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Article

Conservation of the Black-collared Swallow, *Pygochelidon melanoleuca* (Wied, 1820) (Aves: Hirundinidae) in Brazil: potential negative impacts of hydropower plants

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Abstract: We analyzed the overlap of the range of *Pygochelidon melanoleuca* in Brazil with active and planned hydropower plants in the country (current and future scenarios). We used the Random Forest, Maxent and Support Vector Machine algorithms to model the potential range of the species, which we then overlapped with the locations of active and planned hydropower plants in order to calculate how much the potential area of this species is and will be affected by them. Approximately 35% of active hydropower plants currently overlap with the potential distribution area of *P. melanoleuca*, and 44% of planned hydropower plants also coincide with this area. If the implementation of the planned hydropower plants occurs, the suitable habitat necessary for nesting and foraging of *P. melanoleuca* will be severely compromised.
Keywords: *Amazon; Aquatic Ecosystems; Species Distribution Modelling; Neotropics.*

Conservação da andorinha-de-coleira, *Pygochelidon melanoleuca* (Wied, 1820) (Aves: Hirundinidae) no Brasil: potenciais impactos negativos das hidrelétricas

Resumo: Analisamos a sobreposição da distribuição de *Pygochelidon melanoleuca* no Brasil com hidrelétricas ativas e planejadas no país (cenário atual e futuro). Utilizamos os algoritmos Random Forest, Maxent e Support Vector Machine para modelar a distribuição potencial da espécie, então sobrepomos com os locais das usinas hidrelétricas ativas e planejadas para calcular o quanto a área potencial desta espécie é e será afetada por elas. Aproximadamente 35% das hidrelétricas ativas estão sobrepostas com a área de distribuição potencial de *P. melanoleuca* e 44% das hidrelétricas planejadas coincidem com sua área. Se a implementação das hidrelétricas planejadas ocorrer, o habitat necessário para nidificação e forrageamento de *P. melanoleuca* estarão severamente comprometidos.
Palavras-chave: *Amazônia; Ecossistemas Aquáticos; Modelagem de Distribuição de Espécies, Neotrópico.*

Introduction

Aquatic ecosystems are among the most vulnerable to the impact of anthropogenic activities (Dudgeon et al. 2006). The installation of hydropower plants is considered one of the main threats to freshwater biodiversity by drastically changing the landscape, river flow and water temperature, reducing sediment transportation, and hindering or even stopping organisms from moving freely through watercourses (Winemiller et al. 2016, Zarf et al. 2015). The rise in energy demand, associated with a rich and unexplored hydrographic potential, has resulted in an increase of hydroelectric development in the Neotropical Region (Finer & Jenkins 2012). Brazil is among the top five countries with greatest hydropower cumulative potential in the world (IEA 2017), and the installation of approximately 1680 hydropower plants is currently planned for the country (ANEEL 2018).

The Amazonian region is currently one of the most targeted for the implementation of hydroelectric projects in Brazil due to its potential for hydroelectric exploration and the near exhaustion of hydroelectric potential in other regions of the country (Choueri & Azevedo 2017). Indeed, the Brazilian Amazon holds some of the greatest hydropower potential in the world owed to its extensive hydrographic network and topographic variation (Fearnside 2015). Small- and large-scale reservoir projects have already been proposed for the Amazon, with three out of ten mega-reservoirs proposed already completed (e.g., *Belo Monte*, *Santo Antônio*, and *Jirau*), and seven others in the planning stage (Latrubesse et al. 2017). The impacts of such a scaling in hydroelectric development could greatly reduce or even extinguish populations of species such as *Pygochelidon melanoleuca*, which are dependent on fluvial rocky outcrops (Lees et al. 2016).

The Black-collared Swallow, *Pygochelidon melanoleuca* (Wied, 1820) (Aves, Hirundinidae) is associated with rapids and rocky outcrops stretches of medium and large sized rivers (Cherie 1916, Ridgely & Tudor 1989, Hilty 2002, Turner 2020). These rapids are the species main foraging areas with the rocky outcrops serving as its nesting sites during reproductive season (Haverschmidt 1968, Hilty 2002, Barros 2008, Lopes et al. 2013, Lees et al. 2016). The distribution of *P. melanoleuca* extends throughout South America, from southeastern Colombia, southeastern and eastern Venezuela, Guyana, Suriname, French Guyana, Brazil, Bolivia, Paraguay, and northeastern Argentina (Birdlife International 2017). In Brazil, the species is common in the Amazon region at the Negro and Amapá rivers, and along the Madeira, Tapajós, Xingú and Tocantins river basins. Scattered records can also be found in the states of Pernambuco, Bahia, Goiás, Minas Gerais and Paraná (Sick 1997, Straube et al. 2004, Silva et al. 2017).

The global conservation status of *P. melanoleuca* is classified as being of "Least Concern" (BirdLife International 2017), since it has a large range, and an apparently stable population size above the thresholds for the "Vulnerable" category. In Brazil, however, the species was classified as "Near Threatened" (ICMBio 2018), with certain states, like Minas Gerais, considering the species as "Critically Endangered" due to a highly probable population reduction over the next 100 years (Drummond et al. 2008). The main threat to *P. melanoleuca* in Brazil is the loss of these unique habitats due to the installation of hydropower plants (Drummond et al. 2008, Silva et al. 2017). In fact, the implementation of two hydroelectric dams on the Araguari River, Minas Gerais, lead to a decline in populations of this species soon after its discovery in the state (Biovet 2012).

In face of the recent escalation of hydroelectric power development in Brazil, it is imperative to identify suitable areas and potential threats for *P. melanoleuca* populations. This would contribute to more efficient conservation strategies focused on reducing the negative impacts of these enterprises on the species. An efficient way to identify these areas and threats is through predictive species distribution models which are an important tool for biodiversity conservation (Guisan et al. 2013). Such models allow for the identification of priority areas for conservation, and/or areas where species are more vulnerable to anthropic activities. These can then be used by decision-makers to elaborate and implement more effective species conservation planning (Villero et al. 2016).

Although *P. melanoleuca* is not considered an aquatic bird, it relies on aquatic environments for nesting and foraging. Hence, it is also important to consider aquatic ecosystems when planning conservation measures for the species. In the present study we use predictive distribution modeling to (1) provide a potential distribution for *P. melanoleuca* in Brazil; (2) analyze the overlap between active hydropower plants and the potential occurrence areas for the species (current scenario); and (3) analyze the overlap between planned hydropower plants and the potential occurrence areas for the species (future scenario).

Material and Methods

1. Study species

Adults of *Pygochelidon melanoleuca* are approximatelly 14 cm in length and weigh between 10–12 g (Figure 1). The species is commonly found in large lowland rivers with rocky outcrops, preferring more wide and open stretches with exposed stones which it uses for reproduction and nesting during low-water periods (Turner and Rose 1989, Ridgely & Tudor 1989). These areas are currently threatened by the installation of hydropower plants which are predicted to severely compromise these microhabitats in most rivers of the Brazilian and Guiana shields (Lees et al. 2016). The dependence of *P. melanoleuca* on these particular habitats and the lack of recent records in areas where it once occurred (i.e. the Atlantic Forest), has shown that several populations of this species may be endangered (Moreira-Lima 2013).

2. Species occurrence and environmental data

Occurrence data was obtained from three different sources: (1) zoological collections of the Museu Paraense Emílio Goeldi (MPEG), Museu de Zoologia da Universidade de São Paulo (MZUSP), Instituto Nacional de Pesquisas da Amazônia (INPA) and Departamento de Zoologia da Universidade Federal de Minas Gerais (DZUFMG); (2) online databases, such as Global Biodiversity Information Facility (GBIF) (www.gbif.org) and Wikiaves community (http://www.wikiaves.com.br/); and (3) personal sightings and records by different ornithologists. Records without geographical coordinates or with inaccurate coordinates (e.g., coordinates to the municipality of the record) were not included in the analyses. We obtained 237 records of *P. melanoleuca*, of which 87 were excluded for not meeting the requirements for the models.

Figure 1. Juvenile (A) and adult (B) of the Black-collared Swallow (*Pygochelidon melanoleuca*) (Photos: Luiz Alberto 2019).

In order to model the species distribution, we obtained 19 climatic variables representing annual trends, seasonality, and extreme or limiting environmental factors in the WorldClim database (Fick & Hijmans 2017) all of them on a 5 arc-min resolution (~10 km grids). Two topographic variables (terrain slope and altitude) were also obtained from the Hydro-1K global digital elevation model (www.usgs.gov). To reduce data multicollinearity, we performed a Pearson correlation analysis with a matrix containing all variables. Out of 21 variables, 13 were correlated (correlation >70%) and were thus excluded. Models, therefore, were created using the two topographic variables and six climatic variables: maximum temperature of warmest month (Bio5), minimum temperature of coldest month (Bio6), precipitation of wettest month (Bio13), precipitation of the driest month (Bio14), precipitation of the wettest quarter (Bio16), and precipitation of driest quarter (Bio17). After combining the sampling points, we used Moran's I to test for spatial autocorrelation.

3. *Model construction and evaluation*

Different algorithms were used to minimize uncertainty of generated models. Distribution models were built in R 3.4 (R Development Core Team 2012) using the Random Forest (RF) algorithm from the 'randomForest' package (Liaw & Wiener 2002), and the Maxent and Support Vector Machine (SVM) algorithms from the 'dismo' package (Hijmans et al. 2017). A10-km pixel resolution was used for variables in the model building process, with a single record per pixel in order to avoid spatial autocorrelation. We generated 10 partials models for each algorithm. The original occurrence points were split in a way that 20% (test points) were used to evaluate the model and 80% (training points) to build the model, all of them adjusted with the ecological space. Models were evaluated using the TSS (True Skill Statistics) (Allouche et al. 2006) and the AUC (Area Under the Curve) (Fielding & Bell 1997). TSS models were considered useful when presenting a value between 0.5-0.8, and good when above 0.8. Likewise, AUC between 0.7-0.9 indicated useful models, and values above 0.9 indicated good models. Therefore, the final model was obtained from partial models with AUC $\geq$ 0.7 and TSS $\geq$ 0.5.

To generate the final model, we calculated the mean of the AUC and TSS values for each of the partial models obtained from each algorithm by using the 'ensemble' function of the 'sdm' package (Naimi & Araújo 2016). Next, we used the 'ensemble forecast' function to group the partial models (following Araújo & New 2007). This method considers that different errors affect each model differently, so it evaluates all models, reducing errors and producing a more reliable solution (Diniz-Filho et al. 2010). The final potential distribution model for *P. melanoleuca* was cut to the Brazilian territory and overlapped with hydrography to refine the model in light of species dependency on waterbodies (Nori & Rojas-Soto 2019) (Figure 2). Only data from third-order streams was selected, as the species does not occur in small streams (Schauensee & Phelps 1978, Hilty & Brown 1986, Turner 2016). For this purpose, we plotted the Brazilian hydrography using 3 arc-sec resolution files of flow accumulation and flow direction available on the HydroSHEDS database (https://hydrosheds.cr.usgs.gov/hydro.php). We then ordered rivers following the Strahler (1957) classification and added a 10-km buffer around the watercourses. Hydrography was divided in hydrographic regions (Amazon, *Marajó* Atlantic Coast, Northeast Atlantic Coast, *Tocantins, Paraná,* East Atlantic Coast) according to the Level 1 Otto-Codification methodology from the Agência Nacional das Águas (ANA), since these regions are used to guide the planning and management of hydric resources (CNRH 2003).

4. *Overlap with hydropower plants and statistical analyses*

To calculate the percentage of active (current scenario) and planned (future scenario) hydropower plants overlapping the potential distribution area of the species we created a 10-km buffer for each plant. We then transformed the final model into a binary model and extracted the total amount of pixels representing the hydropower plants that overlapped the potential distribution area. Data on the functioning and planned hydropower plants in Brazil was obtained in the Georeferenced Information System of the Electric Sector (ANEEL 2018).

The overlap between hydropower plants and the potential range of *P. melanoleuca* was evaluated with two-way ANOVA in two distinct scenarios: functioning hydropower plants (current scenario) and planned hydropower plants (future scenario). Hydropower plants were the predictor variable and the potential of occurrence (pixel-values in potential occurrence areas) the response variable, with hydropower plants and hydrographic regions as covariates. The two-way ANOVA evaluated the impact of hydropower plants and hydrographic regions on the potential occurrence of the species in each scenario and checked for interactions between both predictors over the response variable. To do so, we extracted the pixel-values from the potential distribution areas with and without hydropower plants.

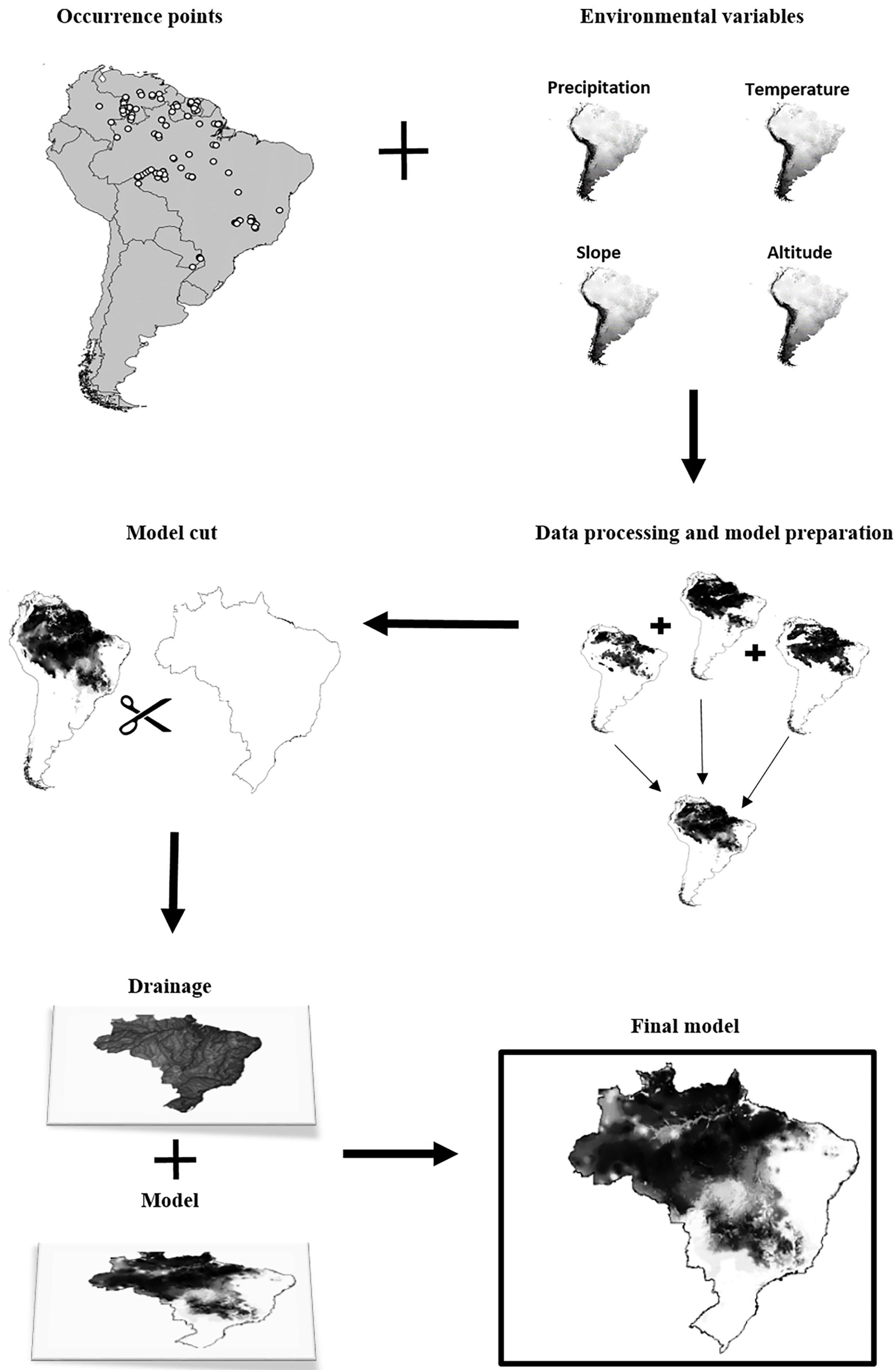

Figure 2. Schematic representation of the model preparation process.

Results

All generated models indicated a higher occurrence probability for *P. melanoleuca* in the Amazon, *Marajó* Atlantic Coast, Northeast Atlantic Coast and *Tocantins* regions, while at the same time, indicating the *Paraná* and East Atlantic Coast regions as having low occurrence probability. The final potential distribution model for the species showed good predictive capacity (TSS = 0.62 ± 0.08; AUC = 0.82 ± 0.07). The partial models generated by Maxent produced models with lower TSS values. The partial models generated by Random Forest and Support Vector Machine indicated good predictive performance (Table S1).

There are currently 653 active hydropower plants in Brazil and plans for the installation of almost 1680 more. Over 80% of active facilities and nearly 80% of planned facilities are located in the *Paraná* and East Atlantic Coast basins. However, most facilities in the *Paraná* and East Atlantic Coast are in areas of low habitat suitability for the species, and areas with greatest occurrence potential for *P. melanoleuca* in these regions have fewer active and planned hydropower plants. The hydropower plants in the Amazon and *Marajó* Atlantic Coast are in areas of high habitat suitability for *P. melanoleuca*. (Table 1).

Approximately 35% of active hydropower plants are in potential distribution areas for the *P. melanoleuca* (Figure 3A), varying according to each hydrographic region ($F = 7.58$; G.L.= 4; $p < 0.01$).

Table 1. Quantity of functioning and planned hydropower plants in Brazil according to the classes of habitat suitability for the occurrence of *Pygochelidon melanoleuca*. Very low 0.0-0.2; Low 0.2-0.4; Average 0.4-0.6; High 0.6-0.8; Very high 0.8-1.0; NA, Unsampled.

Hydrographic regions	Category	Hydropower plants		Total
		Active	Planned	
Amazon	Very low	0	1	**1**
	Low	3	15	**18**
	Average	4	13	**17**
	High	28	81	**109**
	Very high	34	83	**117**
	NA	1	0	**1**
Tocantins	Very low	1	6	**7**
	Low	7	25	**32**
	Average	18	42	**60**
	High	8	48	**56**
	Very high	5	23	**28**
	NA	0	4	**4**
Marajó Atlantic Coast	Very low	0	0	**0**
	Low	0	0	**0**
	Average	0	1	**1**
	High	0	0	**0**
	Very high	3	5	**8**
	NA	0	0	**0**
Northeast Atlantic Coast	Very low	0	0	**0**
	Low	0	0	**0**
	Average	0	0	**0**
	High	0	0	**0**
	Very high	0	0	**0**
	NA	0	0	**0**
East Atlantic Coast	Very low	189	343	**532**
	Low	25	40	**65**
	Average	12	41	**53**
	High	15	49	**64**
	Very high	2	8	**10**
	NA	6	1	**7**
Paraná	Very low	181	510	**691**
	Low	24	59	**83**
	Average	22	59	**81**
	High	34	101	**135**
	Very high	24	116	**140**
	NA	7	5	**12**
Total		653	1679	2.332

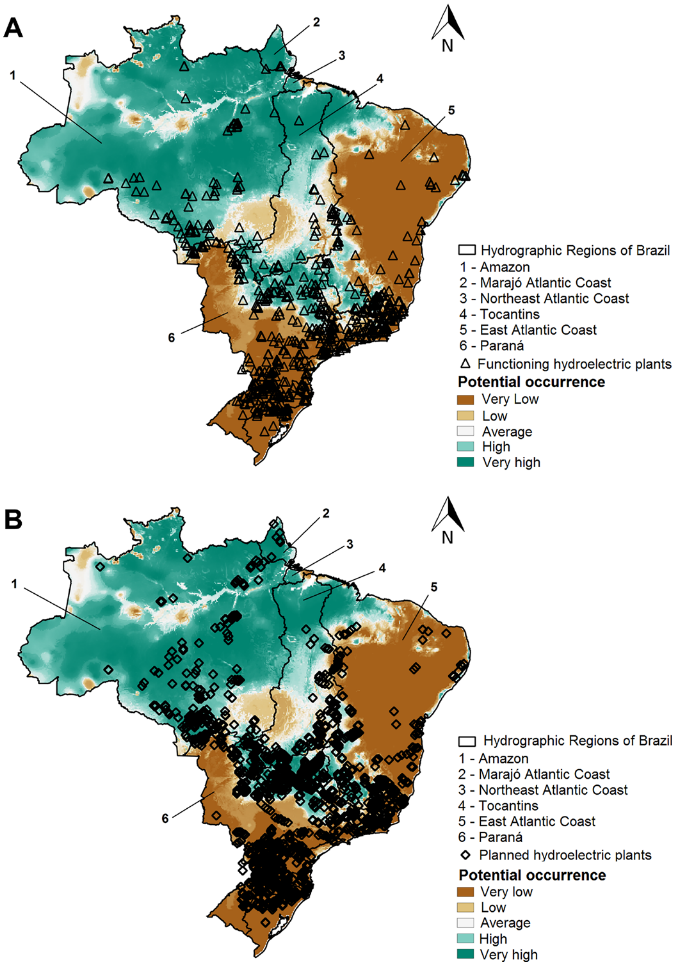

Figure 3. Active and planned hydropower plants (A and B, respectively) on potential occurrence areas of *Pygochelidon melanoleuca* in Brazil.

The *Paraná* and East Atlantic Coast regions have 30.49% and 12.89% of their active facilities within potential distribution areas for the species, respectively (Figure 4A, 4B). In contrast, 96.64% and 100% of active hydropower plants in the Amazon and *Marajó* Atlantic Coast, respectively, are in the species potential distribution area (Figure 4C, 4D).

Over 43% of planned hydropower plants were found to be in potential distribution areas for *P. melanoleuca* (Figure 3B). This overlap with the potential distribution for the species area varied with the geographic region ($F = 18.82$; G.L.= 4; $p < 0.01$). Should all planned hydropower plants be installed, the *Paraná* and East Atlantic Coast regions might respectively have 35.17% and 21.82% of installations within the potential range for the species (Figure 5A, 5B). The same scenario indicates that this overlap can reach 92.33% and 100% in the Amazon and *Marajó* Atlantic Coast regions respectively (Figure 5C, 5D).

Discussion

This study is one of the first Brazil-wide examinations of the overlap between active and planned hydropower plants and the potential occurrence areas of a bird species highly dependent on aquatic ecosystems. This overlap varied with each geographic region, due to the different number of hydropower plants and potential areas for the species. Since the total area affected by each hydropower plant is not available, it is noteworthy that the percentage of suitable area loss for the species could be greater than the one observed herein.

The largest potential distribution areas for *P. melanoleuca* are in the Amazon and *Marajó* Atlantic Coast regions, in which 96.64% and 100% of active hydropower plants, respectively, overlap with potential areas for the species. The impact of these projects on local populations of *P. melanoleuca* must be considered for this region, since most will be located directly over areas with high habitat suitability for the species.

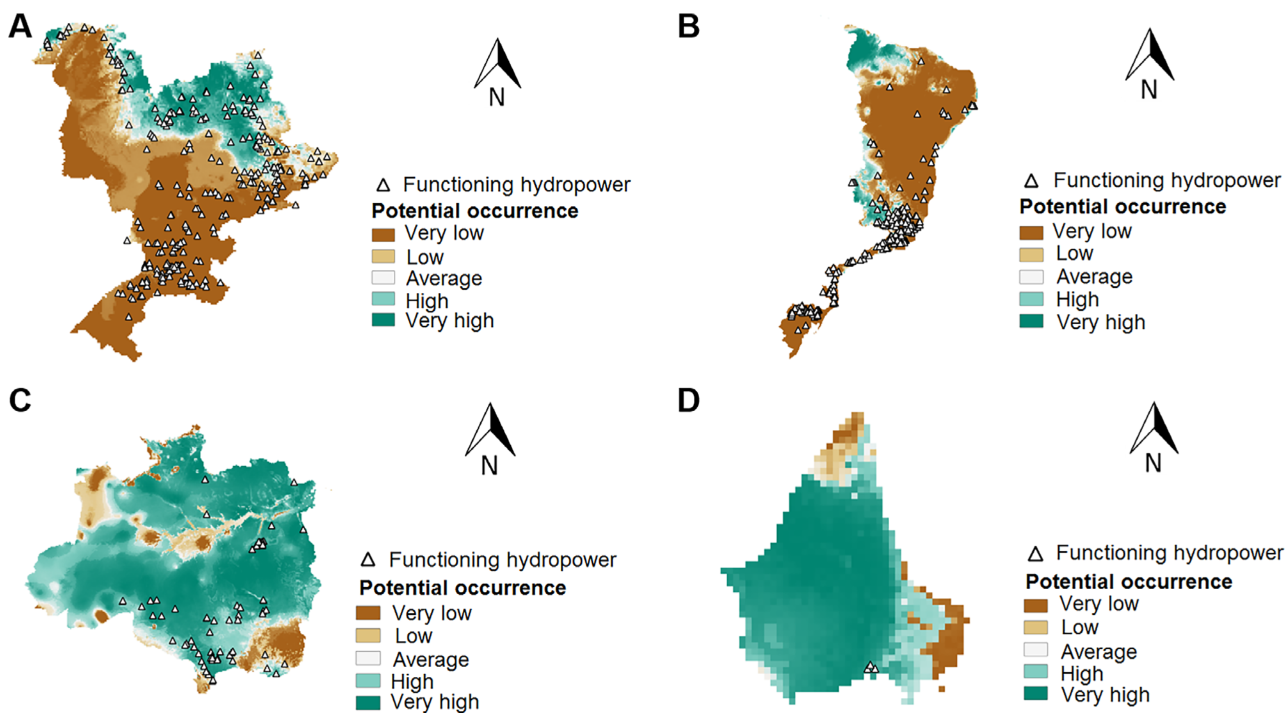

Figure 4. Active hydropower plants within potential occurrence areas of *Pygochelidon melanoleuca* in each hydrographic region: *Paraná* (A), East Atlantic Coast (B), Amazon (C) and *Marajó* Atlantic Coast (D).

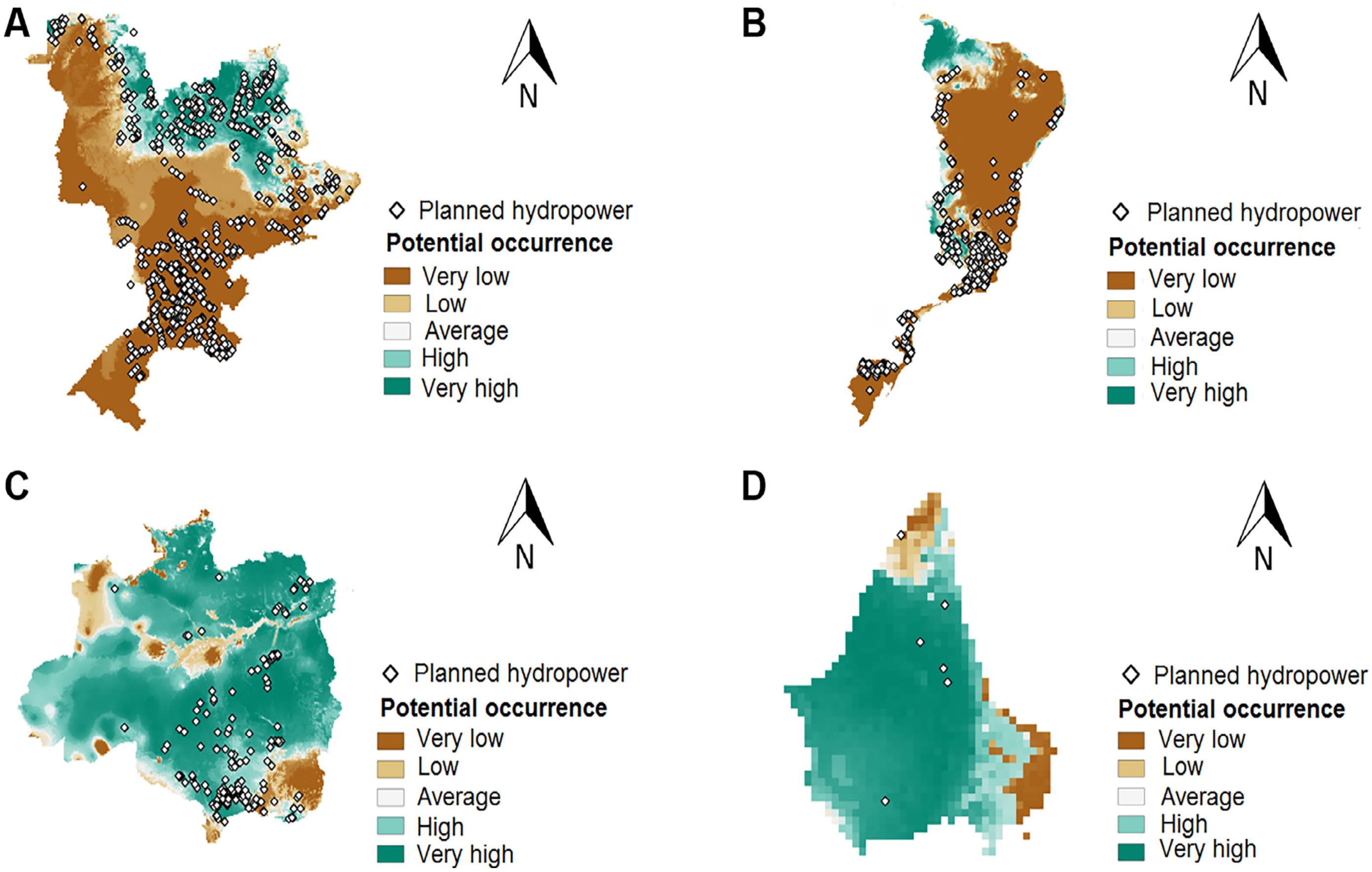

Figure 5. Planned hydropower plants within potential occurrence areas of *Pygochelidon melanoleuca* in each hydrographic region: *Paraná* (A), East Atlantic Coast (B), Amazon (C) and *Marajó* Atlantic Coast (D).

This highlights the need for careful assessment of the impacts caused by these ventures, since decision-making processes tend to underestimate these impacts while overestimating potential benefits (Fearnside 2005).

The distribution of *P. melanoleuca* appears to be more restricted in the *Paraná* basin, southern limit of its range, when compared to its wider distribution in areas such as the Amazon basin. Although our models indicate the *Paraná* basin as having low suitability for *P. melanoleuca*, 30.49% of its hydropower plants are located within potential areas for the species. The *Paraná* hydrographic region holds the largest urban areas in Brazil, and provides around 70% of the electricity produced in the country (Agostinho et al. 2007). The economic development in Brazil in the early 20th century, especially in the *Paraná* hydrographic region, combined with a high availability of water resource and foreign investments, turned hydropower plants into the most suitable means to meet energy demands (Valêncio et al. 1999). Approximately 850 hydropower plants are currently planned for this region (ANEEL 2018), a concerning scenario, since active plants might already have reduced suitable habitats for *P. melanoleuca* in the region. Should new hydropower plants be implemented in the *Paraná* hydrogeographic region, this species might lose a crucial microhabitat for reproduction and foraging, and could even become locally extinct.

Hydropower plants affect biodiversity and compromise ecosystem functioning (Couto & Olden 2018), their operational guidelines for optimizing energy production failing to meet the ecological needs of the biota associated with these ecosystems (Lees et al. 2016). Strategies aiming to reduce the impact of hydropower plants on biodiversity have already been proposed (e.g. Kitzes & Shirley 2015, Kang et al. 2016): controlling water level in reservoirs according to the ecological needs of aquatic birds (Zhang et al. 2016); elaborating an "Adaptive Management Plan" to evaluate the impacts of dam operation on watercourses (Lovich & Melis 2007); including hydrological models to help predict flood and drought patterns that might be linked to biological cycles and ecological processes (Kingsford 2000); researching the impact of reservoir installations on bird populations (e.g., distribution, survival, and reproductive success) (Claassen 2004); and, establishing river sections free of hydropower plants in order to minimize their impact on species populations (Silva et al. 2017). Hydropower plants are an important factor to be considered when planning the conservation of *P. melanoleuca*, since freshwater environments are crucial for maintaining their populations (Silva et al. 2017). The data presented here constitutes only an estimate of the extent to which hydropower plants overlap with the potential distribution areas of *P. melanoleuca* in Brazil, presently and in the future.

In this study, we observed that *P. melanoleuca* is widely distributed in the Amazon, *Marajó* Atlantic Coast, *Tocantins* and Northeast Atlantic Coast hydrographic regions, with a more restricted distribution in the *Paraná* and East Atlantic Coast regions. We also found that the overlap of potential areas of occurrence for the species with hydropower plants in current and future scenarios varied with region, the Amazon and *Marajó* Atlantic Coast regions presenting the highest overlap. In addition, we showed how the overlap between hydropower plants and the potential distribution area of *P. melanoleuca* can indicate a likely reduction of suitable habitat needed for the species to persist.

Supplementary Material

The following online material is available for this article:

Table S1 - Result of the partial distribuion models generated for *Pygochelidon melanoleuca* with the AUC (Area Under Curve) and TSS (True Skill Statistic) values. RF, Random Forest; SVM, Support Vector Machine.

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Associate Editor

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Author Contributions

Gabriele Andreia da Silva: concept and design of the study; data collection; data analysis and interpretation; manuscript preparation; critical revision, adding intelectual content.

Renata Guimarães Frederico: concept and design of the study; data collection; data analysis and interpretation; manuscript preparation; critical revision, adding intelectual content.

Sara Miranda Almeida: concept and design of the study; manuscript preparation; critical revision, adding intelectual content.

Gilberto Nepomuceno Salvador: concept and design of the study; manuscript preparation; critical revision, adding intelectual content.

Gustavo Bernardino Malacco: concept and design of the study; manuscript preparation; critical revision, adding intelectual content.

Celine de Melo: manuscript preparation; critical revision, adding intelectual content.

Conflicts of Interest

The authors declare that they have no conflict of interest related to the publication of this manuscript.

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