Incorporating hypoxia-based habitat compression impacts into the stock assessment process for tropical pelagic billfishes and tunas--- 2015 Progress Report.

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Background

Large areas of cold hypoxic water, known as Oxygen Minimum Zones (OMZs), occur as permanent features in the Eastern tropical Pacific and Eastern tropical Atlantic Oceans (ETP and ETA, Prince and Goodyear, 2006; Prince et al. 2010, Stramma, Prince, Schmitko et al. 2012). This layer is defined by a shallow thermocline at a depth around 25-100 m. The cold hypoxic environment below the thermocline acts as a lower habitat boundary for billfishes and most tunas. As a result, their habitat is compressed and restricted to the shallow mixed layer (Prince and Goodyear 2006; Prince et al. 2010) making them more vulnerable to exploitation by surface fishing gears.

The Atlantic OMZ has expanded over the past 5 decades by about 15%, further compressing the surface layer and progressively increasing the density of billfishes and tunas, as well as their preferred prey, into shallower surface areas of the ETA (Stramma, Prince, Schmitko et al. 2012). This increased density of predators and prey may increase catchability that, in turn, may bias relative abundance estimates obtained from catch rates (Maunder et al. 2006, Bigelow and Maunder 2007, Vanderlaan et al. 2014). Presently, neither large scale environmental influence of the OMZs on habitat use and distribution or any associated changes in fishing practices, have been incorporated into catch rate estimates or stock assessment models (Maunder et al. 2006, Kell et al. 2011, Vanderlaan et al. 2014).

Considering the differences in catchability inside and outside the compression areas, and the possibility that these areas are changing in spatial distribution, warrants development of methods that incorporate OMZ habitat related information into the stock assessment process. (Maunder et al. 2006, Prince et al. 2010). Our primary hypothesis for this work is that longline (LL) catchability of tropical pelagic predators will be higher inside the OMZ area compared to areas outside the OMZ. We analyzed differences in catchability inside and outside of the OMZ for yellowfin tuna (primary target over the first two decades of the LL fishery) and blue marlin (primary bycatch species from the LL fishery).

Catchability coefficients for tropical pelagic billfishes and tunas in the equatorial Atlantic Ocean may increase as a result of expanding OMZs (Prince and Goodyear 2006, Prince et al. 2010, Kell et al. 2011). Unless information related to changes in catchability associated with expanding OMZs are incorporated into the process of CPUE standardization, those changes may be interpreted as changes in relative abundance, which may lead to overly optimistic abundance estimates.

The first step of our proposal was to incorporate water volume (i.e., available habitat) above the OMZ in a 1x1 degree cell as an explanatory variable during the CPUE standardization with GLMs and General Additive Models (GAM),. This was based on the assumption that catchability increases as habitat volume decreases, even if the abundance remains constant. Separate estimates will be made to compare longline and purse seine gears. We used the ETA OMZ area as a first test case because the necessary PSAT data (delta t and DO at depth) for tropical pelagic tuna and billfish are available. In addition, the ETA OMZ size configuration, including expansions over 5 decades, has become better described in more recent work (Stramma, Prince, Schmitko et al. 2012). Hence, critical ETA OMZ size metrics and PSAT vertical habitat use data are now uniquely available for the ETA OMZ.

The second step will be to test whether our relative abundance estimation model is relevant for other ocean areas. Goodyear (2003) introduced a spatially structured simulation model (termed SEEPA) that can be used to produce simulated CPUE data sets. We plan to modify the model to generate data sets with different assumptions about OMZ and fishing effort configurations to examine the robustness of our habitat standardization statistical model to reproduce the simulated abundance trends initially incorporated in the simulator.

The third and final step will be to compare whether the estimates of relative abundance obtained with our habitat standardization procedure make a difference in the outcome of the stock assessment model. We will do that by using the estimates of relative abundance together with the simulated catch to estimate stock status reference points for the simulated stock. This will be done by comparing those estimates with those obtained by a model that did not consider the effect of the OMZ in either catchability or spatial population structure. We will do that by using a spatially explicit population model that uses the OMZ configuration, SST and Delta T behavior from satellite tracked fish movements to define spatial compartments of the population model (Figure 1).

Benefits

Size metrics for the ETA OMZ are available from the last 5 decades. This provides a realistic opportunity to examine possible approaches to addressing the inaccuracies of biased estimates of indices of abundance for billfishes and tunas as a result of habitat compression.

1. OMZ size metrics allow for the effect of temporal changes in catchability resulting from changes in the relative area inside and outside the ETA OMZ to be

removed as a source of variation of catch rates. Hence, providing relative abundance indices that are akin to density measures of hooks and catch per km^2. This should remove the effects of 5 decades of OMZ expansion and the subsequent changes in fishing effort distribution.

2. A fully tested procedure of how to incorporate spatial information on habitat characteristics into the assessment process.

Methods

Model development

Traditionally, we used CPUE as an index of population abundance by assuming that the catchability (q) is a constant over time (t) and space (x,y).

CPUE(t,x,y) = q*N(t,x,y)

This assumption is only true when we are dealing with small spatial scales. At large spatial scales, the changes in vertical temperature structure and DO levels at depth are likely affecting the catchability (q) of those organisms that are sensitive to DO and temperature levels. Thus, our goal was to investigate how vertical temperature structure of the ocean and the minimum DO level affect the vertical distribution of the fish, which lead to the change in their interaction with fishing gear.

The nominal CPUE(t,x,y) is catch C(t,x,y) at time (t) and location (x,y) divided by it corresponding fishing effort EF(t,x,y), which is a function of the catchability q(t,x,y) and the density of the fish N(t,x,y):

$$CPUE(t,x,y) = \frac{C(t,x,y)}{EF(t,x,y)} = q(t,x,y) * N(t,x,y) \qquad (1)$$

Our goal is to find a standardized CPUE ($\widehat{CPUE}$) which is solely a function of fish density N(t,x,y). Thus, we define the catchability q(t,x,y) as a multiple of constant q_0 and CPUE standardization function CSF(t,x,y):

$$q(t,x,y) = q_0 * CSF(t,x,y) \qquad (2)$$

Substitute equation (2) into equation (1), we have:

$$CPUE(t,x,y) = q_0 * CSF(t,x,y) * N(t,x,y) \qquad (3)$$

Divide each side of equation (3) with CSF(t,x,y), we have the standardized $\widehat{CPUE}(t,x,y)$:

$$\widehat{CPUE}(t,x,y) = \frac{CPUE(t,x,y)}{CSF(t,x,y)} = q_o * N(t,x,y) \qquad (4)$$

Thus, our goal is to find the CPUE standardization function CSF(t,x,y). Let us assume that fish and gear interactions under different environment conditions are the driving force of changing catchability. Therefore, a gear interaction function, GIF(t,x,y), was formulated as below:

$$\mathrm{GIF(t,x,y)} = \sum_{d=0}^{n} \mathrm{H_{cdf(d)}} * \mathrm{\Delta Tdep\_pdf(t,d,x,y)} \qquad (5)$$

Where H_{cdf} is the accumulative probability density function (cdf) of hook distribution from the deepest hook to the surface, ΔTdep_pdf is the fish depth distribution probability function based on fish delta T distribution from PSAT data ($\boldsymbol{\Delta}T_{pdf}$), the depth of each $\boldsymbol{\Delta}$T at location (x,y) $\boldsymbol{\Delta}T_{dep(t,x,y)}$, the depth of ≤3.5 ml/L DO threshold at location (x,y) $DO_{dep(t,x,y)}$.

$$\mathrm{\Delta Tdep_{pdf}(t,d,x,y)} = f[\boldsymbol{\Delta T_{pdf}}, \boldsymbol{\Delta T_{dep(t,x,y)}}, \boldsymbol{DO_{dep(t,x,y)}}] \qquad (6)$$

This function involves linear interpretation and re-sampling of $\boldsymbol{\Delta}T_{pdf}$ to redistribute the fish delta T distribution to match the depth bins of the hook cdf. The redistribution is restricted by the depth of $\boldsymbol{\Delta}$T10 and the depth of the minimum DO. A standard gear interaction function (sGIF), is estimated by assuming the depth of $\boldsymbol{\Delta}$T10 and DO_{dep} is the same as the maximum depth of the hook (HD_{max}), and the depth of $\boldsymbol{\Delta}$T is uniformly distributed from surface to HD_{max}:

$$\mathrm{sGIF} = \sum_{d=0}^{n} \mathrm{H}_{\mathrm{cdf(d)}} * \Delta\mathrm{Tdep\_pdf(U)} \qquad (7)$$

Finally, the CPUE standardization function (CSF) is defined as the square root of the ratio between the GIF(t,x,y) and the SGIF:

$$CSF(t,x,y) = \sqrt{\frac{GIF(t,x,y)}{sGIF}} \qquad (8)$$

Data used in modeling

The spatial data at 5°× 5° grid cell of LL fishing effort (number of hooks) and associated catch (number of fish) for the Atlantic industrial longline fisheries (1955-2013) were obtained from the ICCAT Atlantic LL historical database (Task II –Catch & Effort database (T2CE)). For this analysis, only the data from Japanese longline fishing fleets in the tropical Atlantic Ocean operating from 25° S to 25° N were used (Figure 1).

Monthly delta T ($\boldsymbol{\Delta}$t) depth distributions were estimated for $\boldsymbol{\Delta}$t -1 to -10 based on both decadal and monthly oceanic temperature data obtained from World Ocean Atlas 2013 (Fig 2). Quarterly depth distributions of 3.5 ml/L dissolved oxygen (Fig 3) were estimated based on the data from the World Ocean Atlas 2013 and HydroBase 3 upgraded with additional source of Atlantic DO (S. Schmitko, personal communication, 2014), Argo floats that include oxygen data and CCHDO (Clivar Hydrographic Database Office-Website provide website address.).

Fish vertical distributions in relative to surface temperature (ΔT) were obtained from published PSAT tagging data for yellowfin tuna (Hoolihan et al 2014) and blue marlin (Goodyear et al. 2008). As a first approximation longline hook vertical distributions were obtained from Rice et. al. (2007) which is the only Atlantic data with precise hook depth data. These distributions, may not be a fair representation of hook distributions of the Japanese fleet targeting different species in a different environment. Future analyses will establish alternative hook distributions based on proxy hook depth information for the Japanese fleet.

Results

CPUE standardization function (CSF) is depended on the vertical hook distribution, the vertical Δt fish distribution, the depth of ≤3.5 ml/L Do distribution (DO_{dep}), and the depth of Δt distribution (DT_{dep}). If we hold the hook distribution and Δt fish distribution constant, we can determine the effect of DO_{dep} and the depth of Δt. Figure 4 and 6 show the CSF decreases as DO_{dep} and $DT10_{dep}$ increase. At shallow (<50 m) DO_{dep} and $DT10_{dep}$, CSF values are constantly high indicating intense squeezing effect of low DO and shallow thermocline. As DOdep and DT10dep increase beyond 50 m, the CSF becomes more variable. This is due to the presence of the interaction term between DOdep and DT10dep, and also because CSF is derived from all Δts (Δt1 to Δt10). Comparing the two species, the yellowfin tuna has much large CSF range from 0.5 to 1.78 (Figure 4) in comparison to that of blue marlin, from 0.8 to 1.25 (figure 6). This may reflect that yellowfin tuna is distributed over a larger range of depths than blue marlin. Thus, it is much more likely to be squeezed by decreasing DO and Δt depths.

Mean annual CPUE indices were calculated using the GLM delta method, which partitions variance in two components: firstly the proportion of positive catches and, secondly, the positive catches (Lo et al. 1992)). The annual mean nominal CPUE indices (Figure 5A and Figure 7A) were calculated on nominal CPUE data by areas as defined in Figure 1. It is clear that the choice of areal strata has an effect on CPUE calculation. For example, yellowfin tuna annual mean nominal CPUE indices (Figure 5A) inside the OMZ are about twice the value of indices of the outside before 1970, and after 1970 the outside CPUE indices are about twice of the inside. For blue marlin, annual mean nominal CPUE indices outside OMZ are about 2-4 times greater than that of inside OMZ for the entire period from 1956 to 2013. The annual mean standardized CPUE indices were all reduced for all zones (Figure 5b,c, d, Figure 7b,c,d). For both yellowfin tuna and blue marlin, CPUE standardization results in greater changes in the nominal CPUEs trends from inside the OMZ than changes for nominal CPUE trends outside OMZ (Figure 8). Comparing by species, yellowfin tuna has a greater change in the CPUE trend than blue marlin. Averaged over the years, yellowfin CPUE indices reduced by 44% inside the OMZ and 30% outside the OMZ, while blue marlin CPUE indices only reduced by 19% inside the OMZ and 14% outside the OMZ.

Conclusion

As indicated in figures 5 and 7, catchability coefficients for yellowfin tuna, and to a lesser extent for blue marlin, demonstrate differences in catchability inside vs outside the ETA OMZ for the Atlantic LL Fishery (Japan only) from 1955-2013. The focus of this example was for the tropical central Atlantic (25^{o} North & 25^{o} South) as shown in figure 1. These initial findings certainly support extending the work to other important species (i.e. bigeye tuna), improving the representation of hook depth distributions (particularly alternate sources of hook deployment depth from various Atlantic LL fleets), as well as extending the analysis to the full geographical extent of this Atlantic–wide LL fishery (primarily from 45^{o} North and 45^{o} South). As stated in the original proposal (Prince, Dewar et al. 2014) this project was developed as a multi-year effort given the difficulty and complexity of the time consumptive work. Lastly, it was unfortunate that funding was not released until April 2015. This reduced our work on this project to only 5.5 months.

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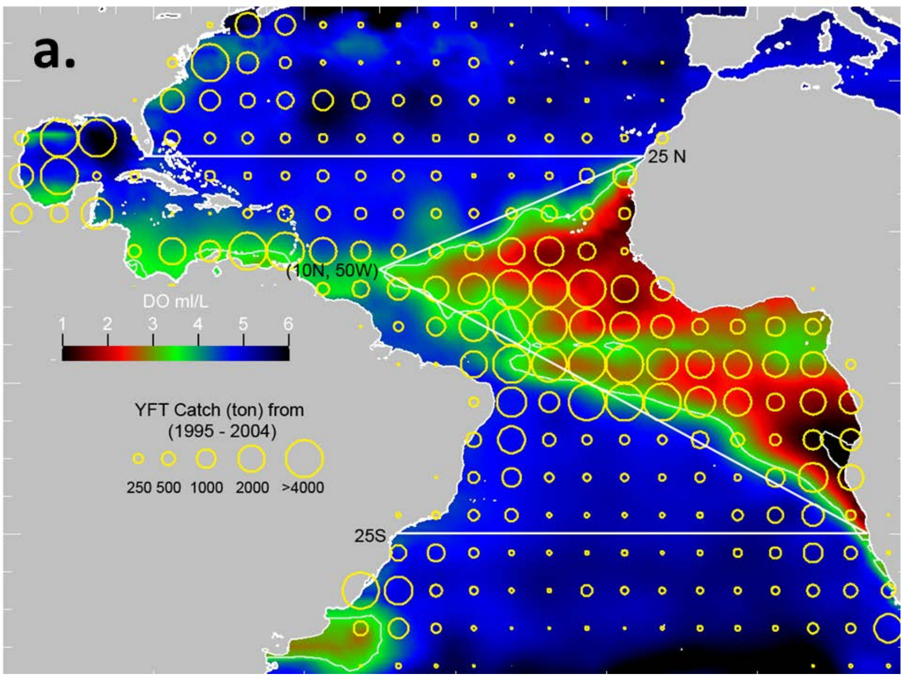
Figures

Figure 1. a) Distribution of yellowfin tuna catches for the period 1995-2004 (source ICCAT) overlaid on a map of dissolved oxygen at 100m depth and b) map of average SST for the period 1995-2004. White lines represent the possible population boundaries to be used in the stock assessment model.



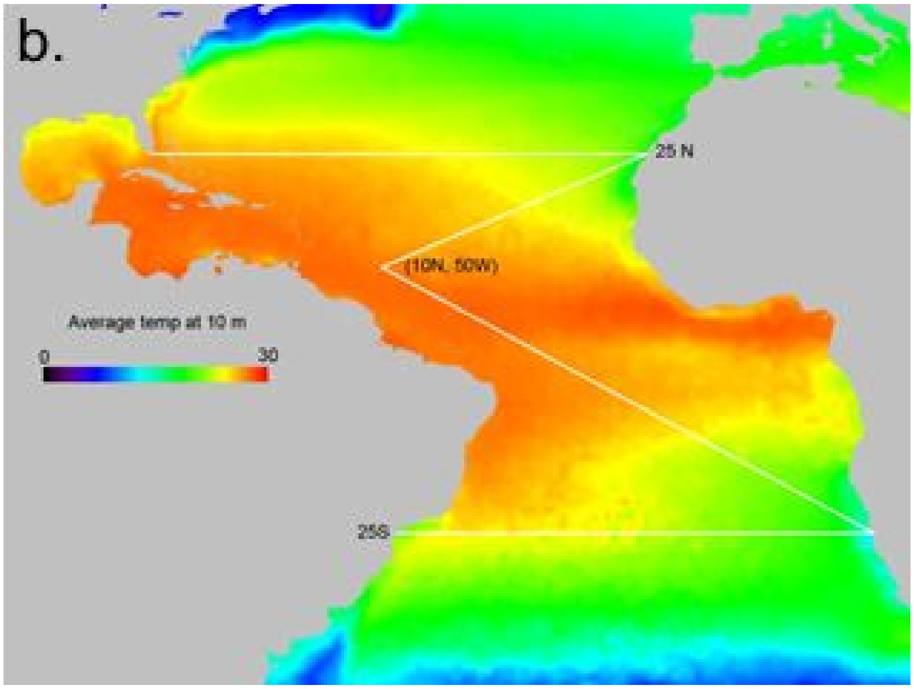

b.
25 N
(10N, 50W)
Average temp at 10 m
0
30
25S

Figure 2. Distribution of Delta T (Δt=-10) depth (m) for August 1960.

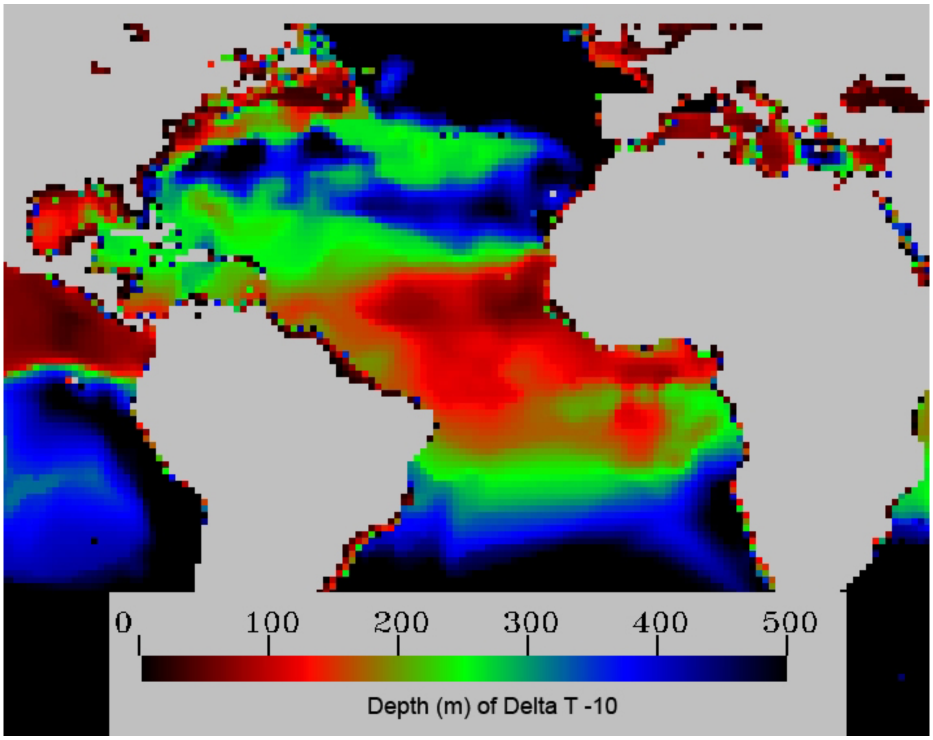


Figure 3. Distribution of ≤3.5 ml/L DO threshold depth (m) during summer 1960.

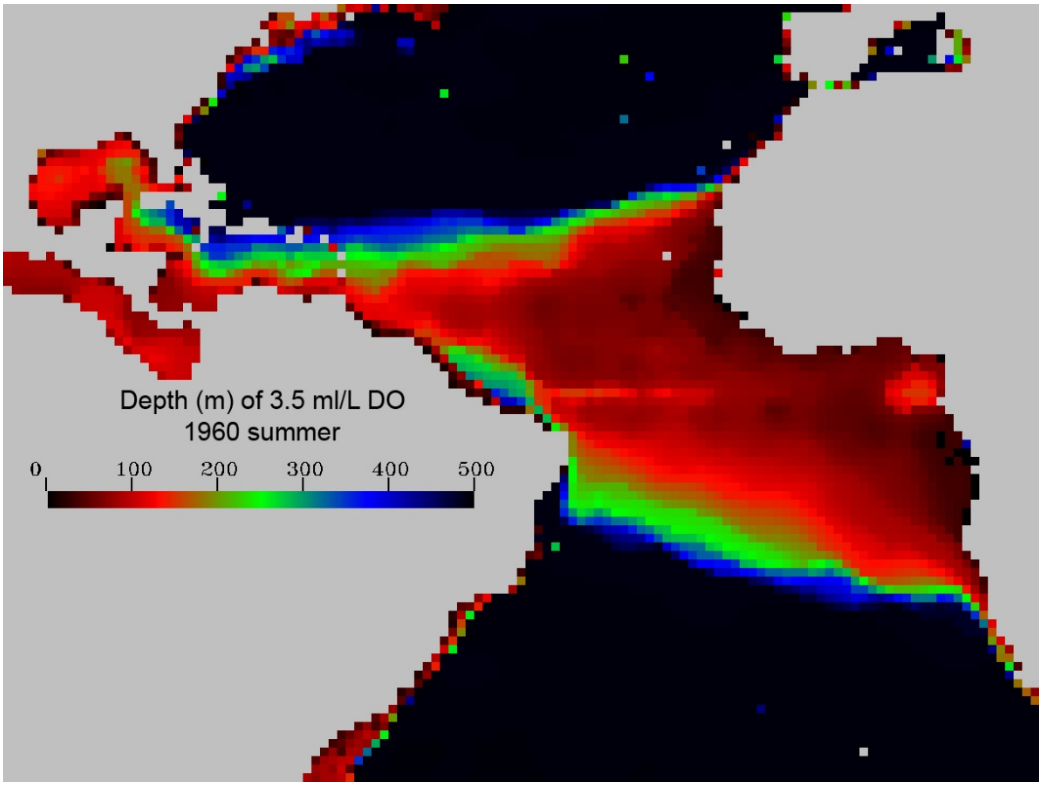


Figure 4. CPUE standardization function of yellowfin tuna derived from yellowfin tuna PSAT data, vertical LL hook distribution, depth of ≤3.5 ml/L dissolved oxygen, and depth of ***Δ***t10 in tropical Atlantic Ocean.

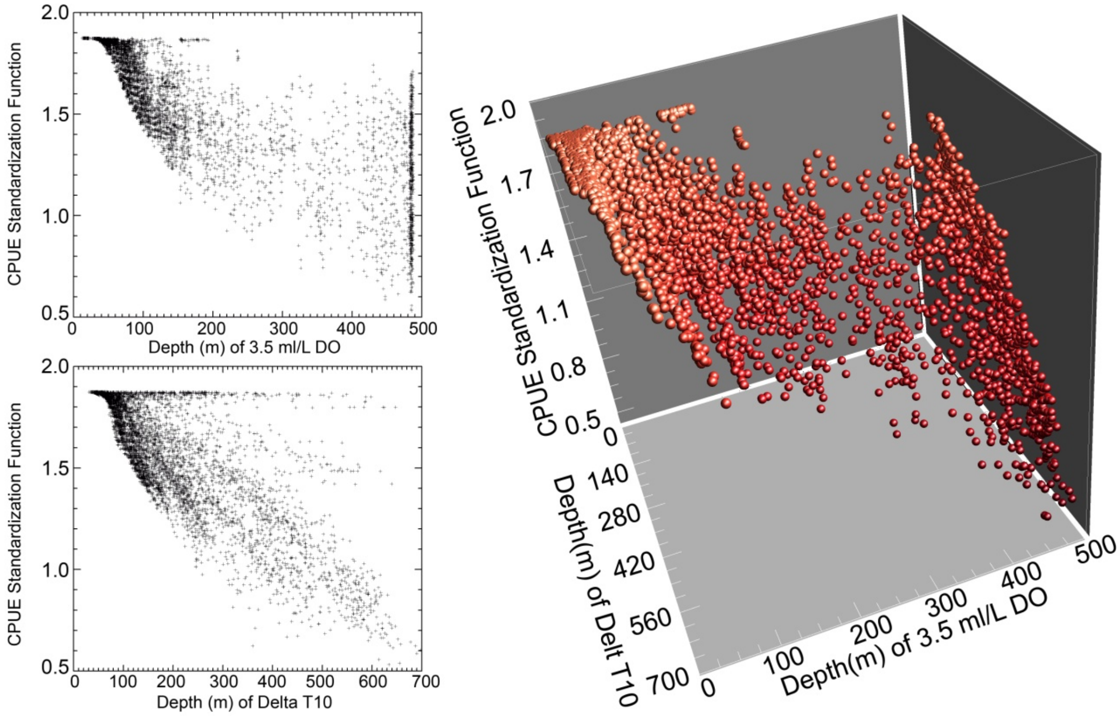


Figure 5. Mean CPUE indices of yellowfin tuna for the tropical Atlantic Ocean. A) Annual mean CPUE indices based on nominal CPUE for all areas (black line), inside OMZ (blue line) and outside OMZ (green line). Comparison of nominal (black line) and standardized (red line) annual mean CPUE indices are shown for all area (B), inside OMZ (C), and outside OMZ (D).

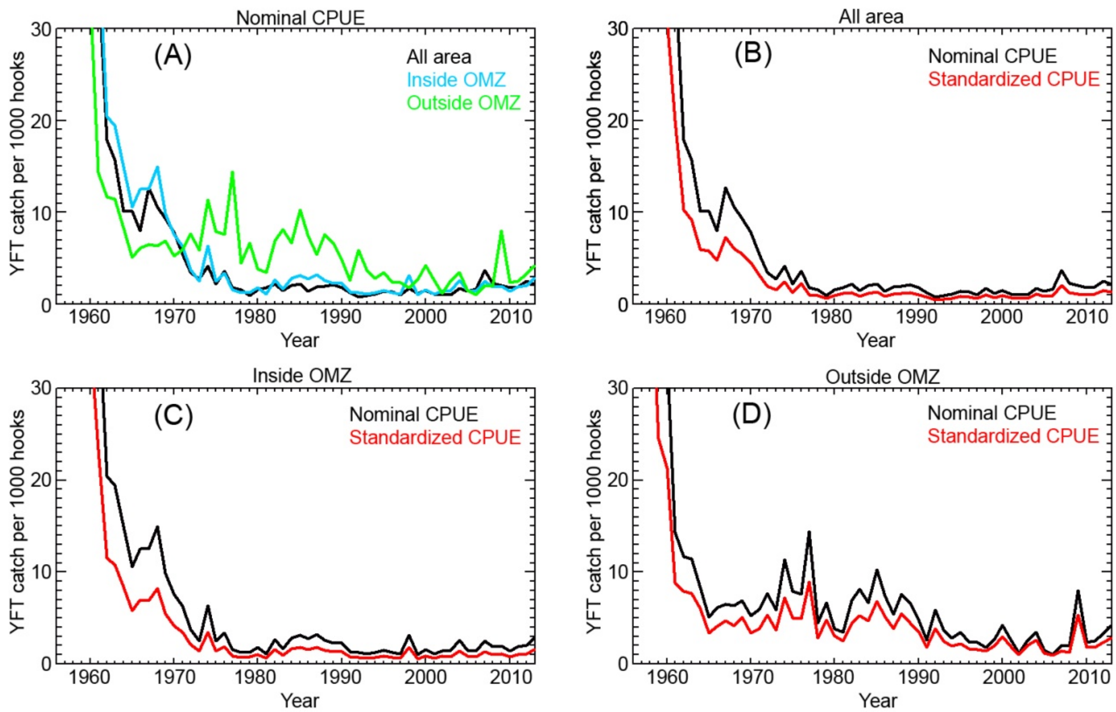


Figure 6. CPUE standardization function of blue marlin derived from blue marlin PSAT data, vertical hook distribution, depth of ≤3.5 ml/L dissolved oxygen, and depth of **𝜟**t10 in tropical Atlantic Ocean.

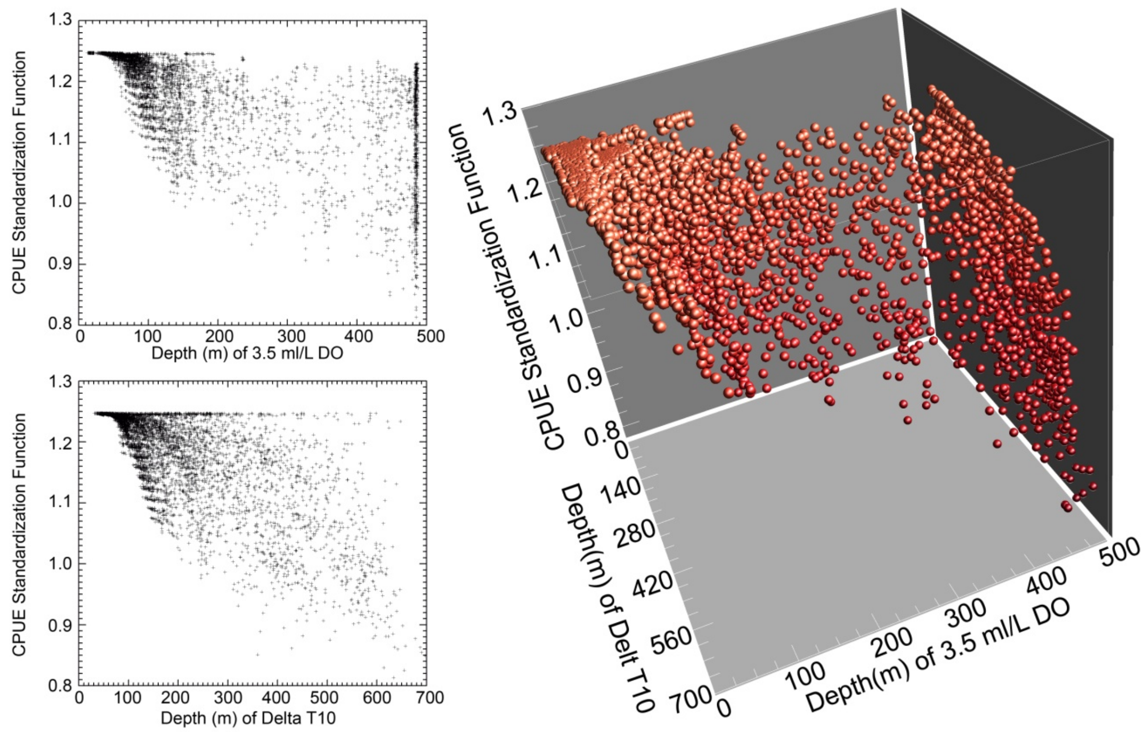


Figure 7. Mean CPUE indices of blue marlin for the tropical Atlantic Ocean. A) Annual mean CPUE indices based on nominal CPUE for all area (black line), inside OMZ (blue line) and outside OMZ (green line). Comparison of nominal (black line) and standardized (red line) annual mean CPUE indices are shown for all area (B), inside OMZ (C), and outside OMZ (D).

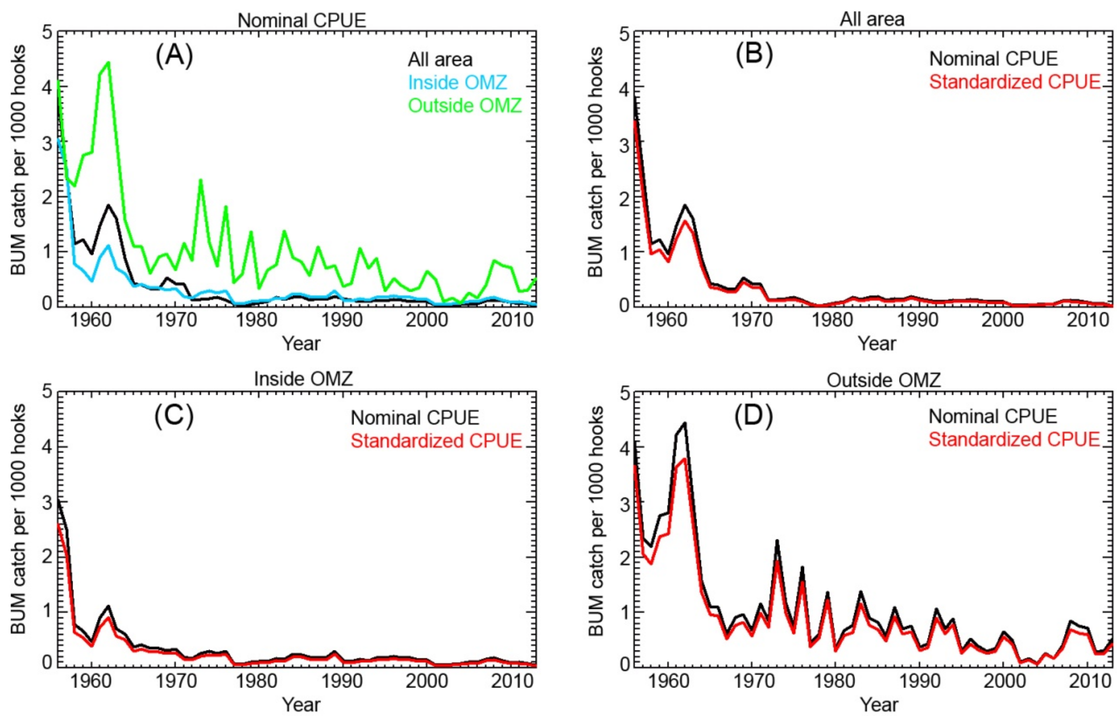


Figure 8. Percent of reduction comparing annual mean standardized CPUE indices to annual mean nominal CPUE indices for yellowfin tuna (A) and blue marlin (B) for inside OMZ (blue line), outside OMZ (green line), and the combined (black line).