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Regular article

A hypothesis of a redistribution of North Atlantic swordfish based on changing ocean conditions

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A R T I C L E I N F O

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A B S T R A C T

Conflicting trends in indices of abundance for North Atlantic swordfish starting in the mid-to late 1990s, in the form of fleet specific catch-per-unit-effort (CPUE), suggest the possibility of a spatial shift in abundance to follow areas of preferred temperature. The observed changes in the direction of the CPUEs correspond with changes in trends in the summer Atlantic Multidecadal Oscillation (AMO), a long term mode of variability of North Atlantic sea surface temperature. To test the hypothesis of a relation between the CPUE and the AMO, the CPUEs were made spatially explicit by re-estimating using an "areas-as-fleets" approach. These new CPUEs were then used to create alternative stock histories. The residuals of the fit were then regressed against the summer AMO. Significant, and opposite, relations were found in the regressions between eastern and western Atlantic areas. When the AMO was in a warm phase, the CPUEs in the western (eastern) areas were higher (lower) than predicted by the assessment model fit. Given the observed temperature tolerance limits of swordfish, it is possible that either their preferred habitat, prey species, or both have shifted spatial distributions resulting in conflicting CPUE indices. Because the available CPUE time series only overlaps with one change in the sign of the AMO (~1995), it is not clear whether this is a directional or cyclical trend. Given the relatively localized nature of many of the fishing fleets, and the difficulty of separating fleet effects from changes in oceanography we feel that it is critical to create CPUE indices by combining data across similar fleets that fish in similar areas. This approach allowed us to evaluate area-specific catch rates which provided the power to detect basin-wide responses to changing oceanography, a critical step for providing robust management advice in a changing climate.

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1. Introduction

Swordfish (*Xiphias gladius*) is a highly migratory species found through the temperate waters of the Atlantic, Pacific and Indian Oceans and the Mediterranean Sea. Like many other highly migratory species, swordfish undertake seasonal migrations in search of food, reproductive success, or a hospitable habitat in which they can flourish for either the short or long term. Broad based physical oceanographic conditions in which the swordfish live, change on a temporal scale much faster than do the environmental preferences of swordfish. As a consequence, their preferred habitat, and the location of this habitat, are not constant in time or space. Swordfish require huge amounts of prey intake to support their migratory and high energy life style and will travel thousands of miles north to higher latitudes within a year in search of their preferred prey. However, since the environmental conditions that are conducive to high prey densities are not the same as those for reproduction, they must then make southern migrations to the tropics in order to maximize their annual reproductive potential (Arocha and Lee, 1996).

Stock assessment models rely upon statistical fits to time series of landings and abundance indices and often age or length composition information to reconstruct historical stock abundance. Generally these time series of catch and indices of relative abundance are in the form of usually standardized catch-per-unit effort (CPUE) data from either fishery dependent data or scientific

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surveys. A fundamental assumption of standardized CPUE-based indices is that they are linearly related to actual abundance through a constant scaling parameter called catchability or the fraction of the population captured by a unit of fishing or survey effort (Arreguín-Sánchez, 1996). In most assessments, there are often multiple and sometimes conflicting indices available, presenting a dilemma as to which indices truly represent the population abundance. Often apparent conflicts can be rectified within age-structured models by allowing for differential selectivity by size or age (Quinn and Deriso, 1999) and by modeling of movement or complicated spatial structure (Cadrin and Secor, 2009).

However, most assessments do not explicitly model the usually time-varying spatial distribution of the stock and so assume that the stock is both homogeneous and time-invariant. It is further assumed that the catchability associated with the estimate of the CPUE is also constant over time and space. However as catchability is a function not only of the gear but also of the spatial availability of the fish, there are many factors that could alter the relationship between CPUE and fish abundance. For example, as fish migrate and redistribute themselves according to changes in preferred habitat, subsequent changes in their densities alter catchability. As a consequence, the observed CPUE in the preferred area can increase while those in the less preferred areas decrease due not to a change in overall stock size, but a change in area specific catchability caused by changes in local density. While it is sometimes possible to account for this phenomena in the CPUE standardization process with appropriate spatial or temporal structure, interannual variation in habitat is often completely confounded with the interannual abundance signal.

In the most recent stock assessment of North Atlantic swordfish conflicting CPUEs generated substantial discussion on how they should be treated and if these indices should be used in the assessment (Anonymous, 2014). The current Atlantic swordfish management units are separated into a north and a south stock delineated by a horizontal line at 5 °N latitude, and we focus on the northern stock assessment for this paper.

CPUE time series from the northern stock showed conflicting trends in the past decade with indices from fisheries operating mostly in the northern latitudes (Canada, Morocco, Portugal) increasing at a relatively high rate while those operating in the more southern and central areas (U.S. and Japan) were decreasing or remained flat. Rather than confronting the assessment model with these conflicting indices, or attempting to determine which ones should be included/excluded in the assessment we sought a mechanistic reconciliation to these apparent contradictions.

In this paper we step through stage one of the swordfish stock assessment process that used CPUEs specific to the country flag of the fishing vessel ("flags-as-fleets") to assemble the assessment model. We used the lack of fit of the estimated population trend to these CPUE indices to construct a hypothesis to explain the trend in the residuals of the fits in the western North Atlantic. Previous pop-up satellite tag (PSAT) studies have suggested that swordfish prefer water temperatures below 28 °C (Lerner et al., 2013; Abecassis et al., 2012; Dewar et al., 2011; Boyce et al., 2008; Sedberry and Loefer, 2001; Nakamura, 1985). This is the basis of the mechanism underlying the hypothesis. The Western Hemisphere Warm Pool (WHWP) is a region of sea surface temperatures (SST) warmer than 28.5 °C that develops west of Central America in the spring, then expands to the tropical Atlantic waters to the east. It has a distinct monthly trend as well as a low frequency cycle. Observing that the WHWP index went through a change in sign from negative (below average in areal size) to positive (above average in areal size) around 1995, we hypothesized that this increase in the area of water warmer than the preferred temperature of swordfish may have led to an increase in the rate or duration of the summer migration of swordfish into more northern regions. It was presumed that this led to a "crowding" effect in the northern areas that could have increased the density and thus the catchability of the fish in those areas. We first step through our original hypothesis: the WHWP is a predictor of swordfish distribution and density in the western North Atlantic using "flags-as-fleets" CPUE's. In step two we proceed to broaden our original hypothesis to one that uses the summer SST anomalies from the Atlantic Multidecadal Oscillation (AMO), a spatially broader oceanographic indicator, coupled with a spatially explicit reanalysis of the CPUE data using an "areas-as-fleets" approach. Thus, the objective of this work was to use a hypothesis testing approach to quantitatively assess the likelihood of a null versus an alternative model configuration that represented two various possible states of nature, namely that the density, and thus the catchability, of northern swordfish has not (or has), changed over time and space in accordance with key environmental indicators.

2. Methods

2.1. "Flags-as-fleets" CPUE

We used standardized, flag-specific (i.e. "flags-as-fleets") indices of abundance provided by the individual Contracting Party, Cooperating non-Contracting Party, Entity or Fishing Entity (CPC) during the ICCAT 2013 Atlantic swordfish data preparatory meeting (Anonymous, 2014a) . The CPCs that provided vessel flag-specific indices that were used in the stock assessment included Canada (Andrushchenko et al., 2014), Japan (Yokawa and Kai, 2014), Portugal (Santos et al., 2014), Spain (García-Cortés et al., 2014), and the United States (Walter et al., 2014). The approximated areas that are fished by each CPC are shown in Fig. 1. Based on decisions made during the data preparatory meeting, the Japanese, Canadian, and United States data were each broken into two time stanzas that represented differences in that particular fleet's fishing operations. In all cases, a Generalized Linear Model (GLM) procedure was used to standardize the nominal CPUE by factors found to be statically significant, however each CPC conducts an independent GLM analyses prior to presentation to the data preparatory meeting. So while CPUE standardization methods between CPCs are generally similar, they can differ in the specific covariates used across the participating CPC's.

2.2. "Areas-as-fleets" CPUE

In addition to the flag-specific indices of abundance, a combined index of abundance (combined across all flags) was also created. Generalized Linear Modeling (GLM) procedures were used to standardize swordfish catch (biomass) and effort (number of hooks) data from the same longline fleets mentioned above with the addition of Morocco (Abid et al., 2014). Main effects included: year, area, quarter, a nation-operation variable accounting for gear and operational differences thought to influence swordfish catchability, and a target variable to account for trips where fishing operations varied according to the main target species. Interactions among main factors were also evaluated. For a complete description of how the CPUE indices were derived see Ortiz et al. (2014). The least square means of the year-area effects were used to estimate 14 individual CPUE indices, each corresponding to a unique area (Fig. 2).

2.3. Other observational data

Monthly values of the WHWP for the years 1948-present were available from the NOAA Earth System Research Laboratory website (http://www.esrl.noaa.gov/psd/data/correlation/whwp.data). A summer index of the WHWP was created by averaging the months August, September, and October, the months that coincide with the northernmost observations of swordfish from the