Optimistic climate mitigation scenario halves projected range loss in a neotropical dolphin

Rodrigo Tardin [a,b,*], Guilherme Maricato [a,c,d,e,f], Jeremy J. Kiszka [e], Mauricio Cantor [g], Israel Maciel [a,d], Gabriel Melo-Santos [a,d,as], Laura May-Collado [h,i], Ana Carolina Meirelles [j], Maria Isabel C. Gonçalves [k,l,m], Fábio G. Daura-Jorge [n], Renata S. Sousa-Lima [m], Yvonnick Le Pendu [o], Benoit de Thoisy [p], Marta J. Cremer [q], Paulo César Simões-Lopes [r], Susana Caballero [s], Marcos R. Rossi-Santos [t], Maria Alice S. Alves [u], Diana C. Freitas [m], Marcos Cesar de Oliveira Santos [v,w], Renan L. Paitach [x], Hector Barrios-Garrido [x,y,z,aa], Aline Athayde [ab,ac], Carla Beatriz Barbosa [ad], Manuela Bassoi [k,l,ae,ax], Carolina P. Bertozzi [af], João Carlos Gomes Borges [ag], Yurasi Briceño [ah], Julio Cardoso [ac], Tomaz Cezimbra [a,c], Kareen De Turris-Morales [y,ai], Camila Domit [aj], Salomé Dussan-Duque [ak], Ninive Edilia Espinoza-Rodriguez [al], Renata Ferreira [m], Luane Ferreira [m], Paulo A.C. Flores [am], Arlaine Francisco [ac], Flávio José de Silva Lima [an], Márcio J.C.A. Lima-Junior [ao], Diana G. Lunardi [m,aw], Natalia Mamede [ap], Milton C.C. Marcondes [f], Stephane P.G. de Moura [aj], Juliana R. Moron [m,av], Alexandre Paro [m], Nara Pavan [m], Monique Pool [aq], Nathali Ristau [ar], Angélica Rodrigues [as], Salvatore Siciliano [at], Isis Bezerra da Silva [m], Mariana Soares [l], Gustavo Toledo [l], Leonardo Wedekin [f,au], Mariana M. Vale [b,c]

[a] *Laboratório de Ecologia e Conservação Marinha, Departamento de Ecologia, Universidade Federal do Rio de Janeiro, 373 Carlos Chagas Filho Avenue, 21941-971, Rio de Janeiro, RJ, Brazil*
[b] *Departamento de Ecologia, Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brazil*
[c] *Programa de Pós-Graduação em Ecologia, Instituto de Biologia, Universidade Federal do Rio de Janeiro, 21941-971, Brazil*
[d] *Programa de Pós-Graduação em Ecologia e Evolução, Instituto de Biologia Roberto Alcantara Gomes, Universidade do Estado do Rio de Janeiro, 20550-013, Brazil*
[e] *Institute of Environment, Department of Biological Sciences, Florida International University, 3000 NE 151th Street, North Miami, FL33181, USA*
[f] *Instituto Baleia Jubarte, Rua Barão do Rio Branco, 125, Caravelas, BA, 45900-000, Brazil*
[g] *Department of Fisheries, Wildlife and Conservation Sciences, Marine Mammal Institute, Oregon State University, 2030 SE Marine Science Drive, Newport, OR, 97365, USA*
[h] *Department of Biology, University of Vermont, 109 Carrigan Drive, Burlington, VT, USA*
[i] *Smithsonian Tropical Research Institute, Apartado Postal, 0843-03092, Panama, Republic of Panama*
[j] *Marine Mammal Research Unit, University of British Columbia, 2020 Main Mall, Vancouver, British Columbia, Canada*
[k] *Parque Científico e Tecnológico do Sul da Bahia, Ilhéus, BA, Brazil*
[l] *Applied Ecology & Conservation Lab, Universidade Estadual de Santa Cruz, Ilhéus, BA, Brazil*
[m] *Laboratory of Bioacoustics/EcoAcoustic Research Hub, Biosciences Center, Universidade Federal do Rio Grande do Norte, Natal, RN, Brazil*
[n] *Departamento de Ecologia e Zoologia, Universidade Federal de Santa Catarina, Florianópolis, SC, Brazil*
[o] *Laboratório em Mamíferos Aquáticos, Departamento de Ciências Biológicas, Universidade Estadual de Santa Cruz, Ilhéus, BA, Brazil*
[p] *Kwata NGO, Cayenne, French Guiana*
[q] *Laboratório de Ecologia e Conservação de Tetrápodes Marinhos e Costeiros, Universidade da Região de Joinville - UNIVILLE, São Francisco do Sul, 89240-000, SC, Brazil*
[r] *Aquatic Mammals Laboratory - LAMAQ, Ecology and Zoology Departament, Universidade Federal de Santa Catarina, Florianópolis, SC, Brazil*
[s] *Department of Marine and Environmental Sciences, Halmos College of Arts and Sciences, Nova Southeastern University, Fort Lauderdale, FL, 33328-2004, USA*
[t] *Laboratory of Acoustic Ecology and Animal Behaviour, Centre for Agrarian, Environmental and Biological Sciences, Universidade Federal do Recôncavo da Bahia, Brazil*
[u] *Departamento de Ecologia, Instituto de Biologia Roberto Alcantara Gomes, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, RJ, Brazil*
[v] *Laboratório de Biologia da Conservação de Mamíferos Aquáticos, Universidade de São Paulo, São Paulo, SP, Brazil*
[w] *Centro de Pesquisa em Biodiversidade e Mudanças Climáticas (CBioClima - FAPESP), Instituto de Biociências - UNESP Universidade Estadual Paulista, SP, Brazil*
[x] *Laboratorio de Ecología General, Centro de Modelado Científico (CMC), Facultad Experimental de Ciencias, La Universidad del Zulia, Maracaibo, Venezuela*

* Corresponding author. Laboratório de Ecologia e Conservação Marinha, Departamento de Ecologia, Universidade Federal do Rio de Janeiro, 373 Carlos Chagas Filho Avenue, 21941-971, Rio de Janeiro, RJ, Brazil.

E-mail address: rhtardin@gmail.com (R. Tardin).

y TropWATER - Centre for Tropical Water and Aquatic Ecosystem Research, James Cook University, Townsville, Australia

z Marine Science Program, Biological and Environmental Science and Engineering Division (BESE). King Abdullah University of Science and Technology (KAUST), Thuwal, 23955, Kingdom of Saudi Arabia

aa King Abdullah University of Science and Technology (KAUST), Beacon Development, KAUST National Transformation Institute, Innovation Cluster, 23955-6900, Kingdom of Saudi Arabia

ab Departamento de Zoologia, Instituto de Biociências, Universidade de São Paulo, São Paulo, SP, Brazil

ac Projeto Baleia à Vista (ProBaV), Ilhabela, SP, Brazil

ad Instituto Argonauta para a Conservação Costeira e Marinha, Av Governador Abreu Sodré, 1065, Pereque-açu, Ubatuba, SP, 11.695-240, Brazil

ae Laboratory of Ecology and Conservation of Marine Megafauna, Institute of Oceanography, Universidade Federal do Rio Grande, Rio Grande, RS, Brazil

af Universidade Estadual Paulista (UNESP), Instituto de Biociências, São Vicente, SP, Brazil

ag Fundação Mamíferos Aquáticos, Brazil

ah Proyecto Sotalia, Venezuela Institute for Scientific Research, Venezuela

ai C&C Consultores Ambientales, Apartadó, Antioquia, Colombia

aj Laboratório de Ecologia e Conservação, Universidade Federal do Paraná, Av. Beira mar, 01, Pontal do Sul, Pontal do Paraná, PR, 83255-000, Brazil

ak Whales & Co., Oxnard, CA, USA

al Centro de Rescate de Especies Amenazadas (CREMA), San Francisco de Coyote, Nandayure, Costa Rica

am Núcleo de Gestão Integrada ICMBio Florianópolis, Instituto Chico Mendes de Conservação da Biodiversidade, Rod. SC-402, s/n, km 01, Jurerê, 88053700, Florianópolis, SC, Brazil

an Universidade do Estado do Rio Grande do Norte (UERN), Programa de Pós-Graduação em Ciências Naturais (PPGCN), Projeto Cetáceos da Costa Branca-UERN/PRODEMA-UFRN, RN, Brazil

ao Laboratório de Ictiologia e Conservação, Universidade Federal de Alagoas, Unidade Educacional Penedo, Av. Beira Rio, s/n, Centro Histórico, Penedo, AL, 57200-000, Brazil

ap Instituto Aqualie, Av José Lourenço Kelmer, 1300 Salas 110, 112 e 114 Centro Comercial São Pedro, São Pedro, Juiz de Fora, 36036-330, MG, Brazil

aq Green Heritage Fund Suriname, Geertruidastr. 24, Paramaribo, Suriname

ar Instituto Amares - Pesquisa e Conservação de Ecossistemas Aquáticos, Instituto Amares, Rua Principal, s/n Distrito de Atins, Barreirinhas, MA, 65590-000, Brazil

as BioMA - Biologia e Conservação de Mamíferos Aquáticos da Amazônia, Universidade Federal Rural da Amazônia, Belém, PA, Brazil

at Departamento de Ciências Biológicas, Escola Nacional de Saúde Pública/Fiocruz, Rua Leopoldo Bulhões, 1.480 - Manguinhos, 21040-900, Rio de Janeiro, RJ, Brazil

au Socioambiental Consultores Associados, Av. Rio Branco Avenue, 380, Room 404, 88015200, Florianópolis, SC, Brazil

av School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia, Canada

aw Molecular Ecology and Evolution Laboratory, Universidade Federal Rural do Semi-Árido, Mossoró, RN, Brazil

ax INCT da Biodiversidade da Amazônia Azul, Universidade Federal do Rio Grande (FURG), Brazil

ARTICLE INFO

ABSTRACT

Ocean warming, acidification, and deoxygenation are expected to intensify without significant climate mitigation. In the tropics, rising ocean temperatures may push marine species to their thermal limits, leading to redistributions and cascading effects on communities and ecosystems. We evaluate how future climate change scenarios could impact the habitat suitability of an endemic species of the western tropical Atlantic Ocean, the Guiana dolphin, *Sotalia guianensis*. Using data from systematic surveys conducted between 1987 and 2023 complemented by open-source databases, we built the most comprehensive occurrence dataset for the species and developed ensemble Species Distribution Models to predict future distributions under the latest CMIP6 projected scenarios—'optimistic' (SSP1-2.6), 'intermediate' (SSP2-4.5), 'pessimistic' (SSP5-8.5)—using expert knowledge to validate model predictions in the present. Our models project substantial range contractions under all climate scenarios. By 2070, under the pessimistic scenario, suitable habitat is expected to decline by 46.9 %, nearly doubling the habitat loss projected under the optimistic scenario (23 %). Guiana dolphins are expected to lose habitat in northeastern Brazil and along the Caribbean coast (except Costa Rica). Remaining suitable areas are expected to become fragmented and confined to southeastern and southern Brazil, where the coastal zone is the most urbanized and degraded. Currently, only 21.6 % of the predicted Guiana dolphin range overlaps with Marine Protected Areas (MPAs), and just 1.8 % is covered by MPAs that prohibit extractive activities—a small proportion expected to decline from 19 % to 14 % in the future. Our study highlights the urgent need to incorporate climate change into conservation strategies for coastal tropical marine predators.

1. Introduction

Coastal and marine ecosystems have undergone warming, acidification, and deoxygenation in recent decades (IPCC, 2019). Future projections warn that these effects will intensify, especially if climate change mitigation efforts fail (e.g., Bryndum-Buchholz et al., 2019). In tropical marine ecosystems, ocean temperatures are reaching or exceeding the thermal limits for many species, triggering phenological changes (e.g., Edwards and Richardson, 2004), declining biomass (e.g., Bryndum-Buchholz et al., 2019), and shifts in geographical range (e.g., Dahms and Killen, 2023). Marine biodiversity is redistributing (Pecl et al., 2017) at an accelerating pace (e.g., Poloczanska et al., 2013; Pinsky et al., 2019), with cold-habitat species shifting poleward to track suitable environmental conditions (e.g., Pinsky et al., 2020; Dahms and Killen, 2023) or facing habitat loss beyond their physiological limits (e. g., Assis et al., 2017; Hodapp et al., 2023), heightening extinction risks, particularly for range-restricted species (Manes et al., 2021).

Species Distribution Modeling (SDM) is a valuable tool to inform conservation actions by projecting how species distributions may change under different climate change scenarios (e.g., McHenry et al., 2019; Hodapp et al., 2023). However, there is a concerning gap in studies focused on marine species (Manes et al., 2021). Most marine SDM research has used emission scenarios from the earlier Coupled Model Intercomparison Project (i.e., CMIP5), available in global databases such as Bio-ORACLE v.2.0 (Assis et al., 2017). Recently, BIO-ORACLE v.3.0 was released with CMIP6 projections based on Socio-Shared Economic Pathways (SSPs), offering higher spatial resolution and 13 additional variables—including chemical variables such as Nitrate, Phosphate, Chlorophyll and others (Assis et al., 2024). This improved database provides an opportunity to reassess the influence of climate change with more reliable predictions and meaningful variables.

Studies on how climate change impacts the spatial and trophic ecology of marine mammals are gaining traction, but much of it has focused on temperate and polar species and ecosystems (e.g., Kaschner et al., 2011; Silber et al., 2017; Hamilton et al., 2019; Peters et al., 2022). For example, exclusively aquatic mammals, such as narwhals (*Monodon

monoceros) and belugas (*Delphinapterus leucas*), have expanded their ranges due to ice sheet melting (e.g., Frouin-Mouy et al., 2017; Chambault et al., 2020), whereas the ranges of polar bears and seals have been shrinking, with demographic consequences (e.g., Hamilton et al., 2019). While cetacean distributions are predicted to shift poleward (e.g., Macleod, 2009; Peters et al., 2022), there has been no comprehensive analysis of the influence of climate change on tropical marine mammal species.

The Guiana dolphin, *Sotalia guianensis*, is a coastal-estuarine habitat specialist, endemic to subtropical and tropical coasts in the western South Atlantic Ocean, ranging from Nicaragua to southern Brazil (Simões-Lopes, 1998; Edwards and Schnell, 2001). Guiana dolphin populations typically consist of individuals with small home ranges (~1–50 km), often exhibiting high site fidelity and/or residency, in discrete populations with limited gene flow (e.g., Espécie et al., 2010; Cantor et al., 2012; Oshima and Santos, 2016; Caballero et al., 2018; Barrios-Garrido et al., 2021; Meirelles et al., 2022; Anibolete et al., 2024). Due to their primary use of estuarine and coastal habitats, Guiana dolphin populations overlap with human activities, including port operations, fishing, tourism, and urban/industrial development on land, resulting in multiple cumulative stressors (e.g., Van Bressem et al., 2009; Azevedo et al., 2017; Barrios-Garrido et al., 2021; Maciel et al., 2023). The species is considered 'Near Threatened' (NT) on the IUCN Red List (Secchi et al., 2018), but regional assessments rank it at higher risk—"Vulnerable" (VU) in Brazil and Colombia, and "Endangered" in French Guiana. In 2018, the International Whaling Commission (IWC/SC67b) designated the Guiana dolphin as a priority species for evaluating conservation status (Domit et al., 2021). Climate change may exacerbate the effects of anthropogenic impacts on Guiana dolphins, highlighting the need to project potential range shifts in the near future.

Here, we evaluate the potential effects of climate change on Guiana dolphin distribution and assess how the current Marine Protected Areas (MPA) network may protect their habitat both now and in the future. We used three climate change scenarios that represent a gradient of climate mitigation efforts (Riahi et al., 2017). The analysis is based on the most comprehensive collaborative dataset on Guiana dolphin occurrences—systematically collected across seven countries over four decades, supplemented by online databases — combined with recent climate model projections from the Couple Model Intercomparison Project Phase 6 (CMIP6). We hypothesize that: (i) the Guiana dolphin distribution range will contract, particularly under the most pessimistic climate projections; (ii) populations near the equator will face greater range contraction than those at higher latitudes; and (iii) the range of the Guiana dolphin will be insufficiently covered by Marine Protected Areas (MPAs).

2. Methods

2.1. Occurrence records

We compiled the most comprehensive dataset of Guiana dolphin sightings (hereafter referred to as occurrences) from primary and secondary sources, covering the period from 1987 to 2023 (Supplementary material A, Table S1, Fig. S1), across the species' known distribution. Sighting survey protocols varied considerably across the Guiana dolphin's range due to logistical and financial constraints. Generally, we used small to medium-sized vessels (5–20 m) following systematic routes at low speeds (10–20 km/h) under favorable weather conditions (Beaufort Sea state ≤3) (Supplementary material A, Table S1). Guiana dolphin detections were made by naked eyes, supplemented by binoculars. Group positions were recorded using handheld GPS devices or by noting the direction and number of reticles from the binoculars (Table S1). Additionally, we gathered Guiana dolphin occurrence records from global (GBIF, AquaMaps, OBIS-SEAMAP, speciesLink) and regional databases (Sistema de Monitoramento de Mamíferos Marinhos - SIMMAM and Portal Brasileiro da Biodiversidade). We removed records with obvious positional errors, such as those inland or grossly outside the species' range. Then, we compiled all primary and secondary occurrence records into a single database. To reduce spatial autocorrelation issues and to avoid non-independent records caused by heterogeneous sampling across data sources, we removed all records <15 km away from each other using the package 'spThin' v. 2.9–1 in the R environment 4.4 (Aiello-Lammens et al., 2015).

2.2. Climatic variables

Based on our database, supplemented by experts' knowledge, we extracted climatic variables within a species-specific polygon constrained to depths of up to 50 m, rather than using the traditional IUCN polygon (up to ~2000 m depth). This approach excluded areas not used by Guiana dolphin, thereby reducing bias in model parameters estimation and performance (Araújo et al., 2019). We then created a buffer of 1 degree of latitude around the northern and southern limits of the species' distribution to accommodate potential range gain from climate change (Braz et al., 2019).

We used the Bio-ORACLE v.3.0 to gather topography and oceanographic and chemical variables at the water surface to model Guiana dolphin distribution at a resolution of 0.05° during two time periods: present (2000–2020) and future (2060–2070) (Assis et al., 2024) (Figure S2.1, Supplementary material B). The goal for 2060–2070 was to understand potential mid-term changes in the distribution of Guiana dolphins. The updated Bio-ORACLE averages 11 climate models and extends biologically relevant data layers from current conditions to the end of the 21st century under Shared Socioeconomic Pathway scenarios (SSP) based on a multi-model ensemble from CMIP6 (Assis et al., 2024).

To create an ecologically plausible model, instead of including all oceanographic, topographic, and chemical variables available, we selected those that could be directly or indirectly relevant to Guiana dolphin, based on the species' biology (Araújo et al., 2019). Variables were then extracted for both present and future climate change scenarios. We excluded variables with high correlation (Spearman correlation >0.7) and multicollinearity (Variance Inflation Factor >3) (Hijmans et al., 2024). Out of 11 relevant variables to Guiana dolphins, seven were retained in our models: distance to the coast, current direction, current speed, primary productivity, slope, salinity, and sea surface temperature (Table S2).

We used three climate change scenarios: SSP1-2.6 (called 'optimistic' hereafter), SSP2-4.5 ('intermediate' hereafter), and SSP5-8.5 ('pessimistic' hereafter). These scenarios reflect how different climate mitigation strategies could influence species range loss due to climate change (e.g., Riahi et al., 2017). Scenario SPP1-2.6 is optimistic, being described as "taking the green road", with global policies and economies aligned with a sustainable path, reaching 1.8 °C of warming above pre-industrial levels in global surface temperature by 2100; SPP2-4.5 follows current trends, being an intermediate scenario that reaches 2.7 °C of warming by 2100; finally, SPP5 the most extreme scenario is described as "taking the highway", with policies and economies aimed for the development of human capital and technologies to manage environmental systems, reaching 4.4 °C by the end of the century (Riahi et al., 2017; IPCC et al., 2021). We refer to SSP1-2.6 as the 'optimistic' scenario, rather than the more ambitious SSP1-1.9 (which envisions 1.4 °C by 2100) because it is increasingly seen as utopian rather than achievable (IPCC et al., 2021; Lamboll et al., 2023).

2.3. Modeling procedures

To model the relationship between Guiana dolphin occurrence and the environment, we followed state-of-the-art best-practices standards (Araújo et al., 2019; Zurell et al., 2020). We used five modelling approaches based on the type of input data: presence-absence models using regression techniques (Generalized Linear Model, Generalized Additive Model), decision trees (Boosted Regression Tree, Random Forest), and

presence-background models using Maximum entropy (MaxEnt). All analyses were conducted using the Biomod2 4.2–4 package in the R environment 4.4. (Thuiller et al., 2024) (Fig. 1).

We generated three sets of pseudo-absences using spatial stratification, creating three times the number of pseudo-absences compared to occurrence records, with a minimum distance of 30 km (Barbet-Massin et al., 2012). We calibrated the models using 70 % of the data for training and 30 % for testing, using a three-fold cross-validation technique. Each model was replicated 10 times with a fixed prevalence of 0.5. We estimated the relative importance of variables by shuffling each variable 100 times and comparing the predictions between the reference

and shuffled models using Pearson correlation (Thuiller et al., 2019). A higher value indicates a greater influence on the model. We evaluated model performance using the True Skill Statistic (TSS) method. Only replicates with a TSS >0.7 were combined into a final ensemble model, weighted-by-TSS mean.

From the continuous predicted suitability values, we generated a binary model, where the threshold (presence or absence) was obtained by maximizing specificity and sensitivity values (Liu et al., 2013). We estimated uncertainty in the ensemble model based on the divergence or agreement of different models' predictions. Values close to 1 indicate that most models agreed on the presence of the species, values close to
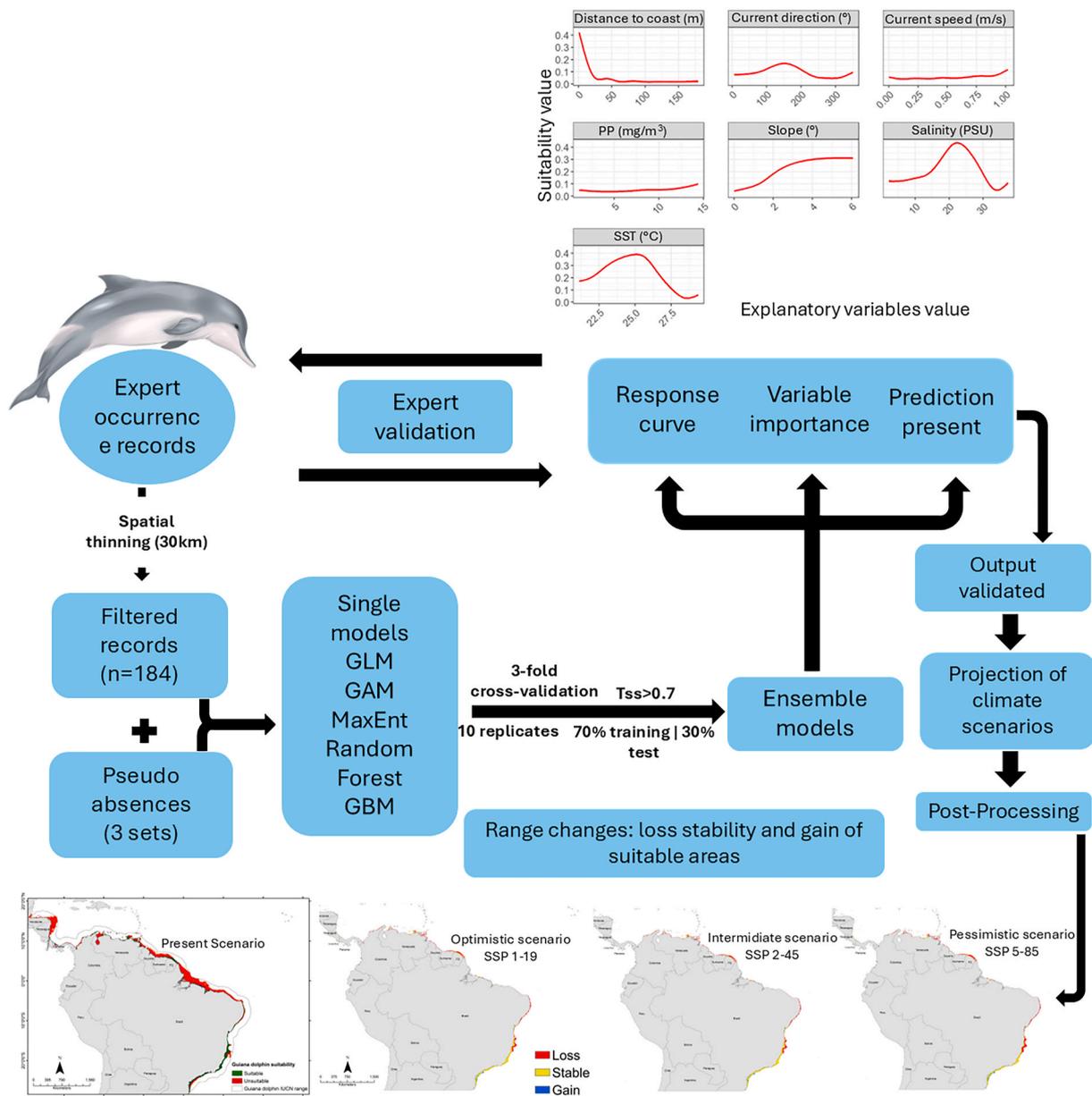
Fig. 1. Flowchart outlining the modeling process for assessing the distribution of the Guiana dolphin, *Sotalia guianensis,* under various climate change scenarios. Initially, occurrence records were collected by over 40 specialists based on their systematic studies of the species and supplemented by online databases. These records were rigorously filtered and used to run 450 models, incorporating three sets of pseudo-absences, five algorithms, ten replicates, and a 3-fold cross-validation approach. Models achieving a TSS (True Skill Statistic) greater than 0.7 were selected to construct an ensemble model. From this ensemble, variable importance, response curves, and mapped predictions were derived and subsequently evaluated by the experts (co-authors). If the model outputs were deemed implausible, adjustments were made, including in order of preference, the inclusion of new occurrence records (if available), spatial rarefaction distances, pseudo-absence strategy, strategy of cross validation and parameter recalibration, if necessary, and/or. Upon validation, the present-day mapped predictions were projected onto three different climate change scenarios. These projections were then compared to determine the percentage of pixels representing stable, unsuitable (range loss), or suitable (range gain) habitat for the species.

0 indicate agreement on absence, and values around 0.5 indicate divergent predictions (Thuiller et al., 2019). We then mapped the weighted-mean ensemble binary model for the present geographic space. Each author independently evaluated the response curves and the mapped predictions for the current study area to validate the model outputs. If predictions were deemed ecologically implausible, we adjusted model parameters to better align with expert ecological knowledge. In this step, parameters were adjusted in the following order: the spatial thinning criteria, pseudo-absence strategy, cross validation strategy and algorithm parameters (Supplementary material E). Once ecological plausibility was achieved by most authors, we extrapolated the present binary predictions to future scenarios to project species presence under 'optimistic', 'intermediate', and 'pessimistic' conditions for 2060–2070.

2.4. Post-processing

To assess whether the Guiana dolphin is projected to lose or gain suitable habitat in the future, we employed the 'raster calculator' tool within ArcGIS 10.8. This process involved subtracting the species' presence or absence predictions for each grid under three climate change models from current conditions. Finally, we overlaid all model predictions (both present and future climate change scenarios) with a layer depicting all existing Marine Protected Areas (MPA), obtained from the World Database of Protected Areas (UNEP-WCMC & IUCN, 2024). Then, we calculated the current coverage of the Guiana dolphin's range within MPAs and assessed whether the proportion of the species range protected would change in the future.

3. Results

After spatially thinning 9055 records, 184 independent occurrence records of the Guiana dolphin were retained. Our ensemble model performed well with a low degree of error (TSS = 0.8, Sensitivity = 96.1, Specificity = 94.3) (Supplementary material C, Fig. S3.1). Three variables were most important (Supplementary material C, Fig. S3.2) in predicting the distribution of the Guiana dolphin: areas close to the coast, moderate to warm waters (SST 23 to 27 °C), and close association with estuarine waters (salinity 18–25 ppm) (Fig. 2).

Under current conditions, Guiana dolphins were predicted to have a suitable range of 107,600 km^2 compared to the 666,161 km^2 of the model calibration area (Table S1 - Supplementary material D), occurring continuously along the southern to northern Brazilian coast, but only intermittently along the Caribbean region and Central America (Fig. 3). Interestingly, our ensemble model did not predict Nicaragua, the northernmost limit of the species, as suitable habitat.

In all future climate change scenarios, Guiana dolphins are projected to lose area, especially along the Caribbean, Guianas, the north, and northeastern Brazil. The range loss varied from 23 % in the 'optimistic' scenario and intensified with the severity of the climate change scenario: 37.5 % in the 'intermediate' scenario, and 46.9 % in the 'pessimistic' (Fig. 4).

We project that only Costa Rica and southeastern-southern Brazil will retain key stable habitats and continuous areas for Guiana dolphins under all three scenarios (Fig. 4). In contrast, most of Panama, Colombia, Venezuela, and the Guiana coast are expected to lose suitable areas as climate change intensifies. For populations in northeastern and northern Brazil, their habitats are projected to become unsuitable under all scenarios (e.g., Pipa, Mucuripe embayment), with only fragmented patches of suitable areas remaining in the states of Pará, Alagoas, Sergipe, and southern Bahia. For example, in southern Bahia, the 'pessimistic' scenario predicts that this region will become mostly unsuitable and fragmented, with only small patches of suitable areas remaining. The area around Abrolhos National Park, further offshore, is predicted to be unsuitable under all scenarios. However, our model projected a gain in the southern limit of the Guiana dolphin range under all scenarios.

Currently, only 21.6 % (23,250 km^2, Table S3) of the Guiana dolphin distribution overlaps with Marine Protected Areas. This overlap is projected to decrease as climate change intensifies by 18.8 % in the 'optimistic', 16.3 % in the 'intermediate', and 14.1 % in the 'pessimistic' scenario (Fig. 5). Only 1.8 % of the species range area is currently covered by MPAs that prohibit extractive activities such as fishing, mining, and dredging. This protection is projected to decrease to 1.2 % in the 'optimistic' scenario, 0.9 % in the 'intermediate' scenario, and 0.7 % in the 'pessimistic' scenario (Fig. 5). However, the range lost outside MPAs is projected to be twice that lost within MPAs (Supplementary material D, Figure S4.1).
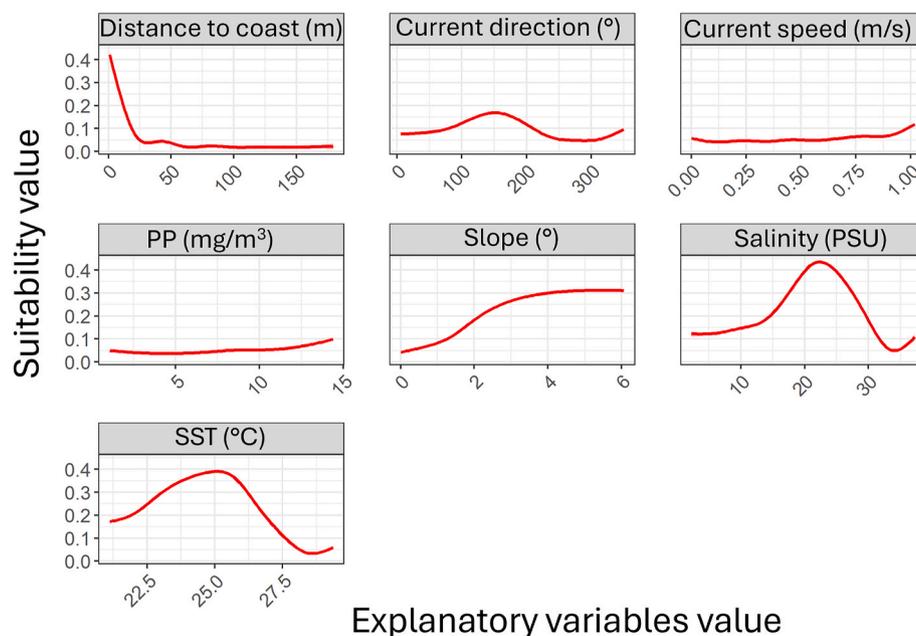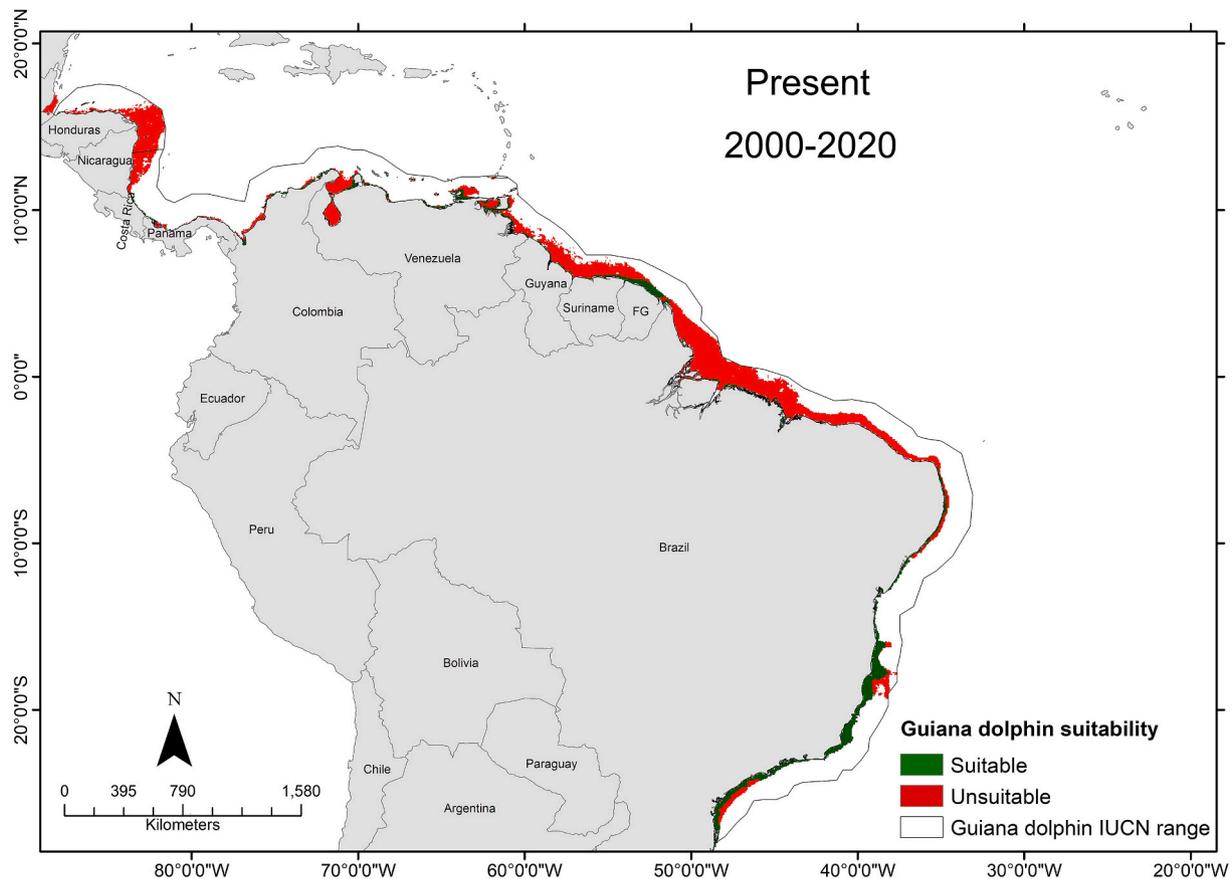

Fig. 2. Response curves from a weighted-mean ensemble model depicting the relationship between habitat suitability for the Guiana dolphin, *Sotalia guianensis*, and each explanatory variable. SST = Sea Surface Temperature.

Fig. 3. Predicted distribution of the Guiana dolphin, *Sotalia guianensis*, under present climatic conditions (2000–2020). The ensemble weighted-mean model highlights suitable and unsuitable areas, revealing that the International Union for Conservation of Nature (IUCN) range polygon overestimates the species distribution (. FG = French Guiana.

4. Discussion

Our models project that climate change mitigation could reduce Guiana dolphins' range loss by up to half by 2070. These losses are projected to be more pronounced in lower latitudes, driven by the contraction and fragmentation of suitable habitats for Guiana dolphins. Existing Marine Protected Areas (MPAs) offer insufficient protection across much of the current species' range, and our models predict that this situation will deteriorate further over the next 40 years. These findings support our hypothesis that the Guiana dolphin's distribution range would contract, particularly under the most pessimistic climate projections and near the equator, and that its range would be insufficiently covered by current MPAs.

### 4.1. Projected distribution of Guiana dolphin

Our findings suggest that Guiana dolphins in northern and northeastern Brazil, the Guianas, and the Caribbean Sea are at higher risk of local extinction as their environmental conditions are predicted to become unsuitable. Similar coastal areas at these latitudes have already shown signs of decline in pelagic species, such as sharks, over the past few decades (Chaudhary et al., 2021), and should experience a loss of primary productivity, biomass, and species richness in the next 70 years (IPCC, 2019). Increased sea surface temperatures in these areas may have direct and indirect effects on Guiana dolphins. For example, higher temperatures may lead to outbreaks of infectious diseases, such as morbillivirus and influenza A (e.g., Kebke et al., 2022), which could directly affect Guiana dolphin populations. Extended periods of marine heatwaves, which are expected to increase by 20 to 50-fold in the future, may affect Guiana dolphin survival and breeding, as has been observed

for the tucuxi, *Sotalia fluviatilis*, and the boto, *Inia geoffrensis*, in the Amazon region (Fleischmann et al., 2024). Indirectly, changes in prey distribution and abundance may negatively impact foraging success (Nagelkerken et al., 2023).

Under the 'optimistic' climate change scenario, the loss of the Guiana dolphin range is predicted to be half of that in the most 'pessimistic' projections. In the optimistic scenario, extensive areas along the coast of Colombia, Venezuela (e.g., Maracaibo Lake System and Eastern Upwelling System), northern (e.g., Pará state), and northeastern Brazil (e. g., Bahia and Sergipe states) would remain suitable for Guiana dolphin. However, as climate change worsens, these areas are projected to become unsuitable, emphasizing the importance of climate mitigation for protecting biodiversity and the ecosystem services it provides.

Our models predict that Guiana dolphin distribution is smaller than the IUCN range polygon (Table S1, Supplementary material D). While this reduced range does not meet the criteria for categorizing the species as 'vulnerable' under IUCN Criterion B2, it provides the critical insight that the species is less widespread than previously thought. In fact, IUCN range maps are known to overestimate the distribution of many species, making improved range maps highly needed, since they are important to inform conservation actions (Brooks et al., 2019).

Nicaragua, the northernmost limit of the species, was predicted as unsuitable both in current and future scenarios. To date, only two published studies have documented the species in the area (Carr and Bonde, 2000; Edwards and Schnell, 2001). In Nicaragua, between 1992 and 1998, Guiana dolphins (but originally identified as *S. fluviatilis*) were reported to be common along the eastern coast of Miskito (Carr and Bonde, 2000; Edwards and Schnell, 2001). Since then, no aerial or boat surveys have been done to follow up the status of Guiana dolphins in this area (May-Collado, personal communication). Nicaragua is
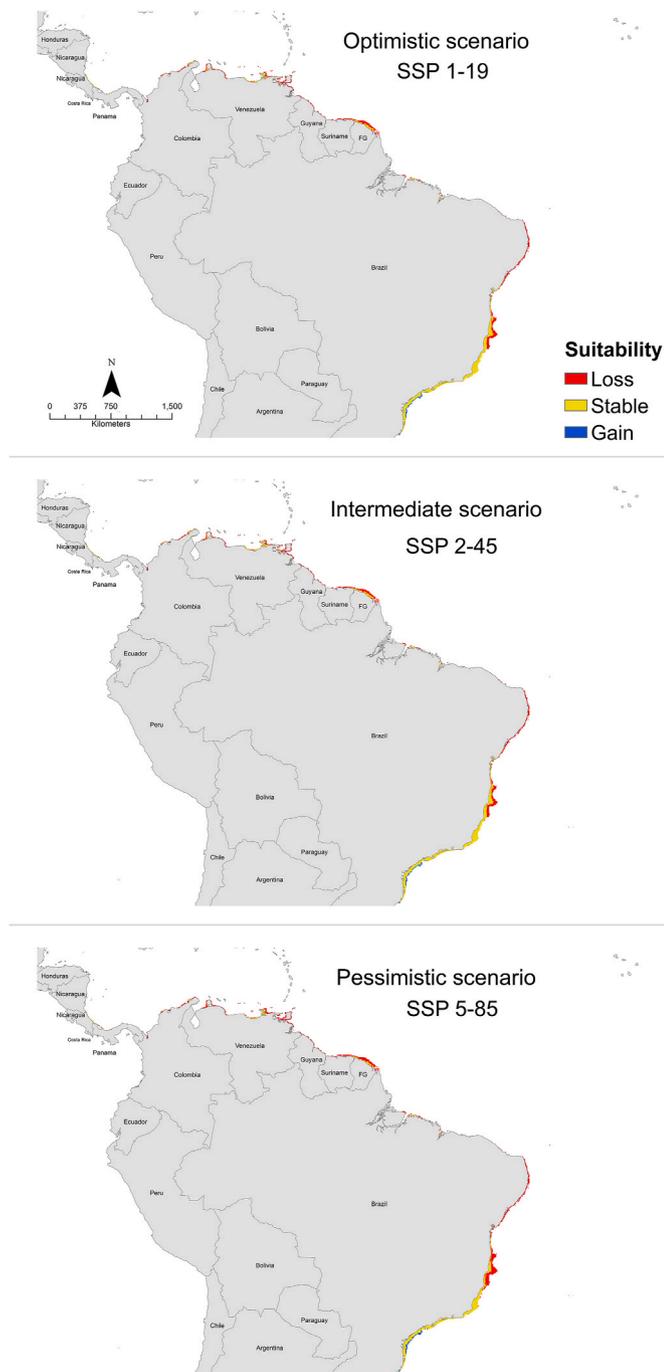
Fig. 4. Guiana dolphin, *Sotalia guianensis*, range changes under different climate change scenarios modeled by a weighted-mean ensemble model. Scenarios: optimistic SSP1-26 (top), intermediate SSP2-45 (middle), and pessimistic SSP5-85 (bottom) for years 2060–70. The models indicate a range loss in the northeastern and northern regions of Brazil, and throughout the Caribbean Sea, worsening under more severe climate change scenarios.

characterized by saline waters (35–36 ppm) and high temperatures (28–28.5 °C) (Fig. S1, Supplementary material B), which exceed the ecological threshold predicted by the model's response curves (Fig. 2). Under climate change scenarios, water temperatures are expected to rise even further. In the 'pessimistic' scenario, an increase of 1.5–1.6 °C is projected, making the area increasingly unsuitable for the species (Fig. S1, Supplementary material B). However, increased sampling effort is needed to confirm the absence of the species or to redefine the northern limit of its distribution.
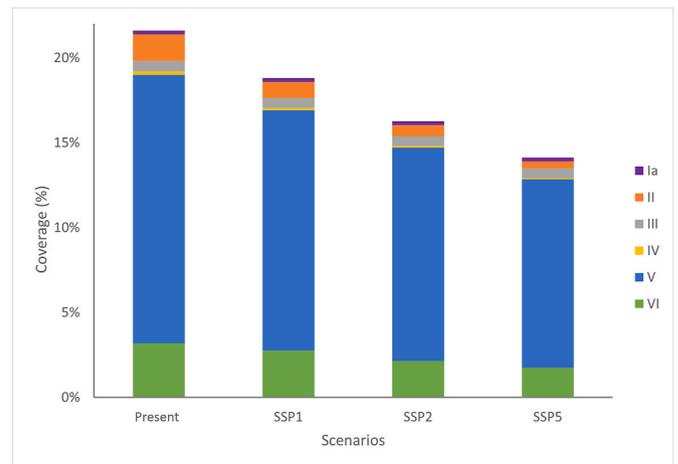
Fig. 5. Percentage of the predicted range of Guiana dolphin, *Sotalia guianensis*, covered by Marine Protected Areas (MPAs). Most of the range is covered by MPAs categories (V and VI) where the presence of human activities, such as fishing, tourism, and/or port activities, are common. Present period covers 2000–2020 while future time periods span 2060–70.

Our models also show that Guiana dolphin distribution is currently more fragmented than previously thought (e.g., da Silva et al., 2010; de Jesus-Lobo et al., 2021). Under climate change scenarios, this fragmentation is expected to intensify. Generally, smaller and fragmented populations tend to experience a reduction in genetic diversity, and when isolated, inbreeding can lead to the fixation of deleterious genes, reducing individual fitness and their ability to adapt to extreme and unpredicted climatic events (Caballero et al., 2018). The strong site fidelity, low dispersal capabilities (e.g., Rossi-Santos et al., 2007; Barrios-Garrido et al., 2016; Anibolete et al., 2024), and restricted gene flow (Caballero et al., 2018) of Guiana dolphin should exacerbate these impacts.

Guiana dolphins in Costa Rica and southeastern to southern Brazil could inhabit key stable areas under all climate change scenarios. Despite the expected warming and increase in salinity in Costa Rica (see Figs. S4 and S5 – supplementary material B), current speed and direction are projected to remain stable, likely maintaining the counterclockwise circulation of the Columbia-Panama Gyre, which increases local productivity (Andrade and Barton, 2000). Along the southeastern-southern Brazilian axis, SST and salinity are predicted to remain stable across all scenarios, reinforcing these areas as potential climate refugia for the species. However, some of these populations are already experiencing rapid human-induced environmental changes. For example, in northeastern, southeastern, and southern Brazil, Guiana dolphin habitats are located near industrial and large port areas (e.g., Azevedo et al., 2017; de Jesus-Lobo et al., 2021; Maciel et al., 2023; Meirelles et al., 2023) and are subject to bycatch in coastal fisheries (e.g., Freitas et al., 2021) and exposed to the tourism industry (e.g., Moura et al., 2019). The synergistic and cumulative effects of these activities are driving population declines, with consequences for their behavior and health (e.g., Guanabara Bay: Azevedo et al., 2017; Paranaguá Estuarine Complex: de Jesus-Lobo et al., 2021; Sepetiba Bay: Maciel et al., 2023). In contrast, Guiana dolphin in Costa Rica overlap with a Natural Wildlife Refuge and a RAMSAR site (wetland designated to be of international importance under the RAMSAR convention). There, the dolphins do not seem to face the same level of human pressure as those in other parts of their range. Boat presence is relatively low, incidental mortality in fishing gear has not been confirmed, and the tourism industry around these dolphins is limited (May-Collado et al., 2017).

It is important to acknowledge some caveats in our approach and on our results. The scarcity of records along large stretches of the northern-northeastern coast of Brazil and the Caribbean coast (Fig. S1 -

Supplementary material A) is due to limited research efforts in these areas, which may cause the model to inflate the species' degree of range fragmentation. Our models have omission errors in these regions (e.g., Ceara state coastal area), so these results should be interpreted cautiously. One potential explanation for this bias is that Guiana dolphins in these regions may inhabit more saline, open coastal waters instead of the brackish inland waters of bays and estuaries, where this species is more commonly observed. When a species uses a broad range of habitat types, the relationships between predictors can be obscured when data on species occurrence is compiled across different habitats.

Extreme events, such as marine heat waves, were not considered. Given that these events are expected to increase 50-fold this century (Pörtner et al., 2019), they have the potential to drastically alter fish distribution and biomass across a wide range of species (e.g., Thompson et al., 2022). However, data with the required spatial and temporal resolution to account for extreme events are not yet readily available. We recommend making such data available so that future studies can better capture the dynamic nature of climatic variability in marine predators.

4.2. Marine Protected Areas and future directions

Marine protected areas (MPAs) within the Guiana dolphins' range are relatively small (Mean $\pm$ SD = 201 $\pm$ 424 km^2), poorly connected (May-Collado et al., 2016) and were not specifically designed to target this species. Additionally, they currently cover less than a quarter of the species' known range, making them unlikely to significantly contribute to its conservation. Most of these MPAs are concentrated along Brazil's northern coast and southeastern-southern axis. Across the Guiana dolphin's distribution, only four MPAs are specifically intended to protect the species. However, their management plans do not provide adequate goals for this purpose. MPAs that prohibit extractive activities and have the highest potential for biodiversity protection and recovery cover less than 2 % of the Guiana dolphin's distribution, limiting their potential to safeguard the species. These more restrictive MPAs are also small and poorly connected, making them likely ineffective for Guiana dolphin protection (Supplementary material C, Fig. S3). However, well-designed, small-sized MPAs located in regions with high densities of Guiana dolphins and their prey are likely to be at least partially effective.

Our analysis indicates that if climate change is not mitigated, MPAs' coverage area could decrease to 34.8 % along the Guiana dolphin distribution, with less than 15 % coverage in the "pessimistic" scenario. Additionally, many of these MPAs permit fishing, port, and tourist activities, which can undermine their role in safeguarding Guiana dolphin habitats and food resources (e.g., Wedekin et al., 2010; Macedo et al., 2020; Tardin et al., 2020). However, we highlight that most of the range loss is expected to occur outside MPAs (Supplementary material B, Fig. S2), reinforcing their potential as climate refugia. Since climate change refugia can facilitate the long-term persistence of species across generations, they represent a promising nature-based solution to mitigate climate change (Keppel and Kavousi, 2015; Cooley et al., 2022). However, the role of MPAs in providing climate refugia for marine megafauna remains to be properly investigated.

We recommend that both proactive and reactive conservation measures should be taken (see Brooks et al., 2006). As a reactive approach, in the short-term, we recommend strengthening existing MPAs and establishing new ones in southeastern Colombia, central and northern Venezuela and northern Brazil, where Guiana dolphins are projected to lose habitat but retaining small patches of stable habitat, particularly under 'optimistic' and 'intermediate' climate scenarios. These areas may serve as potential local refugia in the future.

Proactively, we suggest implementing new MPAs in regions where Guiana dolphins are expected to have less intense or no range loss from climate change, such as southeastern-southern Brazil. This approach would protect the climate refugia habitats of Guiana dolphins and their

prey, but also help some populations under intense anthropogenic stressors (e.g., Guanabara Bay: Azevedo et al., 2017; Paranaguá Estuarine Complex: Moura et al., 2021; Sepetiba Bay: Maciel et al., 2023).

The creation of MPAs can benefit from systematic conservation planning, a structured approach to identify and prioritize areas for biodiversity conservation while maximizing ecological, social, and economic benefits (Margules and Pressey, 2000). As discussed earlier, there are important gaps in occurrence data for the Guiana dolphin. Our study, along with previous work (de Jesus-Lobo et al., 2021), highlights areas where Guiana dolphin surveys are most needed across its entire range, such as Nicaragua, Guyana, Suriname, and some parts of northern Brazil. Our models predict that these regions are currently suitable for Guiana dolphins but will face severe range contraction in the future, especially under a 'pessimistic' scenario. Urgent allocation of limited research resources to these and other poorly sampled areas within the Guiana dolphin distribution will unveil crucial life history and population parameters needed to update conservation status at the regional level, inform the creation of new protected areas, and management of existing ones. Lastly, adequate means of control and law enforcement should accompany those MPAs, to ensure their efficiency on the field.

5. Conclusion

Our study highlights that climate change is expected to fragment and reduce the total range of suitable areas for Guiana dolphins. However, the climate mitigation associated with the most optimistic scenario (SSP1-2.9) is expected to reduce the Guiana dolphin range loss in half. The current network of Marine Protected Areas (MPAs) is not enough to protect dolphin habitats both currently and in the future. That is particularly concerning since Guiana dolphins face unprecedented challenges from multiple and cumulative human activities, which are likely to be exacerbated by climate change over the next four decades. The creation of carefully placed and controlled MPAs or the change in the management of existing ones could increase the resilience of the Guiana dolphin to climate change by removing additional stressors on the species.

CRediT authorship contribution statement

Rodrigo Tardin: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Guilherme Maricato:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation. **Jeremy J. Kiszka:** Writing – review & editing, Validation, Investigation, Data curation. **Mauricio Cantor:** Writing – review & editing, Validation, Investigation, Data curation. **Israel Maciel:** Writing – review & editing, Validation, Investigation, Data curation. **Gabriel Melo-Santos:** Writing – review & editing, Validation, Investigation, Data curation. **Laura May-Collado:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Ana Carolina Meirelles:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Maria Isabel C. Gonçalves:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Fábio G. Daura-Jorge:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Renata S. Sousa-Lima:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Yvonnick Le Pendu:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Benoit de Thoisy:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Marta J. Cremer:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Paulo César Simões-Lopes:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Susana Caballero:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Marcos R. Rossi-Santos:** Writing – review & editing, Validation, Investigation,

Funding acquisition, Data curation. **Maria Alice S. Alves:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Diana C. Freitas:** Writing – review & editing, Validation, Investigation, Data curation. **Marcos Cesar de Oliveira Santos:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Renan L. Paitach:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Hector Barrios-Garrido:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Aline Athayde:** Writing – review & editing, Validation, Investigation, Data curation. **Carla Beatriz Barbosa:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Manuela Bassoi:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Carolina P. Bertozzi:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **João Carlos Gomes Borges:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Yurasi Briceño:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Julio Cardoso:** Validation, Investigation, Funding acquisition, Data curation. **Tomaz Cezimbra:** Writing – review & editing, Validation, Investigation, Data curation. **Kareen De Turris-Morales:** Writing – review & editing, Validation, Investigation, Data curation. **Camila Domit:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Salomé Dussan-Duque:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Ninive Edilia Espinoza-Rodriguez:** Validation, Investigation, Funding acquisition, Data curation. **Renata Ferreira:** Writing – review & editing, Validation, Investigation, Data curation. **Luane Ferreira:** Validation, Investigation, Data curation. **Paulo A.C. Flores:** Validation, Investigation, Funding acquisition, Data curation. **Arlaine Francisco:** Validation, Investigation, Data curation. **Flávio José de Silva Lima:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Márcio J.C.A. Lima-Junior:** Validation, Investigation, Data curation. **Diana G. Lunardi:** Validation, Investigation, Data curation. **Natalia Mamede:** Validation, Investigation, Data curation. **Milton C.C. Marcondes:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation. **Stephane P.G. de Moura:** Writing – review & editing, Validation, Investigation, Data curation. **Juliana R. Moron:** Validation, Investigation, Data curation. **Alexandre Paro:** Validation, Investigation, Data curation. **Nara Pavan:** Validation, Investigation, Data curation. **Monique Pool:** Validation, Investigation, Funding acquisition, Data curation. **Nathali Ristau:** Validation, Investigation, Funding acquisition, Data curation. **Angélica Rodrigues:** Validation, Investigation, Funding acquisition, Data curation. **Salvatore Siciliano:** Validation, Investigation, Funding acquisition, Data curation. **Isis Bezerra da Silva:** Validation, Investigation, Data curation. **Mariana Soares:** Validation, Investigation, Data curation. **Gustavo Toledo:** Validation, Investigation, Data curation. **Leonardo Wedekin:** Writing – review & editing, Validation, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Mariana M. Vale:** Writing – review & editing, Validation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

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

Acknowledgments

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2025.107800.

Data availability

Data will be made available on request.

References

Aiello-Lammens, M.E., Boria, R.A., Radosavljevic, A., Vilela, B., Anderson, R.P., 2015. spThin: an R package for spatial thinning of species occurrence records for use in ecological niche models. Ecography 38 (5), 541–545. https://doi.org/10.1111/ecog.01132.

Andrade, C.A., Barton, E.D., 2000. Eddy development and motion in the Caribbean Sea. J. Geophys. Res.: Oceans 105 (11), 26191–26201.

Anibolete, D., Maricato, G., Maciel, I., Tardin, R., 2024. Guiana dolphin movements across three decades between Sepetiba and Ilha Grande bays in southeastern Brazil. Ocean Coast. Res. 72, e24051. https://doi.org/10.1590/2675-2824072.23094.

Araújo, M.B., Anderson, R.P., Márcia Barbosa, A., Beale, C.M., Dormann, C.F., Early, R., Garcia, R.A., Guisan, A., Maiorano, L., Naimi, B., O'Hara, R.B., Zimmermann, N., Rahbek, C., 2019. Standards for distribution models in biodiversity assessments. Sci. Adv. 5 (1), eaat4858. https://doi.org/10.1126/sciadv.aat4858.

Assis, J., Berecibar, E., Claro, B., Alberto, F., Reed, D., Raimondi, P., Serrão, E.A., 2017. Major shifts at the range edge of marine forests: the combined effects of climate changes and limited dispersal. Sci. Rep. 7 (1), 44348. https://doi.org/10.1038/srep44348.

Assis, J., Fernández Bejarano, S.J., Salazar, V.W., Schepers, L., Gouvêa, L., Fragkopoulou, E., Leclercq, F., Vanhoorne, B., Tyberghein, L., Serrão, E.A., Verbruggen, H., de Clerck, O., 2024. Bio-ORACLE v3.0. Pushing marine data layers to the CMIP6 Earth System Models of climate change research. Global Ecol. Biogeogr. 33 (4), e13813. https://doi.org/10.1111/geb.13813.

Azevedo, A.D.F., Carvalho, R.R., Kajin, M., Van Sluys, M., Bisi, T.L., Cunha, H.A., Lailson-Brito Jr, J., 2017. The first confirmed decline of a delphinid population from Brazilian waters: 2000–2015 abundance of *Sotalia guianensis* in Guanabara Bay, South-eastern Brazil. Ecol. Indic. 79, 1–10. https://doi.org/10.1016/j.ecolind.2017.03.045.

Barbet-Massin, M., Jiguet, F., Albert, C.H., Thuiller, W., 2012. Selecting pseudo-absences for species distribution models: how, where and how many? Methods Ecol. Evol. 3 (2), 327–338. https://doi.org/10.1111/j.2041-210X.2011.00172.x.

Barrios-Garrido, H., Turris-Morales, D., Nash, C.M., Delgado-Ortega, G., Espinoza-Rodriguez, N., 2016. Acoustic parameters of Guiana dolphin (*Sotalia guianensis*) whistles in the southern gulf of Venezuela. Aquat. Mamm. 42 (2). https://doi.org/10.1578/AM.42.2.2016.127.

Barrios-Garrido, H., de Turris-Morales, K., Espinoza-Rodriguez, N.E., 2021. Guiana dolphin (*Sotalia guianensis*) in the Maracaibo Lake System, Venezuela: conservation, threats, and population overview. Front. Mar. Sci. 7, 594021. https://doi.org/10.3389/fmars.2020.594021.

Braz, A.G., Lorini, M.L., Vale, M.M., 2019. Climate change is likely to affect the distribution but not parapatry of the Brazilian marmoset monkeys (*Callithrix spp.*). Divers. Distrib. 25 (4), 536–550. https://doi.org/10.1111/ddi.12872.

Brooks, T.M., Mittermeier, R.A., Da Fonseca, G.A., Gerlach, J., Hoffmann, M., Lamoreux, J.F., Mittermeier, C.G., Pilgrim, J.D., Rodrigues, A.S., 2006. Global biodiversity conservation priorities. Science 313 (5783), 58–61. https://doi.org/10.1126/science.1127609.

Brooks, T.M., Pimm, S.L., Akçakaya, H.R., Buchanan, G.M., Butchart, S.H., Foden, W., Hilton-Taylor, C., Hoffmann, M., Jenkins, C.N., Joppa, L., Li, B.V., Menon, V., Ocampo-Peñuela, N., Rondinini, C., 2019. Measuring terrestrial area of habitat (AOH) and its utility for the IUCN Red List. Trends Ecol. Evol. 34 (11), 977–986. https://doi.org/10.1016/j.tree.2019.06.009.

Bryndum-Buchholz, A., Tittensor, D.P., Blanchard, J.L., Cheung, W.W., Coll, M., Galbraith, E.D., Jennings, S., Maury, O., Lotze, H.K., 2019. Twenty-first-century climate change impacts on marine animal biomass and ecosystem structure across ocean basins. Glob. Change Biol. 25 (2), 459–472. https://doi.org/10.1111/gcb.14512.

Caballero, S., Hollatz, C., Rodríguez, S., Trujillo, F., Baker, C.S., 2018. Population structure of riverine and coastal dolphins *Sotalia fluviatilis* and *Sotalia guianensis*: patterns of nuclear and mitochondrial diversity and implications for conservation. J. Hered. 109 (7), 757–770. https://doi.org/10.1093/jhered/esy049.

Cantor, M., Wedekin, L.L., Daura-Jorge, F.G., Rossi-Santos, M.R., Simões-Lopes, P.C., 2012. Assessing population parameters and trends of Guiana dolphins (Sotalia guianensis): An eight-year mark-recapture study. Marine Mammal Science 28 (1), 63–83.

Carr, T., Bonde, R.K., 2000. Tucuxi (Sotalia fluviatilis) occurs in Nicaragua, 800 km north of its previously known range. Marine Mammal Science 16 (2), 447–452.

Chambault, P., Tervo, O.M., Garde, E., Hansen, R.G., Blackwell, S.B., Williams, T.M., Dietz, R., Albertsen, C.M., Laidre, K.L., Nielsen, N.H., Richard, P., Sinding, M.H.S., Schmidt, H.C., Heide-Jørgensen, M.P., 2020. The impact of rising sea temperatures on an Arctic top predator, the narwhal. Sci. Rep. 10 (1), 18678. https://doi.org/10.1038/s41598-020-75658-6.

Chaudhary, C., Richardson, A.J., Schoeman, D.S., Costello, M.J., 2021. Global warming is causing a more pronounced dip in marine species richness around the equator. Proc. Natl. Acad. Sci. 118 (15), e2015094118. https://doi.org/10.1073/pnas.2015094118.

Cooley, S., Schoeman, D., Bopp, L., Boyd, P., Donner, S., Ghebrehiwet, D.Y., Ito, S.-I., Kiessling, W., Martinetto, P., Ojea, E., Racault, M.-F., Rost, B., Skern-Mauritzen, M., 2022. Oceans and coastal ecosystems and their services. In: Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Rama, B. (Eds.), Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 379–550. https://doi.org/10.1017/9781009325844.005.

da Silva, V.M.F., Fettuccia, D., Rodrigues, E.D.S., Edwards, H., Moreno, I.B., Moura, J.F., Wedekin, L.L., Bazzalo, M., Emin-Lima, N.R., Carmo, N.A.S., Siciliano, S., Utreras, V., 2010. Report of the working group on distribution, habitat characteristics and preferences, and group size. Lat. Am. J. Aquatic Mamm. 31–38. https://doi.org/10.5597/lajam00151.

Dahms, C., Killen, S.S., 2023. Temperature change effects on marine fish range shifts: a meta-analysis of ecological and methodological predictors. Glob. Change Biol. 29 (16), 4459–4479. https://doi.org/10.1111/gcb.16770.

de Jesus-Lobo, A., Wedekin, L.L., Sobral-Souza, T., Le Pendu, Y., 2021. Potential distribution of Guiana dolphin (*Sotalia guianensis*): a coastal-estuarine and tropical habitat specialist. J. Mammal. 102 (1), 308–318. https://doi.org/10.1093/jmammal/gyaa153.

Edwards, M., Richardson, A.J., 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. Nature 430 (7002), 881–884. https://doi.org/10.1038/nature02808.

Edwards, H.H., Schnell, G.D., 2001. Status and ecology of *Sotalia fluviatilis* in the Cayos Miskito reserve, Nicaragua. Mar. Mamm. Sci. 17 (3), 445–472. https://doi.org/10.1111/j.1748-7692.2001.tb00998.x.

Espécie, M.A., Tardin, R.H., Simão, S.M., 2010. Degrees of residence of Guiana dolphins (*Sotalia guianensis*) in Ilha Grande Bay, south-eastern Brazil: a preliminary assessment. J. Mar. Biol. Assoc. U. K. 90 (8), 1633–1639. https://doi.org/10.1017/S0025315410000125.

Fleischmann, A.S., Papa, F., Hamilton, S., Melack, J., Forsberg, B., Val, A., Collischonn, W., Laipelt, L., Rossi, J., Andrade, B.C., Mendel, B., Alves, P., Glorize, M., Custodio, L., Gomes, M.C., Hymans, D., Keppe, I., Mendes, R., Gomes, R., Silva, P., Vieira, C., Xavier, R., Zumak, A., Ruhoff, A., Zhou, W., MacIntyre, S., Martins, E., Filizola, N., Marinho, R., Severo, E., Frias, M., Oliveira, R., Lauretto, L., Gravena, W., Coelho, A., Perez, H., Mota, S., Nasser, M., Moreira, D., Santos, L., Peleja, J.R., Marmontel, M., 2024. Extreme warming of Amazon waters in a changing climate. Earth. https://doi.org/10.31223/X56D9T [preprint].

Freitas, D.C., dos Santos, J.E.A., da Silva, P.C.M., Lunardi, V.O., Lunardi, D.G., 2021. Are dolphin-watching boats routes an effective tool for managing tourism in marine protected areas? Ocean Coast Manag. 211, 105782. https://doi.org/10.1016/j.ocecoaman.2021.105782.

Frouin-Mouy, H., Kowarski, K., Martin, B., Bröker, K., 2017. Seasonal trends in acoustic detection of marine mammals in Baffin bay and Melville bay, Northwest Greenland. Arctic 70 (1), 59–76. http://www.jstor.org/stable/26379724.

Hamilton, C.D., Vacquié-Garcia, J., Kovacs, K.M., Ims, R.A., Kohler, J., Lydersen, C., 2019. Contrasting changes in space use induced by climate change in two Arctic marine mammal species. Biol. Lett. 15 (3), 20180834. https://doi.org/10.1098/rsbl.2018.0834.

Hodapp, D., Roca, I.T., Fiorentino, D., Garilao, C., Kaschner, K., Kesner-Reyes, K., Froese, R., 2023. Climate change disrupts core habitats of marine species. Glob. Change Biol. 29 (12), 3304–3317. https://doi.org/10.1111/gcb.16612.

IPCC, 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157964.

IPCC, 2021. Summary for policymakers. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3–32. https://doi.org/10.1017/9781009157896.001.

Kaschner, K., Tittensor, D.P., Ready, J., Gerrodette, T., Worm, B., 2011. Current and future patterns of global marine mammal biodiversity. PLoS One 6 (5), e19653. https://doi.org/10.1371/journal.pone.0019653.

Kebke, A., Samarra, F., Derous, D., 2022. Climate change and cetacean health: impacts and future directions. Philos. Trans. R. Soc. Lond. B Biol. Sci. 377 (1854), 20210249. https://doi.org/10.1098/rstb.2021.0249.

Keppel, G., Kavousi, J., 2015. Effective climate change refugia for coral reefs. Glob. Change Biol. 21 (8), 2829–2830. https://doi.org/10.1111/gcb.12936.

Lamboll, R.D., Nicholls, Z.R., Smith, C.J., Kikstra, J.S., Byers, E., Rogelj, J., 2023. Assessing the size and uncertainty of remaining carbon budgets. Nat. Clim. Change 13 (12), 1360–1367. https://doi.org/10.1038/s41558-023-01848-5.

Liu, C., White, M., Newell, G., 2013. Selecting thresholds for the prediction of species occurrence with presence-only data. J. Biogeogr. 40 (4), 778–789. https://doi.org/10.1111/jbi.12058.

Macedo, H.S., Flores, P.A., Steenbock, W., Medeiros, R.P., 2020. Have you seen the dolphins? Dolphin watching participatory monitoring in a Brazilian multiple-use Marine Protected Area. Mar. Prot. Areas 361–378. https://doi.org/10.1016/B978-0-08-102698-4.00019-8.

Maciel, I.S., Maricato, G., Marqui, L., Anibolete, D., Belderrain, T., Figueiredo, L.D., França, S., Oliveira, B., Alves, M.A.S., Tardin, R.H., 2023. 20 years of research on the Guiana dolphin population of Sepetiba Bay, southeastern Brazil: what has changed? Aquat. Conserv. Mar. Freshw. Ecosyst. 33 (9), 940–954. https://doi.org/10.1002/aqc.3985.

MacLeod, C.D., 2009. Global climate change, range changes and potential implications for the conservation of marine cetaceans: a review and synthesis. Endanger. Species Res. 7 (2), 125–136. https://doi.org/10.3354/esr00197.

Manes, S., Costello, M.J., Beckett, H., Debnath, A., Devenish-Nelson, E., Grey, K., Jenkins, R., Khan, T.M., Kiessling, W., Krause, C., Maharaj, S.S., Midgley, G.F., Price, J., Talukdar, G., Vale, M.M., 2021. Endemism increases species' climate change risk in areas of global biodiversity importance. Biol. Conserv. 257, 109070. https://doi.org/10.1016/j.biocon.2021.109070.

Margules, C.R., Pressey, R.L., 2000. Systematic conservation planning. Nature 405 (6783), 243–253.

May-Collado, L.J., Zambrana-Torrelio, C., Agnarsson, I., 2016. Global spatial analyses of phylogenetic conservation priorities for aquatic mammals. In: Pellens, R., Grandcolas, P. (Eds.), Biodiversity Conservation and Phylogenetic Systematics: Preserving Our Evolutionary Heritage in an Extinction Crisis. Springer International Publishing, Sorbonne, pp. 305–318. https://doi.org/10.1007/978-3-319-22461-9_15.

May-Collado, L.J., Amador-Caballero, M., Casas, J.J., Gamboa-Poveda, M.P., Garita-Alpízar, F., Gerrodette, T., González-Barrientos, R., Hernández-Mora, G., Palacios, D.M., Palacios-Alfaro, J.D., Pérez, B., Rasmussen, K., Trejos-Lasso, L., Rodríguez-Fonseca, J., 2017. Ecology and conservation of cetaceans of Costa Rica and Panama.

In: Rossi, M.R., Finkl, C.W. (Eds.), Advances in Marine Vertebrate Research in Latin America: Technological Innovation and Conservation. Springer International Publishing, Berlin, pp. 293–319. https://doi.org/10.1007/978-3-319-56985-7_12.

McHenry, J., Welch, H., Lester, S.E., Saba, V., 2019. Projecting marine species range shifts from only temperature can mask climate vulnerability. Glob. Change Biol. 25 (12), 4208–4221. https://doi.org/10.1111/gcb.14828.

Meirelles, A.C.O., Choi-Lima, K.F., Campos, T.M., Monteiro-Filho, E.L.A., Lotufo, T.M.D. C., 2022. Abundance and effect of health status on apparent survival of Guiana dolphins, *Sotalia guianensis*, in an open embayment in north-eastern Brazil. Aquat. Conserv. Mar. Freshw. Ecosyst. 32 (6), 1022–1040. https://doi.org/10.1002/aqc.3804.

Meirelles, A.C.O., Choi-Lima, K.F., Campos, T.M., Monteiro-Filho, E.L.A., Lotufo, T.M.C., 2023. Habitat use of Guiana dolphin *Sotalia guianensis* in a heavily urbanized embayment. Mar. Ecol. Prog. Ser. 722, 195–206. https://doi.org/10.3354/meps14430.

Moura, J.F., Pivari, D., Pagliani, B., 2019. Environmental factors related to group size and habitat use of Guiana dolphins from São Marcos Bay, Amazon coast. Trop. Ecol. 60 (3), 426–432. https://doi.org/10.1007/s42965-019-00041-0.

Moura, S.P., Cantor, M., Broadhurst, M.K., Domit, C., 2021. Environmental and behavioral factors influencing individual variation in spatial use by Guiana dolphins (*Sotalia guianensis*). J. Mammal. 102 (4), 1009–1019. https://doi.org/10.1093/jmammal/gyab056.

Nagelkerken, I., Allan, B.J., Booth, D.J., Donelson, J.M., Edgar, G.J., Ravasi, T., Mellin, C., 2023. The effects of climate change on the ecology of fishes. PLoS Clim. 2 (8), e0000258. https://doi.org/10.1371/journal.pclm.0000258.

Oshima, J.E.F., Santos, M.C.O., 2016. Guiana dolphin home range analysis based on 11 years of photo-identification research in a tropical estuary. J. Mammal. 97 (2), 599–610. https://doi.org/10.1093/jmammal/gyv207.

Pecl, G.T., Araújo, M.B., Bell, J.D., Blanchard, J., Bonebrake, T.C., Chen, I.-C., Clark, T. D., Colwell, R.K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R.A., Griffis, R.B., Hobday, A.J., Janion-Scheepers, C., Jarzyna, M.A., Jennings, S., Lenoir, J., Linnetved, H.I., Martin, V.Y., McCormack, P.C., McDonald, J., Mitchell, N.J., Mustonen, T., Pandolfi, J.M., Pettorelli, N., Popova, E., Robinson, S.A., Scheffers, B.R., Shaw, J.D., Sorte, C.J.B., Strugnell, J.M., Sunday, J. M., Tuanmu, M.-N., Vergés, A., Villanueva, C., Wernberg, T., Wapstra, E., Williams, S.E., 2017. Biodivers. redistrib. under climate change: impacts on ecosystems and human well-being. Science 355 (6332), eaai9214. https://doi.org/10.1126/science.aai9214.

Peters, K.J., Stockin, K.A., Saltré, F., 2022. On the rise: climate change in New Zealand will cause sperm and blue whales to seek higher latitudes. Ecol. Indic. 142, 109235. https://doi.org/10.1016/j.ecolind.2022.109235.

Pinsky, M.L., Eikeset, A.M., McCauley, D.J., Payne, J.L., Sunday, J.M., 2019. Greater vulnerability to warming of marine versus terrestrial ectotherms. Nature 569 (7754), 108–111. https://doi.org/10.1038/s41586-019-1132-4.

Pinsky, M.L., Selden, R.L., Kitchel, Z.J., 2020. Climate-driven shifts in marine species ranges: scaling from organisms to communities. Ann. Rev. Mar. Sci 12 (1), 153–179. https://doi.org/10.1146/annurev-marine-010419-010916.

Poloczanska, E.S., Brown, C.J., Sydeman, W.J., Kiessling, W., Schoeman, D.S., Moore, P. J., Brander, K., Bruno, J.F., Buckley, L.B., Burrows, M.T., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C.V., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F., Thompson, S.A., Richardson, A.J., 2013. Global imprint of climate change on marine life. Nat. Clim. Change 3 (10), 919–925. https://doi.org/10.1038/nclimate1958.

Pörtner, H.O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Weyer, N.M., 2019. The ocean and cryosphere in a changing climate. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, 1155, pp. 10–1017.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Crespo Cuaresma, J., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Tavoni, M., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Change 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Rossi-Santos, M.R., Wedekin, L.L., Monteiro-Filho, E.D.A., 2007. Habitat use of the Guiana dolphin, *Sotalia guianensis* (cetacea, delphinidae), in the caravelas river estuary, eastern Brazil. Lat. Am. J. Aquatic Mamm. 111–116. https://doi.org/10.1017/S0025315407055683.

Secchi, E., Santos, M.C.O., Reeves, R., 2018. *Sotalia Guianensis* (Errata Version Published in 2019). The IUCN Red List of Threatened Species 2018. https://doi.org/10.2305/IUCN.UK.2018-2.RLTS.T181359A144232542.en e. T181359A144232542.

Silber, G.K., Lettrich, M.D., Thomas, P.O., Baker, J.D., Baumgartner, M., Becker, E.A., Boveng, P., Dick, D.M., Fiechter, J., Forcada, J., Forney, K.A., Griffis, R.B., Hare, H. A., Hobday, A.J., Howell, D., Laidre, K.L., Mantua, N., Quakenbush, L., Santora, J.A., Stafford, K.M., Spencer, P., Stock, C., Sydeman, W., van Houtan, K., Waples, R.S., 2017. Projecting marine mammal distribution in a changing climate. Front. Mar. Sci. 4, 413. https://doi.org/10.3389/fmars.2017.00413.

Simões-Lopes, P.C., 1998. Intraspecific agonistic behavior of *Tursiops truncatus* (Cetacea, Delphinidae) during dolphin-human cooperative fishing in southern Brazil. Biotemas 11 (2), 165–171.

Tardin, R.H., Maciel, I.S., Espécie, M.A., Melo-Santos, G., Simão, S.M., Alves, M.A.S., 2020. Modelling habitat use by the Guiana dolphin, *Sotalia guianensis*, in south-eastern Brazil: effects of environmental and anthropogenic variables, and the adequacy of current management measures. Aquat. Conserv. Mar. Freshw. Ecosyst. 30 (4), 775–786. https://doi.org/10.1002/aqc.3290.

Thompson, A.R., Ben-Aderet, N.J., Bowlin, N.M., Kacev, D., Swalethorp, R., Watson, W., 2022. Putting the Pacific marine heatwave into perspective: the response of larval fish off southern California to unprecedented warming in 2014–2016 relative to the previous 65 years. Glob. Change Biol. 28 (5), 1766–1785. https://doi.org/10.1111/gcb.16010.

Thuiller, W., Guéguen, M., Renaud, J., Karger, D.N., Zimmermann, N.E., 2019. Uncertainty in ensembles of global biodiversity scenarios. Nat. Commun. 10 (1), 1446. https://doi.org/10.1038/s41467-019-09519-w.

Thuiller, W., Georges, D., Gueguen, M., Engler, R., Breiner, F., Lafourcade, B., Patin, R., Blancheteau, H., 2024. biomod2: ensemble platform for species distribution modeling. R package version 4.2–6-1. https://biomodhub.github.io/biomod2/.

UNEP-WCMC & IUCN, 2024. Protected Planet: the World Database on Protected Areas (WDPA) [Online]. June 2024. UNEP-WCMC & IUCN, Cambridge, UK. Available at: www.protectedplanet.net.

Van Bressem, M.F., de Oliveira Santos, M.C., de Faria Oshima, J.E., 2009. Skin diseases in Guiana dolphins (*Sotalia guianensis*) from the Paranaguá estuary, Brazil: a possible indicator of a compromised marine environment. Mar. Environ. Res. 67 (2), 63–68. https://doi.org/10.1016/j.marenvres.2008.11.002.

Wedekin, L.L., Daura-Jorge, F.G., Simões-Lopes, P.C., 2010. Habitat preferences of Guiana dolphins, *Sotalia guianensis* (cetacea: delphinidae), in Norte bay, southern Brazil. J. Mar. Biol. Assoc. U. K. 90 (8), 1561–1570. https://doi.org/10.1017/S0025315410001414.

Zurell, D., Franklin, J., König, C., Bouchet, P.J., Dormann, C.F., Elith, J., Merow, C., 2020. A standard protocol for reporting species distribution models. Ecography 43 (9), 1261–1277.