0.63	−0.34
	NDVI	**0.82**	0.22	0.19	−0.50
TRAE	AMT	0.25	**−0.73**	**−0.69**	0.08
	AP	0.54	0.08	−0.13	**−0.82**
	ELE	0.04	−0.64	**0.66**	0.24
	NDVI	**0.80**	0.21	0.27	0.52
TUFA	AMT	0.25	**−0.80**	−0.64	0.08
	AP	0.52	0.04	−0.12	**−0.83**
	ELE	0.03	−0.55	**0.72**	0.26
	NDVI	**0.82**	0.24	0.25	0.49
UPDU	AMT	0.44	0.37	**−0.52**	−0.36
	AP	0.42	**−0.61**	−0.20	0.30
	MINCM	−0.23	0.58	−0.45	**0.78**
	ELE	0.10	0.31	**−0.60**	0.35
	NDVI	**0.76**	0.26	0.35	0.23
XOPY	AMT	0.13	−0.45	**−0.65**	**0.68**
	AP	**0.68**	−0.02	0.21	0.01
	ELE	0.11	−0.19	−0.40	**−0.65**
	NDVI	**0.70**	−0.02	0.08	−0.09
	DR	−0.12	**−0.87**	0.61	−0.33
ZOCA	AMT	0.36	−0.64	**0.84**	−0.07
	AP	0.48	−0.07	−0.33	**−0.75**
	ELE	0.03	**−0.69**	−0.40	0.46
	NDVI	**0.80**	0.35	−0.16	0.47

Appendix H. Statistics (mean and standard deviation) of the model adjustment for each potential habitat suitability model of the selected bird species. Codes for bird species are presented in Appendix 1.

ACRON	B	P(B = 0)	Bcont(20)	AVI	CVI
AGLI	0.34(0.58)	0.39(0.23)	0.10(0.51)	0.48(0.31)	0.44(0.30)
AGMI	0.34(0.64)	0.39(0.35)	−0.16(0.50)	0.52(0.30)	0.14(0.28)
AGTH	0.52(0.62)	0.32(0.41)	0.34(0.38)	0.50(0.199	0.45(0.18)
ANCO	0.88(0.10)	0.12(0.10)	0.77(0.14)	0.48(0.25)	0.40(0.22)
ANPA	0.41(0.64)	0.33(0.30)	0.29(0.60)	0.44(0.29)	0.32(0.29)
APSP	0.92(0.19)	0.08(0.19)	0.69(0.29)	0.54(0.16)	0.53(0.16)
ASAN	0.80(0.389	0.16(0.26)	0.64(0.31)	0.52(0.21)	0.50(0.21)
ASMO	0.31(0.48)	0.51(0.27)	0.08(0.37)	0.55(0.24)	0.26(0.23)
ASPY	0.24(0.31)	0.64(0.12)	−0.14(0.42)	0.49(0.23)	0.10(0.22)
CIOU	0.22(0.60)	0.43(0.23)	0.08(0.54)	0.50(0.42)	0.40(0.42)
CIPA	0.11(0.53)	0.55(0.26)	0.02(0.54)	0.38(0.26)	0.33(0.26)
CIPL	0.21(0.77)	0.30(0.31)	0.16(0.70)	0.50(0.46)	0.39(0.43)
CUCU	0.42(0.63)	0.31(0.26)	0.16(0.49)	0.50(0.30)	0.48(0.29)
ELAL	0.22(0.60)	0.45(0.28)	−0.12(0.54)	0.60(0.39)	0.12(0.38)
ERPH	0.22(0.65)	0.39(0.25)	−0.12(0.61)	0.54(0.35)	0.22(0.32)
GEAN	0.30(0.38)	0.58(0.22)	0.22(0.40)	0.52(0.21)	0.29(0.20)
GECU	0.28(0.62)	0.40(0.27)	−0.18(0.37)	0.40(0.16)	0.12(0.19)
GERU	0.14(0.51)	0.59(0.30)	−0.08(0.50)	0.56(0.35)	0.31(0.33)
HIRU	0.32(0.53)	0.52(0.36)	0.06(0.50)	0.51(0.31)	0.23(0.31)
HYPE	0.49(0.64)	0.29(0.33)	0.01(0.65)	0.48(0.25)	0.25(0.29)
LEAE	0.17(0.69)	0.42(0.37)	0.14(0.61)	0.46(0.34)	0.16(0.35)
LERU	0.74(0.25)	0.26(0.25)	0.20(0.45)	0.45(0.22)	0.21(0.21)
MIPA	0.42(0.43)	0.50(0.32)	0.01(0.59)	0.51(0.19)	0.19(0.18)
MOBO	0.11(0.57)	0.54(0.31)	−0.14(0.46)	0.55(0.44)	0.16(0.43)
MUAL	0.15(0.56)	0.51(0.27)	−0.03(0.55)	0.51(0.36)	0.50(0.35)
MUMC	0.26(0.52)	0.53(0.32)	0.02(0.49)	0.53(0.29)	0.30(0.28)
NERU	0.32(0.51)	0.52(0.34)	−0.07(0.55)	0.48(0.27)	0.12(0.26)
PHFR	0.28(0.48)	0.57(0.33)	−0.01(0.62)	0.50(0.30)	0.21(0.28)
PHGA	0.62(0.55)	0.22(0.22)	0.39(0.48)	0.45(0.26)	0.22(0.21)

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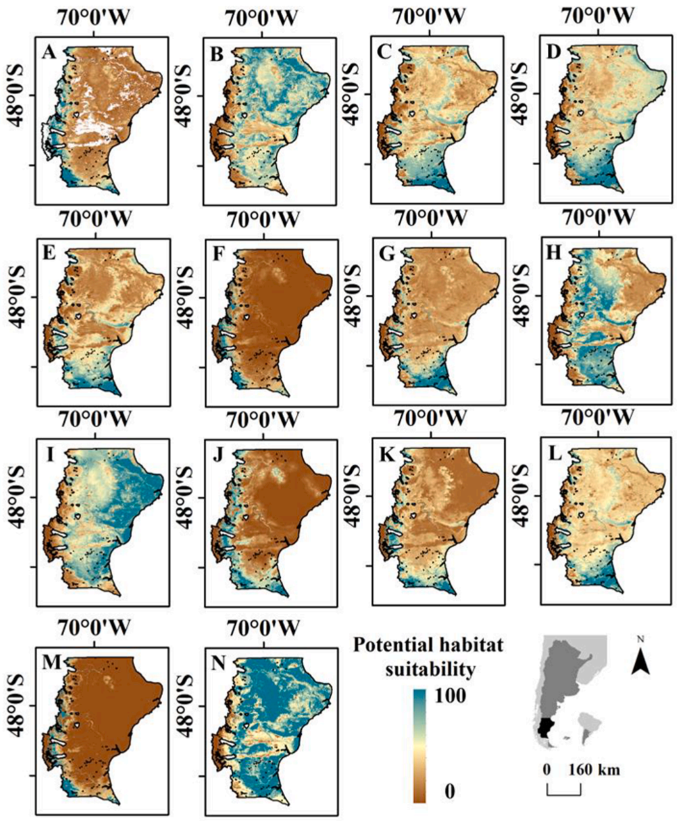
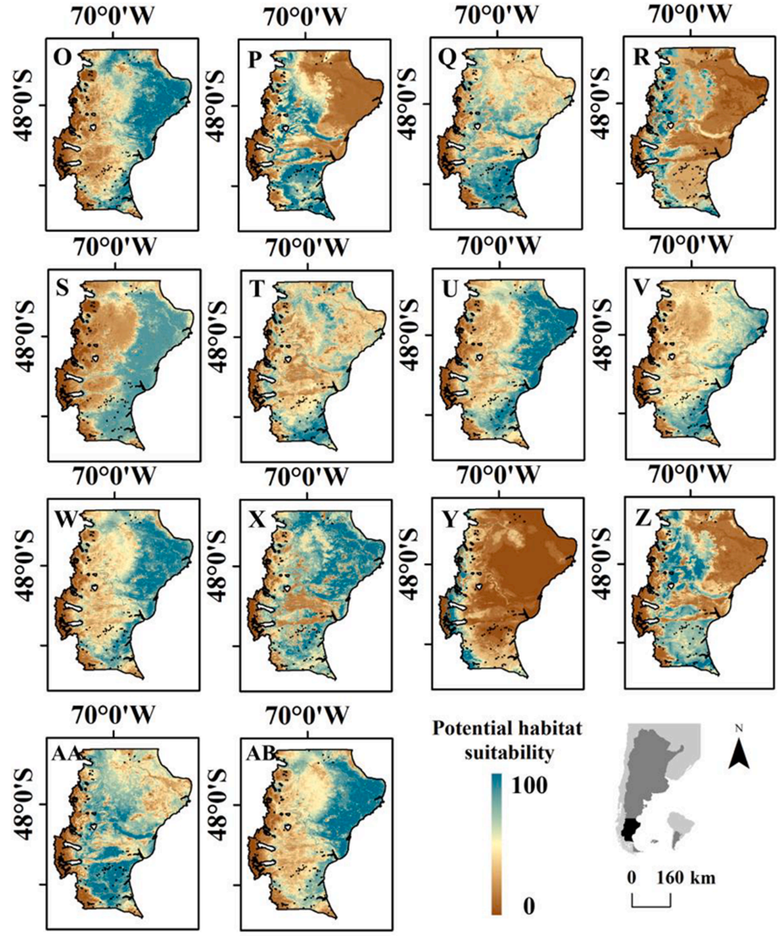
ACRON	B	P(B = 0)	Bcont(20)	AVI	CVI
PHPA	0.60(0.55)	0.25(0.26)	0.42(0.62)	0.55(0.31)	0.53(0.31)
PHRA	0.26(0.57)	0.48(0.31)	0.15(0.43)	0.45(0.25)	0.34(0.26)
PHUN	0.02(0.66)	0.43(0.28)	−0.08(0.44)	0.47(0.41)	0.38(0.41)
PREL	0.36(0.50)	0.50(0.34)	0.10(0.45)	0.49(0.27)	0.36(0.26)
PTTA	0.40(0.66)	0.29(0.23)	0.18(0.48)	0.50(0.34)	0.50(0.34)
PYAL	0.42(0.48)	0.46(0.32)	0.27(0.43)	0.45(0.20)	0.45(0.20)
PYCY	0.42(0.51)	0.42(0.29)	−0.20(0.44)	0.49(0.22)	0.16(0.20)
SCMA	0.17(0.68)	0.39(0.28)	0.07(0.56)	0.55(0.42)	0.54(0.41)
SIAU	0.20(0.68)	0.35(0.21)	0.09(0.55)	0.62(0.46)	0.57(0.45)
SILE	0.72(0.43)	0.20(0.23)	0.19(0.57)	0.45(0.20)	0.27(0.17)
SPBA	0.54(0.39)	0.42(0.32)	−0.16(0.46)	0.50(0.17)	0.14(0.16)
STLO	0.78(0.33)	0.22(0.33)	0.34(0.55)	0.48(0.24)	0.24(0.21)
TAME	0.63(0.58)	0.19(0.17)	0.08(0.52)	0.47(0.24)	0.19(0.24)
TRAE	0.69(0.65)	0.13(0.31)	0.12(0.54)	0.48(0.28)	0.21(0.24)
TUFA	0.64(0.52)	0.24(0.28)	0.35(0.40)	0.49(0.28)	0.34(0.26)
UPDU	0.38(0.42)	0.50(0.24)	−0.03(0.45)	0.48(0.17)	0.19(0.17)
XOPY	0.74(0.41)	0.18(0.18)	0.51(0.38)	0.53(0.18)	0.52(0.18)
ZOCA	0.26(0.66)	0.38(0.29)	−0.26(0.56)	0.45(0.22)	0.12(0.22)

B = Boyce index, P(B = 0) = proportion of validation points, Bcont(20) = continuous Boyce index, AVI = absolute validation index, CVI = contrast validation index.

Appendix I. Maps of potential habitat suitability (PHS) for the selected 47 bird species in Santa Cruz province, where light grey shows low, dark grey shows medium, and black shows high habitat suitability areas. A = *Agriornis lividus*, B = *A. micropterus*, C = *Agelaius thilius*, D = *Anthus correndera*, E = *Anairetes parulus*, F = *Aphrastura spinicauda*, G = *Asthenes anthoides*, H = *A. modesta*, I = *A. pyrrholeuca*, J = *Cinclodes oustaleti*, K = *C. patagonicus*, L = *Cistothorus platensis*, M = *Curaeus curaeus*, N = *Elaenia albiceps chilensis*, O = *Eremobius phoenicurus*, P = *Geositta antarctica*, Q = *G. cunicularia*, R = *G. rufipennis*, S = *Hirundo rustica*, T = *Hymenops perspicillatus*, U = *Leptasthenura aegithaloides*, V = *Lessonia rufa*, W = *Mimus patagonicus*, X = *Molothrus bonariensis*, Y = *Muscisaxicola albilora*, Z = *M. maculirostris*, AA = *Neoxolmis rufiventris*, AB = *Phrygilus fruticeti*, AC = *P. gayi*, AD = *P. patagonicus*, AE = *Phytotoma rara*, AF = *P. unicolor*, AG = *Progne elegans*, AH = *Pteroptochos tarnii*, AI = *Pygarrhichas albogularis*, AJ = *Pygochelidon cyanoleuca*, AK = *Scytalopus magellanicus*, AL = *Sicalis auriventris*, AM = *S. lebruni*, AN = *Spinus barbatus*, AO = *Sturnella loyca*, AP = *Tachycineta meyeni*, AQ = *Troglodytes aedon*, AR = *Turdus falcklandii*, AS = *Upucerthia dumetaria*, AT = *Xolmis pyrope*, and AU = *Zonotrichia capensis*.

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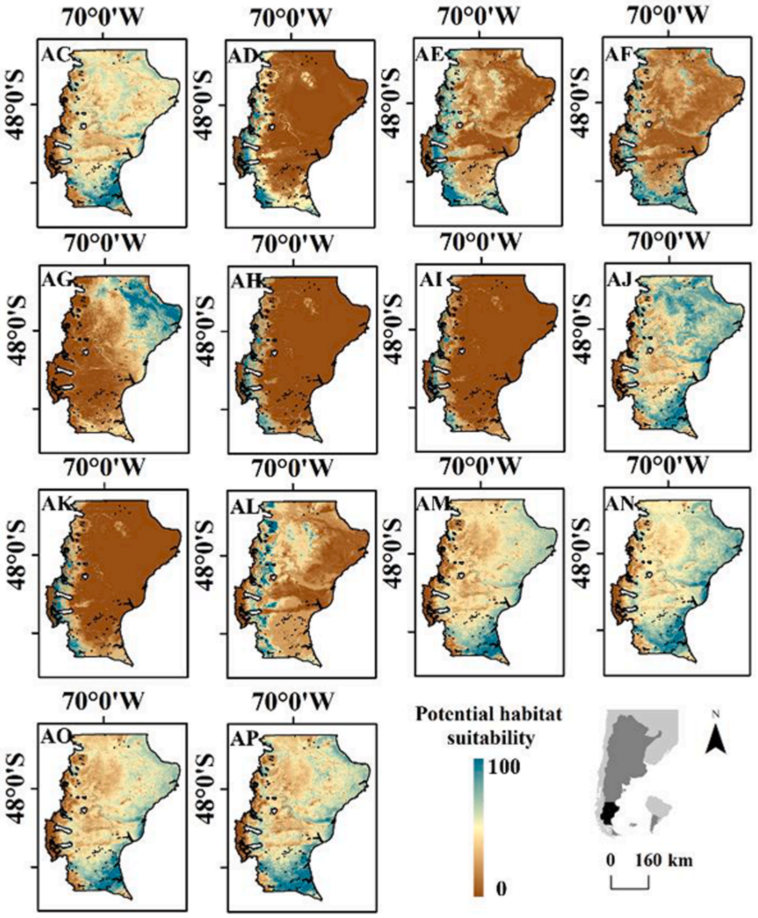

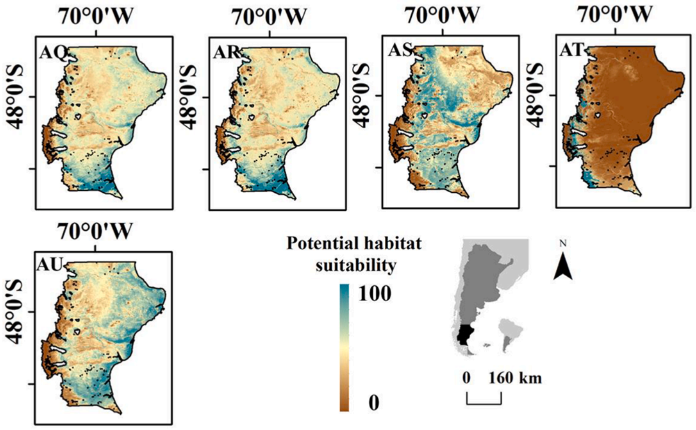

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