

1 **Using temporally explicit habitat suitability models to infer the migratory pattern of a
2 large mobile shark**

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27

28 **Abstract**

29 Conservation and management measures for large mobile sharks are more effective when
30 information on migratory patterns and environmental cues are known. In the absence of long-
31 term monitoring data or tracking programs, available information is based on occasional
32 catch/sighting records from a variety of sources, usually constrained in space and time. This
33 study demonstrates the utility of developing temporally explicit habitat suitability (HS) models
34 to infer the migratory pattern of large mobile sharks. Bimonthly presence-only HS models
35 (MaxEnt algorithm) were developed for the broadnose sevengill shark *Notorynchus cepedianus*
36 in the South-west Atlantic based on an exhaustive collection of data records, and ecologically
37 relevant predictors. The six final models showed good predictive power and were evaluated
38 with independent data. A migratory pattern characterized by two main displacements was
39 inferred from the models. We show that HS models can be applied as a no-cost desk-based
40 alternative to infer broad-scale movements of large mobile sharks. This methodology is relevant
41 as an important first step toward informing management plans in data-poor and financially
42 limited regions, or under urgent conservation need.

43

44 **KEYWORDS** apex predator, large-scale movements, Maxent, *Notorynchus cepedianus*,
45 temporally explicit models

46

47 1. INTRODUCTION

48 Understanding the spatial ecology of large mobile sharks and related species is a major task in
49 current marine studies because it has strong implications for their management and
50 conservation. In fact, these studies are critical to tackle well-defined conservation challenges
51 and priorities for sharks (Heupel et al. 2015; Dulvy et al. 2017; Stein et al. 2018), as the concern
52 about their global status increases (Dulvy et al. 2014). In particular, determining the habitat
53 preferences and the wide-ranging migratory pattern within various zones is crucial for
54 evaluating the effectiveness of local fishing regulations on the sustainability and conservation
55 of shark species (Papastamatiou and Lowe 2012). In addition, large-scale movements of these
56 animals are complex and depend on intrinsic population processes, as well as on choices of
57 habitat suitability in highly dynamic environments (Schick et al. 2008). Many of these
58 complexities are further jeopardized by anthropogenic activities along their extensive
59 movements (Lascelles et al. 2014). Therefore, detailed knowledge of the distribution, habitat
60 use and movements at a large spatial scale is required to design and understand the effects of
61 management and conservation measures (e.g., marine protected areas) for the populations of
62 large mobile shark species.

63 The broad methodological spectra of species distribution modeling have become a
64 common toolbox in science to understand and predict the horizontal spatiotemporal distribution
65 of species. These methods use occurrence data to predict habitat suitability based on a
66 correlative model of the environmental conditions that meet a species' ecological requirements
67 (Elith and Leathwick 2009). In the marine realm, species distribution models have recently
68 acquired great relevance in ecological studies, and their usage has increased exponentially
69 (Robinson et al. 2017). In particular, these models have been applied widely in marine
70 conservation ecology to understand the role of environmental covariates in determining the
71 distribution and habitat use of mobile species (e.g., Lucifora et al. 2015). The wide

72 spatiotemporal scale of analysis that can be achieved through the use of large databases (e.g.,
73 historical data, citizen science programs), opened up the possibility to investigate distribution
74 patterns of wide-ranging marine species that are difficult, and sometimes impossible, to address
75 using other methods. Albeit, studies incorporating a temporal component (e.g., monthly or
76 seasonal habitat suitability) of analysis to understand the temporal use of areas by species
77 remain scarce (e.g., Welch et al. 2018). Furthermore, the inferences made from these models
78 are only as good as the models themselves, and sometimes their field validation is particularly
79 problematic or impossible given the cost-prohibitive technology available to assess how well
80 the models are. In fact, most large-scale movements and migrations of large mobile sharks are
81 currently inferred using expensive techniques such as electronic tagging. Therefore, the use of
82 occurrence points and environmental data to estimate species' habitat suitability allows us to
83 conduct studies in both conservation and basic science when technology is unaffordable or does
84 not match the scale of the study.

85 In the South-west Atlantic (SWA), there is a scarcity of funding for tracking studies of
86 marine megafauna, and sharks are no exception. In comparison, while to date no acoustic
87 tracking studies on sharks have been carried out in Argentina, Australia has implemented the
88 Integrated Marine Observing System's Animal Tracking Facility with at least 771 sharks and
89 69 rays been tracked so far (Brodie et al. 2018a). Further examples of regional disparity in shark
90 large-scale movement studies include satellite tagging concentration in the North Atlantic,
91 eastern Pacific and Oceania (Queiroz et al. 2019), whereas to date only five tope sharks (Cuevas
92 et al. 2014) and 12 shortfin mako sharks (Santos et al. 2018) have been satellite tagged in
93 Argentina and Uruguay, respectively. Therefore, in the SWA large-scale movements and
94 seasonality of large-bodied sharks has been exclusively inferred by other means, including
95 conventional tag and recapture (e.g., Irigoyen et al. 2015; Jaureguizar et al. 2018) and catch
96 data (e.g., Lucifora et al. 2005a, 2005b) methods.

97 The SWA support high richness of shark, ray and skate species (Menni et al. 2010;
98 Colonello et al. 2014). Probably as a result of strong endemism in the region (Lucifora et al.
99 2012; Stein et al. 2018) and high overlap with fishing grounds (e.g., Van Der Molen et al. 1998;
100 Góngora et al. 2009; Cortés and Waessle 2017), many of these species are under constant threat.
101 In fact, recent studies have demonstrated that large predatory sharks have suffered population
102 declines in coastal (Barbini et al. 2015; Irigoyen and Trobbiani 2016) and shelf (Barreto et al.
103 2016; Bornatowski et al. 2018) areas of the SWA. Local and regional efforts have been made
104 during the last 15 years to develop management and conservation measures, which are in line
105 with national and regional action plans (i.e., PAN-Tiburón Uruguay [Domingo et al. 2008],
106 PAN-Tiburón Argentina [CFP 2009], and PAR-Tiburón [CTMFM 2018]). The mitigation
107 measures of fishing effort are mainly related to minimum landing sizes, annual catch quotas,
108 and areas closed to trawling (see PAN- and PAR-Tiburón for a compilation of these measures).
109 Nevertheless, the implementation of these measures is affected by the interaction of different
110 fisheries (industrial, artisanal and recreational), as well as different jurisdictions and legislation.

111 The broadnose sevengill shark *Notorynchus cepedianus* (Péron, 1807) is a large top
112 predator in most temperate coastal ecosystems of the world (Barnett et al. 2012). Available
113 information about their habitat preferences and migratory behavior suggests that sevengill
114 sharks are highly mobile (Ebert 1989; Barnett et al. 2011; Williams et al. 2012). Satellite and
115 acoustic tracked sevengill males in southeast Tasmania performed extended northward seasonal
116 migrations (*c.* 1 000 km), and their return to the tagging site supported long-range site fidelity
117 (Barnett et al. 2011). Further evidence from acoustically tagged sevengill sharks also indicates
118 broad-scale coastal movements (*c.* 600 km) across estuarine embayments of western USA
119 (Williams et al. 2012). In the SWA, a paucity of data exists on the migratory behavior and
120 habitat preferences of sevengill sharks. However, the evidence from elsewhere in the world and
121 the strong seasonality in coastal areas of Argentina (Jaureguizar et al. 2004, 2015; Lucifora et

122 al. 2005a; Cedrola et al. 2009; Irigoyen et al. 2015, 2018, 2019; De Wysiecki et al. 2018) and
123 Uruguay (Silveira et al. 2018) suggest that the species is capable of large-scale movements
124 across SWA.

125 The goal of this study is to (i) determine bimonthly habitat suitability of *N. cepedianus*
126 in the SWA based on an exhaustive collection of catch records, and use the predictions to infer
127 its migratory pattern, assuming that its displacements are driven by ecologically and
128 biologically relevant physical and biotic variables. In addition, we intend (ii) to investigate
129 possible juvenile-adult differences in migratory movements, and (iii) to identify the most
130 critical distribution area/s of neonates.

131

132 **2. MATERIALS AND METHODS**

133

134 **2.1 Study area**

135 The study region comprises the entire known geographic distribution of *N. cepedianus* in the
136 SWA (Fig. 1). To date, the northernmost and southernmost documented records of the species
137 are located at Cananéia, state of São Paulo, Brazil ($25^{\circ}00'S$ – $47^{\circ}52'W$, Sadowsky 1969), and at
138 Dungeness cape, Magallanes Province, Chile ($52^{\circ}23'S$ – $68^{\circ}27'W$, Guzmán and Campodónico
139 1976), respectively. Available data included in this study are from coastal and inner shelf waters
140 within the 200 m isobath, which agrees with the maximum depth at which sevengill sharks have
141 been found worldwide (i.e., based on catch data, Compagno 2009), and also covers a large
142 proportion of the depth range reported for the species in Tasmania (i.e., based on tracking data,
143 Stehfest et al. 2014). Areas known to be inaccessible for *N. cepedianus* as a result of ecological
144 barriers were not accounted for in the study, including the main low-salinity (< 25) water masses
145 (Río de la Plata and Lagoa dos Patos). Islas Malvinas area was also removed from the study
146 extent because no historical records of the species exist there. The resulting study area
147 comprises parts of marine coastal and shelf jurisdictions of Argentina, Brazil, Chile and
148 Uruguay.

149 The study region is known for its marked seasonality in oceanographic conditions,
150 which is characteristic of temperate climates. Oceanographic processes of the region are in part
151 a result of two strong currents that are responsible for sound dynamism in oceanic circulation,
152 the Malvinas and Brazil currents (Palma et al. 2008; Matano et al. 2010). The Río de la Plata is
153 also a distinctive feature in the SWA with an average freshwater discharge of $\sim 21\ 500\ m^3 s^{-1}$
154 (Pasquini and Depetris 2007), representing an important input of dissolved matter and nutrients
155 into the ocean that ultimately benefits many coastal marine species (Acha et al. 2008).

156

157 **2.2 Data collection**

158 Occurrence data were gathered from a variety of sources in an attempt to include all possible
159 records (Table 1). For each *N. cepedianus* record to be considered in the study, reliable
160 information about the locality, month and year of the catch was mandatory, although more
161 precise data (i.e., geographic coordinates and date) were constantly sought. Total length (L_T)
162 and sex were also recorded when available to differentiate between juvenile and adult stages,
163 and sexes. Male and female specimens larger than 170 and 190 cm respectively were considered
164 adults, a decision supported by a recent regional study that includes reproductive hormone
165 analyses of the species (Irigoyen et al. 2018). Unsexed specimens were considered adults in
166 sizes larger to the mean value between male and female size thresholds (i.e., 180 cm). When L_T
167 was not available but total mass (M_T) was known, the latter was used to obtain L_T using the $L_T -$
168 M_T relationships reported in Irigoyen et al. (2018). These relationships were preferred over
169 previous ones (Cedrola et al. 2009) because they include specimens in a wider length range and
170 from different areas across the SWA. All records of sharks smaller or equal to 50 cm L_T or those
171 presenting evidence of an open/fresh yolk-sac wound were considered neonates. The fishing
172 method was also recorded to inform decisions in model tuning.

173 Mining of public social media contents was done using various terms covering country-
174 based common names of the species, including ‘tiburón gatopardo’ (Argentina), ‘tiburón
175 pintaroja’ (Uruguay), ‘cação-bruxa’ and ‘tintureira’ (Brazil), and slight variations of them (i.e.,
176 separating or omitting words, omitting accent mark or hyphen). Only posts including
177 images/videos of the catch were taken into consideration to aid for proper species-level
178 identification and avoid anecdotal occurrence data errors (McKelvey et al. 2008). On
179 Facebook™, a more in-deep, retrospective search was performed by scrolling through freely
180 accessible pictures of public fishing groups and angler profiles. In many cases, missing details
181 regarding the catch were gathered by personally contacting anglers or commenting on posts.

182 Due to anglers rarely measured or weighed *N. cepedianus* catches, L_T was visually estimated
183 from images and videos by scaling against recognizable objects of known size (e.g., fishing
184 equipment, knife) or standard human measures (e.g., hand width, arm length). Sex
185 (presence/absence of claspers) and yolk-sac wound condition (healed/unhealed) were also
186 recorded from multimedia archives when possible. However, a conservative approach was
187 followed while gathering social media data, knowing the potential biases that can be introduced
188 to the data set, thus this information was left blank when minimal confusion or uncertainty
189 arose.

190 On-board scientific surveys and commercial fishing (observer programs) records were
191 only obtained for Argentina and the Argentine-Uruguayan Common Fishing Zone, and were
192 provided by Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP), Secretaría de
193 Pesca de Chubut, and Centro de Investigación Aplicada y Transferencia Tecnológica en
194 Recursos Marinos Almirante Storni (CIMAS). Data sets from the Brazilian shelf were not
195 obtained. This type of information consists of binary fishing trawls with *N. cepedianus* catch
196 (i.e., presence) or no catch (i.e., absence). However, an early exploration of the data indicated
197 that trawls failed to represent the spatial and temporal extent of the study, which motivated us
198 to only keep presence records for modeling along with the records from other sources. Observer
199 data were carefully filtered for false positives by professional personnel at the institutions.

200

201 **2.3 Environmental data**

202 A set of environmental static (no temporal change) and dynamic (temporal change) predictors
203 describing distance to habitat, topography, water column, and food source were thoughtfully
204 selected to determine habitat suitability of sevengill sharks (Table 2). Selected predictors are
205 known to have direct or indirect [e.g., through prey availability, Barnett and Semmens (2012)]
206 effect on shark and ray movement and habitat use (Schlaff et al. 2014), and are widely used in

207 both species distribution modeling (Bradie and Leung 2017) and elasmobranch remote sensing
208 studies (Williamson et al. 2019). The mean monthly values of dynamic predictors were assumed
209 to reflect their mean effect on *N. cepedianus* distribution in each month.

210 Distance to the coast was included to evidence the true coastal habitat use exerted by
211 sevengill sharks (Compagno 2009). A variable of distance to marine inlets was constructed as
212 a result of recent compiling evidence in the region suggesting that these sharks aggregate
213 seasonally in coastal inlets with a complete marine regime (Irigoyen et al. 2018, 2019).
214 Additional topographic features such as depth and slope are intended to describe the importance
215 of demersal habits of sevengill sharks.

216 Temporal variations in physical conditions of the water column were determined by
217 time series analysis of sea surface temperature and diffuse attenuation coefficient K490 satellite
218 imagery (2003-2018, Aqua MODIS satellite availability). Diffuse attenuation is indicative of
219 the amount of dissolved sediments in the water describing turbid areas, which is interpreted as
220 a possible source of protection for the species in the region, especially for the young. Distance
221 to thermal fronts [derived from sea surface temperature images following Scales et al. (2014a)]
222 was computed to describe the importance of coastal (< 50 km) temperature gradients as a proxy
223 of coastal food source due to enhancement of primary production (Alemany et al. 2009; Scales
224 et al. 2014b). Although other meaningful dynamic predictors (i.e., sea surface salinity, and
225 chlorophyll-*a* concentration) were originally considered, they showed high correlation (> 0.8,
226 Pearson correlation analysis) compared to the rest, and were discarded to avoid redundancy in
227 environmental description.

228 Biotic factors are also important drivers for shark movements, in particular prey
229 availability (Schlaff et al. 2014). Since pinniped chunks often comprise bulky prey items in
230 juvenile and adult sevengill sharks in the region (Crespi-Abril et al. 2003; Lucifora et al. 2005a;
231 Irigoyen et al. 2018, 2019), food source was also characterized by computing the minimal

232 Euclidean distance to any pinniped breeding colony along the coast of the SWA. Location of
233 breeding colonies was taken from published information and guidance by professionals in the
234 subject for the southern elephant seal *Mirounga leonina* (Campagna and Lewis 1992), the South
235 American sea lion *Otaria flavescens* (Túnez et al. 2008), and the South American fur seal
236 *Arctocephalus australis* (Crespo et al. 2015).

237 All predictors were prepared prior to modeling. Firstly, unusual monthly values for the
238 region, based on published variable ranges (i.e., Saraceno et al. 2005; Wang et al. 2009;
239 Guerrero et al. 2014), were removed from satellite images to avoid detection errors near the
240 shoreline, and then interpolated from neighboring cells using the *focal* function (R package
241 ‘raster’). Secondly, all variables were rasterized and cropped to the spatial extent of the study
242 area. The grain size was set at 0.041° spatial resolution to match the greatest original resolution
243 among satellite-derived predictors, while lesser or greater resolution variables were resampled
244 to 0.041° using the *projectRaster* function (R package ‘raster’). Finally, predictor layers were
245 averaged and stacked bimonthly for modeling.

246

247 **2.4 Model building**

248 The algorithm based on the concept of Maximum Entropy, named MaxEnt, was used for
249 modeling (Phillips et al. 2006, 2017). MaxEnt estimates habitat suitability by first constraining
250 possible distributions with the environmental information at the location of presence records,
251 and then finding the distribution that maximizes entropy (Elith et al. 2011; Merow et al. 2013).
252 This approach has outperformed other methods in a variety of applications in the marine
253 environment (e.g., Monk et al. 2010; Derville et al. 2018).

254 Six temporally explicit MaxEnt models were developed to determine temporally-
255 explicit habitat suitability of *N. cepedianus* across the SWA and to infer its migratory pattern
256 (Objective i). Shark stage-explicit models were not possible due to fragmentary information

257 and a low number of samples (i.e., less than 10). However, available information on stage was
258 used to better interpret the models and to identify possible stage-specific underlying processes
259 (Objective ii). Sevengill neonates were thought to have a limited capacity to perform extended
260 migratory movements, and hence their records were excluded from the models but used to
261 determine their spatial and temporal occurrence in the region (Objective iii).

262

263 *2.4.1 Sampling bias and background selection*

264 To tackle the objectives of the study, occurrence data were first geographically split into two
265 collections to account for sampling bias introduced by the distinct fishing technics and gears by
266 which the species is caught in the SWA. This is a result of the true coastal habitat use exhibited
267 by sevengill sharks that makes the species prone to be caught by a variety of coastal fisheries.
268 One collection included records from sport, artisanal and research-driven fisheries that operated
269 in a shore-based, kayak or boat fashion across nearshore waters (typically less than 10 km from
270 the coast). The other collection consisted of records from onboard scientific surveys and
271 observer programs, which operated on medium to large vessels across continental shelf waters.
272 This latter collection was used for modeling, while nearshore records were used as an
273 independent set of data to evaluate results. Due to constraints in sample size (i.e., less than 10
274 per model), data were modeled on a bimonthly basis.

275 To reduce sampling bias and spatial autocorrelation, duplicated records at any pixel in
276 any model were first removed. Spatial thinning was then applied to neighboring records to help
277 reduce the clustering of biased sampling (Fourcade et al. 2014). This procedure was carried out
278 through the R package ‘spThin’ using a randomization approach (Aiello-Lammens et al. 2015).
279 The thinning algorithm calculates the pair-wise distances between records and randomly
280 removes neighboring ones based on a user-defined thinning distance. A conservative thinning

281 distance of 10 km was chosen to make sure the largest possible number of records is retained
282 (Boria et al. 2014).

283 The background extent was determined by means of a target group background
284 approach (Phillips et al. 2009). Target groups were selected by seeking into morphologically
285 similar shark species thought to occupy fairly overlapping ecological niches that are equally
286 likely to be caught by the main fishing methods in the SWA shelf. Selected species were the
287 school shark *Galeorhinus galeus*, the sand tiger shark *Carcharias taurus*, and the copper shark
288 *Carcharhinus brachyurus*, for which reliable records from scientific campaigns were obtained.
289 *Notorynchus cepedianus* and target group records were then pooled to obtain the most
290 biologically meaningful background for modeling. Considering the dispersal capabilities of
291 sevengill sharks, 100 km circular buffer areas of selected geographic extent were created around
292 each record and then merged into a single polygon. Background localities were obtained from
293 environmental raster stacks masked by this polygon. This method ensured that presences and
294 background cells shared the same sampling bias, canceling its effects in the models (Phillips
295 and Dudík 2008). For each model, 10 000 background localities were randomly sampled from
296 the corresponding targeted background and used to represent the environment across the
297 landscape of interest.

298

299 2.4.2 Calibration and evaluation

300 It has been demonstrated that MaxEnt default settings do not always lead to the best model
301 performance (Shcheglovitova and Anderson 2013; Radosavljevic and Anderson 2014).
302 Therefore, for each of the six model scenarios, we compared candidate models of differing
303 complexity by means of the R package ‘kuenm’ for an automated calibration and evaluation
304 protocol (Cobos et al. 2019). Each bimonthly set of occurrence records was first randomly split
305 in 75% for model training and 25% for model testing. We then constructed a suite of 217

306 candidate models with 31 combinations of feature classes (linear, quadratic, hinge, product and
307 threshold) and seven regularization multipliers (0.5, 1, 1.5, 2, 3, 4 and 5), in order to compare
308 a wide range of model complexities in each bimonthly period. Most significant (partial receiver
309 operating characteristic scores) and best performing (omission rate at a threshold E = 10%; i.e.,
310 false-negative rate) models among candidate models were narrowed down based on the
311 Akaike's Information Criterion corrected for small sample size (AICc), a useful method to
312 quantify both model goodness-of-fit and complexity (Warren and Seifert 2011). A delta AICc
313 value of ≤ 2 was chosen as a criterion to select the best few models from among each bimonthly
314 candidate model set.

315 First, for each best model in each bimonthly period, a more accurate model was created
316 by averaging over ten bootstrap replicates. To do this, we used the full set of occurrences and
317 the best parameterizations selected that corresponded to each period, and the cloglog output
318 format (Phillips et al. 2017). These models were then transferred to the SWA region and further
319 tested with corresponding sets of independent data (i.e., nearshore records not included in the
320 models). To consolidate results, one best final model was selected and evaluated in each
321 bimonthly period to have the smallest omission rate (E = 10%) when tested on independent
322 data. Additionally, response curves were constructed for the six final models to show how
323 predictors affected the predicted probability of habitat suitability, as the variable of interest is
324 changed while the others are held constant.

325

326 2.4.3 Extrapolation risk

327 The six final models were used to predict temporally explicit habitat suitability of *N. cepedianus*
328 in the region of the SWA. Important limitations arise when predicting into areas where data
329 were not collected and thus not taken into consideration for modeling (Warren and Seifert
330 2011). Transferring the model in such a way can usually be translated into significant

331 differences in predictor range values between sampled and projected areas, decreasing the
332 model's predictive ability in the latter ones (Eger et al. 2017). Therefore, to identify areas of
333 greater extrapolation risk and to prevent overinterpretation in predicted outcomes, we
334 calculated the mobility-oriented parity index (MOP, Owens et al. 2013) that it is implemented
335 in the 'kuenm' package. The MOP metric compares multivariate environmental distances
336 between the selected background and the SWA region to which models are transferred. Values
337 of zero indicate strict extrapolation.

338

339 **3. RESULTS**

340 A total of 2 040 occurrences of *N. cepedianus* were compiled in this study (from 1961 to 2018);
341 1 741 of these corresponded to coastal records and 299 to shelf records (detailed figures in
342 Table S1). The northernmost coastal record (800 mm of L_T female captured on 09 June 2016 at
343 24°24'S–46°51'W Peruíbe, São Paulo, Brazil) represents a northward extension of nearly 115
344 km to the known distribution range of *N. cepedianus* in the SWA. Final raster layers of all
345 predictors from which background data was extracted for the models can be found in Fig. S1.

346 The six final models showed good discrimination on held-out data with varying MaxEnt
347 parametrization (AUC scores > 0.75) and were assessed with independent data (omission rate
348 scores < 0.06, Table 3). Suitable areas (HS index > 0.5) generally occurred adjacent to the coast
349 and showed temporal differences in their location across the SWA (Fig. 2a). The clustering of
350 northern and southern suitable areas was especially evident during the periods February–March
351 and June–July. Broad areas of the SWA corresponding to southern Brazil and Argentina
352 presented strict extrapolation, meaning that the environment in these areas was not represented
353 in the sampled areas (Fig. S2). Specific areas with year-round historical records of sevengills
354 included the southern Río de la Plata boundary (~36°–38°S), San Matías gulf and Valdés
355 peninsula (~41°–43°S), and northern San Jorge gulf (~45°–46°S) (Fig. 2b).

356 There were no signs of clear spatial segregation between juveniles and adults (Fig. 2b).
357 However, juveniles reached lower latitudes than adults. Adult occurrences showed signs of
358 clustering between June and September. Neonates occurred from September to May in
359 nearshore waters of Uruguay and northern Argentina (33°–41°S, Fig. 3), being not recorded the
360 rest of the year or elsewhere in the SWA.

361 Distance to coast was the most important contributor in the models, whereas distance to
362 thermal front, distance to pinniped colony, depth and diffuse attenuation K490 were important
363 seasonally (Table 3). Sea surface temperature, distance to marine inlet and slope contributed to

364 a lesser extent in the models. Dependence of suitable areas to predictor variables is shown in
365 Fig. S3. Suitable areas were generally associated with closer distances to shore, thermal fronts
366 and pinniped colonies, and also with shallower and turbid waters.

367

368 **4. DISCUSSION**

369 In the last 30 years, diverse research questions on the spatial ecology of large mobile sharks
370 have been answered through tracking devices, since they provide the most direct and reliable
371 information about these predators in their natural environment. However, the use of these tools
372 is concentrated in parts of the world with developed scientific programs (Hammerschlag et al.
373 2011; Hussey et al. 2015). In this sense, a desk-based method such as the temporally explicit
374 habitat suitability models applied here provides an alternative option to explore spatial ecology
375 questions in parts of the world where the cost for tracking technology remains unaffordable.
376 The use of data sources based on citizen activities (e.g., recreational fishing) brings the
377 opportunity to exploit a spatial and temporal magnitude of analysis usually not replicable by
378 any scientific program. For example, it allows us to incorporate records covering the entire
379 known distribution of a broadly distributed coastal species in a particular region. Another
380 advantage is the use of a great variety of data sources, some of them that are not used otherwise.
381 The method, although applied here to a large mobile predatory shark species, has the potential
382 to be applied for the study of distribution patterns and migratory movements of other mobile
383 marine taxa. If sufficient size and sex information of a species is available, models have the
384 potential to be used to investigate habitat use and determine critical habitats of the different
385 members of the population. Despite clear limitations, inference by this method may constitute
386 an important first step toward informing management plans in data-poor regions. It can also
387 provide quick and valuable information under urgent conservation needs.

388 The SWA constitutes a good example of a region that can benefit from the method
389 presented here. The region is known to have an important representation of marine
390 elasmobranch taxa, from common species like *N. cepedianus* to endemic ones like many
391 representatives of the Rajiformes order (Figueroa et al. 2013; Last et al. 2016). Efforts to study
392 the spatial ecology of these species are ongoing, typically employing affordable and

conventional methods (i.e., mark-recapture) highly biased to commercially important species (e.g., *Mustelus schmitti* Pérez et al. 2014). Other attempts focused on high order predator species but with limited results. For example, Irigoyen et al. (2015) tagged 13 sevengill and 228 tope (*Galeorhinus galeus*) sharks off Argentina among which only two of the latter were recaptured, providing the first evidence on the long-distance movement of the species. Jaureguizar et al. (2018) further report information on an additional tope shark recapture supporting past proposed migratory hypothesis of the species. However, the spatial ecology of this group of fishes remains largely unknown, probably as a result of financial limitations and data gaps. In this sense, the method applied here is an affordable and complementary approach to current tagging efforts in the region.

403

404 **Habitat suitability and predicted migratory pattern**

405 The characterization of suitable habitat for *N. cepedianus* in the SWA and its location
406 throughout the year suggest that at least some individuals perform extended intra-annual
407 latitudinal movements. For instance, models indicated that only an area (~40°–45°S) part of
408 northern Patagonia comprises suitable habitat year-round, whereas in the rest of the SWA
409 (~25°–40°S and ~45°–53°S) suitable areas occur seasonally. These results agree with recent
410 studies determining a year-round occurrence and a warm season occurrence in northern
411 (Irigoyen et al. 2018) and central (Irigoyen et al. 2019) Patagonian marine inlets, respectively.
412 Based on this seasonality and the clustering observed in June–July in the Río de la Plata
413 estuarine area, we infer that two possible displacements would define the main migratory
414 pattern of the species, both occurring in the fall-winter period (April–September). The
415 northward displacement is characterized by individuals moving from Patagonian (~40°–47°S)
416 to Río de la Plata (~33°–37°S) coastal waters. Individuals seem to aggregate in the Río de la
417 Plata area and Uruguayan coast during cold months (June–July). The southward displacement

418 is determined by a return migration across coastal waters, reaching extreme latitudes between
419 February and March. This dynamic process is governed by seasonal fluctuations in the location
420 of water temperature gradients, and the use of turbid coastal waters during June–July. In warmer
421 months, sharks stray southwards to extreme latitudes across coastal areas likely driven by the
422 use of pinniped colonies as seasonal feeding grounds. It is important to note, however, that the
423 proposed model of migration does not necessarily apply to the whole population. For example,
424 part of the population may move to deeper areas in winter instead of northern locations (e.g.,
425 Stehfest et al. 2014), staying the year-round in its core area of latitudinal distribution (~40–
426 45°S). Therefore, these results should be interpreted with caution, and ideally in combination
427 with direct movement evidence from tracking or mark-recapture studies.

428 The distinct clustering observed in the Río de la Plata estuarine area and Uruguayan
429 coast during the period June–July is likely to be a result of the northward migration event of
430 part of the population. This event could be associated to pregnant females selecting critical
431 coastal habitats to maximize survivorship and development of the young, such as turbid (e.g.,
432 Chin et al. 2013), warm (e.g., Hight and Lowe 2007; Elisio et al. 2017), or high productive
433 waters (Heupel et al. 2007). Neonates were found in the area as early as September supporting
434 this hypothesis. Neonates were also found until May in other coastal areas of northern Argentina
435 (~35°–41°S), suggesting that parturition is not localized but spread out in a broader region and
436 period. The presence of juveniles together with adult individuals during parturition may be
437 explained by the fact that the area also constitutes a critical habitat for the young, as recently
438 discussed for the southern area of the Río de la Plata estuary (Milessi et al. 2019). The clustering
439 observed in February–March, although less clear, was only represented by juveniles that may
440 remain in the area before their first migration. Because of the general spatial continuity of shark
441 records, we hypothesize that the species constitutes one population in the region.

442

443 **Species-specific considerations**

444 The migratory pattern inferred in the present study is consistent with the large-scale movement
445 behavior and regional site fidelity of tracked *N. cepedianus* documented in temperate waters of
446 southeast Australia (Barnett et al. 2011; Stehfest et al. 2014). Barnett et al. (2011) provided
447 evidence that sevengill males perform northern migrations during fall-winter in search of
448 foraging grounds, whereas some females remain close to southern coastal areas and others move
449 to deeper offshore waters (Stehfest et al. 2014). In accordance with Barnett et al. (2011) and
450 despite no sex-specific results were obtained in the present study, our findings suggest that
451 during fall-winter some individuals migrate north, whereas others remain in southern coastal
452 areas. Seasonality and sex biases were also evident for *N. cepedianus* occurring in coastal
453 habitats along the west coast of USA (Ebert 1989; Williams et al. 2011), and individuals
454 undertook long-distance migrations and returned to the same place in consecutive years
455 (Williams et al. 2012; Ketchum et al. 2017). These findings may also be related to past reports
456 (Ebert 1989, 1996) and more recent evidence on a biennial/triennial reproductive cycle of the
457 species (Awruch et al. 2014; Irigoyen et al. 2018). Therefore, mounting evidence from different
458 parts of the world suggests regional-scale use of coastal habitats, seasonal use of the same
459 estuarine areas (i.e., site fidelity), and intrapopulation variation in the migratory behavior (i.e.,
460 partial and/or differential migration) for this widespread species of shark, all factors giving
461 shape to its population structure (Chapman et al. 2015). As stated by Abrantes and Barnett
462 (2011), *N. cepedianus* may regulate the overall community structure and dynamics through
463 migratory connectivity, highlighting the role of this top order predator in marine ecosystems
464 (Barnett et al. 2012).

465 Water temperature and turbidity gradients constitute important drivers for *N. cepedianus*
466 large-scale horizontal movements, as determined in the present and previous studies.
467 Temperature fluctuations are known to have direct (through physiological stress) or indirect

468 (through prey availability) effects on coastal shark's distribution and movement (Speed et al.
469 2010; Schlaff et al. 2014). In Tasmanian waters, temperature indirectly affected *N. cepedianus*
470 occurrence by influencing the distribution of their main prey (Barnett and Semmens 2012). It
471 has also been determined that frontal areas constitute foraging hotspots for marine vertebrates,
472 including large sharks, due to enhanced primary productivity (Scales et al. 2014b). Turbid
473 environments represent important grounds for juvenile sharks that may benefit from decreased
474 predatory risk, increased abundance of prey, and facilitated hunting strategies (e.g., Chin et al.
475 2013; Yates et al. 2015). In the present study, *N. cepedianus* parturition location and timing
476 may be a strategy for increased survival of neonates and young juveniles by using the services
477 provided by the turbid environments along the coastal shelves of northern Argentina and
478 Uruguay.

479 Results further suggest that intrinsic processes of prey populations may influence *N.*
480 *cepedianus* movement behavior. For example, recent studies in Patagonian bays argued that *N.*
481 *cepedianus* peak of abundance coincided with a higher abundance of southern elephant seal
482 (*Mirounga leonina*) pups (Irigoyen et al. 2018), and South American sea lion (*Otaria*
483 *flavescens*) pups (Irigoyen et al. 2019), both important prey. In our study, distance to pinniped
484 colonies was of importance during warm periods, suggesting a link between the pinnipeds
485 breeding season and the arrival of sharks with foraging purposes. As foraging is not limited to
486 pinniped prey, other important prey may play a part in driving *N. cepedianus* movements;
487 examples of these are franciscana dolphin *Pontoporia blainvilliei* (Brownell Jr. 1975), weakfish
488 *Cynoscion guatucupa*, smoothhound shark *Mustelus schmitti*, eagle ray *Myliobatis* spp.
489 (Chiaramonte and Pettovello 2000; Lucifora et al. 2005a), Brazilian menhaden *Brevoortia*
490 *aurea* (A.C. Milessi, Comisión de Investigaciones Científicas de la Provincia de Buenos Aires,
491 La Plata, Argentina, personal communication, 2019), Patagonian blennie *Eleginops*
492 *maclovinus*, and plownose chiamaera *Callorhinichus callorynchus* (N. Bovcon, Secretaría de

493 Pesca de la Provincia del Chubut, Rawson, Argentina, personal communication, 2019). Future
494 models on distributional aspects of *N. cepedianus* may be improved by including a broader set
495 of biotic predictors, as recently demonstrated for migrating monarch butterflies (Kass et al.
496 2019). Due to ontogenetic dietary shift in *N. cepedianus* (Ebert 2002; Lucifora et al. 2005a;
497 Braccini 2008; Abrantes and Barnett 2011), future stage-explicit models would also benefit
498 from a broader set of biotic predictors describing the distribution of different prey and their own
499 key habitats.

500

501 **Final considerations**

502 In recent years, conservation management of chondrichthyans has been undergoing
503 development and enforcement in the SWA. Most of the national efforts are framed in National
504 Action Plans (i.e., PAN-Tiburón Uruguay [Domingo et al. 2008], PAN-Tiburón Argentina
505 [CFP 2009]), intended to warrant conservation and sustainable management of sharks, rays and
506 chimaeras nationwide. These plans currently comprise state authorities' legislation to close
507 certain areas to fishing, and also the implementation of catch limits and good fishing practices
508 (e.g., release of individuals larger than 160 cm L_T , shark finning ban). However, the success of
509 these approaches ultimately depends on matching the spatial and temporal scale of movements
510 and the demographic structure of the species. This is a hard task for highly mobile species like
511 large predatory sharks. Based on the results of the present study, seasonally closed areas for
512 bottom trawling fall within the spatial and temporal scale of *N. cepedianus* migratory process
513 (e.g., 'Condrietos' and 'El Rincón' temporal closures in Argentina). However, legislation
514 needs to be established in agreement with different national and international jurisdictions. For
515 example, Buenos Aires is the only province of Argentina to have fishing legislation in place to
516 prohibit the killing of large sharks in sport fisheries, covering a highly limited section of the
517 coastal habitats in which most apex sharks are distributed. Legislation in the remaining coastal

518 territories is limited, while sharks are only protected in relatively small no-take marine reserves
519 [for a review see Venerus and Cedrola (2017)]. National and Regional Action Plans represent
520 a good framework to develop suitable habitat analyses in order to design measures to preserve
521 large mobile sharks whose migratory patterns involve different local and international
522 legislation.

523 Large sharks that perform large-scale migrations impose important challenges for
524 fishery management (e.g., Heupel et al. 2015; Daly et al. 2018), and nations are on the need to
525 implement directed strategies for their sustainable exploitation and conservation. Most recent
526 shark fisheries management strategies are planning for dynamic processes of the populations
527 (Pressey et al. 2007), which require temporally explicit information about population
528 movements and structure (Maxwell et al. 2015; Welch and McHenry 2018). While these
529 promising strategies are under study in developed regions of the world, developing nations lack
530 the capacity, resources, and data to implement them, relying on the closure of temporally static
531 areas to shark fisheries or fisheries with high levels of shark by-catch. To develop sustainable
532 fishing activities and more effective measures of protection for sharks, alternative methods
533 based on available data must be implemented to answer relevant questions in data-poor
534 management or species scenarios. Under these circumstances, studies increasingly demonstrate
535 the value of data based on local ecological knowledge (e.g., Bonfil et al. 2018; Lopes et al.
536 2019), social media mining (e.g., Araujo et al. 2017) and citizen science (e.g., Brodie et al.
537 2015, 2018b), as a source of affordable yet reliable information for marine spatial planning.

538

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551 **REFERENCES**

- 552 Abrantes, K.G., and Barnett, A. 2011. Intrapopulation variations in diet and habitat use in a
 553 marine apex predator, the broadnose sevengill shark *Notorynchus cepedianus*. Mar. Ecol.
 554 Prog. Ser. **442**: 133–148. doi:10.3354/meps09395.
- 555 Acha, M.E., Mianzan, H., Guerrero, R., Carreto, J., Giberto, D., Montoya, N., and Carignan,
 556 M. 2008. An overview of physical and ecological processes in the Rio de la Plata
 557 Estuary. Cont. Shelf Res. **28**(13): 1579–1588. doi:10.1016/j.csr.2007.01.031.
- 558 Aiello-Lammens, M.E., Boria, R.A., Radosavljevic, A., Vilela, B., and Anderson, R.P. 2015.
 559 spThin: An R package for spatial thinning of species occurrence records for use in
 560 ecological niche models. Ecography **38**(5): 541–545. doi:10.1111/ecog.01132.
- 561 Alemany, D., Acha, E.M., and Iribarne, O. 2009. The relationship between marine fronts and
 562 fish diversity in the patagonian shelf large marine ecosystem. J. Biogeogr. **36**(11): 2111–
 563 2124. doi:10.1111/j.1365-2699.2009.02148.x.
- 564 Araujo, G., Snow, S., So, C.L., Labaja, J., Murray, R., Colucci, A., and Ponzo, A. 2017.
 565 Population structure, residency patterns and movements of whale sharks in Southern
 566 Leyte, Philippines: results from dedicated photo-ID and citizen science. Aquat. Conserv.
 567 Mar. Freshw. Ecosyst. **27**(1): 237–252. doi:10.1002/aqc.2636.
- 568 Awruch, C.A., Jones, S.M., Asorey, M.G., and Barnett, A. 2014. Non-lethal assessment of the
 569 reproductive status of broadnose sevengill sharks (*Notorynchus cepedianus*) to determine
 570 the significance of habitat use in coastal areas. Conserv. Physiol. **2**(1): cou013.
 571 doi:10.1093/conphys/cou013.
- 572 Barbini, S.A., Lucifora, L.O., and Figueroa, D.E. 2015. Using opportunistic records from a
 573 recreational fishing magazine to assess population trends of sharks. Can. J. Fish. Aquat.
 574 Sci. **72**(12): 1853–1859. doi:10.1139/cjfas-2015-0087.
- 575 Barnett, A., and Semmens, J.M. 2012. Sequential movement into coastal habitats and high

- 576 spatial overlap of predator and prey suggest high predation pressure in protected areas.
- 577 Oikos **121**(6): 882–890. doi:10.1111/j.1600-0706.2011.20000.x.
- 578 Barnett, A., Abrantes, K.G., Stevens, J.D., and Semmens, J.M. 2011. Site fidelity and sex-
- 579 specific migration in a mobile apex predator: Implications for conservation and
- 580 ecosystem dynamics. Anim. Behav. **81**(5): 1039–1048.
- 581 doi:10.1016/j.anbehav.2011.02.011.
- 582 Barnett, A., Braccini, J.M., Awruch, C.A., and Ebert, D.A. 2012. An overview on the role of
- 583 Hexanchiformes in marine ecosystems: biology, ecology and conservation status of a
- 584 primitive order of modern sharks. J. Fish Biol. **80**(5): 966–990. doi:10.1111/j.1095-
- 585 8649.2012.03242.x.
- 586 Barreto, R., Ferretti, F., Flemming, J.M., Amorim, A., Andrade, H., Worm, B., and Lessa, R.
- 587 2016. Trends in the exploitation of South Atlantic shark populations. Conserv. Biol.
- 588 **30**(4): 792–804. doi:10.1111/cobi.12663.
- 589 Bonfil, R., Ricaño-Soriano, M., Mendoza-Vargas, O.U., Méndez-Loeza, I., Pérez-Jiménez,
- 590 J.C., Bolaño-Martínez, N., and Palacios-Barreto, P. 2018. Tapping into local ecological
- 591 knowledge to assess the former importance and current status of sawfishes in Mexico.
- 592 Endanger. Species Res. **36**: 213–228. doi:10.3354/esr00899.
- 593 Boria, R.A., Olson, L.E., Goodman, S.M., and Anderson, R.P. 2014. Spatial filtering to
- 594 reduce sampling bias can improve the performance of ecological niche models. Ecol.
- 595 Modell. **275**: 73–77. doi:10.1016/j.ecolmodel.2013.12.012.
- 596 Bornatowski, H., Angelini, R., Coll, M., Barreto, R.R.P., and Amorim, A.F. 2018. Ecological
- 597 role and historical trends of large pelagic predators in a subtropical marine ecosystem of
- 598 the South Atlantic. Rev. Fish Biol. Fish. **28**(1): 241–259. doi:10.1007/s11160-017-9492-
- 599 z.
- 600 Braccini, J.M. 2008. Feeding ecology of two high-order predators from south-eastern

- 601 Australia: the coastal broadnose and the deepwater sharpnose sevengill sharks. Mar.
602 Ecol. Prog. Ser. **371**: 273–284. doi:10.3354/meps07684.
- 603 Bradie, J., and Leung, B. 2017. A quantitative synthesis of the importance of variables used in
604 MaxEnt species distribution models. J. Biogeogr. **44**(6): 1344–1361.
605 doi:10.1111/jbi.12894.
- 606 Brodie, S., Hobday, A.J., Smith, J.A., Everett, J.D., Taylor, M.D., Gray, C.A., and Suthers,
607 I.M. 2015. Modelling the oceanic habitats of two pelagic species using recreational
608 fisheries data. Fish. Oceanogr. **24**(5): 463–477. doi:10.1111/fog.12122.
- 609 Brodie, S., Lédée, E.J.I., Heupel, M.R., Babcock, R.C., Campbell, H.A., Gledhill, D.C.,
610 Hoenner, X., Huveneers, C., Jaine, F.R.A., Simpfendorfer, C.A., Taylor, M.D., Udyawer,
611 V., and Harcourt, R.G. 2018a. Continental-scale animal tracking reveals functional
612 movement classes across marine taxa. Sci. Rep. **8**(1): 1–9. doi:10.1038/s41598-018-
613 21988-5.
- 614 Brodie, S., Litherland, L., Stewart, J., Schilling, H.T., Pepperell, J.G., and Suthers, I.M.
615 2018b. Citizen science records describe the distribution and migratory behaviour of a
616 piscivorous predator, *Pomatomus saltatrix*. ICES J. Mar. Sci. **75**(5): 1573–1582.
617 doi:10.1093/icesjms/fsy057.
- 618 Brownell Jr., R.L. 1975. Progress Report on the Biology of the Franciscana Dolphin,
619 *Pontoporia blainvilleyi*, in Uruguayan Waters. J. Fish. Res. Board Canada **32**(7): 1073–
620 1078. doi:10.1139/f75-127.
- 621 Campagna, C., and Lewis, M. 1992. Growth and distribution of a southern elephant seal
622 colony. Mar. Mammal Sci. **8**(4): 387–396. doi:10.1111/j.1748-7692.1992.tb00053.x.
- 623 Cedrola, P. V., Caille, G.M., Chiaramonte, G.E., and Pettovello, A.D. 2009. Demographic
624 structure of broadnose seven-gill shark, *Notorynchus cepedianus*, caught by anglers in
625 southern Patagonia, Argentina. Mar. Biodivers. Rec. **2**: 1–5.

- 626 doi:10.1017/s1755267209990558.
- 627 Chapman, D.D., Feldheim, K.A., Papastamatiou, Y.P., and Hueter, R.E. 2015. There and
628 Back Again: A Review of Residency and Return Migrations in Sharks, with Implications
629 for Population Structure and Management. *Ann. Rev. Mar. Sci.* **7**(1): 547–570.
630 doi:10.1146/annurev-marine-010814-015730.
- 631 Chiaramonte, G.E., and Pettovello, A.D. 2000. The biology of *Mustelus schmitti* in southern
632 Patagonia, Argentina. *J. Fish Biol.* **57**(4): 930–942. doi:10.1006/jfb.2000.1358.
- 633 Chin, A., Tobin, A.J., Heupel, M.R., and Simpfendorfer, C.A. 2013. Population structure and
634 residency patterns of the blacktip reef shark *Carcharhinus melanopterus* in turbid coastal
635 environments. *J. Fish Biol.* **82**(4): 1192–1210. doi:10.1111/jfb.12057.
- 636 Cobos, M.E., Townsend Peterson, A., Barve, N., and Osorio-Olvera, L. 2019. Kuenm: An R
637 package for detailed development of ecological niche models using Maxent. *PeerJ*
638 **2019**(2): 1–15. doi:10.7717/peerj.6281.
- 639 Colonello, J.H., Cortés, F., and Massa, A.M. 2014. Species richness and reproductive modes
640 of chondrichthyans in relation to temperature and fishing effort in the Southwestern
641 Atlantic Shelf (34–54° S). *Fish. Res.* **160**: 8–17. doi:10.1016/j.fishres.2014.04.015.
- 642 Comisión Técnica Mixta del Frente Marítimo (CTMFM). 2018. Plan de Acción Regional para
643 la conservación y pesca sustentable de los condrictios del área del Tratado del Río de la
644 Plata y su Frente Marítimo. CTMFM, Buenos Aires, Argentina.
- 645 Compagno, L.J.V. 2009. *Notorynchus cepedianus*. In IUCN Red List of Threatened Species:
646 e.T39324A10200310. Available from
647 <https://www.iucnredlist.org/species/39324/10200310> (accessed 9 Dec 2019).
- 648 Consejo Federal Pesquero (CFP). 2009. Plan de Acción Nacional para la Conservación y el
649 Manejo de Condrictios (tiburones, rayas y quimeras) en la República Argentina. CFP
650 Resolution No. 06/2009, Buenos Aires, Argentina.

- 651 Cortés, F., and Waessle, J.A. 2017. Hotspots for porbeagle shark (*Lamna nasus*) bycatch in
652 the southwestern atlantic (51°S-57°S). *Can. J. Fish. Aquat. Sci.* **74**(7): 1100–1110.
653 doi:10.1139/cjfas-2016-0114.
- 654 Crespi-Abril, A.C., García, N.A., Crespo, E.A., and Coscarella, M.A. 2003. Consumption of
655 marine mammals by broadnose sevengill shark *Notorynchus cepedianus* in the northern
656 and central Patagonian shelf. *Lat. Am. J. Aquat. Mamm.* **2**(2): 101–107.
657 doi:10.5597/lajam00038.
- 658 Crespo, E.A., Schiavini, A.C.M., García, N.A., Franco-Trecu, V., Goodall, R.N.P.,
659 Rodríguez, D., Stenghel Morgante, J., and de Oliveira, L.R. 2015. Status, population
660 trend and genetic structure of South American fur seals, *Arctocephalus australis*, in
661 southwestern Atlantic waters. *Mar. Mammal Sci.* **31**(3): 866–890.
662 doi:10.1111/mms.12199.
- 663 Cuevas, J.M., García, M., and Di Giacomo, E. 2014. Diving behaviour of the critically
664 endangered tope shark *Galeorhinus galeus* in the Natural Reserve of Bahia San Blas,
665 northern Patagonia. *Anim. Biotelemetry* **2**(1): 1–6. doi:10.1186/2050-3385-2-11.
- 666 Daly, R., Smale, M.J., Singh, S., Anders, D., Shivji, M., Clare, C.A., Lea, J.S.E., Sousa, L.L.,
667 Wetherbee, B.M., Fitzpatrick, R., Clarke, C.R., Sheaves, M., and Barnett, A. 2018.
668 Refuges and risks: evaluating the benefits of an expanded MPA network for mobile apex
669 predators. *Divers. Distrib.* **24**(9): 1217–1230. doi:10.1111/ddi.12758.
- 670 De Wysiecki, A.M., Milessi, A.C., Wiff, R., and Jaureguizar, A.J. 2018. Highest catch of the
671 vulnerable broadnose sevengill shark *Notorynchus cepedianus* in the south-west Atlantic.
672 *J. Fish Biol.* **92**(2): 543–548. doi:10.1111/jfb.13532.
- 673 Derville, S., Torres, L.G., Iovan, C., and Garrigue, C. 2018. Finding the right fit: comparative
674 cetacean distribution models using multiple data sources and statistical approaches.
675 *Divers. Distrib.* **24**(11): 1657–1673. doi:10.1111/ddi.12782.

- 676 Domingo, A., Forselledo, R., Miller, P., and Passadore, C. 2008. Plan de Acción Nacional
677 para la conservación de condrictios en las pesquerías uruguayas. DINARA, Montevideo,
678 Uruguay.
- 679 Dulvy, N., Fowler, S., Musick, J., Cavanagh, R., Kyne, P., Harrison, L., Carlson, J.,
680 Davidson, L.N., Fordham, S., Francis, M., Pollock, C., Simpfendorfer, C., Burgess, G.,
681 Carpenter, K., Compagno, L.J., Ebert, D., Gibson, C., Heupel, M., Livingstone, S.,
682 Sanciangco, J., Stevens, J., Valenti, S., and White, W. 2014. Extinction risk and
683 conservation of the world's sharks and rays. *Elife* **3**: 1–34. doi:10.7554/eLife.00590.
- 684 Dulvy, N.K., Simpfendorfer, C.A., Davidson, L.N.K., Fordham, S. V., Bräutigam, A., Sant,
685 G., and Welch, D.J. 2017. Challenges and Priorities in Shark and Ray Conservation.
686 *Curr. Biol.* **27**(11): R565–R572. doi:10.1016/j.cub.2017.04.038.
- 687 Ebert, D.A. 1989. Life history of the sevengill shark, *Notorynchus cepedianus* Peron, in two
688 northern California bays. *Calif. Fish Game* **75**: 102–112.
- 689 Ebert, D.A. 1996. Biology of the sevengill shark *Notorynchus cepedianus* (Peron, 1807) in the
690 temperate coastal waters of Southern Africa. *S. Afr. J. Mar. Sci.* **17**: 93–103.
691 doi:10.2989/025776196784158545.
- 692 Ebert, D.A. 2002. Ontogenetic changes in the diet of the sevengill shark (*Notorynchus*
693 *cepedianus*). *Mar. Freshw. Res.* **53**(2): 517–523. doi:10.1071/MF01143.
- 694 Eger, A.M., Curtis, J.M.R., Fortin, M.J., Côté, I.M., and Guichard, F. 2017. Transferability
695 and scalability of species distribution models: a test with sedentary marine invertebrates.
696 *Can. J. Fish. Aquat. Sci.* **74**(5): 766–778. doi:10.1139/cjfas-2016-0129.
- 697 Elisio, M., Colonello, J.H., Cortés, F., Jaureguizar, A.J., Somoza, G.M., and Macchi, G.J.
698 2017. Aggregations and reproductive events of the narrownose smooth-hound shark
699 (*Mustelus schmitti*) in relation to temperature and depth in coastal waters of the south-
700 western Atlantic Ocean (38–42°S). *Mar. Freshw. Res.* **68**(4): 732–742.

- 701 doi:10.1071/MF15253.
- 702 Elith, J., and Leathwick, J.R. 2009. Species Distribution Models: Ecological Explanation and
703 Prediction Across Space and Time. *Annu. Rev. Ecol. Evol. Syst.* **40**(1): 677–697.
704 doi:10.1146/annurev.ecolsys.110308.120159.
- 705 Elith, J., Phillips, S.J., Hastie, T., Dudik, M., Chee, Y.E., and Yates, C.J. 2011. A statistical
706 explanation of MaxEnt for ecologists: online appendices. *Divers. Distrib.* **17**(1): 1–18.
707 doi:10.1111/j.1472-4642.2010.00725.x.
- 708 Figueroa, D.E., Barbini, S.A., Scenna, L.B., Belleggia, M., Delpiani, G.E., and Spath, M.C.
709 2013. El endemismo en las rayas de la Zona Común de Pesca Argentino-Uruguaya.
710 Frente Marítimo **23**: 95–104.
- 711 Fourcade, Y., Engler, J.O., Rödder, D., and Secondi, J. 2014. Mapping species distributions
712 with MAXENT using a geographically biased sample of presence data: A performance
713 assessment of methods for correcting sampling bias. *PLoS One* **9**(5): 1–13.
714 doi:10.1371/journal.pone.0097122.
- 715 Góngora, M.E., Bovcon, N.D., and Cochia, P.D. 2009. Ictiofauna capturada incidentalmente
716 en la pesquería de langostino patagónico *Pleoticus muelleri* Bate, 1888. *Rev. Biol. Mar.*
717 *Oceanogr.* **44**(3): 583–593. doi:10.4067/s0718-19572009000300006.
- 718 Guerrero, R.A., Piola, A.R., Fenco, H., Matano, R.P., Combes, V., Chao, Y., James, C.,
719 Palma, E.D., Saraceno, M. and Strub, P.T. 2014. The salinity signature of the cross-shelf
720 exchanges in the Southwestern Atlantic Ocean: Satellite observations. *J Geophys. Res.*
721 *Oceans* **119**(11): 7794–7810. doi:10.1002/2014JC010113.
- 722 Guzmán, L., and Campodónico, I. 1976. *Notorynchus cepedianus* (Peron, 1807) en la entrada
723 oriental del Estrecho de Magallanes (Elasmobranchii, Hexanchiidae). *Anales Inst.*
724 *Patagonia* **7**: 207–210.
- 725 Hammerschlag, N., Gallagher, A.J., and Lazarre, D.M. 2011. A review of shark satellite

- 726 tagging studies. *J. Exp. Mar. Bio. Ecol.* **398**(1–2): 1–8. doi:10.1016/j.jembe.2010.12.012.
- 727 Heupel, M.R., Carlson, J.K., and Simpfendorfer, C.A. 2007. Shark nursery areas: concepts,
728 definition, characterization and assumptions. *Mar. Ecol. Prog. Ser.* **337**: 287–297.
729 doi:10.3354/meps337287.
- 730 Heupel, M.R., Simpfendorfer, C.A., Espinoza, M., Smoohey, A.F., Tobin, A., and
731 Peddemors, V. 2015. Conservation challenges of sharks with continental scale
732 migrations. *Front. Mar. Sci.* **2**: 1–7. doi:10.3389/fmars.2015.00012.
- 733 Hight, B. V., and Lowe, C.G. 2007. Elevated body temperatures of adult female leopard
734 sharks, *Triakis semifasciata*, while aggregating in shallow nearshore embayments:
735 evidence for behavioral thermoregulation? *J. Exp. Mar. Bio. Ecol.* **352**(1): 114–128.
736 doi:10.1016/j.jembe.2007.07.021.
- 737 Hussey, N.E., Kessel, S.T., Aarestrup, K., Cooke, S.J., Cowley, P.D., Fisk, A.T., Harcourt,
738 R.G., Holland, K.N., Iverson, S.J., Kocik, J.F., Flemming, J.E.M., and Whoriskey, F.G.
739 2015. Aquatic animal telemetry: A panoramic window into the underwater world.
740 *Science* **348**(6240): 1255642. doi:10.1126/science.1255642.
- 741 Irigoyen, A., and Trobbiani, G. 2016. Depletion of trophy large-sized sharks populations of
742 the argentinean coast, south-western atlantic: Insights from fishers' knowledge. *Neotrop.
743 Ichthyol.* **14**(1). doi:10.1590/1982-0224-20150081.
- 744 Irigoyen, A., Sibbald, C., Cuestas, M., Cristiani, F., and Trobbiani, G. 2015. Patrones
745 estacionales de abundancia en el Golfo Nuevo y migración a lo largo de la plataforma
746 Argentina de cazones (*Galeorhinus galeus* [Linnaeus 1758]) y gatopardos (*Notorynchus
747 cepedianus* [Péron 1807]) (Argentina). *Ecol. Austral* **25**(2): 144–148.
- 748 Irigoyen, A.J., De Wysiecki, A.M., Trobbiani, G., Bovcon, N., Awruch, C.A., Argemi, F., and
749 Jaureguizar, A.J. 2018. Habitat use, seasonality and demography of an apex predator:
750 Sevengill shark *Notorynchus cepedianus* in Northern Patagonia. *Mar. Ecol. Prog. Ser.*

- 751 **603**: 147–160. doi:10.3354/meps12715.
- 752 Irigoyen, A.J., Bovcon, N., Trobbiani, G., De Wysiecki, A.M., Argemi, F., and Jaureguizar,
753 A.J. 2019. Habitat use, seasonality and demography of the broadnose sevengill shark
754 *Notorynchus cepedianus* in central Patagonia: Another piece of the puzzle. *Austral Ecol.*
755 **44**(8): 1463–1470. doi:10.1111/aec.12820.
- 756 Jaureguizar, A.J., Menni, R., Guerrero, R., and Lasta, C. 2004. Environmental factors
757 structuring fish communities of the Río de la Plata estuary. *Fish. Res.* **66**(2–3): 195–211.
758 doi:10.1016/S0165-7836(03)00200-5.
- 759 Jaureguizar, A.J., Cortés, F., Milessi, A.C., Cozzolino, E., and Allega, L. 2015. A trans-
760 ecosystem fishery: Environmental effects on the small-scale gillnet fishery along the Río
761 de la Plata boundary. *Estuar. Coast. Shelf Sci.* **166**: 92–104.
762 doi:10.1016/j.ecss.2014.11.003.
- 763 Jaureguizar, A.J., Argemi, F., Trobbiani, G., Palma, E.D., and Irigoyen, A.J. 2018. Large-
764 scale migration of a school shark, *Galeorhinus galeus*, in the Southwestern Atlantic.
765 *Neotrop. Ichthyol.* **16**(1): 1–6. doi:10.1590/1982-0224-20170050.
- 766 Kass, J.M., Anderson, R.P., Espinosa-Lucas, A., Juárez-Jaimes, V., Martínez-Salas, E.,
767 Botello, F., Tavera, G., Flores-Martínez, J.J., and Sánchez-Cordero, V. 2019. Biotic
768 predictors with phenological information improve range estimates for migrating monarch
769 butterflies in Mexico. *Ecography* **43**(3): 341–352. doi:10.1111/ecog.04886.
- 770 Ketchum, J.T., Slager, C.J., Buckhorn, M.L., Nosal, A.P., and Peter Klimley, A. 2017.
771 Residency and long-distance movements of sevengill sharks (*Notorhynchus cepedianus*)
772 tagged in San Francisco Bay. *Anim. Biotelemetry* **5**(1): 1–9. doi:10.1186/s40317-017-
773 0141-z.
- 774 Lascelles, B., Notarbartolo Di Sciara, G., Agardy, T., Cuttelod, A., Eckert, S., Glowka, L.,
775 Hoyt, E., Llewellyn, F., Louzao, M., Ridoux, V., and Tetley, M.J. 2014. Migratory

- 776 marine species: their status, threats and conservation management needs. *Aquat.*
777 *Conserv. Mar. Freshw. Ecosyst.* **24**: 111–127. doi:10.1002/aqc.2512.
- 778 Last, P.R., and Stevens, J.D. 2009. *Sharks and Rays of Australia*. CSIRO Publishing,
779 Collingwood, Australia.
- 780 Lopes, P.F.M., Verba, J.T., Begossi, A., and Pennino, M.G. 2019. Predicting species
781 distribution from fishers' local ecological knowledge: a new alternative for data-poor
782 management. *Can. J. Fish. Aquat. Sci.* **76**(8): 1423–1431. doi:10.1139/cjfas-2018-0148.
- 783 Lucifora, L.O., Menni, R.C., and Escalante, A.H. 2005a. Reproduction, abundance and
784 feeding habits of the broadnose sevengill shark *Notorynchus cepedianus* in north
785 Patagonia, Argentina. *Mar. Ecol. Prog. Ser.* **289**: 237–244. doi:10.3354/meps289237.
- 786 Lucifora, L.O., Menni, R.C., and Escalante, A.H. 2005b. Reproduction and seasonal
787 occurrence of the copper shark, *Carcharhinus brachyurus*, from north Patagonia,
788 Argentina. *ICES J. Mar. Sci.* **62**(1): 107–115. doi:10.1016/j.icesjms.2004.09.003.
- 789 Lucifora, L.O., García, V.B., Menni, R.C., and Worm, B. 2012. Spatial patterns in the
790 diversity of sharks, rays, and chimaeras (Chondrichthyes) in the Southwest Atlantic.
791 *Biodivers. Conserv.* **21**(2): 407–419. doi:10.1007/s10531-011-0189-7.
- 792 Lucifora, L.O., Barbini, S.A., Di Giacomo, E.E., Waessle, J.A., and Figueiroa, D.E. 2015.
793 Estimating the geographic range of a threatened shark in a data-poor region: *Cetorhinus*
794 *maximus* in the South Atlantic Ocean. *Curr. Zool.* **61**(5): 811–826.
795 doi:10.1093/czoolo/61.5.811.
- 796 Matano, R.P., Palma, E.D., and Piola, A.R. 2010. The influence of the Brazil and Malvinas
797 Currents on the Southwestern Atlantic Shelf circulation. *Ocean Sci.* **6**(4): 983–995.
798 doi:10.5194/os-6-983-2010.
- 799 Maxwell, S.M., Hazen, E.L., Lewison, R.L., Dunn, D.C., Bailey, H., Bograd, S.J., Briscoe,
800 D.K., Fossette, S., Hobday, A.J., Bennett, M., Benson, S., Caldwell, M.R., Costa, D.P.,

- 801 Dewar, H., Eguchi, T., Hazen, L., Kohin, S., Sippel, T., and Crowder, L.B. 2015.
- 802 Dynamic ocean management: defining and conceptualizing real-time management of the
- 803 ocean. *Mar. Policy* **58**: 42–50. doi:10.1016/j.marpol.2015.03.014.
- 804 McKelvey, K.S., Aubry, K.B., and Schwartz, M.K. 2008. Using Anecdotal Occurrence Data
- 805 for Rare or Elusive Species: The Illusion of Reality and a Call for Evidentiary Standards.
- 806 *Bioscience* **58**(6): 549–555. doi:10.1641/b580611.
- 807 Menni, R.C., Jaureguizar, A.J., Stehmann, M.F.W., and Lucifora, L.O. 2010. Marine
- 808 biodiversity at the community level: zoogeography of sharks, skates, rays and chimaeras
- 809 in the southwestern Atlantic. *Biodivers. Conserv.* **19**(3): 775–796. doi:10.1007/s10531-
- 810 009-9734-z.
- 811 Merow, C., Smith, M.J., and Silander, J.A. 2013. A practical guide to MaxEnt for modeling
- 812 species' distributions: what it does, and why inputs and settings matter. *Ecography*
- 813 **36**(10): 1058–1069. doi:10.1111/j.1600-0587.2013.07872.x.
- 814 Milessi, A.C., De Wysiecki, A.M., and Jaureguizar, A.J. 2019. Trophic ecology of young-of-
- 815 the-year elasmobranchs in a critical habitat within the Río de la Plata outer estuarine
- 816 waters. *Austral Ecol.* **44**(2): 290–299. doi:10.1111/aec.12673.
- 817 Monk, J., Ierodiaconou, D., Versace, V.L., Bellgrove, A., Harvey, E., Rattray, A., Laurenson,
- 818 L., and Quinn, G.P. 2010. Habitat suitability for marine fishes using presence-only
- 819 modelling and multibeam sonar. *Mar. Ecol. Prog. Ser.* **420**: 157–174.
- 820 doi:10.3354/meps08858.
- 821 Owens, H.L., Campbell, L.P., Dornak, L.L., Saupe, E.E., Barve, N., Soberón, J., Ingenloff,
- 822 K., Lira-Noriega, A., Hensz, C.M., Myers, C.E., and Peterson, A.T. 2013. Constraints on
- 823 interpretation of ecological niche models by limited environmental ranges on calibration
- 824 areas. *Ecol. Modell.* **263**: 10–18. doi:10.1016/j.ecolmodel.2013.04.011.
- 825 Palma, E.D., Matano, R.P., and Piola, A.R. 2008. A numerical study of the Southwestern

- 826 Atlantic Shelf circulation: Stratified ocean response to local and offshore forcing. *J.
827 Geophys. Res. Ocean.* **113**(11): 1–22. doi:10.1029/2007JC004720.
- 828 Papastamatiou, Y.P., and Lowe, C.G. 2012. An analytical and hypothesis-driven approach to
829 elasmobranch movement studies. *J. Fish Biol.* **80**(5): 1342–1360. doi:10.1111/j.1095-
830 8649.2012.03232.x.
- 831 Pasquini, A.I., and Depetris, P.J. 2007. Discharge trends and flow dynamics of South
832 American rivers draining the southern Atlantic seaboard: an overview. *J. Hydrol.* **333**(2–
833 4): 385–399. doi:10.1016/j.jhydrol.2006.09.005.
- 834 Pérez, M., Braccini, M., and Cousseau, M.B. 2014. Use of conventional tags in a country with
835 little experience in marine fishes tagging. *Lat. Am. J. Aquat. Res.* **42**(1): 258–263.
836 doi:10.3856/vol42-issue1-fulltext-21.
- 837 Phillips, S.J., and Dudík, M. 2008. Modeling of species distributions with Maxent: New
838 extensions and a comprehensive evaluation. *Ecography* **31**(2): 161–175.
839 doi:10.1111/j.0906-7590.2008.5203.x.
- 840 Phillips, S.J., Anderson, R.P., and Schapire, R.E. 2006. Maximum entropy modeling of
841 species geographic distributions. *Ecol. Modell.* **190**(3-4): 231–259.
842 doi:10.1016/j.ecolmodel.2005.03.026
- 843 Phillips, S.J., Dudík, M., Elith, J., Graham, C.H., Lehmann, A., Leathwick, J., and Ferrier, S.
844 2009. Sample selection bias and presence-only distribution models: Implications for
845 background and pseudo-absence data. *Ecol. Appl.* **19**(1): 181–197. doi:10.1890/07-
846 2153.1.
- 847 Phillips, S.J., Anderson, R.P., Dudík, M., Schapire, R.E., and Blair, M.E. 2017. Opening the
848 black box: an open-source release of Maxent. *Ecography* **40**(7): 887–893.
849 doi:10.1111/ecog.03049.
- 850 Pressey, R.L., Cabeza, M., Watts, M.E., Cowling, R.M., and Wilson, K.A. 2007.

- 851 Conservation planning in a changing world. *Trends Ecol. Evol.* **22**(11): 583–592.
- 852 doi:10.1016/j.tree.2007.10.001.
- 853 Queiroz, N., Humphries, N.E., Couto, A., Vedor, M., da Costa, I., Sequeira, A.M.M.,
- 854 Mucientes, G., Santos, A.M., Abascal, F.J., Abercrombie, D.L., Abrantes, K., Acuña-
- 855 Marrero, D., Afonso, A.S., Afonso, P., Anders, D., Araujo, G., Arauz, R., Bach, P.,
- 856 Barnett, A., Bernal, D., Berumen, M.L., Bessudo Lion, S., Bezerra, N.P.A., Blaison, A.
- 857 V., Block, B.A., Bond, M.E., Bonfil, R., Bradford, R.W., Braun, C.D., Brooks, E.J.,
- 858 Brooks, A., Brown, J., Bruce, B.D., Byrne, M.E., Campana, S.E., Carlisle, A.B.,
- 859 Chapman, D.D., Chapple, T.K., Chisholm, J., Clarke, C.R., Clua, E.G., Cochran, J.E.M.,
- 860 Crochelet, E.C., Dagorn, L., Daly, R., Cortés, D.D., Doyle, T.K., Drew, M., Duffy,
- 861 C.A.J., Erikson, T., Espinoza, E., Ferreira, L.C., Ferretti, F., Filmalter, J.D., Fischer,
- 862 G.C., Fitzpatrick, R., Fontes, J., Forget, F., Fowler, M., Francis, M.P., Gallagher, A.J.,
- 863 Gennari, E., Goldsworthy, S.D., Gollock, M.J., Green, J.R., Gustafson, J.A., Guttridge,
- 864 T.L., Guzman, H.M., Hammerschlag, N., Harman, L., Hazin, F.H.V., Heard, M., Hearn,
- 865 A.R., Holdsworth, J.C., Holmes, B.J., Howey, L.A., Hoyos, M., Hueter, R.E., Hussey,
- 866 N.E., Huvaneers, C., Irion, D.T., Jacoby, D.M.P., Jewell, O.J.D., Johnson, R., Jordan,
- 867 L.K.B., Jorgensen, S.J., Joyce, W., Keating Daly, C.A., Ketchum, J.T., Klimley, A.P.,
- 868 Kock, A.A., Koen, P., Ladino, F., Lana, F.O., Lea, J.S.E., Llewellyn, F., Lyon, W.S.,
- 869 MacDonnell, A., Macena, B.C.L., Marshall, H., McAllister, J.D., McAuley, R., Meijer,
- 870 M.A., Morris, J.J., Nelson, E.R., Papastamatiou, Y.P., Patterson, T.A., Peñaherrera-
- 871 Palma, C., Pepperell, J.G., Pierce, S.J., Poisson, F., Quintero, L.M., Richardson, A.J.,
- 872 Rogers, P.J., Rohner, C.A., Rowat, D.R.L., Samoilys, M., Semmens, J.M., Sheaves, M.,
- 873 Shillinger, G., Shivji, M., Singh, S., Skomal, G.B., Smale, M.J., Snyders, L.B., Soler, G.,
- 874 Soria, M., Stehfest, K.M., Stevens, J.D., Thorrold, S.R., Tolotti, M.T., Towner, A.,
- 875 Travassos, P., Tyminski, J.P., Vandeperre, F., Vaudo, J.J., Watanabe, Y.Y., Weber, S.B.,

- 876 Wetherbee, B.M., White, T.D., Williams, S., Zárate, P.M., Harcourt, R., Hays, G.C.,
877 Meekan, M.G., Thums, M., Irigoien, X., Eguiluz, V.M., Duarte, C.M., Sousa, L.L.,
878 Simpson, S.J., Southall, E.J., and Sims, D.W. 2019. Global spatial risk assessment of
879 sharks under the footprint of fisheries. *Nature* **572**(7770): 461–466. doi:10.1038/s41586-
880 019-1444-4.
- 881 Radosavljevic, A., and Anderson, R.P. 2014. Making better Maxent models of species
882 distributions: complexity, overfitting and evaluation. *J. Biogeogr.* **41**(4): 629–643.
883 doi:10.1111/jbi.12227.
- 884 Robinson, N.M., Nelson, W.A., Costello, M.J., Sutherland, J.E., and Lundquist, C.J. 2017. A
885 systematic review of marine-based Species Distribution Models (SDMs) with
886 recommendations for best practice. *Front. Mar. Sci.* **4**: 1–11.
887 doi:10.3389/fmars.2017.00421.
- 888 Sadowsky, V. 1969. First record of broad-snouted seven-gilled shark from Cananéia, coast of
889 Brazil. *Bol. do Inst. Ocean.* **18**(1): 33–35. doi:10.1590/s0373-55241969000100004.
- 890 Santos, C.C., Domingo, A., Carlson, J., Natanson, L.J., Cortes, E., Miller, P., Hazin, F.,
891 Travassos, P., Mas, F., and Coelho, R. 2018. Habitat Use and Migrations of Shortfin
892 Mako in the Atlantic Using Satellite Telemetry. *Collect. Vol. Sci. Pap. ICCAT* **75**(3):
893 445–456.
- 894 Saraceno, M., Provost, C., and Piola, A.R. 2005. On the relationship between satellite-
895 retrieved surface temperature fronts and chlorophyll *a* in the western South Atlantic. *J.*
896 *Geophys. Res. Ocean.* **110**(11): 1–16. doi:10.1029/2004JC002736.
- 897 Scales, K.L., Miller, P.I., Embling, C.B., Ingram, S.N., Pirotta, E., and Votier, S.C. 2014a.
898 Mesoscale fronts as foraging habitats: composite front mapping reveals oceanographic
899 drivers of habitat use for a pelagic seabird. *J. R. Soc. Interface* **11**(100).
900 doi:10.1098/rsif.2014.0679.

- 901 Scales, K.L., Miller, P.I., Hawkes, L.A., Ingram, S.N., Sims, D.W., and Votier, S.C. 2014b.
 902 On the front line: frontal zones as priority at-sea conservation areas for mobile marine
 903 vertebrates. *J. Appl. Ecol.* **51**(6): 1575–1583. doi:10.1111/1365-2664.12330.
- 904 Schick, R.S., Loarie, S.R., Colchero, F., Best, B.D., Boustany, A., Conde, D.A., Halpin, P.N.,
 905 Joppa, L.N., McClellan, C.M., and Clark, J.S. 2008. Understanding movement data and
 906 movement processes: current and emerging directions. *Ecol. Lett.* **11**(12): 1338–1350.
 907 doi:10.1111/j.1461-0248.2008.01249.x.
- 908 Schlaff, A.M., Heupel, M.R., and Simpfendorfer, C.A. 2014. Influence of environmental
 909 factors on shark and ray movement, behaviour and habitat use: a review. *Rev. Fish Biol.*
 910 *Fish.* **24**(4): 1089–1103 doi:10.1007/s11160-014-9364-8.
- 911 Shcheglovitova, M., and Anderson, R.P. 2013. Estimating optimal complexity for ecological
 912 niche models: A jackknife approach for species with small sample sizes. *Ecol. Modell.*
 913 **269**: 9–17. doi:10.1016/j.ecolmodel.2013.08.011.
- 914 Silveira, S., Laporta, M., Pereyra, I., Mas, F., Doño, F., Santana, O., and Fabiano, G. 2018.
 915 Análisis de la captura de condrictios en la pesca artesanal oceánica de Uruguay,
 916 Atlántico Sudoccidental. *Frente Marítimo* **25**: 301–324.
- 917 Speed, C.W., Field, I.C., Meekan, M.G., and Bradshaw, C.J.A. 2010. Complexities of coastal
 918 shark movements and their implications for management. *Mar. Ecol. Prog. Ser.* **408**:
 919 275–293. doi:10.3354/meps08581.
- 920 Stehfest, K.M., Patterson, T.A., Barnett, A., and Semmens, J.M. 2014. Intraspecific
 921 differences in movement, dive behavior and vertical habitat preferences of a key marine
 922 apex predator. *Mar. Ecol. Prog. Ser.* **495**: 249–262. doi:10.3354/meps10563.
- 923 Stein, R.W., Mull, C.G., Kuhn, T.S., Aschliman, N.C., Davidson, L.N.K., Joy, J.B., Smith,
 924 G.J., Dulvy, N.K., and Mooers, A.O. 2018. Global priorities for conserving the
 925 evolutionary history of sharks, rays and chimaeras. *Nat. Ecol. Evol.* **2**(2): 288–298.

- 926 doi:10.1038/s41559-017-0448-4.
- 927 Túnez, J.I., Cappozzo, H.L., and Cassini, M.H. 2008. Natural and anthropogenic factors
928 associated with the distribution of South American sea lion along the Atlantic coast.
929 *Hydrobiologia* **598**(1): 191–202. doi:10.1007/s10750-007-9150-x.
- 930 Van Der Molen, S., Caille, G., and González, R. 1998. By-catch of sharks in Patagonian
931 coastal trawl fisheries. *Mar. Freshw. Res.* **49**(7): 641–644. doi:10.1071/mf98005.
- 932 Venerus, L.A., and Cedrola, P. V. 2017. Review of marine recreational fisheries regulations
933 in Argentina. *Mar. Policy* **81**: 202–210. doi:10.1016/j.marpol.2017.03.007.
- 934 Wang, M., Son, S.H., and Harding, L.W. 2009. Retrieval of diffuse attenuation coefficient in
935 the Chesapeake Bay and turbid ocean regions for satellite ocean color applications. *J.*
936 *Geophys. Res. Ocean.* **114**(10): C10011. doi:10.1029/2009JC005286.
- 937 Warren, D.L., and Seifert, S.N. 2011. Ecological niche modeling in Maxent: the importance
938 of model complexity and the performance of model selection criteria. *Ecol. Appl.* **21**(2):
939 335–342. doi:10.1890/10-1171.1.
- 940 Welch, H., and McHenry, J. 2018. Planning for dynamic process: an assemblage-level
941 surrogate strategy for species seasonal movement pathways. *Aquat. Conserv. Mar.*
942 *Freshw. Ecosyst.* **28**(2): 337–350. doi:10.1002/aqc.2857.
- 943 Welch, H., Pressey, R.L., and Reside, A.E. 2018. Using temporally explicit habitat suitability
944 models to assess threats to mobile species and evaluate the effectiveness of marine
945 protected areas. *J. Nat. Conserv.* **41**: 106–115. doi:10.1016/j.jnc.2017.12.003.
- 946 Wessel, P., and W.H.F., Smith. 1996. A global, self-consistent, hierarchical, high-resolution
947 shoreline database. *J. Geophys. Res.* **101**: 8741–8743. doi:10.1029/96JB00104.
- 948 Williams, G.D., Andrews, K.S., Farrer, D.A., Bargmann, G.G., and Levin, P.S. 2011.
949 Occurrence and biological characteristics of broadnose sevengill sharks (*Notorynchus*
950 *cepedianus*) in Pacific Northwest coastal estuaries. *Environ. Biol. Fishes* **91**(4): 379–388.

- 951 doi:10.1007/s10641-011-9797-z.
- 952 Williams, G.D., Andrews, K.S., Katz, S.L., Moser, M.L., Tolimieri, N., Farrer, D.A., and
953 Levin, P.S. 2012. Scale and pattern of broadnose sevengill shark *Notorynchus*
954 *cepedianus* movement in estuarine embayments. J. Fish Biol. **80**(5): 1380–1400.
955 doi:10.1111/j.1095-8649.2011.03179.x.
- 956 Williamson, M.J., Tebbs, E.J., Dawson, T.P., and Jacoby, D.M.P. 2019. Satellite remote
957 sensing in shark and ray ecology, conservation and management. Front. Mar. Sci. **6**: 1–
958 23. doi:10.3389/fmars.2019.00135.
- 959 Yates, P.M., Heupel, M.R., Tobin, A.J., and Simpfendorfer, C.A. 2015. Ecological drivers of
960 shark distributions along a tropical coastline. PLoS One **10**(4): 1–18.
961 doi:10.1371/journal.pone.0121346.
- 962

Tables

Table 1. Brief description of *Notorynchus cepedianus* occurrence data sources consulted in the study.

Source	Brief description
<i>Published literature</i>	Peer-reviewed papers, books and conference abstracts
<i>Grey literature</i>	Institutional reports and journals, and fishing magazines (Spanish and Portuguese)
<i>Social media</i>	Facebook™, YouTube™, Instagram™, Google™ searches, and fishing blogs and forums
<i>Scientific campaigns</i>	On-vessel, shore-based and fishery landings surveys
<i>Commercial fishing</i>	Observer programs
<i>Ichthyological collections</i>	Museums, research institutions and universities
<i>Professional contact</i>	Email-based requests
<i>Fishing tournaments</i>	Trophies

Table 2. Description of environmental predictors used for modeling habitat suitability of *Notorynchus cepedianus* in the South-west Atlantic.

Predictor	Source	Spatial resolution	Range (min – max)	Unit	Period
Static					
Distance to coast	GSHHGD http://www.soest.hawaii.edu/pwessel/gshhg/index.html	0.016°	0.1 – 417	km	N/A
Depth	ERDDAP http://coastwatch.pfeg.noaa.gov/erddap/griddap/etopo180.html	0.016°	-200 – 0	m	N/A
Slope	Derived from bathymetry using the <i>terrain</i> function in R package ‘raster’	0.016°	0 – 1.63	Angle degrees	N/A
Distance to marine inlet	Created using the <i>gDistance</i> function in R package ‘rgeos’	0.041°	0 – 16.66	Decimal degrees	N/A
Distance to pinniped colony	Created using the <i>gDistance</i> function	0.041°	0 – 6.52	Decimal degrees	N/A
Dynamic					
Sea surface temperature	ERDDAP http://coastwatch.pfeg.noaa.gov/erddap/griddap/erdMH1sstmday.html	0.041°	5.89 – 24.89	°C	Jan/03–Jan/18
Distance to thermal front	Derived from sea surface temperature. Created using the <i>gDistance</i> function	0.041°	0 – 12.85	Decimal degrees	Jan/03–Jan/18
Diffuse attenuation K490	ERDDAP http://coastwatch.pfeg.noaa.gov/erddap/griddap/erdMH1kd490mday.html	0.041°	0 – 1.72	m ⁻¹	Jan/03–Jan/18

ERDDAP = Environmental Research Division’s Data Access Program

PODAAC = Physical Oceanography Distributed Active Archive Center

GSHHGD = Global Self-consistent, Hierarchical, High-resolution Geography Database

Table 3. Final models describing the bimonthly variation of habitat suitability for *Notorynchus cepedianus* in the South-west Atlantic. Predictor contributing the most to each model is highlighted in bold.

Period	N_{occ}	N_{ind}	N_{tgb}	FC	RM	OR at 10%	AUC±SD	Predictor contribution (%)							
								SST	dfSST	Dist	Depth	Slope	dInlet	Pinn	K490
Dec-Jan	31	30	227	1	3	0.000	0.852±0.030	9.8	21.8	62.6	2.7	0.7	0.3	1.4	0.7
Feb-Mar	39	40	122	1	2	0.029	0.819±0.025	2.6	0.3	48.5	1.3	3.0	7.7	34.7	1.9
Apr-May	18	23	60	lp	3	0.000	0.751±0.049	6.2	46.6	34.8	0.0	0.6	4.8	6.6	0.5
Jun-Jul	32	22	167	p	2	0.000	0.904±0.021	5.3	2.1	27.1	8.0	0.2	12.4	25.1	19.8
Aug-Sep	22	20	205	q	3	0.053	0.850±0.025	0.4	24.4	67.5	5.4	1.8	0.9	0.9	0.6
Oct-Nov	45	34	388	lq	2	0.029	0.868±0.015	0.7	15.1	56.9	21.9	1.0	0.1	1.4	2.9

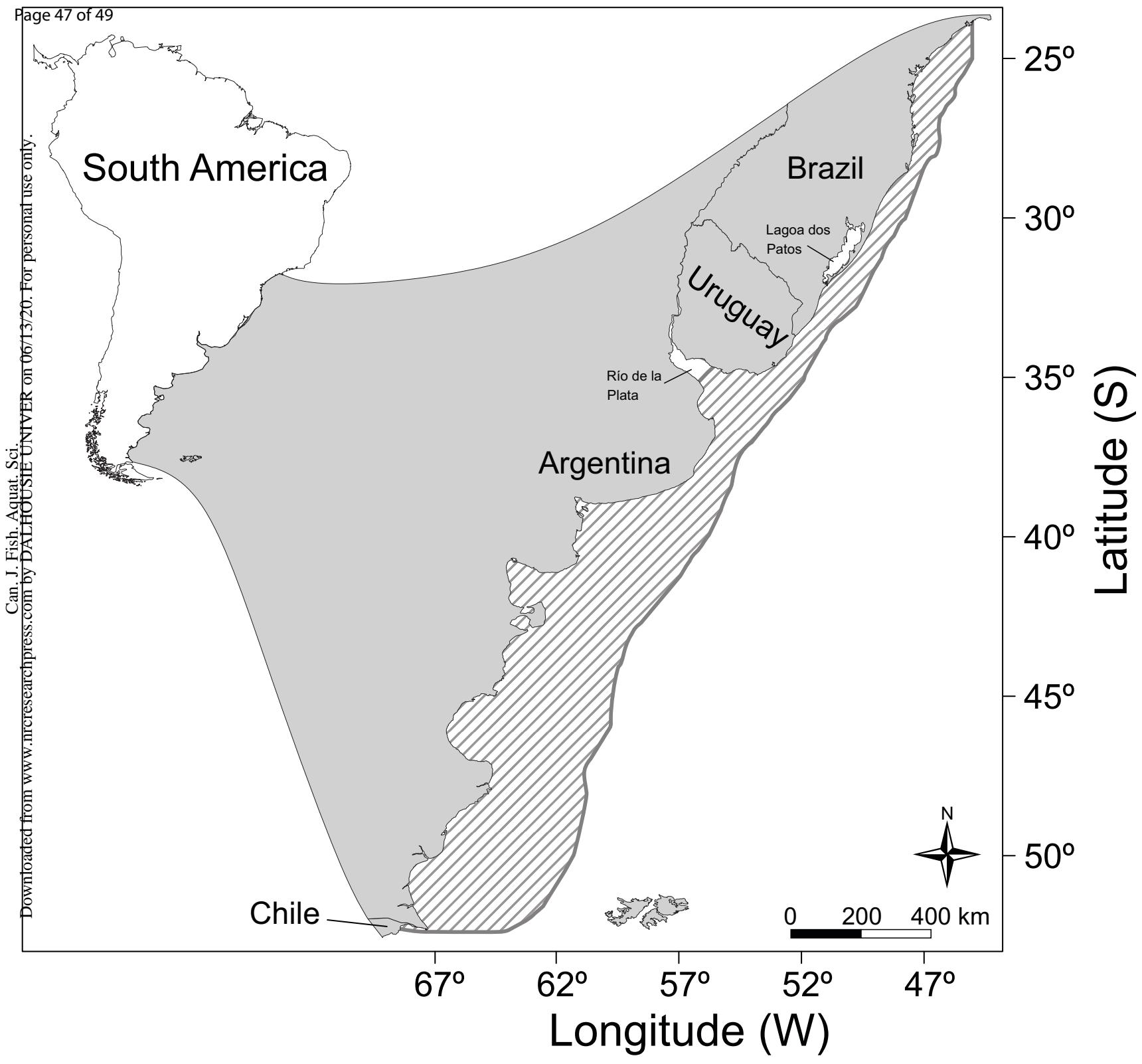
N_{occ} = number of occurrences in models; N_{ind} = number of occurrences in independent data; N_{tgb} = number of occurrences in target group background; FC = feature classes; RM = regularization multiplier; OR = omission rate at 10% error during evaluation with N_{ind} ; SST = sea surface temperature; dfSST = distance to thermal front; Dist = distance to coast; dInlet = distance to marine inlet; Pinn = distance to pinniped colony; K490 = diffuse attenuation coefficient K490; AUC±SD = averaged Area Under Curve values over ten replicate runs and its standard deviation.

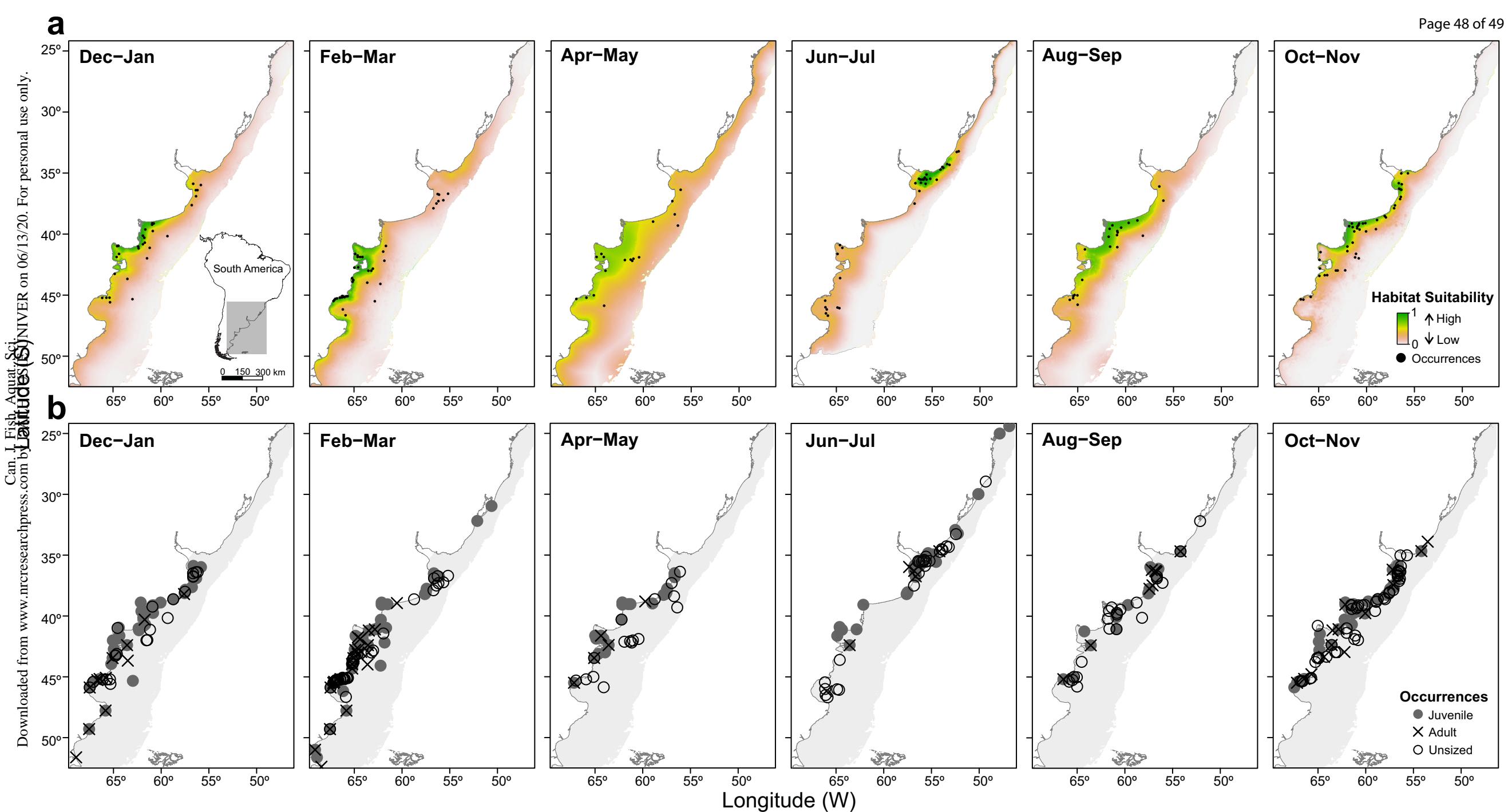
Figure captions

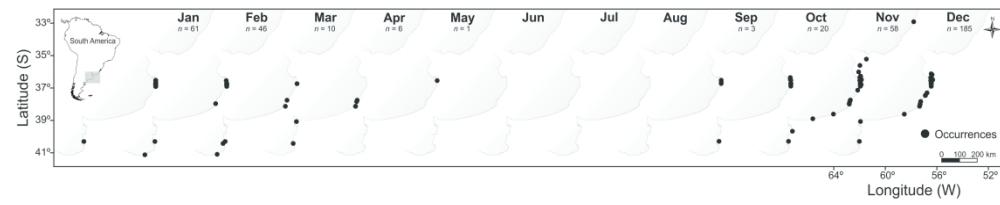
Figure 1. Map of the study extent (shaded area) representing the latitudinal distribution of *Notorynchus cepedianus* in the South-west Atlantic based on occurrences recorded to date. Map was created in the R environment using shorelines from the Global, Self-consistent, Hierarchical, High-resolution Shoreline Database (Wessel and Smith 1996).

Figure 2. Final MaxEnt model predictions showing the bimonthly distribution of suitable habitat for *Notorynchus cepedianus* across the South-west Atlantic, and occurrences used for modelling **(a)**. Location of all occurrences (except neonates) recorded in the study for which stage was either known (juvenile/adult) or not known (unsized) is also shown **(b)**. Note that important inconsistencies in occurrences between **a** and **b** plots are expected because of two reasons: 1- all occurrences are considered (i.e., coastal and shelf) in the **b** plots, 2- no spatial filtering/thinning was applied in the **b** plots. Prediction in Jun-Jul is incomplete in southern areas as a result of an incomplete diffuse attenuation K490 predictor due to cloud coverage (see Fig. S1). Maps were created in the R environment using shorelines from the Global, Self-consistent, Hierarchical, High-resolution Shoreline Database (Wessel and Smith 1996).

Figure 3. Monthly location of *Notorynchus cepedianus* neonate occurrences in the South-west Atlantic. Maps were created in the R environment using shorelines from the Global, Self-consistent, Hierarchical, High-resolution Shoreline Database (Wessel and Smith 1996).







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