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A PRELIMINARY ANALYSIS OF SPATIOTEMPORAL PATTERNS IN SWORDFISH HABITAT DISTRIBUTIONS

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SUMMARY

A species distribution model (SDM) for swordfish that was in the development stage has been finalized. The model used detailed biological and oceanographic data to define the spatial distribution of Swordfish. The SDM adequately predicted Swordfish habitat (and thus fish) distributions such that it was found suitable for investigations into the spatiotemporal distribution of habitat. Results of this preliminary investigation supports the current hypothesized stock boundaries between the north and south Atlantic stocks used for management. Both the north and south Atlantic may be experiencing an expansion of habitat. This could result in decreased density of swordfish into a larger area and/or change MSY production metrics. A more detailed examination of this possibility is recommended.

KEYWORDS

Swordfish, Habitat, Species Distribution, Oceanography

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1. Introduction

The Swordfish Species Distribution Model (SDM) described here updates the cumulated and ongoing work to refine previously presented models. While previous work described the model in terms of a stationary snapshot in time, a more thorough examination was made of more finer resolution of the spatiotemporal emergent properties than had previously been undertaken. The work presented here goes provides a “next level” understanding of the various environments factors used and touches on investigation of the model sensitivities to the individual habitat factors. The objective of this work was explore possible patterns, cycles or other temporal trends that may be significant in estimating the abundance or distribution of the species that may affect estimated indices of abundance based on catch per unit effort data.

2. Methods

We built a swordfish Species Distribution Model (SDM) based on the methods outlined in Goodyear (2015). The SDM describes the spatial and temporal distribution of habitat using species-specific affinity curves for the habitat variables utilized. The SDM was dimensioned by 1x1 degree latitude and longitude, 46 depth layers, year and month. Oceanographic variables were obtained from the Community Earth System Model (CESM) (Danabasoglu et al. 2012). These five measurements were used to create individual three-dimensional habitat “cubes” for the years and months 1986-2005. The SDM requires detailed information on habitat use by swordfish and this information was obtained from pop-up satellite (PSAT) data from swordfish in the Atlantic. In cooperation with other ICCAT CPCs (Portugal, Canada, Spain and USA) PSAT data was contributed and shared via a single OwnCloud website, this effort is intended to be continued as more PSAT data becomes available. Habitat variables were chosen based on those fulfilling the broad environmental and biological needs of swordfish including depth, oxygen, temperature and forage. Habitat specific affinity curves were built from observational data and/or published values. These affinity curves were subsequently used to estimate the swordfish habitat suitability and abundance of each modeled cube. No distinction between the distribution of the species and the distribution of its habitat, and use the term abundance to refer to predicted values. All predicted values are relative magnitude of the habitat suitability by latitude, longitude, year and month in values per km^2, summed over all 46-depth layers of the model. At each monthly time step, fish are redistributed elsewhere within the modeled grid to conserve total abundance based on the relative values of the habitat.

3. Results

3.1 Habitat affinities. To support a fuller understanding of the Swordfish species distribution model, the habitat factor affinities curves presented in Forrestal and Schirripa (2020) are reviewed here. Six different environmental factors were used to describe to describe Swordfish habitat: (1) ocean depth, (2) temperature tolerance, (3) temperature preference, (4) dissolved oxygen, (5) zooplankton concentration, and (6) sea surface gradient (**Figure 1**). Factors were selected on a first principals basis and based on knowledge of the biology of the species both from direct observation made from Pop-up Satellite Tags (PSAT) or though inference derived from the scientific literature.

3.2 Inferences from stepwise model building. To understand the influence that each environmental factor had the overall emergent properties, a stepwise evaluation of the model building was undertaken.

3.2.1 Temperature. The spatial distribution of predicted Swordfish habitat based on including only temperature tolerance and preference in the SDM is shown in **Figure 2A**. Temperature is one of the most frequently used habitat factors used to describe fish distribution. Although Swordfish have been shown to exhibit a temperature preference, they have a very wide thermal tolerance. Therefore, temperature alone explained only a very small degree of the predicted habitat. The temperature only model predicted a large homogeneous habitat map that showed very little if any structure.

3.2.2 Temperature + oxygen. The spatial distribution of predicted Swordfish habitat based on including only temperature tolerance and oxygen is shown in **Figure 2B**.Although brief excursions into hypoxic conditions are possible or even routine, at some level the concentration of oxygen must be a limiting factor. The temperature + oxygen model added obvious structure to the predicted habitat distribution. The introduction of oxygen to the model resulted in habitat becoming less dense and revealed the shape of the oxygen minimum zone (OMZ) across the middle Atlantic. The OMZ primarily effects the vertical distribution of habitat. Because the densities described are summed over the entire vertical column, so the effects of the OMZ may not be obvious without an examination of the distribution by the molded depth layers.

3.2.3 Temperature + oxygen + zooplankton. Swordfish habitat resulting from including temperature tolerance and preference, oxygen and zooplankton is shown in **Figure 2C**. Adding zooplankton to the model greatly increased the heterogeneity and complexity to the predicted habitat. The zooplankton factor added the prediction high-density habitat is the southernmost region of the model space. A second feature that revealed itself was an area of increased habitat density in the Gulf of Guinea and Ascension Island. This area is known to be highly productive and supports a large tropical tuna fishery.

3.2.4 Temperature + oxygen + zooplankton + sea surface gradient. The spatial distribution of predicted Swordfish habitat resulting from including temperature tolerance and preference, oxygen, zooplankton and sea surface gradient is shown in **Figure 2D**. Adding sea surface height to the model created a high density of habitat in the northern most region of the modeled area. The high-density habitat was centered on Georges Bank, a location of high Swordfish catch. Adding zooplankton also decreased the extreme densities of habitat in the southern most region.

3.3 Predicted distributions in the latitude-longitude plane.

The annual mean habitat density for 1958-2019 is shown in **Figure 3**. Examination of the habitat map reveals three areas of relatively high densities of habitat. The first area is spans from approximately 15 degrees latitude to the north and encompasses the entire east-west extent of the Atlantic Ocean. The highest densities occurs on and around Georges Bank and continues eastward to the west coast of Portugal. The second area of high relative density is narrow corridor occurring from the east coast of Brazil at the equator and extending eastward into the Gulf of Guinea. This corridor splits two areas of relatively low-density habitat, one roughly off the coast of Dakar and the other off the coast of Angola.

3.4 Time-varying predicted distributions.

3.4.1 Predicted distribution by calendar quarter. The distribution of predicted swordfish habitat for 1958-2019 by calendar quarter is shown in **Figure 4**. Inspection of the map of predicted densities in the first quarter show a relatively expanded habitat in the northern Atlantic and a more concentrated habitat in the southern Atlantic (**Figure 4A**). These predicted seasonal densities match the known within-year migratory patterns of Swordfish. In the first quarter of the year in the northern hemisphere, Swordfish are dispersed throughout their range but favoring warmer equatorial region waters. Portuguese observer data of Swordfish encounters are generally wide and dispersed in the first quarter. By the second quarter of the year , when Swordfish spawning peaks off the east coast of Florida, the density map indicate the beginning of habitat concentration (and presumably Swordfish movement) in the northern Atlantic and a habitat expansion in the southern Atlantic. (**Figure 4B**).

Inspection of the maps of predicted densities demonstrated the models ability to capture the within year migration of Swordfish in the north Atlantic from the equatorial regions in the quarter 1 to the northern regions in quarter 3. Conversely, the maps also show how the model was able to predict the within year migration of Swordfish in the south Atlantic from the equatorial regions in quarter 3 to the southern regions in quarter 1.

A seasonal trend in density was evident in the southern Atlantic with the highest densities being created in the first quarter of the year (Jan-Mar). Conversely, Swordfish CPUE off South Africa had a definitive seasonal trend, with catch rates higher in winter (July - October) than the rest of the year (da Silva et al. 2017, Denham 2020). However, Denham (2020) noted that this seasonal pattern might have been in part due to seasonal operations of Joint-Venture vessels operating predominantly off the East coast of Southern Africa, an area not included in this study.

In an effort to help validate the SDM model predictions the location of Portuguese vessels observed to have caught Swordfish were overlaid on the habitat predictions. Association between location of catches of Swordfish and their predicted habitat is indirect validation at best. Nonetheless, there was apparent agreement between the observer locations and the predicted habitat in some areas. Many of the observed locations were found to follow the contours of the predicted habitat. This was especially true off the West Coast of Africa were observations occurred along the perimeter of low density habitat and fishing the above described corridor leading into the Gulf of Guinea.

3.4.2 Predicted distribution by year. The upper 50th percentile of the distribution data was subset and used to represent a "core" habitat. Examination of the distribution of this core habitat revealed two distinct areas; one is the furthest northern region of the modeled area and another in the furthest southern region (**Figure 5**). These two area were tracked by decade in an attempt to gain inferences regarding long-term changes in the spatial distribution of Swordfish over time. To facilitate comparison between years, density maps of the core habitat were created using the same absolute value (i.e. as opposed to relative) for the minimum and maximum isopleths. Examination of the subsequent maps revealed that the northern region of the two core regions was decreasing in density over time. Conversely, the southern region of the two core regions was increasing over the same period. This is most easily seen in the change in the 1.7 isopleth over the decades (**Figure 5**). In the north, the movement of the 1.7 isopleth to the north over time indicates that the density in that region is decreasing. In a similar fashion in the southern region of core habitat, the movement of the 1.7 isopleth to the south indicates an increase in density in that area.

3.4.3 Changes in predicted distribution in space. To investigate these changes in density the data were examined by arbitrary area (**Figure 6A**) and individual year. The densities in northwest Atlantic (Area 2) were relatively high from 1958 to 1978, but then began a long and continuous downward trend (**Figure 6**). Similar trends, but to a lesser extent, were evident in in the northeast Atlantic (Areas 1). An opposite trend was evident in in the southeastern Atlantic (Area 6) and to a lesser extent the southwest (Area 5). Schirripa et al. (2017) hypothesized that long-term Swordfish distribution was associated with changes in the Atlantic Multidecadal Oscillation (AMO). When a plot of the AMO was overlaid on the trends in density by area, there was an apparent, albeit rudimentary, agreement between the trends in Areas 2 and 6 and the AMO (**Figure 6B**). Although these two trends have similarities to the trends in the Atlantic Multidecadal Oscillation, the time series is too short to make a determination regarding the hypothesis that Swordfish distribution is associated with changes in the AMO. We feel that these findings are deserving of closer examination.

4. Discussion

The results of this study suggest the Swordfish SDM is sufficiently parameterized to describe the spatiotemporal habitat of Atlantic Swordfish. The model can be used for further studies of Swordfish distribution that go into greater detail that this work. It should be noted that this study investigate Swordfish in only 2-dimmensions and further work is needed to investigate the habitat in the third dimension of depth.

The SDM is sufficient for inclusion into the longline simulator (LLSIM) for which it was originally designed. The habitat coefficients produced from the model are also suitable for inclusion in Swordfish CPUE standardization for most ICCAT CPCs contributing them. The habitat coefficients produced from this work are a synthesis of a suite of habitat variables in three-dimensional space and over time. As such, they should be superior to any more generalized measure of habitat such as sea surface temperature. To take the most advantage of the habitat coefficients in a CPUE standardization the depth of hook, or a proxy there of, is needed to most effectively describe the habitat where the hook was fished.

The maps of predicted Swordfish habitat densities support the current ICCAT hypothesized north/south stock boundary. This boundary, however, may not be absolute or static in time. The north (south) Atlantic may be experiencing an expansion (contraction) of Swordfish habitat. This could result in decreased density of swordfish into a larger area and/or change MSY production metrics. A more detailed examination of this possibility is recommended.

In stock assessment long term CPUE time series are given great value, but the longer the series the higher the probability that there has been a change in habitat distribution; possibly changing catchability over time. Including habitat information can improved CPUE standardization as well possibly resolve conflicting CPUEs.

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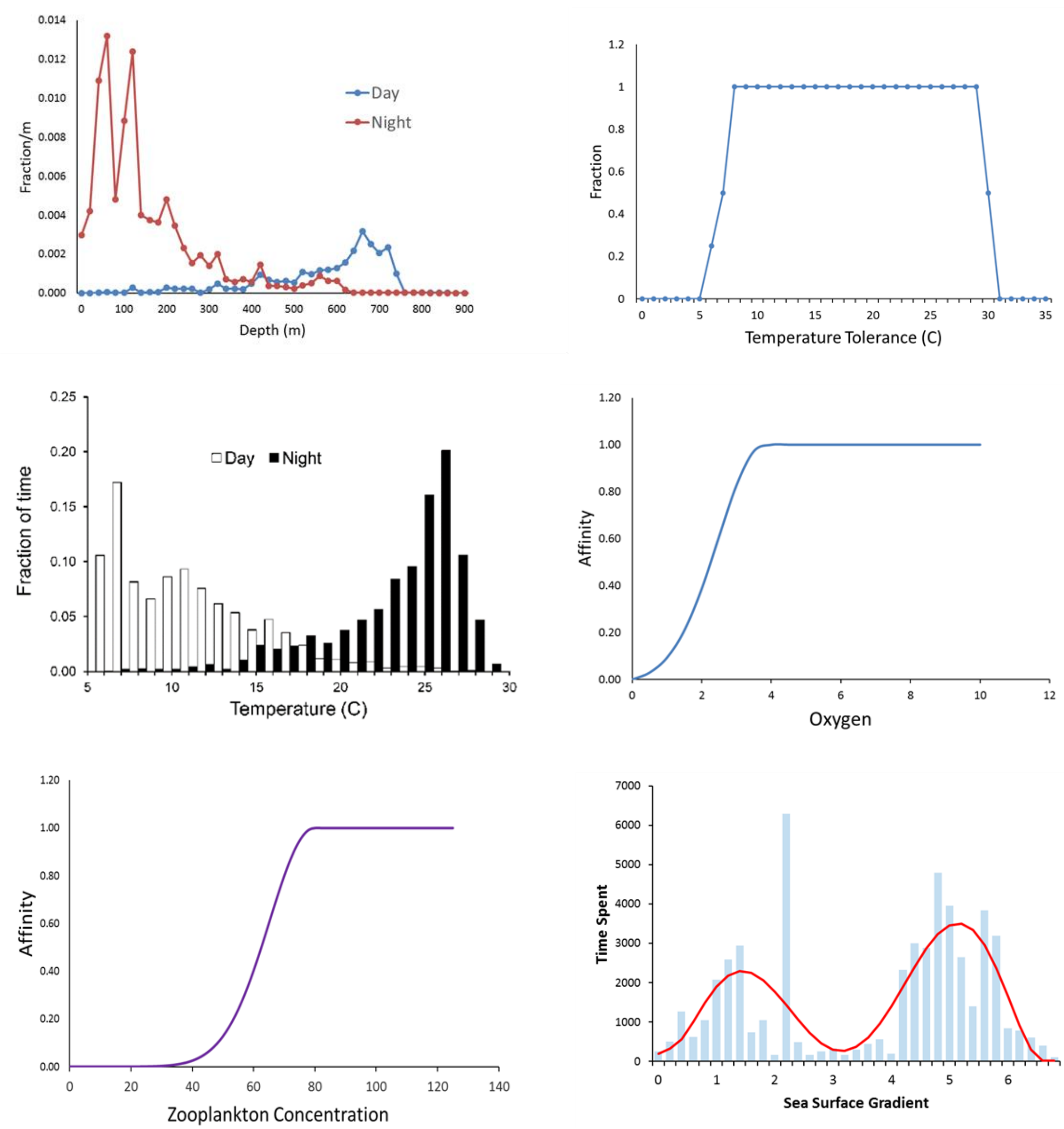

Figure 1. Habitat environmental variables and affinity functions used in the Swordfish Species Distribution Model

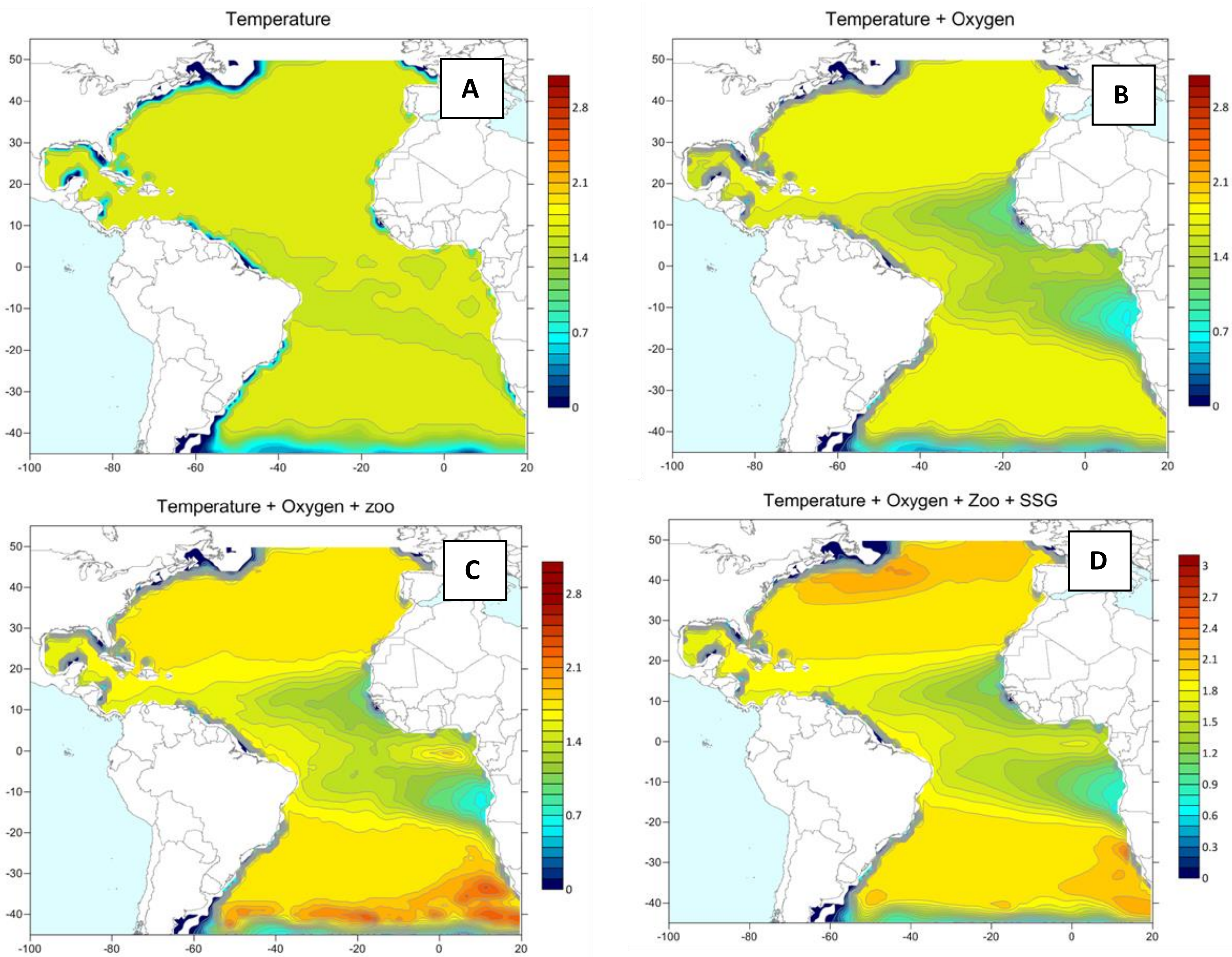

Figure 2. Predicted Swordfish habitat distribution based on a stepwise addition of environmental factors: temperature tolerance and preference (A); temperature + oxygen (B); temperature + oxygen + zooplankton (C); and temperature + oxygen + zooplankton + sea surface gradient (D).

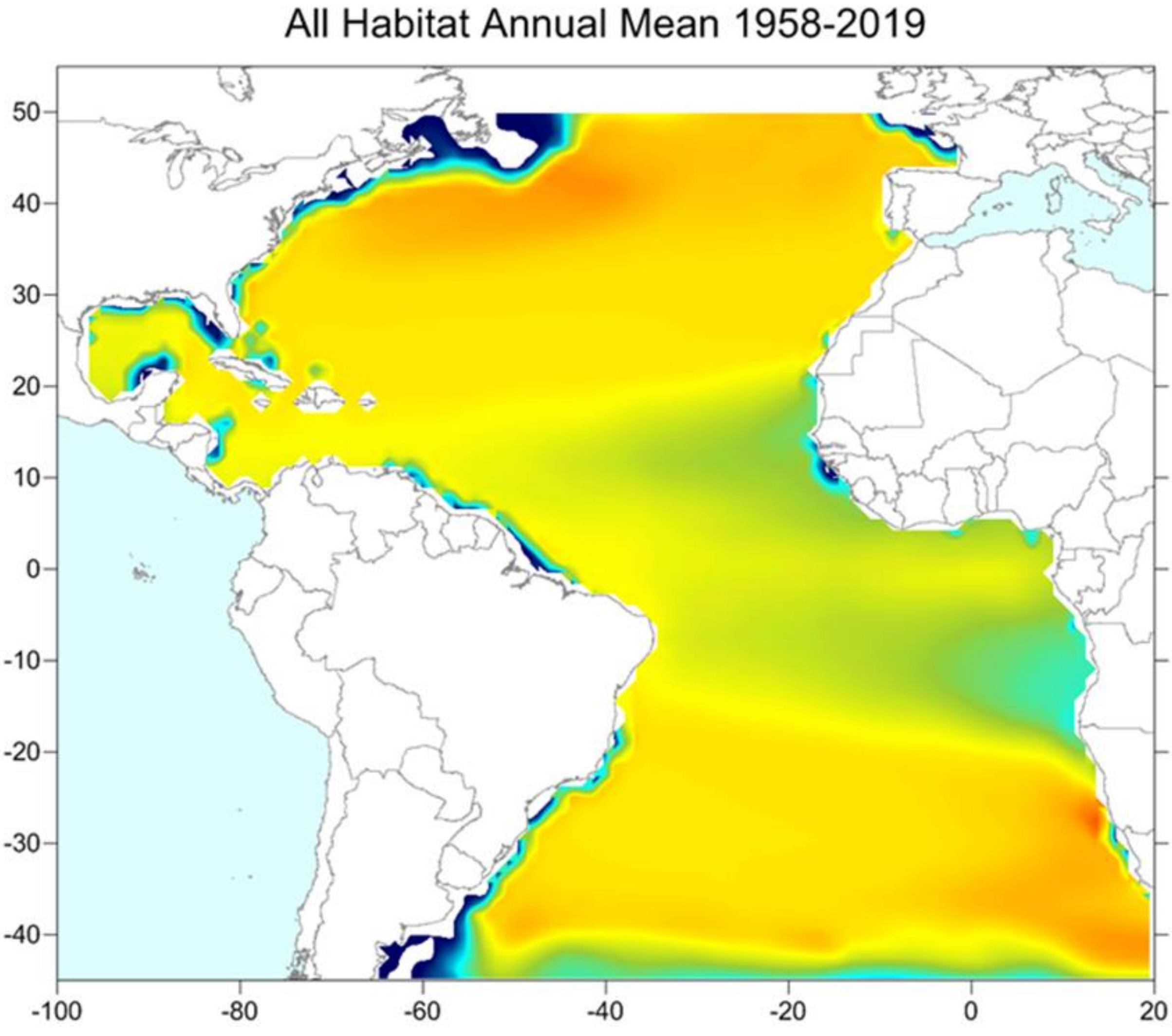

Figure 3. Predicted distribution of Swordfish habitat averaged of the year 1958-2019

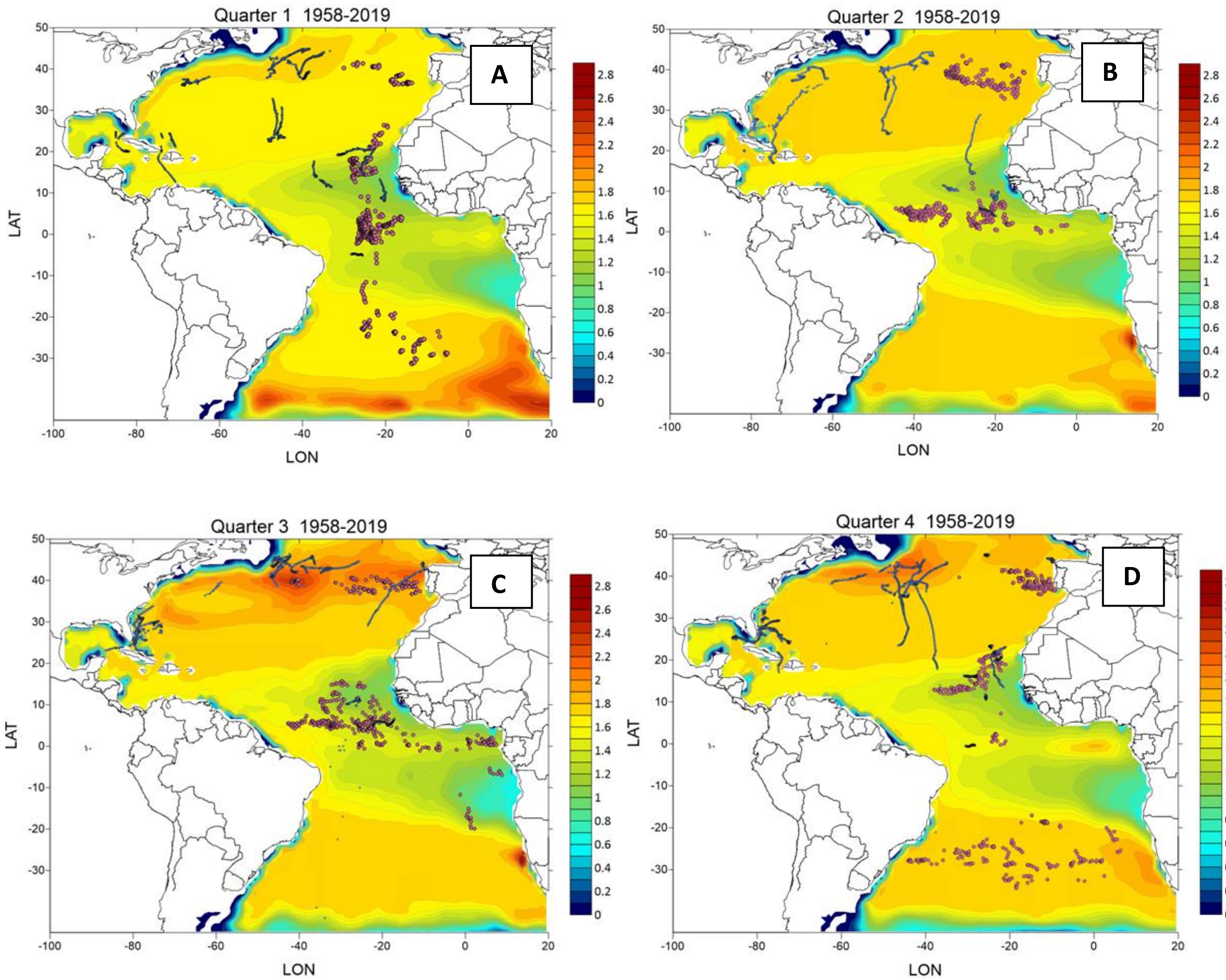

Figure 4. Predicted distribution of Swordfish habitat by calendar quarter averaged of the year 1958-2019; PSAT tag tracks (blue dots) encounters with Swordfish from the Portuguese observer program (purple dots).

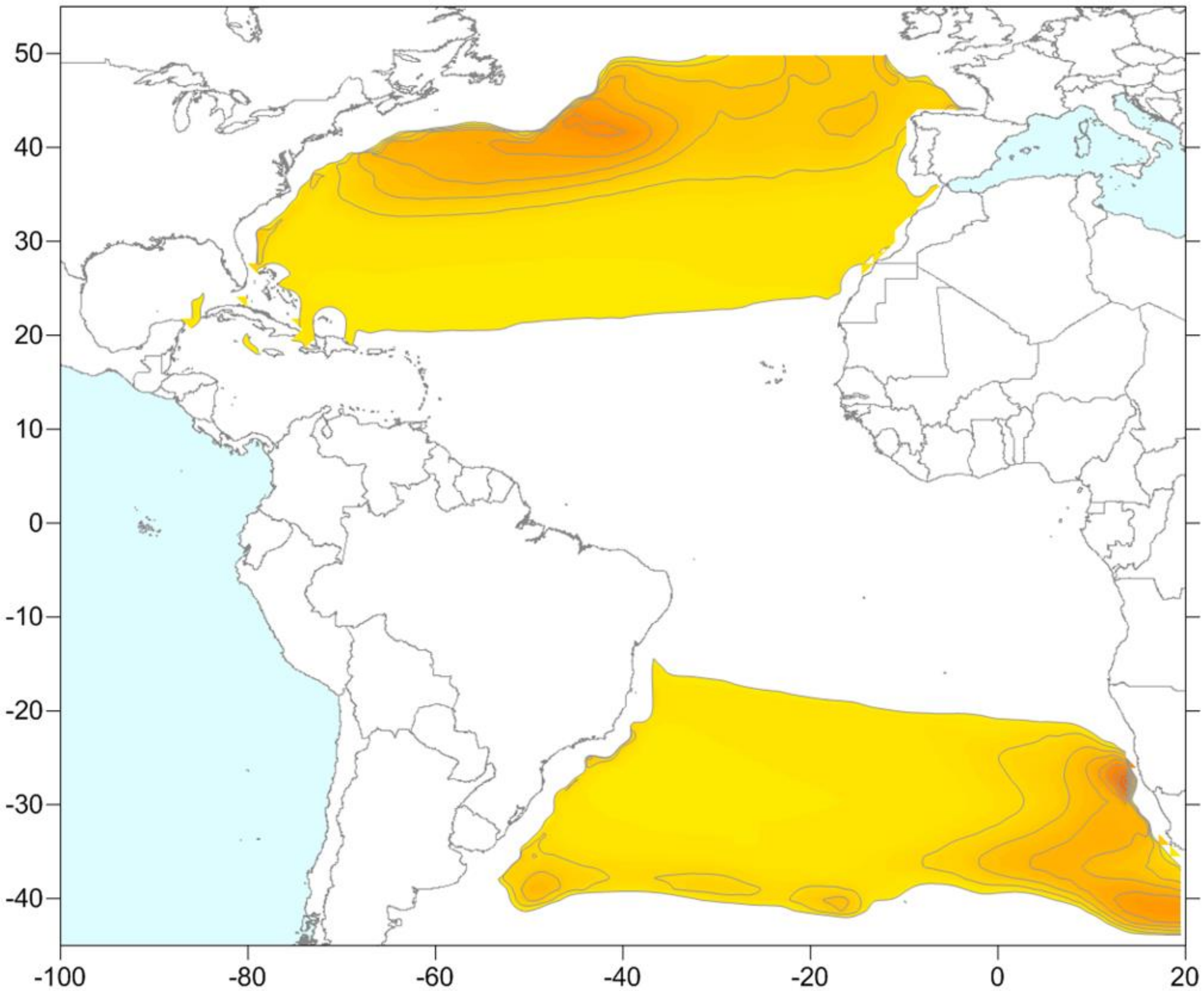

Figure 5. Predicted distribution of the top 50% of the densest habitat averaged of the year 1958-2019

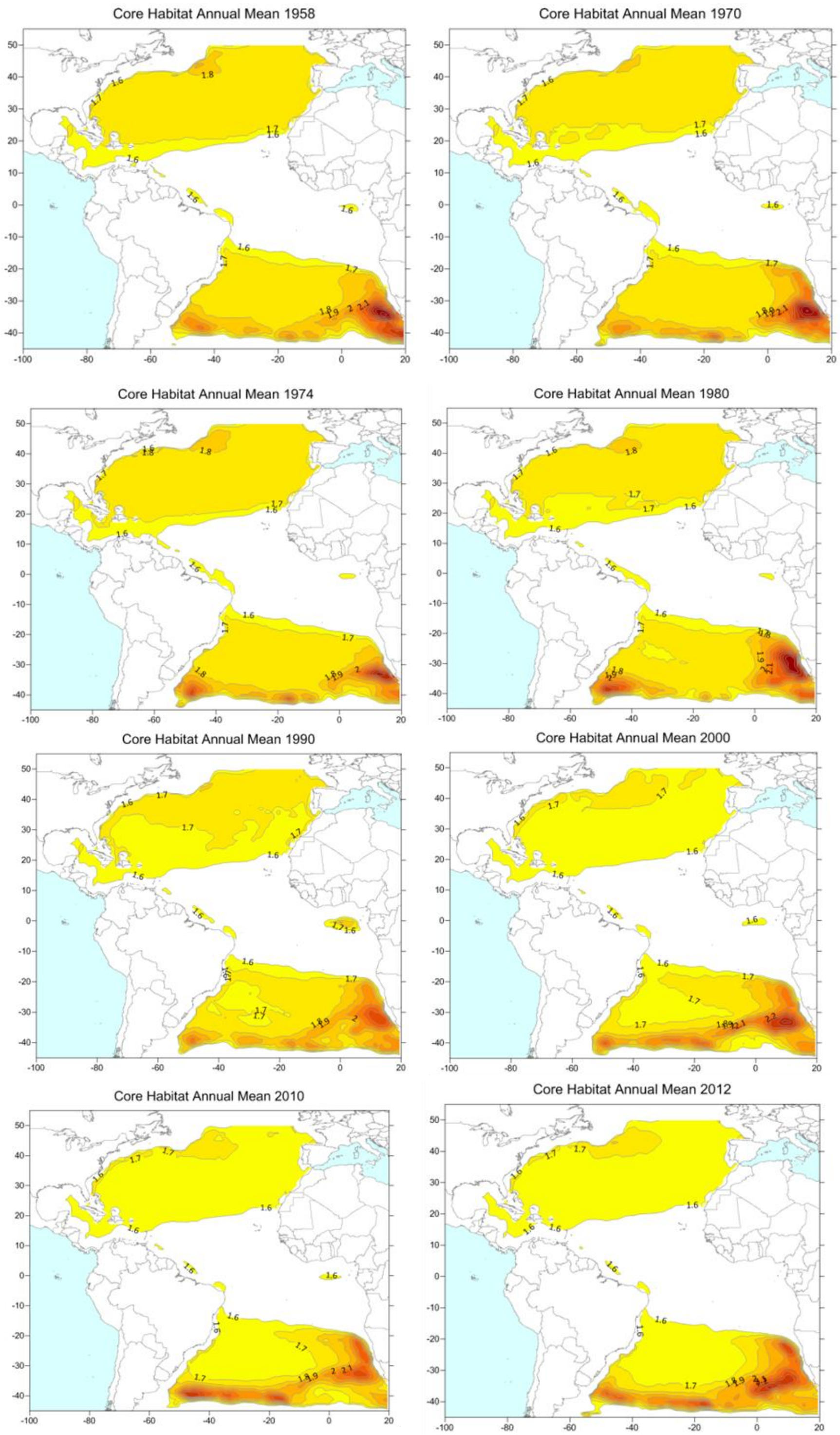

Figure 6. Predicted distribution of the densest top 50% of all Swordfish habitat by decade.

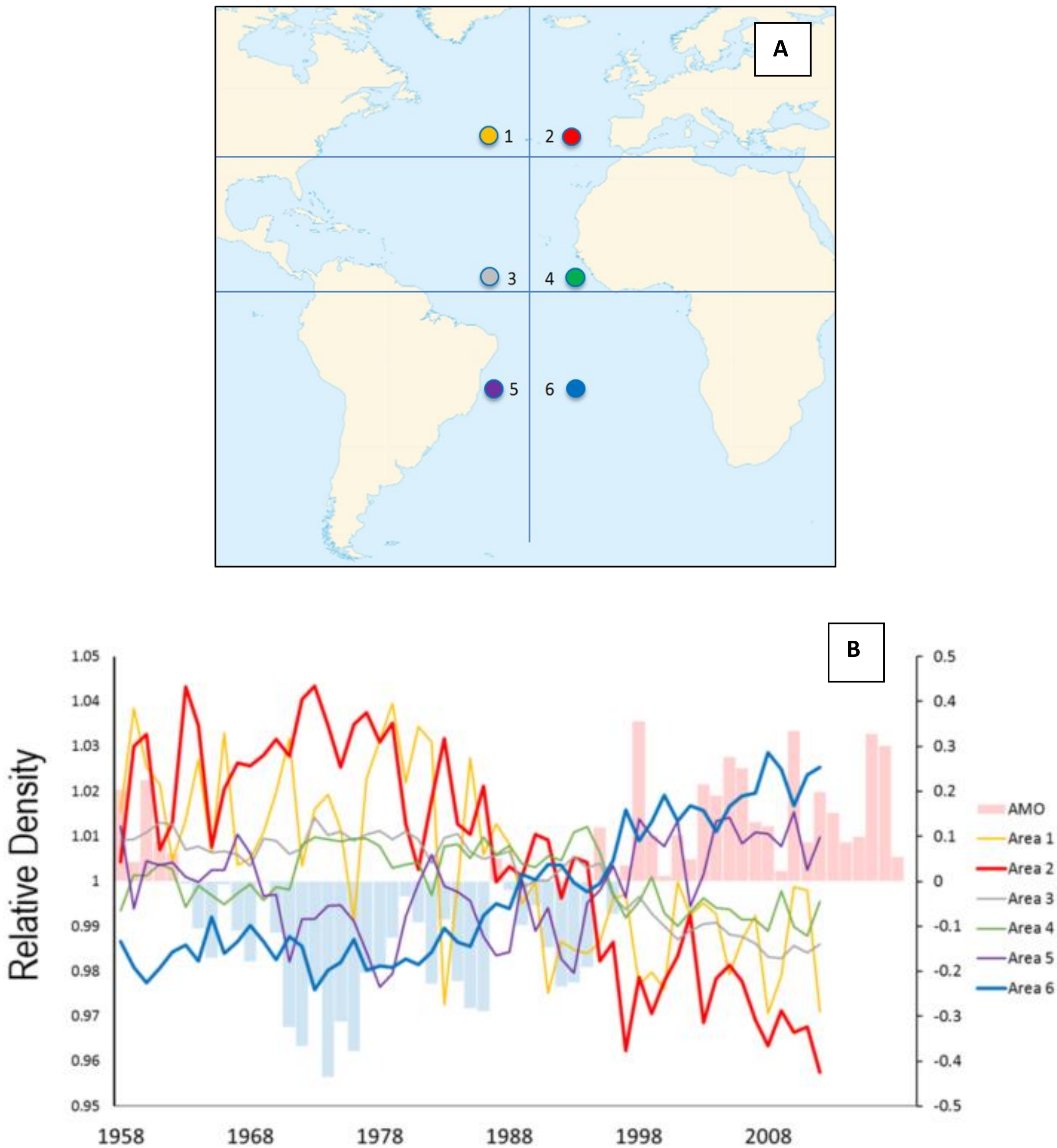

Figure 6. Annual standardized predicted habitat densities of Swordfish by area (A) and year (B). These trends are overlaid on top of the Atlantic Multidecadal Oscillation (AMO).