

Supplement 1

Section S1. ODMAP Word file.

Population-scale habitat use of school sharks *Galeorhinus galeus* (Triakidae) in the Southwest Atlantic: insights from temporally explicit niche modelling and habitat associations

– ODMAP Protocol –

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Overview

Authorship

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Model objective

Model objective: Mapping and transfer

Target output: continuous and binary habitat suitability

Focal Taxon

Focal Taxon: The school shark (*Galeorhinus galeus*)

Location

Location: Southwest Atlantic

Scale of Analysis

Spatial extent: -70.2, -37.1, -59.05, -21.5 (xmin, xmax, ymin, ymax)

Spatial resolution: ~4 km

Temporal extent: from 1934 to 2021

Temporal resolution: single period

Boundary: natural

Biodiversity data

Observation type: citizen science, field survey, satellite and acoustic tracking, standardised monitoring data, social media

Response data type: presence-only

Predictors

Predictor types: climatic, habitat

Hypotheses

Hypotheses: Based on current knowledge of school shark distribution, we hypothesize that the species potential distribution includes temperate coastal regions of the Southwest Atlantic.

Assumptions

Model assumptions: we model a regional habitat patch of the Grinellian niche (abiotic niche) of the species, corresponding to Southwest Atlantic regional population, which may not fully represent its full Hutchinsonian population niche (environmental niche). Conceptually, we framed our analysis in the Eltonian Noise Hypothesis, which is based on the assumption that at geographic scales (i.e. regional, population-level), climatic variables (also termed ‘scenopoetic’) fundamentally shape the niche, whereas biotic interactions represent a ‘noise’ and their effects may be averaged-out (Soberón & Nakamura 2009). In addition, we assume the species is in equilibrium with the environment, all relevant predictors are included in the models, records are representative of the whole distribution of the species in the Southwest Atlantic, and sampling biases and environmental clustering were accounted for.

Algorithms

Modelling techniques: maxent

Model complexity: candidate models with differing complexity (varying feature classes and regularization multipliers) were evaluated.

Model averaging: median of best models predictions was calculated to consolidate final predictions.

Workflow

Model workflow: automated calibration and evaluation protocol for MaxEnt to compare candidate models of differing complexity (Cobos et al. 2019). This protocol allows selecting the most significant, best-performing, and simplest models.

Software

Software: modelling was performed through the kuenm R package (Cobos et al., 2019) that uses the maxent.jar file (version 3.4.1). Niche ellipsoids analysis was performed using the ellipsenm R package (Cobos et al., 2020).

Code availability: R code is available on GitHub (Agustindewy/School_shark_SWA)

Data availability: most records compiled in this study are made available in Supplement 2, only raw occurrences from INIDEP are excluded because they have confidentiality agreements in place. However, all occurrence point data used for calibration are available in Supplement 3.

Data

Biodiversity data

Taxon names: *Galeorhinus galeus*

Ecological level: species, populations

Data sources: *Southwest Atlantic*: Catch records in research cruises and observer programs from the Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP). Biodiversity data from the Global Biodiversity Information Facility (GBIF). Biodiversity data from the Ocean Biodiversity Information System (OBIS). Catch data available in published and grey literature. Catch data available in social media posts (only from Facebook). Mining of Facebook records was done using various terms covering country-based common names of the species, including “tiburón cazón” (Argentina), “tiburón trompa de cristal” (Uruguay), and slight variations of them (i.e., separating or omitting words, omitting accent mark or hyphen). Only posts including images or videos of the catch were taken into consideration to aid for proper species level identification and avoid anecdotal occurrence data errors. The search was performed by scrolling through freely accessible pictures of public fishing groups and angler profiles. In many cases, missing details regarding the catch were gathered by personally contacting anglers or commenting on posts. However, a conservative approach was followed while gathering social media data, knowing the potential biases that can be introduced to the data set; thus, shark occurrences were not recorded when minimal confusion or uncertainty arose.

Occurrences detailed in Supplement 2.

Sampling design: no sampling design to be reported.

Sample size: the total number of school shark records compiled is 9597.

Clipping: a 1000 km-buffer mask was used for model calibration. Because in the Southwest Atlantic a 1000 km buffer reaches areas of the Pacific, a spatial polygon was further used to erase unwanted remote areas for calibration. This polygon erased areas west of -69.4 of longitude and it was defined based on the shortest 1000 km distance from the southernmost record available towards the Pacific, but considering the coastline.

Scaling: records were environmentally filtered to reduce clustering and potential sampling biases. We used the 'envSample' custom function, 0.5 °C sea surface temperature and 10 m depth filter values (Varela et al. 2014).

Cleaning: outlier and odd presence data were removed based on procedures in Cobos et al. (2018). Presences on land were removed.

Background data: 10,000 background records were randomly obtained from calibration areas in each case. Calibration areas corresponded to polygons based on 1000-km buffer areas around filtered occurrence records.

Errors and biases: citizen science and social media data were not used as calibration records to avoid potential biases related to misidentification, poor georeferencing and overrepresentation of the coast.

Data partitioning

Training data: models were generated using a random sample of 75% of occurrence data for training and 25% for testing.

Validation data: training data subsets were used to create candidate models and testing data subsets to evaluate them based on significance (partial ROC) and omission rates (5% omission error). Then, model complexity was calculated on models created with the complete set of occurrences (AICc scores). Please refer to Cobos et al. (2019) for further details.

Test data: citizen science and social media data were used as independent data sets for the final evaluation of models based on 5% omission rate.

Predictor variables

Predictor variables: bathymetry (meters). Sea surface temperature (SST, degrees Celcius). SST thermal fronts (degrees Celcius). Diffuse attenuation coefficient Kd490 (1/meters).

Data sources: the surface water variables were downloaded from the Aqua MODIS satellite (monthly composites, January 2003 to December 2020) at a resolution of ~1 arcmins, whereas bathymetry from the MARSPEC data layers at a resolution of ~0.5 arcmins (Sbrocco & Barber 2013).

Spatial extent: -70.2, -37.1, -59.05, -21.5 (xmin, xmax, ymin, ymax)

Spatial resolution: bathymetry: ~0.5 arcmins, the rest: ~1 arcmins

Coordinate reference system: EPSG: 4326

Temporal extent: 01/2003-12/2020

Temporal resolution: single time frame

Data processing: layers were masked by the shoreline polygon and the calibration areas.

Transfer data

Not applicable.

Model

Variable pre-selection

Variable pre-selection: variables were pre-selected to be ecologically and biologically relevant to the species. When possible, only proximal/direct drivers of distribution were included, avoiding to include a great deal of non-relevant predictors in competing models.

Multicollinearity

Multicollinearity: multicollinearity between predictors was addressed via the Pearson correlation analysis. Only weakly correlated (-0.7 – 0.7) predictors were retained.

Model settings

maxent: featureSet (lq, lp, lqp), featureRule (We only considered the subset of features that yield the simplest responses, characterised by linear and bell shapes.), regularizationMultiplierSet (Sequence from 0.1 to 2 by 0.1 increments, plus 2.5, 3, 4, 5, 7, and 10). Output format (logistic).

Model settings (extrapolation): not applicable.

Model estimates

Parameter uncertainty: final model uncertainty was considered from two sources. One, the effect of 10 bootstrap replicates of each best model. Two, the effect of different parametrization of median averaging of best-selected models following protocol in Cobos et al. (2019).

Variable importance: predictor importance was assessed with the jackknife analysis included in the MaxEnt algorithm. It calculates the percent contribution that represents the sum of regularized gain that correspond to each variable every time the algorithm is run during training iterations.

Model selection - model averaging - ensembles

Model averaging: not applicable.

Analysis and Correction of non-independence

Spatial autocorrelation: none non-independence analyses were carried out.

Threshold selection

Threshold selection: binary predictions based on 5th and 10th Minimum Training Presence (MTP). We considered areas with habitat suitability above the threshold as ‘suitable’ and those below as ‘not suitable’.

Assessment

Performance statistics

Performance on validation data: most significant (partial receiver operating characteristic scores, partial ROC) and best-performing (omission rate at a threshold $E = 5\%$; i.e., false-negative rate) models among candidate models were narrowed down based on the Akaike’s information criterion corrected for ample size (AICc). A $\Delta AICc$ value of ≤ 2 was chosen as a criterion to select the best few models from among each candidate model set. Please refer to Cobos et al. (2019) for further details.

Performance on test data: omission rate (5% omission error)

Plausibility check

Response shapes: we used partial dependence plots to check the ecological plausibility of fitted species-environment relationships.

Prediction

Prediction output

Prediction unit: Predictions of habitat suitability expressed as continuous and binary scales.

Post-processing: No post-processing.

Uncertainty quantification

Algorithmic uncertainty: Range uncertainty around 10 bootstrap replicates in each model calibration.

Input data uncertainty: Not applicable.

Parameter uncertainty: Maximum and minimum median mosaics as a measure of final prediction uncertainty.

Scenario uncertainty: Not applicable.

Novel environments: Not applicable.

Section S2. Reference list for all peer-reviewed and grey articles with school shark (*Galeorhinus galeus*) reports consulted in this study. Last revision 30 May 2021.

Reference list

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Section S3. Tables

Table S1. Seasonal habitat associations of female (♀) and male (♂) school sharks (*Galeorhinus galeus*) in the Southwest Atlantic. The min and max indicate the observed range of habitat values covered by 95% of the cumulated frequency curves of both total shark occurrences with biological data, $f(t)$, and those with a specific sex (female and male), $g(t)$. Bold numbers indicate significant results.

	$f(t)$		$g(t)$				$f(t) - g(t)$				$g(t)_{\text{♀}} - g(t)_{\text{♂}}$	
	min	max	min		max		D_{max}		$p\text{-value}$		D_{max}'	$p\text{-value}'$
			♀	♂	♀	♂	♀	♂	♀	♂		
Latitude S (°)												
summer	36.01	45.76	36.40	36.01	43.47	43.47	0.601	0.615	<0.001	<0.001	0.029	1.000
autumn	29.30	46.71	38.04	37.02	44.31	45.07	0.735	0.683	<0.001	<0.001	0.205	0.186
winter	32.75	46.29	34.14	34.40	42.77	42.92	0.516	0.502	<0.001	<0.001	0.345	0.005
spring	32.26	45.92	34.57	35.81	41.94	44.16	0.445	0.323	<0.001	<0.001	0.280	0.005
Bathymetry (m)												
summer	10.53	100.80	9.19	9.63	94.09	92.31	0.323	0.264	<0.001	<0.001	0.118	0.297
autumn	18.71	268.02	11.86	13.57	144.65	144.65	0.469	0.316	<0.001	<0.001	0.235	0.113
winter	18.36	134.82	11.82	13.61	118.78	150.86	0.708	0.540	<0.001	<0.001	0.330	0.015
spring	10.09	152.80	6.72	6.72	149.42	149.42	0.598	0.348	<0.001	<0.001	0.297	0.003
SST (°C)												
summer	14.90	22.41	16.12	16.20	22.37	22.37	0.589	0.593	<0.001	<0.001	0.066	0.891
autumn	12.85	24.65	12.93	13.65	18.57	18.57	0.722	0.688	<0.001	<0.001	0.196	0.247
winter	8.65	16.04	8.87	9.04	13.60	13.26	0.556	0.507	<0.001	<0.001	0.355	0.006
spring	9.75	18.63	12.29	10.19	15.81	15.61	0.490	0.323	<0.001	<0.001	0.243	0.011
SST fronts (°C)												
summer	0.02	0.20	0.02	0.03	0.20	0.20	0.135	0.105	0.004	0.049	0.080	0.741
autumn	0.01	0.11	0.01	0.01	0.11	0.12	0.389	0.419	<0.001	<0.001	0.096	0.965
winter	0.00	0.24	0.01	0.01	0.14	0.21	0.125	0.267	0.546	<0.001	0.306	0.017
spring	0.01	0.20	0.01	0.01	0.21	0.21	0.123	0.055	0.260	0.891	0.116	0.662
Coefficient Kd490 (m⁻¹)												
summer	0.08	0.35	0.08	0.08	0.47	0.55	0.367	0.417	<0.001	<0.001	0.100	0.447
autumn	0.04	0.26	0.10	0.10	0.23	0.25	0.440	0.494	<0.001	<0.001	0.141	0.626
winter	0.08	0.52	0.11	0.10	0.59	0.54	0.464	0.352	<0.001	<0.001	0.364	0.003
spring	0.09	0.40	0.09	0.09	0.47	0.49	0.233	0.194	0.001	0.001	0.115	0.641

D_{max} = observed absolute maximum vertical distance between $f(t)$ and $g(t)$ curves; $D_{\text{max}}' = D_{\text{max}}$ between $g(t)_{\text{♀}}$ and $g(t)_{\text{♂}}$ curves; $p\text{-value}$ = probability of observing a value of randomized D_{max} equal to or greater than the observed D_{max} ; $p\text{-value}' = D_{\text{max}}' p\text{-value}$; SST = sea surface temperature.

Table S2. Seasonal habitat associations of adult and juvenile school sharks (*Galeorhinus galeus*) in the Southwest Atlantic. The min and max indicate the observed range of habitat values covered by 95% of the cumulated frequency curves of both total shark occurrences with biological data, $f(t)$, and those with a specific maturity stage (adult and juvenile), $g(t)$. Bold numbers indicate significant results.

	$f(t)$		$g(t)$				$f(t) - g(t)$				$g(t)_{adu} - g(t)_{juv}$	
	min	max	min		max		D_{max}		p -value		D_{max}'	p -value'
			adult	juvenile	adult	juvenile	adult	juvenile	adult	juvenile		
Latitude S (°)												
summer	36.01	45.76	36.73	36.01	43.66	43.47	0.582	0.625	<0.001	<0.001	0.262	0.007
autumn	29.30	46.71	38.66	37.02	45.07	43.22	0.696	0.782	<0.001	<0.001	0.359	0.005
winter	32.75	46.29	34.70	34.14	42.33	44.01	0.536	0.501	<0.001	<0.001	0.604	<0.001
spring	32.26	45.92	36.18	35.81	43.70	43.30	0.327	0.399	<0.001	<0.001	0.392	<0.001
Bathymetry (m)												
summer	10.53	100.80	7.40	10.98	107.05	66.39	0.116	0.308	0.185	<0.001	0.297	0.001
autumn	18.71	268.02	11.86	11.86	144.65	144.65	0.198	0.454	0.079	<0.001	0.298	0.046
winter	18.36	134.82	13.61	11.82	150.86	134.82	0.342	0.658	<0.001	<0.001	0.403	0.001
spring	10.09	152.80	6.72	6.72	152.80	80.88	0.211	0.602	0.002	<0.001	0.397	<0.001
SST (°C)												
summer	0.08	0.35	0.08	0.08	0.23	0.55	0.474	0.425	<0.001	<0.001	0.122	0.381
autumn	0.04	0.26	0.10	0.10	0.20	0.20	0.380	0.585	<0.001	<0.001	0.225	0.187
winter	0.08	0.52	0.10	0.08	0.42	0.59	0.305	0.437	<0.001	<0.001	0.534	<0.001
spring	0.09	0.40	0.10	0.09	0.47	0.47	0.133	0.380	0.130	<0.001	0.287	0.006
SST fronts (°C)												
summer	14.90	22.41	16.12	16.20	21.96	22.41	0.544	0.617	<0.001	<0.001	0.343	<0.001
autumn	12.85	24.65	12.93	15.23	18.57	18.57	0.682	0.797	<0.001	<0.001	0.431	<0.001
winter	8.65	16.04	10.03	8.83	12.77	13.60	0.534	0.526	<0.001	<0.001	0.505	<0.001
spring	9.75	18.63	10.19	10.49	15.25	15.25	0.327	0.443	<0.001	<0.001	0.211	0.065
Coefficient Kd490 (m⁻¹)												
summer	0.02	0.20	0.02	0.02	0.20	0.21	0.170	0.135	0.023	0.005	0.246	0.010
autumn	0.01	0.11	0.01	0.01	0.11	0.11	0.262	0.455	0.017	<0.001	0.223	0.300
winter	0.00	0.24	0.00	0.01	0.25	0.17	0.328	0.095	<0.001	0.625	0.371	0.002
spring	0.01	0.20	0.01	0.01	0.21	0.13	0.055	0.079	0.965	0.742	0.069	0.988

D_{max} = observed absolute maximum vertical distance between $f(t)$ and $g(t)$ curves; $D_{max}' = D_{max}$ between $g(t)_{adu}$ and $g(t)_{juv}$ curves; p -value = probability of observing a value of randomized D_{max} equal to or greater than the observed D_{max} ; p -value' = D_{max}' p -value; SST = sea surface temperature.

Section S4. Figures

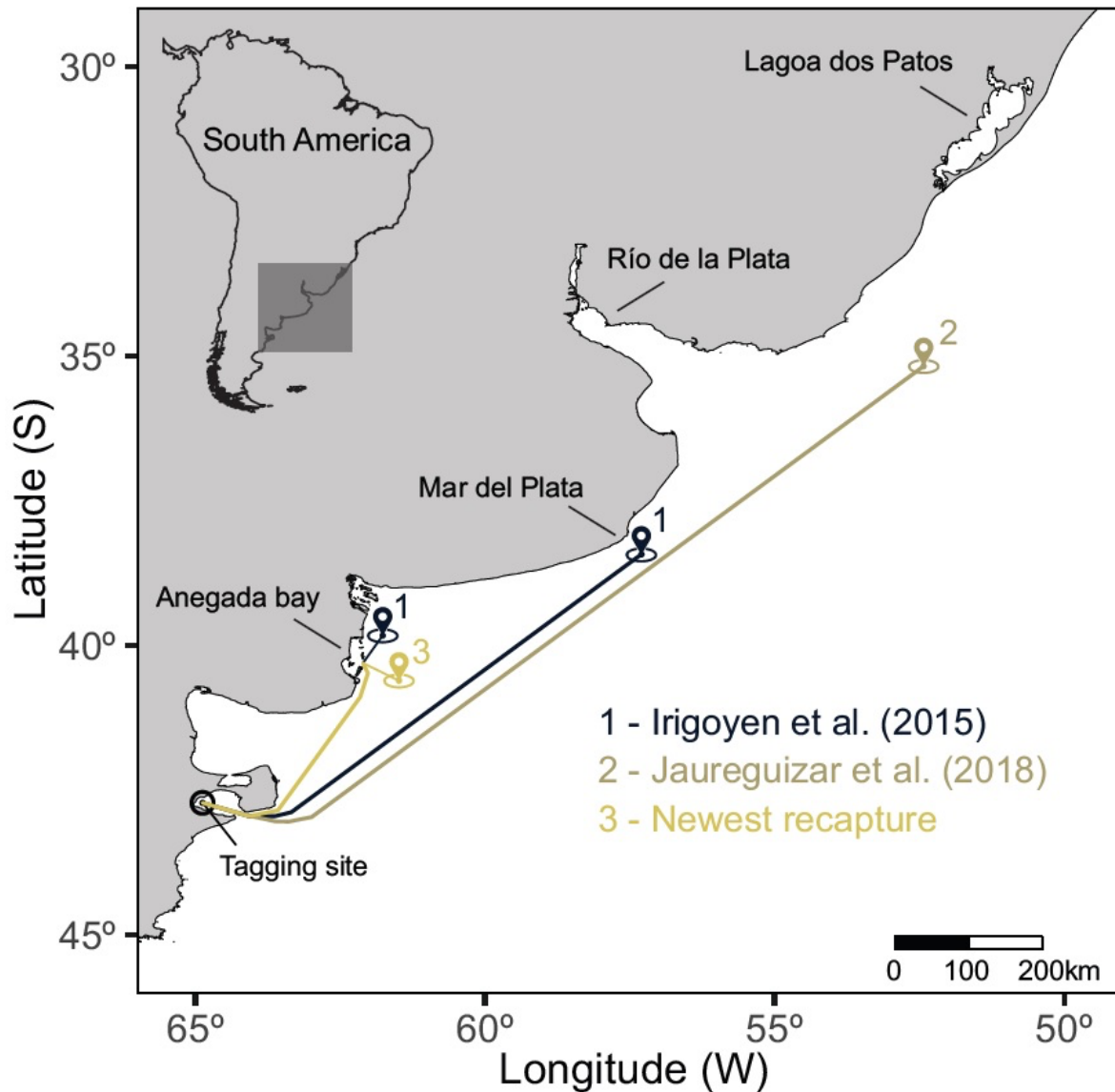


Figure S1. Newest recapture of school shark *Galeorhinus galeus* in the Southwest Atlantic. This new recapture corresponds to a female that measured 130 cm total length tagged on 22nd February 2015 near Puerto Madryn, Argentina (Tagging site). This individual was recaptured in Anegada bay (shortest path from tagging site ~430 km) on 7th November 2021 after 2451 days at liberty (~6.7 years). Tagging procedures can be found in Jaureguizar et al. (2018). Previously published recaptures in the region are shown for comparison.

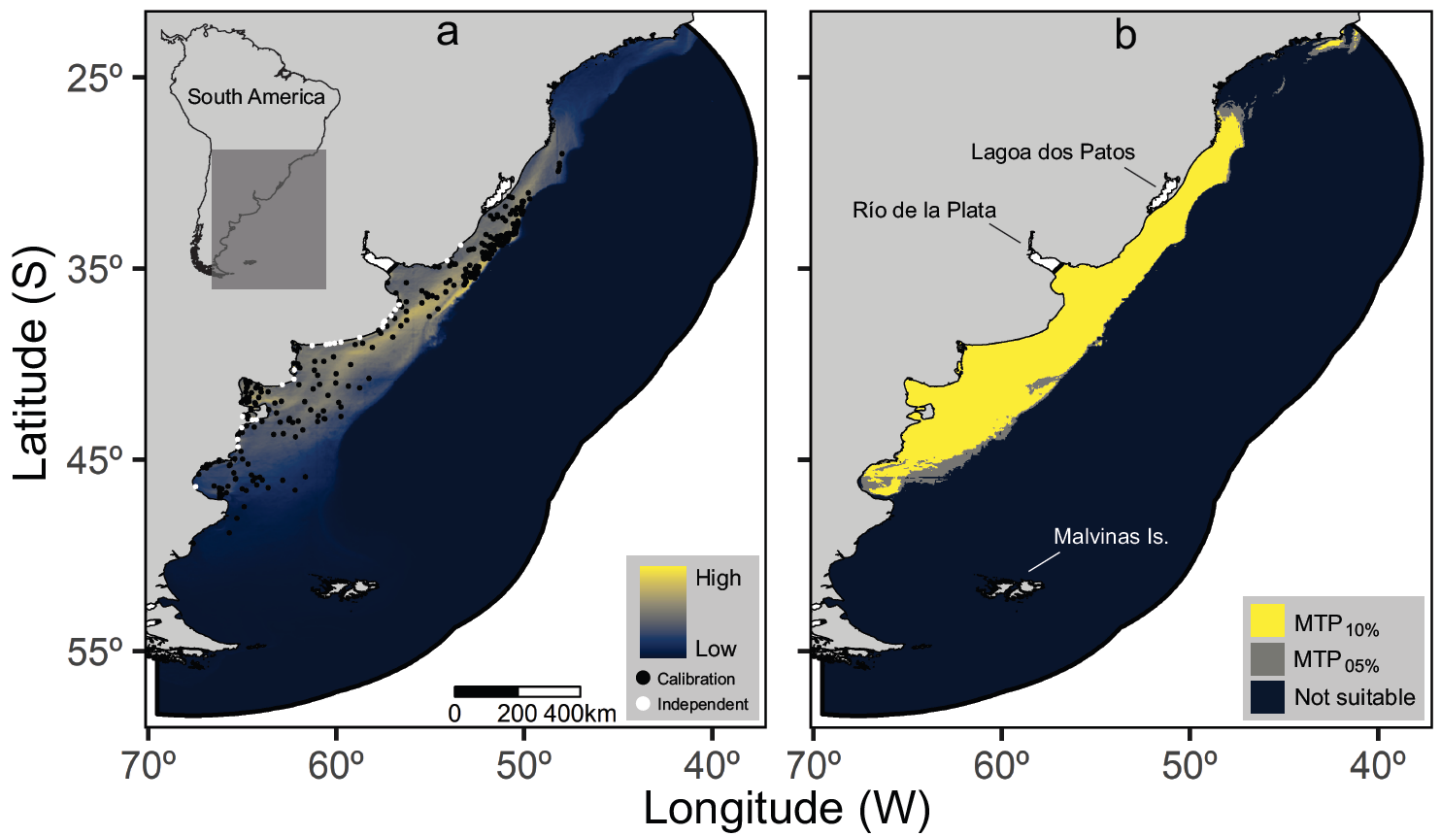


Figure S2. Habitat suitability predictions for the annual model (**a**- continuous, **b**- binary) of school shark (*Galeorhinus galeus*) population in the Southwest Atlantic region. Predictions are restricted to the calibration area (black polygon). The location of calibration points used for modelling and independent records for model evaluation are shown in **a**- for exemplification. Note inner Río de la Plata and Lagoa dos Patos areas were excluded from calibration. Binary outputs were defined by 10% and 5% error minimum training presence (MTP) thresholds.

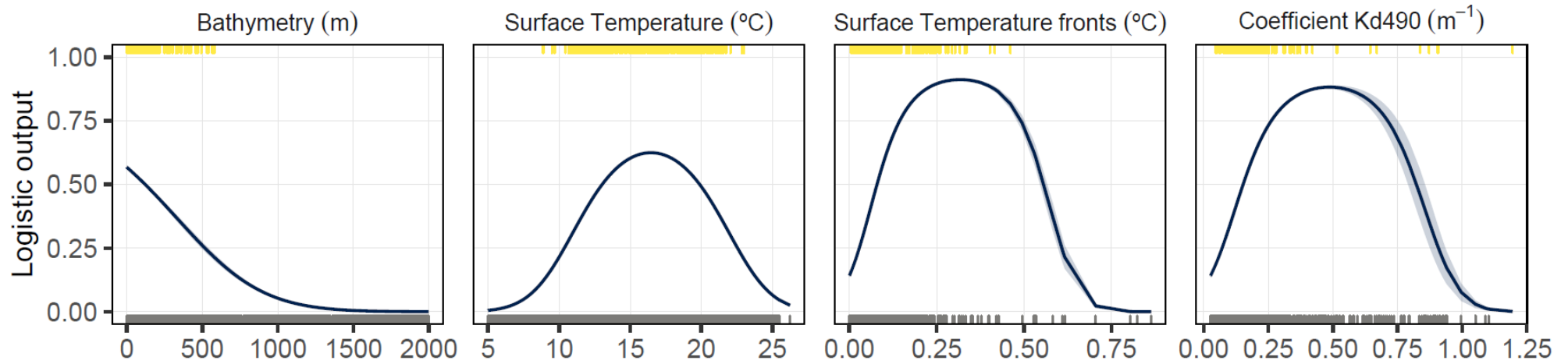


Figure S3. Response plots of predictor variables used in the annual model of school shark (*Galeorhinus galeus*) subpopulation in the Southwest Atlantic region. The curves show how the prediction (logistic output) changes as each predictor is varied, keeping all other predictors at their average value. The lines represent the mean response and the shaded area correspond to 1 standard deviation of the variability generated with 10 replicate runs. Top rugs show predictor values at presence locations, while bottom rugs show the available values from 10000 background locations randomly sampled from the calibration area. Plots were created using ‘SDMtune’ R package (Vignali et al. 2020).

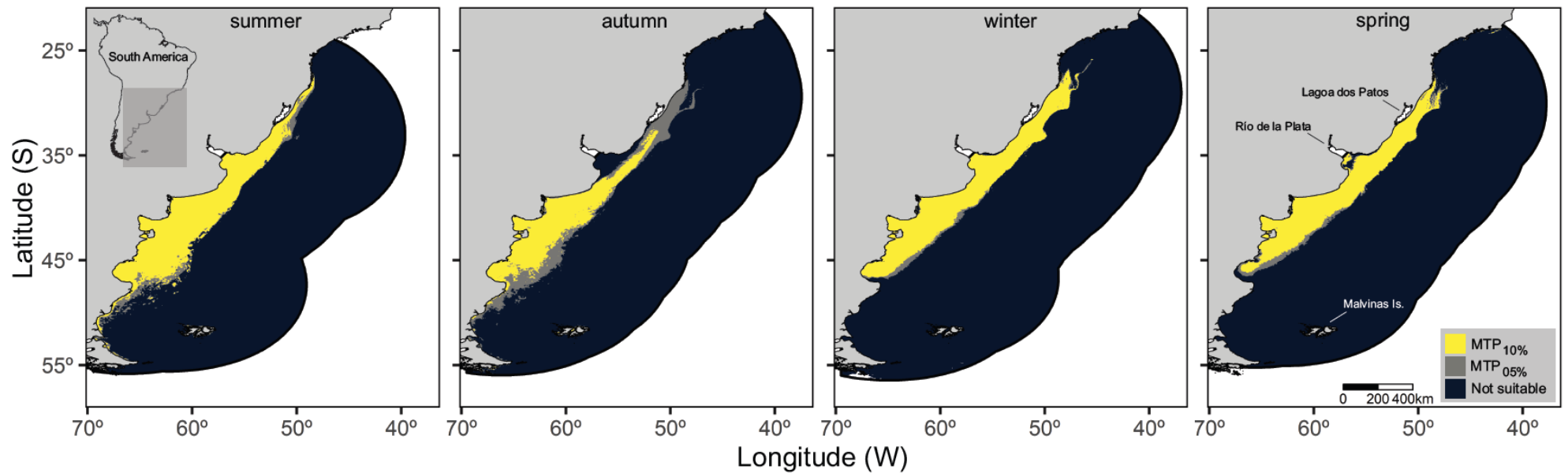


Figure S4. Binary habitat suitability predictions for the seasonal models of school shark (*Galeorhinus galeus*) population in the Southwest Atlantic region. Predictions are restricted to the calibration area (black polygon). Note inner Río de la Plata and Lagoa dos Patos areas were excluded from calibration. Binary outputs were defined by 10% and 5% error minimum training presence (MTP) thresholds.

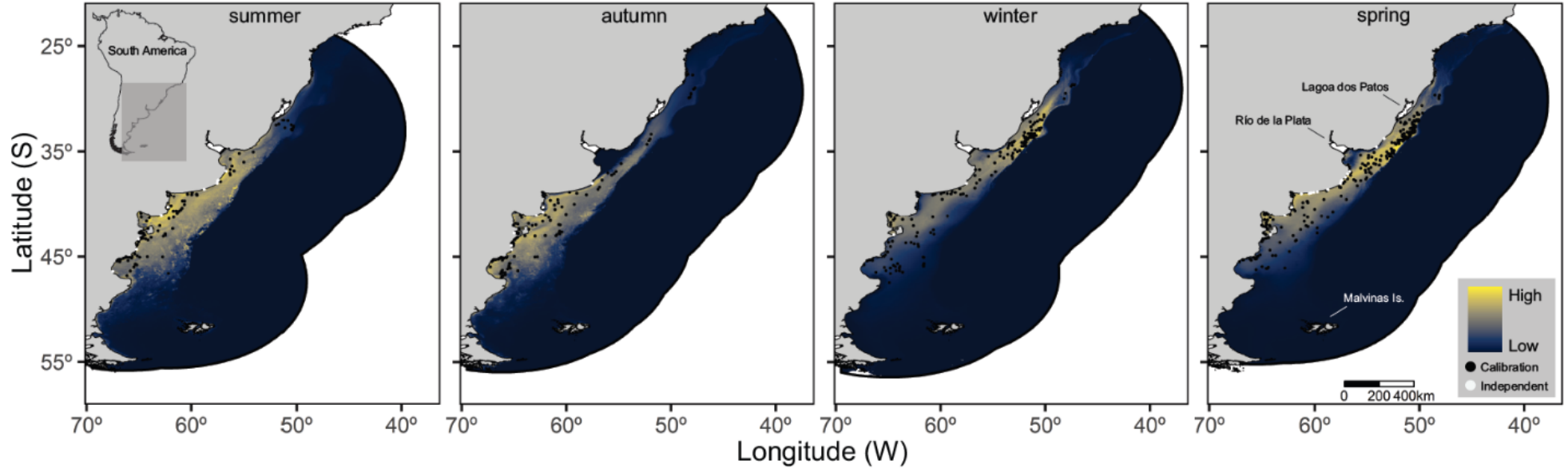


Figure S5. Continuous habitat suitability predictions for the seasonal models of school shark (*Galeorhinus galeus*) subpopulation in the Southwest Atlantic region. Predictions are restricted to the calibration area (black polygon). The location of calibration points used for modelling and independent records for model evaluation are shown for each season. Note inner Río de la Plata and Lagoa dos Patos areas were excluded from calibration. Binary outputs were defined by 10% and 5% error minimum training presence (MTP) thresholds.

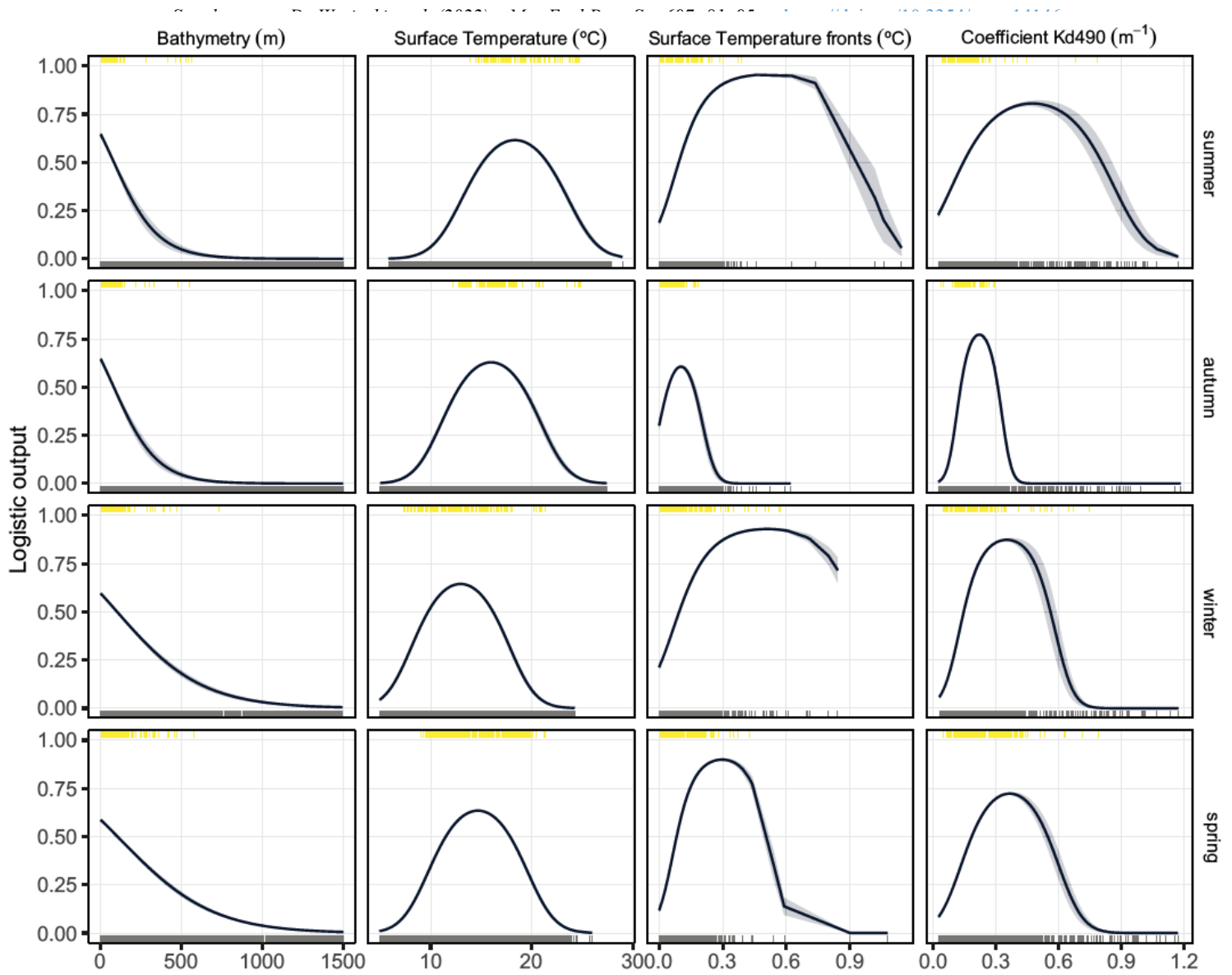


Figure S6. Response plots of predictor variables used in the seasonal models of school shark (*Galeorhinus galeus*) subpopulation in the Southwest Atlantic region. The curves show how the prediction (logistic output) changes as each predictor is varied, keeping all other predictors at their average value. The lines represent the mean response and the shaded area correspond to 1 standard deviation of the variability generated with 10 replicate runs. Top rugs show predictor values at presence locations, while bottom rugs show the available values from 10000 background locations randomly sampled in the calibration area. Plots were created using 'SDMtune' R package (Vignali et al. 2020).

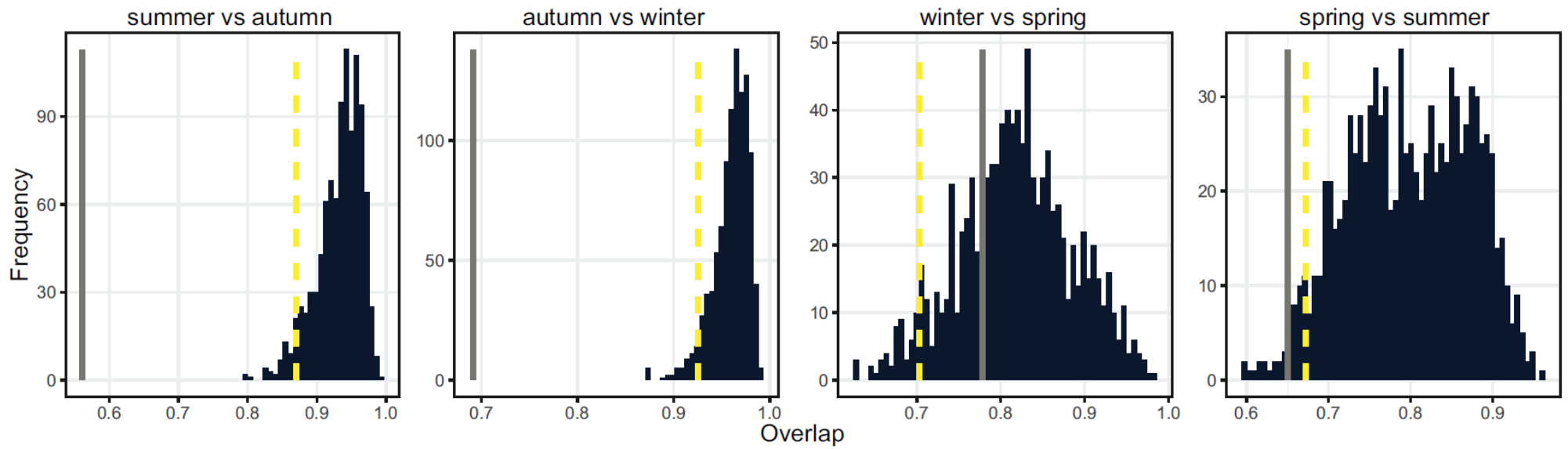


Figure S7. Statistical test results for the observed overlap (solid line) and 5% confidence limit (dashed line) of the frequency distribution of 1000 Monte-Carlo simulations constructed from randomly sampling the background with an n equal to the number of records for each niche.

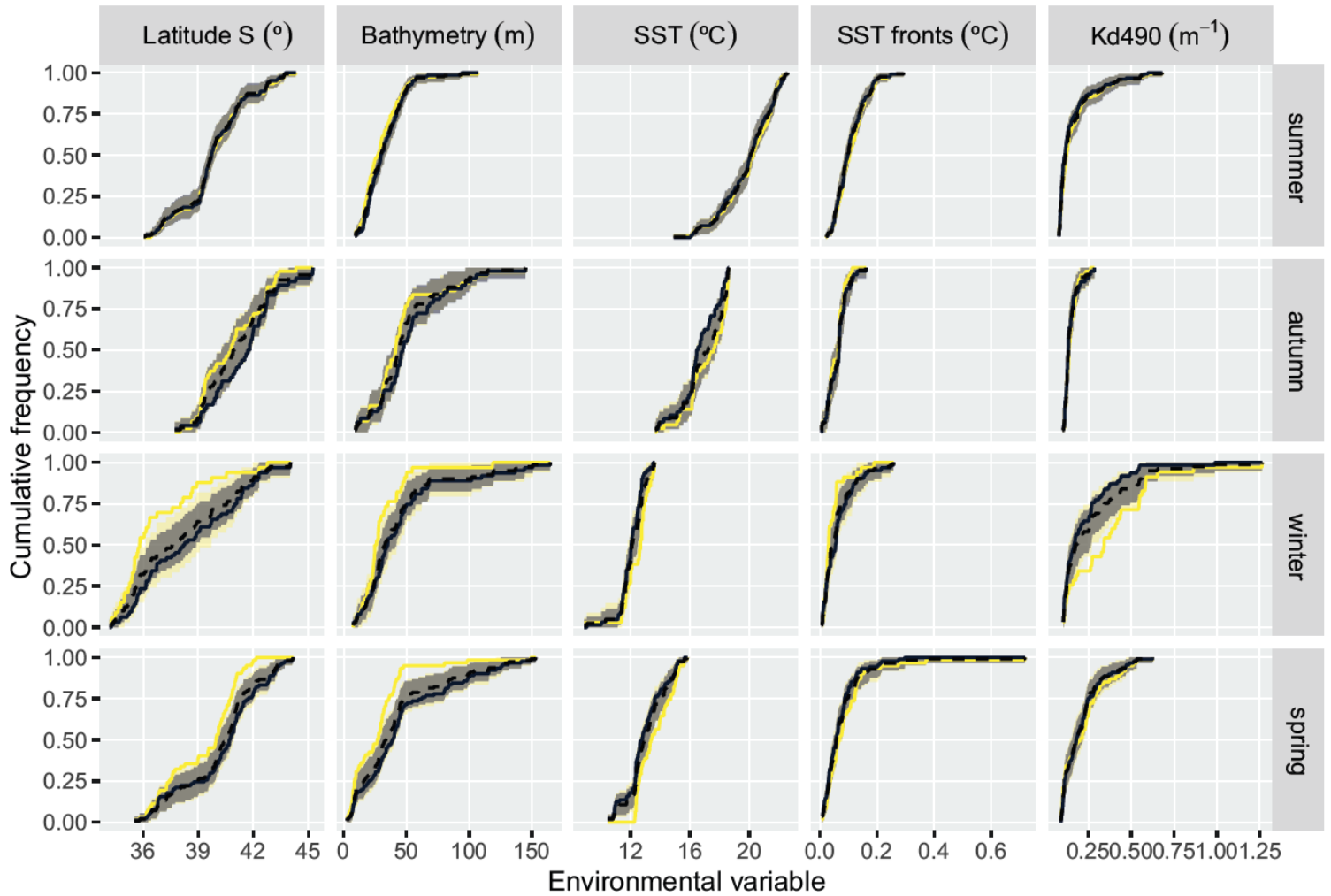


Figure S8. Seasonal habitat associations by sex of school sharks (*Galeorhinus galeus*) in the Southwest Atlantic. The dashed lines show the cumulated frequency curves of all shark occurrences with sex information, $f(t)$. The solid lines show the sex-specific cumulated frequency curve, $g(t)$, corresponding to males (darker colour) and females (lighter colour), respectively. The shaded areas represent the 95% confidence intervals for each $g(t)$ based on 1000 bootstrap replicates with replacement. SST = sea surface temperature.

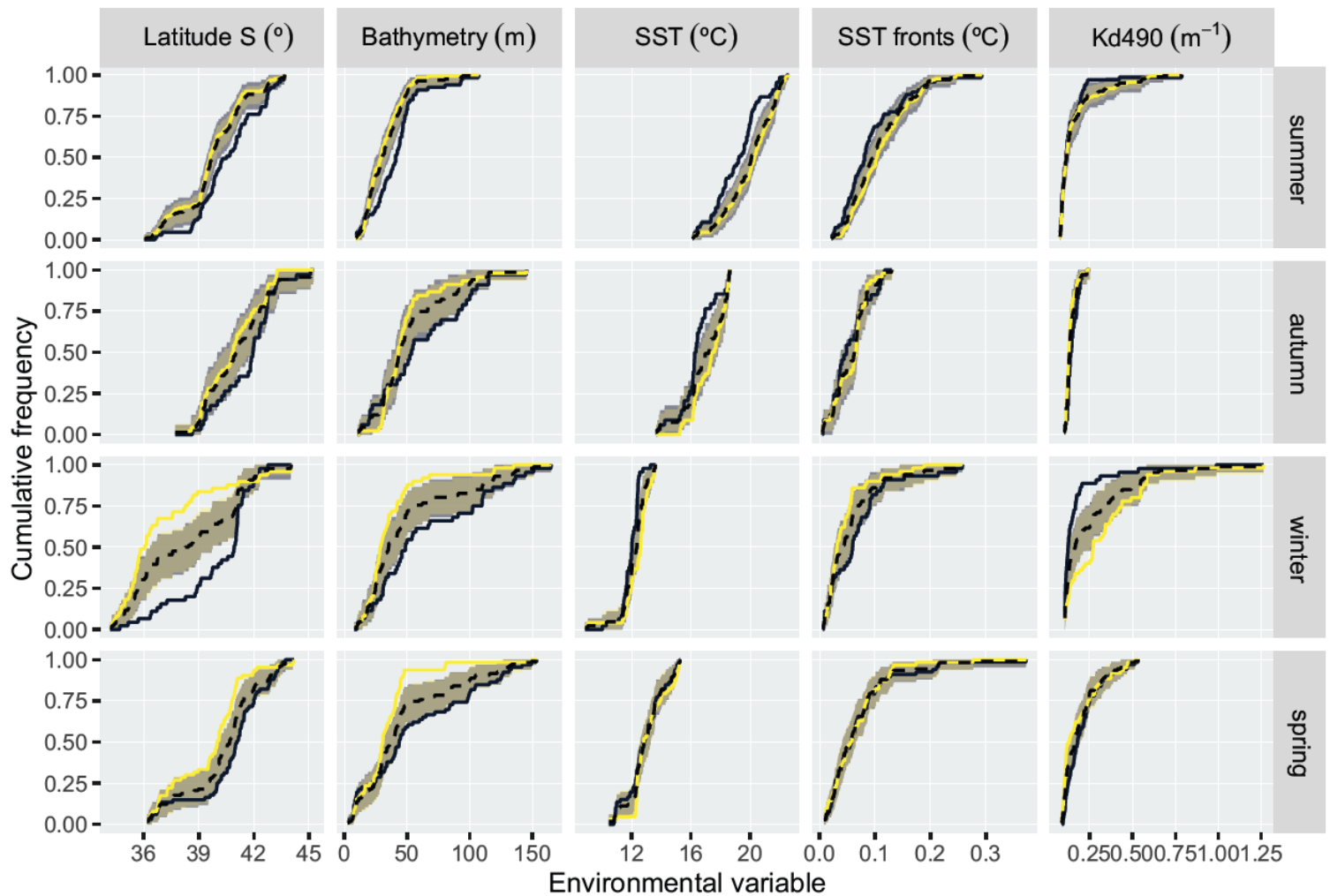


Figure S9. Seasonal habitat associations by maturity stage of school sharks (*Galeorhinus galeus*) in the Southwest Atlantic. The dashed lines show the cumulated frequency curves of all shark occurrences with size information, $f(t)$. The solid lines show the maturity stage-specific cumulated frequency curve, $g(t)$, corresponding to adults (darker colour) and juveniles (lighter colour), respectively. The shaded areas represent the 95% confidence intervals for each $g(t)$ based on 1000 bootstrap replicates with replacement. SST = sea surface temperature.