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Estimation of a Post-IFQ Commercial Vertical Line Abundance Index for Gulf of Mexico Red Snapper Using Reef Fish Observer Data

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August 2022

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Introduction

There are concerns that catch-per-unit-effort (CPUE) abundance indices based on commercial fleet landings may not be valid after implementation of individual fishing quotas (IFQs) for selected grouper-snapper species in the Gulf of Mexico (GOM). For example, discards of scamp and yellowmouth grouper were primarily smaller fish at or below the legal minimum length before IFQs were implemented in 2010; however, discards post-IFQ included larger legal-sized fish as well as sublegal fish (Smith et al. 2020). These findings suggest that a fundamental change may have occurred in the catch-effort relationship of legal-sized fish, the basis for commercial fleet CPUE indices of abundance derived from logbooks, before and after implementation of IFQs.

To address these concerns, a novel CPUE index was developed in 2020-2021 for scamp and yellowmouth grouper for the commercial fleet using data from the reef fish observer program (Smith et al. 2021). Observer observations of catch include both kept and discarded fish, and are thus not directly impacted by changes in management regulations (e.g., minimum size, catch quotas, etc.). This methodology was applied to develop commercial fleet CPUE indices for red snapper for SEDAR 74.

Methods

Data Sources

The principal data source was the reef fish observer program in which scientific observers on commercial fishing vessels recorded detailed information on catch and effort for a subset of trips (Scott-Denton et al. 2011). The reef fish observer program began in July 2006; complete calendars years 2007-2019 were used for development of an annual index of abundance for GOM red snapper. Analyses focused on vertical line gears (e.g., handlines, electric and hydraulic reels aka bandit reels), which accounted for the majority of commercial trips reporting catches of Red Snapper as well as observer observations.

Supplemental data sources were utilized to delineate the GOM spatial area for analysis, including the commercial coastal logbook program and NOAA bathymetric databases.

Spatial Sample Frame

A spatial sample frame was developed for the Gulf of Mexico (**Fig. 1**), comprised of 500 x 500m UTM (universal transverse mercator) grid cells, i.e., sample units. Depth at the center point of each grid cell was obtained from NOAA bathymetry data.

Index Estimation Approach

Annual CPUE and associated variance of red snapper were estimated using a Hurwitz-Thompson ratio-of-means estimator for a stratified sample frame (Jones et al. 1995; Lohr 2010), which accommodated varying levels of fishing effort among observer samples. Computations were carried out as follows for a given year. Mean catch $\bar{y}$ in stratum h was computed by

$$\bar{y}_h = \frac{1}{n_h} \sum_i y_{hi} \quad ,$$

where y_{hi} is catch per sample unit *i* in stratum h, and n_h is sample size. Similarly, mean effort $\bar{x}$ in stratum *h* was computed by

$$\bar{x}_h = \frac{1}{n_h}\sum_i x_{hi} \quad .$$

Previous analyses for scamp/yellowmouth grouper identified line-hours as the most appropriate effort variable for CPUE estimation (Smith et al. 2021). Sample frame mean catch and effort were respectively computed by

$$\bar{y}_{st} = \sum_h w_h \, \bar{y}_h \qquad (1)$$

and

$$\bar{x}_{st} = \sum_h w_h \, \bar{x}_h \quad , \qquad (2)$$

with the stratum weighting factor given by

$$w_h = \frac{N_h}{\sum_h N_h} \quad , \qquad (3)$$

the stratum proportion of total possible sample units *N* in the sample frame. Mean CPUE for the sample frame was estimated as the ratio of mean catch and mean effort,

$$\overline{CPUE}_{st} = \frac{\bar{y}_{st}}{\bar{x}_{st}} \quad . \qquad (4)$$

Variance computations utilized the estimate of $\overline{CPUE}_{st}$ (eq. 4). Sample variance $s^2(y|x)$ for the ratio-of-means estimator for stratum h was computed by

$$s_h^2(y|x) = \frac{\sum_i (y_{hi} - \overline{CPUE}_{st} x_{hi})^2}{n_h - 1} \quad . \qquad (5)$$

Variance of mean CPUE in stratum h was estimated by,

$$var[\overline{CPUE}_h] = \left(1 - \frac{n_h}{N_h}\right) \frac{s_h^2(y|x)}{n_h \bar{x}_h^2} \quad ,$$

and the survey frame variance was given by

$$var[\overline{CPUE}_{st}] = \sum_h w_h^2 var[\overline{CPUE}_h] \quad .$$

Survey frame standard error was computed by

$$SE[\overline{CPUE}_{st}] = \sqrt{var[\overline{CPUE}_{st}]} \quad ,$$

which was in turn used to compute the coefficient of variation (CV) for mean CPUE,

$$CV[\overline{CPUE}_{st}] = \frac{SE[\overline{CPUE}_{st}]}{\overline{CPUE}_{st}} \quad . \qquad (6)$$

Confidence intervals for mean CPUE were constructed in the usual manner using

$$95\%\ CI(\overline{CPUE}_{st}) = \overline{CPUE}_{st} \pm t_{\alpha=0.05,df} SE(\overline{CPUE}_{st}) \quad ,$$

in which degrees of freedom (df) was computed as the total sample size $(\sum_h n_h)$ minus the number of strata (Lohr 2010).

The associated length frequency distribution for $\overline{CPUE}_{st}$ was computed in the following manner. Stratum CPUE was scaled to stratum total sample units N_h

$$\hat{Y}_h = \overline{CPUE}_h \times N_h$$

and multiplied by stratum proportion of length L to obtain the stratum total $\hat{Y}$ at length L,

$$\hat{Y}(L)_h = \hat{Y}_h \times p(L)_h \quad .$$

These were summed over all strata to obtain the survey frame total $\hat{Y}$ at length L

$$\hat{Y}(L)_{st} = \sum_h \hat{Y}(L)_h \quad ,$$

and then converted to relative proportion of length L,

$$p(L)_{st} = \frac{\hat{Y}(L)_{st}}{\sum_h \hat{Y}_h} \quad . \qquad (7)$$

The above computational formulae comprised a general estimation framework for estimating an annual abundance index for GOM red snapper; however, actual application required specification of many aspects of the estimation process, including delineation of the spatial sample frame relevant for red snapper (i.e., sample units with nonzero probability of capture), standardization of effort units for varying gear characteristics, and designation of an efficient stratification scheme for controlling estimate precision.

Generalized Linear Regression Techniques

Generalized linear regression analysis was used to guide specification of various aspects of the estimation process described above, including evaluating relationships between catch and effort and relationships between CPUE and potential stratification variables (e.g., depth). Two components of relative abundance (i.e., catch or CPUE), presence-absence (i.e., occurrence) and catch when present, were evaluated with respect to relationships with continuous and/or categorical explanatory variables. In this approach, separate regression models were developed for occurrence (p) and catch when present (u) as functions of a given covariate. The two functions were multiplied together to obtain relationships between relative abundance and given covariates. This approach alleviated the problem of highly-skewed, non-normal catch or CPUE observations with high frequency of zero values often encountered with fishery sampling data, but also provided insight to the nature of influence of a given covariate on relative abundance, e.g., does the covariate affect the probability of occurrence (presence-absence), the magnitude of abundance when present, or both?

Regression models were developed in two steps. The first step developed exploratory models for p=f(X) and u=f(X) to provide insight to: (i) the model form of the mean relationship between a given response and explanatory variable, i.e., linear, quadratic, asymptotic, etc.; and

(ii) an appropriate probability density function (pdf) for describing model error. The second step used the model form and error pdf identified in step 1 to fit final models for p=f(X) and u=f(X).

Gear Designation Analysis: Hook Characteristics and Reel Types

There was considerable variation in hook characteristics among fishers using vertical line gear. Observer-recorded information on hook type (e.g., J-hooks, circle hooks), hook shape (e.g., straight, angled), and hook dimensions (see **Fig. 2A**) were evaluated for potential differences in length frequency distributions and thus potential differences in CPUE. Combinations of hook characteristics with differing size-selectivities were used to assign hook categories for subsequent analyses.

A second aspect of varying gear characteristics was the potential effects of hand vs. mechanical reels (electric and hydraulic combined) on CPUE. This effect was evaluated with generalized linear regression analysis in which catch was the response variable, effort (line-hours) was a continuous covariate, subregion-depth was a categorical blocking covariate, and reel type was a categorical treatment covariate. Gear type categories were then designated based on the analyses of hook characteristics and reel types.

Valid Sample Unit for Red Snapper

The geo-referenced observer data were used to define the depth range where red snapper occur; however, it was not possible to distinguish reef from non-reef habitat within this depth range due to the lack of a comprehensive benthic habitat map for the GOM. Species co-occurrence analysis following methods of Mackenzie et al. (2006) was thus used to identify valid red snapper sample units (500 x 500 m grid cells), i.e., sample units with a non-zero probability of catching red snapper. A species interaction factor (SIF) was computed to evaluate the association between a target species and other species in the catch. The SIF is the ratio of the observed co-occurrence of species A (target) and species B (other) to the expected co-occurrence,

$$SIF = \frac{observed\ co{-}occurrence}{expected\ co{-}occurrence} = \frac{p(A,B)}{p(A)p(B)} \ .$$

The observed co-occurrence p(A,B) was estimated as the proportion of sample units capturing both species, while the expected co-occurrence was estimated as the proportion of sample units capturing species A, p(A), multiplied by the proportion of sample units capturing species B, p(B). A value of SIF equal to 1 indicates the species were caught together purely by chance, SIF values greater than 1 indicate a positive association, and values less than 1 indicate a negative association. A chi-square test for the hypothesis H0: SIF=1 was computed from a 2x2 contingency table of the form,

Sample units with neither species	Sample units with species B but not species A
Sample units with species A but not species B	Sample units with both species A & B

Standard sample size guidelines of n≥5 for each cell of the contingency table were applied to eliminate low occurrence species from the analysis.

To control for spatial variation in occurrence *p* for red snapper (species A) and potential associated species (species B), SIF analysis was carried out for different depth intervals and geographical subregions within the GOM, i.e., a depth-subregion 'blocking' scheme as defined in randomized block experimental designs. Depth blocks were defined from evaluation of occurrence-depth relationships for red snapper using logistic regression. For subregions, the GOM was divided using statistical zones into West (zones 13-21), Central (zones 7-12), and East (zones 1-6) blocks following the recommendations of the Stock ID working group. Additional spatial analysis of red snapper occurrence was conducted to determine the southern boundary for the East subregion along Florida's Gulf Coast.

Effort Standardization Among Gears

Effort units were standardized among gear types to enable pooling observer data by gears into a single dataset for index estimation. Effort standardization was carried out for each geographic subregion using Robson's (1966) fishing power approach. The fishing power method stems from the fundamental catch equation,

$$C = F\bar{N} = fq\bar{N} \quad ,$$

where C is catch, F is the instantaneous fishing mortality rate, $\bar{N}$ is average stock abundance, f is nominal fishing effort, and q is catchability. Catchability q, the fraction of the stock removed per unit of effort, usually differs among gears; thus, CPUE for gear 1 can be expressed as

$$\frac{C_1}{f_1} = q_1\bar{N}$$

and CPUE of gear 2 can be expressed as

$$\frac{C_2}{f_2} = q_2\bar{N} \quad .$$

Fishing power is defined as the relative catchability of one gear in terms of another,

$$\lambda_1 = \frac{\frac{C_1}{f_1}}{\frac{C_{2=s}}{f_{2=s}}} = \frac{q_1}{q_{2=s}} \quad . \tag{8}$$

The effort of gear 1 is multiplied by fishing power to express the CPUE of gear 1 in terms of CPUE of the standard gear,

$$\frac{C_1}{f_1\lambda_1} = \frac{C_s}{f_s} \quad .$$

In this example, gear 2 was designated as the 'standard', but any gear can be selected as the standard.

Fishing power was evaluated with generalized linear regression analysis in which catch was the response variable, effort (line-hours) was a continuous covariate, year-depth was a categorical time-space blocking covariate, and gear type was a categorical treatment covariate. For the compound pdf regression model, separate fishing power estimates were obtained for occurrence (p) and catch when present (u). Fishing power for CPUE, λ(CPUE), was obtained by multiplying λ(p) and λ(u).

Stratification Analysis

The standardized catch and line-hours dataset was used to identify an effective spatial stratification scheme for ratio-of-means CPUE estimates. The objective of spatial stratification is to partition the sample frame into subareas (i.e., strata) of low, moderate, and high sample variance s^2 (eq. 5), which will in turn minimize the variance (and thus CV) of sample frame estimates of $\overline{CPUE}_{st}$ (Lohr 2010). Analyses were conducted separately for each geographic subregion, focused on depth as a potential stratification variable, and were carried out in two steps. First, generalized linear regression was used to analyze relationships between occurrence or catch when present and the space covariate depth. For these models, line-hours was included as a continuous covariate, and year was included as a categorical time covariate. These regression analyses identified a suite of feasible stratification schemes for depth (e.g., two depth intervals, four depth intervals, etc.).

The second step computed the survey design metric n*, the projected sample size to achieve a specified precision, to compare stratification schemes. Computations of n* for the ratio-of-means CPUE estimator (eq. 4) were carried out using

$$n* = \frac{\left(\sum_h \frac{w_h s(y|x)_h}{\bar{x}_h}\right)^2}{V + \frac{1}{N}\sum_h w_h \frac{s(y|x)_h^2}{\bar{x}_h^2}} , \qquad (9)$$

where the desired variance V was expressed in terms of a target CV for $\overline{CPUE}_{st}$,

$$V = (CV[\overline{CPUE}_{st}] \cdot \overline{CPUE}_{st})^2 .$$

Eq. 9 presumes Neyman allocation of sample units among strata, which takes into account both stratum size and variance; consequently, n* is a metric of the stratification effect on estimate precision independent from the allocation effect. The n* results were used to select the stratification scheme for estimating the CPUE index.

Results

Initial filtering steps restricted observer data to vertical line gears, and excluded observations with missing location information (i.e., latitude-longitude). This enabled assignment of observations at specific fishing locations to a unique 500 x 500 m grid cell with associated depth information (**Fig. 1**). For analysis, a sample unit was defined as a 500 x 500 m grid cell sampled by observers on a given vertical line trip.

Gear Designation: Hook Characteristics

Red snapper length frequency distributions were found to differ with respect to hook type (J-hooks vs. circle hooks) as well as hook size. Data were subsequently filtered to include circle hooks, which accounted for over 90% of observations, for two distinct hook size categories (small and large) based on hook shaft length measurements taken by observers (**Fig 2**).

Valid Sample Unit for Red Snapper

Designation of the depth-subregion blocking scheme for species association analyses is illustrated in **Figs. 3** and **4**. Red snapper were captured on vertical line gear within a depth range of 10 m to 160 m. Occurrence *p*, the proportion of sample units where at least one red snapper was captured, was low at shallow and deep depths, and was highest at moderate depths (**Fig. 3**). Three depth blocks were defined accordingly: (1) 10-25 m, average $p \approx 0.32$; (2) 25-85 m, average $p \approx 0.67$; and (3) 85-140 m, average $p \approx 0.39$. The deepest category (140-160 m) was subsequently excluded from analysis due to insufficient sample sizes within GOM geographic zones (East, Central, West; **Fig. 4**). The southern boundary of the East subregion was set at 26 degrees latitude, due to a combination of sparse observer coverage of vertical line trips and near-zero occurrence of red snapper in shallow depths in the area south of 26 degrees.

Species association analysis was conducted considering red snapper as the target species (species A) and other species (species B) as the potential co-occurring species. Analyses were carried out by species and depth-subregion block for small circle hooks (C_SM, **Table 1**) and large circle hooks (C_LG, **Table 2**). For hook category C_SM, sample size constraints were satisfactory for analysis of associations between red snapper and 48 other species, of which 11 were positively associated in one or more depth-subregion block. These associated species were predominately groupers, porgies, jacks, and other reef fishes (**Table 1**). For hook category C_LG, sample size constraints were satisfactory for analysis of associations between red snapper and 36 other species, of which 12 were positively associated in one or more depth-subregion block. The associated species were predominately snappers, groupers, grunts, jacks, sea basses, and other reef fishes (**Table 2**).

The results of **Tables 1** and **2** were used to filter the observer data by hook category and depth-subregion block to include valid red snapper sample units which had a nonzero probability of capture. Valid sample units were defined as those with catches of red snapper or a positively associated species.

Gear Designation Analysis: Reel Type

Regression relationships for catch dependent on reel-hours were analyzed for hand and mechanical reels within C_SM and C_LG hook categories. The model covariate for reel type was not significant for logistic regression analysis of occurrence and gamma pdf regression analysis of catch when present for both C_MED and C_LRG hook categories. Data for hand and mechanical reels were pooled within each hook category for subsequent analyses.

Effort Standardization Among Gears

Before carrying out generalized regression estimation of fishing power for the C_SM and C_LG hook categories, the relationship between catch and the continuous effort covariate reel-hours was refined. First, large values of reel-hours exceeding the 99th percentile were excluded as outliers for each hook category. Second, analyses were conducted following Smith et al. (2021) to identify the maximum threshold value for effort above which mean catch remained more or less constant (**Fig. 5**). For both small and large circle hook categories, the maximum effort threshold was estimated to be 3.0 reel-hours. Sample unit effort observations were adjusted accordingly by setting effort values > 3.0 reel-hours to the maximum threshold value.

Regression relationships for catch dependent on reel-hours were then analyzed for hand and mechanical reels within C_SM and C_LG hook categories. The model covariate for reel type was significant for both small and large circle hook categories. Four gear types were designated for fishing power analysis: (i) small circle hooks, hand reels; (ii) small circle hooks, mechanical reels; (iii) large circle hooks, hand reels; and (iv) large circle hooks, mechanical reels.

Model-predicted estimates of occurrence p, catch when present u, CPUE, and relative fishing power λ are provided in **Table 3**. Hook category C_SM with mechanical reels was selected as the standard gear. Effort for the other gears were converted to that of the standard gear, and the data were pooled for subsequent estimation of the CPUE index.

Stratification Analysis

Regression analysis indicated from two to three potential strata for depth, as illustrated for the East subregion in **Fig. 6**. The logistic regression example in **Fig. 6A** shows delineation of a 2-strata scheme for depth based on occurrence p, with depth strata intervals of 10-30m and 30-80m. In contrast, the gamma pdf regression example in **Fig. 6B** shows delineation of a slightly different 2-strata depth scheme based on catch when present u, with depth strata intervals of 10-25m and 25-80m. Sampling in depths deeper than 80m was sparse and intermittent over the 2007-2019 time period; consequently, this stratum was eliminated from the East subregion sample frame. Analysis of these differing stratification schemes using the survey design metric n*(10%), the projected sample size to achieve a 10% CV for mean CPUE, identified the 2-strata depth scheme with intervals of 10-25m and 25-80m as the most effective with respect to spatial partitioning of sample variance for CPUE (**Table 4**). Analysis for the Central and West subregions identified 3-strata depth schemes as the most effective for CPUE index estimation (**Table 5**).

Annual CPUE Index and Length Composition, 2007-2019

Sample sizes by depth strata and year for the Eastern subregion are given in **Table 6**. Estimates of the reef fish observer abundance index for Eastern GOM Red Snapper for 2007-2019 are provided in **Table 7** for the commercial vertical line fleet. The standardized index (scaled to mean CPUE for 2007-2019) time-series is graphed in **Fig. 7**, which also shows the 95% confidence intervals. The estimates suggest that Eastern GOM Red Snapper abundance was relatively low during 2007-2008, increased to a stable level during 2009-2015, and then sharply increased in the most recent years 2016-2019. The CVs of the estimates ranged from 5 to 28%, with an average of 13% over the 2007-2019 time frame.

Sample sizes by depth strata and year for the Central subregion are given in **Table 8**. Estimates of the reef fish observer abundance index for Central GOM Red Snapper for 2007-2019 are provided in **Table 9**. The standardized index (scaled to mean CPUE for 2007-2019) time-series is graphed in **Fig. 8**, which also shows the 95% confidence intervals. The estimates suggest that Central GOM Red Snapper abundance was generally lower during 2007-2012 and generally higher during 2013-2019. The CVs of the estimates ranged from 6 to 30%, with an average of 12% over the 2007-2019 time frame.

Sample sizes by depth strata and year for the West subregion are given in **Table 10**. Estimates of the reef fish observer abundance index for Western GOM Red Snapper for 2007-2019 are provided in **Table 11**. The standardized index (scaled to mean CPUE for 2007-2019) time-series is graphed in **Fig. 9**, which also shows the 95% confidence intervals. The estimates suggest that Western GOM Red Snapper abundance was generally stable during 2007-2019. The CVs of the estimates ranged from 7 to 22%, with an average of 12% over the 2007-2019 time frame.

The standardized CPUE time-series and accompanying population length compositions (eq. 7) for the three subregions were provided to the stock assessment analysts via the S-Drive.

Discussion

This study applied the methods of Smith et al. (2021) to develop an index of abundance for GOM Red Snapper using data from the reef fish observer program, focusing on the commercial vertical line fleet. Some advantages of these data were that vertical line fishing and corresponding observer sampling locations encompassed the principal geographical and depth range of Red Snapper in the GOM. Observer catch observations included both kept and discarded fish, and thus were not directly affected by management regulations (e.g., minimum size, IFQs, etc.), which is a common issue identified for indices developed using logbook data. The main disadvantage was that the observer data are fishery-dependent, with the inherent uncertainty as to whether the sampled observations constituted a truly representative sample of the Red Snapper stock. Aside from that fundamental question, analysis techniques accounted for varying gear characteristics (e.g., hook types, hook sizes, reel types) and varying effort (e.g., number of reels, fishing time at a location, etc.), which are typical for fishery-dependent sampling data, in the estimation procedure. The resulting abundance indices indicated generally increasing Red Snapper stocks in the Eastern and Central GOM and a stable stock in the Western GOM during 2007-2019. The precision of the estimates was quite good with an average annual CV of about 12% or 13% in the three subregions.

The methodology for developing the observer abundance index employed a complementary mixture of parametric regression model techniques and nonparametric survey design techniques. Parametric, model-based analyses were used to analyze species co-occurrence, specify maximum effort thresholds, standardize effort among gears, and identify potential stratification variables and stratification schemes. Nonparametric, design-based analyses were used to test and identify optimal stratification schemes, and to produce the annual estimates of CPUE and associated CV for the abundance index. This approach using a variety of methods was designed with the express purpose of minimizing potential bias and maximizing precision of regional stock annual CPUE estimates for Red Snapper (see Smith et al. 2021).

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Table 1. Results of Red Snapper species association analysis by region and depth categories for GOM vertical lines, hook size C_SM (small circle hooks). Color coding: green, positive association; yellow, no association; red, negative association; blank, insufficient data for analysis.

		East			Central			West		
Family/Group	**Species**	**10-25 m**	**25-85 m**	**85-140 m**	**10-25 m**	**25-85 m**	**85-140 m**	**10-25 m**	**25-85 m**	**85-140 m**
Snappers	Gray Snapper									
	Lane Snapper									
	Vermilion Snapper									
Groupers	Gag									
	Red Grouper									
	Scamp									
	Snowy Grouper									
	Speckled Hind									
	Warsaw Grouper									
	Yellowedge Grouper									
Grunts	Pinfish									
	Tomtate									
	White Grunt									
Porgies	Jolthead Porgy									
	Knobbed Porgy									
	Littlehead Porgy									
	Red Porgy									
	Saucereye Porgy									
	Whitebone Porgy									
Jacks	Almaco Jack									
	Banded Rudderfish									
	Greater Amberjack									
	Lesser Amberjack									
Tilefishes	Blueline Tilefish									
	Goldface Tilefish									
	Sand Tilefish									
Other Reef	Bigeye									
	Creole-Fish									
	Gray Triggerfish									
	Short Bigeye									
	Spotted Moray									
	Squirrelfish									
Sea Basses	Bank Sea Bass									
	Black Sea Bass									
	Longtail Bass									
	Rock Sea Bass									
	Sand Perch									
	Tattler									
Sharks	Atlantic Sharpnose Shark									
	Silky Shark									
Mackerels/Tunas	Blue Runner									
	Chub Mackerel									
	Little Tunny									
Other	Bluefish									
	Cubbyu									
	Leopard Toadfish									
	Remora									
	Sharksucker									

Table 2. Results of Red Snapper species association analysis by region and depth categories for GOM vertical lines, hook size C_LG (large circle hooks). Color coding: green, positive association; yellow, no association; red, negative association; blank, insufficient data for analysis.

		East			Central			West		
Family/Group	**Species**	**10-25 m**	**25-85 m**	**85-140 m**	**10-25 m**	**25-85 m**	**85-140 m**	**10-25 m**	**25-85 m**	**85-140 m**
Snappers	Gray Snapper		green			yellow				
	Lane Snapper		red			yellow				
	Vermilion Snapper		green			yellow				
Groupers	Black Grouper		yellow							
	Gag	green	green	yellow	green	red	yellow			yellow
	Goliath Grouper		yellow							
	Red Grouper	red	red		yellow	red				
	Scamp		green	yellow		yellow	yellow			yellow
	Snowy Grouper						yellow			
	Speckled Hind		green	yellow						
	Warsaw Grouper									yellow
	Yellowedge Grouper									yellow
Grunts	Tomtate		red			yellow				
	White Grunt	green	red		yellow	yellow				
Porgies	Jolthead Porgy		yellow							
	Knobbed Porgy		red							
	Littlehead Porgy		yellow							
	Red Porgy		yellow	yellow		yellow				
	Saucereye Porgy		yellow							
Jacks	Almaco Jack		green			yellow	yellow			yellow
	Banded Rudderfish		green			red				
	Greater Amberjack		green			red	yellow		red	yellow
Other Reef	Gray Triggerfish	green	green			yellow		yellow		
	Spotted Moray		yellow							
Sea Basses	Black Sea Bass	green			red	red				
	Sand Perch		red			yellow				
Sharks	Atlantic Sharpnose Shark		green			yellow				
	Blacknose Shark		yellow		yellow					
	Nurse Shark		yellow			yellow				
	Sandbar Shark					yellow				
	Silky Shark		yellow							
	Tiger Shark		yellow							
Mackerels/Tunas	King Mackerel		yellow							
	Little Tunny		yellow							
Other	Leopard Toadfish		yellow							
	Sharksucker		yellow			yellow				

Table 3. Effort standardization results for GOM Red Snapper for two hook size categories, C_SM (small circle hooks) and C_LG (large circle hooks), paired with two reel types, hand and mechanical. **(A)** Model-predicted estimates of occurrence p, catch when present u, CPUE (p times u), and relative fishing power λ(CPUE) considering small circle hooks with mechanical reels (C_SM_MECH) as the standard gear. **(B)** Relative fishing power of occurrence p and catch when present u, the components of CPUE.

(A)

Gear	Predicted p	Predicted u	Predicted CPUE	λ(CPUE)
C_SM_MECH	0.7098	14.290	10.143	1.000
C_LG_MECH	0.7664	10.927	8.374	0.826
C_SM_HAND	0.6433	13.322	8.571	0.845
C_LG_HAND	0.6742	10.663	7.188	0.709

(B)

Gear	λ(p)	λ(u)	λ(CPUE)
C_SM_MECH	1.000	1.000	1.000
C_LG_MECH	1.080	0.765	0.826
C_SM_HAND	0.906	0.932	0.845
C_LG_HAND	0.950	0.746	0.709

Table 4. Sample size projections (n*) to achieve a 10% CV for Red Snapper CPUE estimates for various stratification schemes in the East subregion. Data were evaluated for the recent time period 2016-19. The highlighted stratification was used to estimate the CPUE annual index.

Design	Description	n*(10%)
Simple Random	1 stratum	396.8
Depth only, 2-strata A	10-25m, 25-80m	350.6
Depth only, 2-strata B	10-30m, 30-80m	372.5

Table 5. Strata possible sample units and associated weighting factors for selected depth stratification schemes in the **(A)** East, **(B)** Central, and **(C)** West subregions.

(A) East

Stratum Code	Description	Possible Sample Units N_h	Weighting Factor w_h
D1	10 m ≤ depth < 25 m	45,907	0.2260
D2	25 m ≤ depth < 80 m	157,255	0.7740

(B) Central

Stratum Code	Description	Possible Sample Units N_h	Weighting Factor w_h
D1	10 m ≤ depth < 55 m	148,441	0.7834
D2	55 m ≤ depth < 80 m	19,288	0.1018
D3	80 m ≤ depth ≤ 140 m	21,752	0.1148

(C) West

Stratum Code	Description	Possible Sample Units N_h	Weighting Factor w_h
D1	10 m ≤ depth < 70 m	316,975	0.7871
D2	70 m ≤ depth < 105 m	59,572	0.1479
D3	105 m ≤ depth ≤ 140 m	26,182	0.0650

Table 6. Observer program sample sizes by depth strata (**Table 5A**) and year for the East subregion Red Snapper commercial vertical line index.

	Stratum sample size n_h	
Year	**D1**	**D2**
2007	8	279
2008	7	303
2009	15	204
2010	66	430
2011	89	661
2012	103	1429
2013	120	540
2014	28	462
2015	28	825
2016	87	784
2017	2	455
2018	10	148
2019	4	77

Table 7. Reef fish observer CPUE index time-series for Eastern GOM Red Snapper for the commercial vertical line fleet. Effort units are standardized line-hours. The relative index was scaled to mean CPUE for 2007-2019.

Year	**n**	**Mean Effort**	**Mean Catch**	**Nominal CPUE**	**Relative Index**	**CV**
2007	287	1.146	0.727	0.634	0.397	0.146
2008	310	1.304	0.993	0.762	0.477	0.140
2009	219	1.167	1.532	1.312	0.822	0.142
2010	496	1.073	1.431	1.334	0.835	0.099
2011	750	1.304	1.771	1.358	0.851	0.073
2012	1532	1.325	1.485	1.121	0.702	0.053
2013	660	1.150	1.373	1.194	0.748	0.081
2014	490	0.990	1.324	1.337	0.837	0.111
2015	853	1.059	1.538	1.453	0.910	0.190
2016	871	0.991	3.207	3.236	2.027	0.085
2017	457	0.987	2.353	2.383	1.493	0.279
2018	158	1.053	2.944	2.797	1.752	0.141
2019	81	1.231	2.260	1.836	1.150	0.204

Table 8. Observer program sample sizes by depth strata (**Table 5B**) and year for the Central subregion Red Snapper commercial vertical line index.

	Stratum sample size n_h		
Year	**D1**	**D2**	**D3**
2007	191	46	28
2008	34	40	17
2009	152	47	8
2010	238	32	11
2011	296	106	16
2012	822	287	108
2013	377	43	10
2014	350	69	18
2015	824	144	28
2016	537	66	27
2017	197	68	16
2018	111	73	16
2019	124	24	28

Table 9. Reef fish observer CPUE index time-series for Central GOM Red Snapper for the commercial vertical line fleet. Effort units are standardized line-hours. The relative index was scaled to mean CPUE for 2007-2019.

Year	n	Mean Effort	Mean Catch	Nominal CPUE	Relative Index	CV
2007	265	1.059	7.864	7.427	0.868	0.109
2008	91	0.981	8.664	8.831	1.032	0.296
2009	207	0.939	2.735	2.914	0.340	0.093
2010	281	1.046	5.216	4.985	0.582	0.124
2011	418	1.072	6.824	6.365	0.744	0.105
2012	1217	1.043	6.650	6.376	0.745	0.070
2013	430	0.944	11.116	11.772	1.375	0.087
2014	437	1.028	8.373	8.143	0.951	0.089
2015	996	1.025	9.303	9.078	1.061	0.063
2016	630	0.907	11.821	13.034	1.523	0.069
2017	281	0.998	13.868	13.889	1.623	0.112
2018	200	1.237	8.250	6.667	0.779	0.164
2019	176	1.070	12.618	11.790	1.377	0.110

Table 10. Observer program sample sizes by depth strata (**Table 5C**) and year for the West subregion Red Snapper commercial vertical line index.

	Stratum sample size n_h		
Year	**D1**	**D2**	**D3**
2007	82	28	14
2008	71	25	26
2009	22	30	6
2010	25	30	10
2011	46	89	13
2012	136	68	51
2013	29	13	6
2014	64	18	38
2015	209	75	67
2016	111	59	15
2017	85	47	16
2018	47	21	25
2019	92	47	21

Table 11. Reef fish observer CPUE index time-series for Western GOM Red Snapper for the commercial vertical line fleet. Effort units are standardized line-hours. The relative index was scaled to mean CPUE for 2007-2019.

Year	n	Mean Effort	Mean Catch	Nominal CPUE	Relative Index	CV
2007	124	1.167	21.571	18.484	0.640	0.103
2008	122	0.951	33.040	34.736	1.202	0.147
2009	58	0.982	35.755	36.411	1.260	0.221
2010	65	1.273	39.895	31.333	1.084	0.153
2011	148	1.493	36.712	24.583	0.851	0.117
2012	255	1.298	22.915	17.650	0.611	0.102
2013	48	1.303	30.822	23.663	0.819	0.182
2014	120	1.544	47.039	30.461	1.054	0.112
2015	351	1.320	38.241	28.965	1.002	0.066
2016	185	1.677	54.196	32.321	1.118	0.081
2017	148	1.325	38.137	28.790	0.996	0.133
2018	93	1.410	54.614	38.723	1.340	0.116
2019	160	1.254	37.095	29.574	1.023	0.079

Figure 1. Map of the spatial sample unit grid for the Gulf of Mexico. The inset shows individual 500 x 500m UTM (universal transverse mercator) grid cells (cell area 250,000 m^2); depth at the center point of each cell was obtained from NOAA bathymetry data.

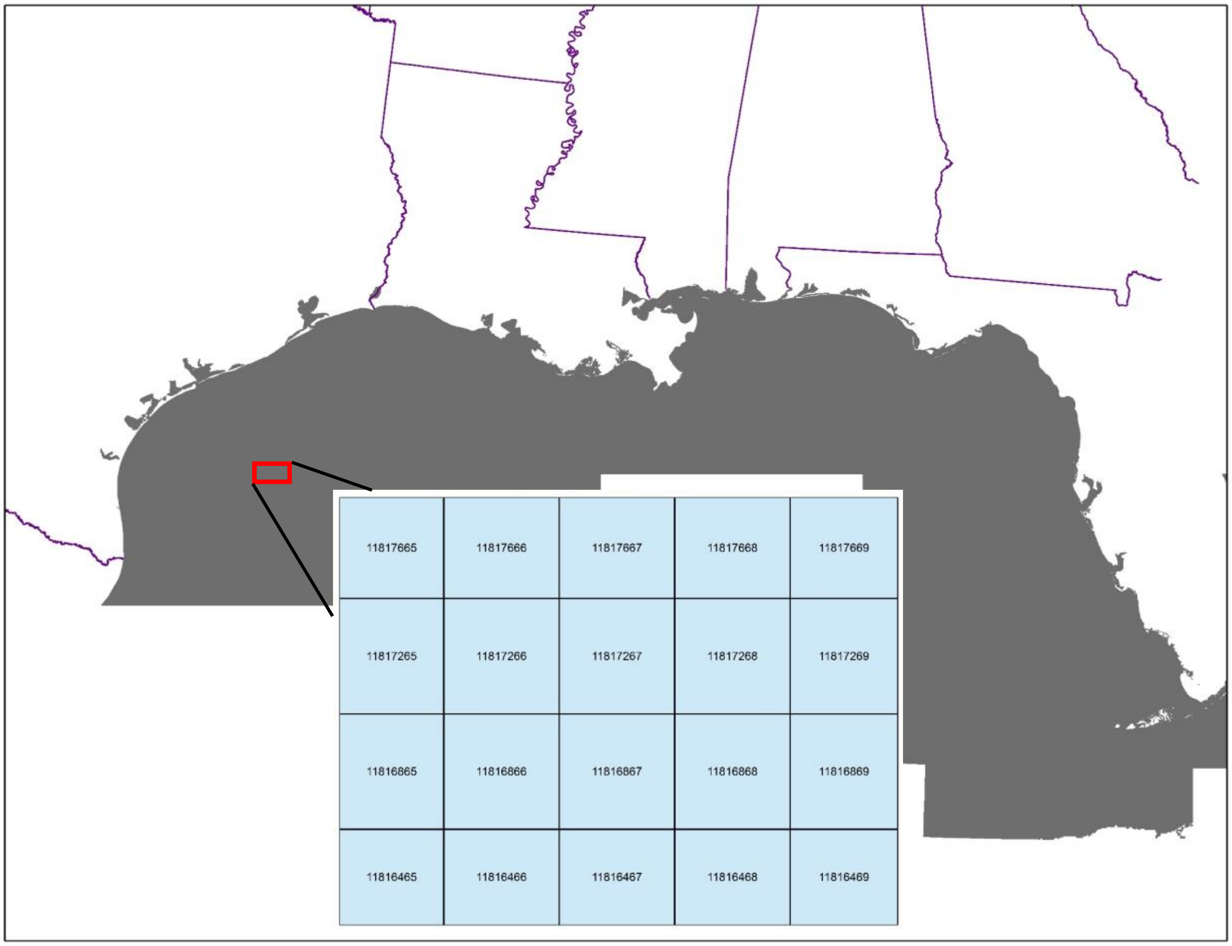
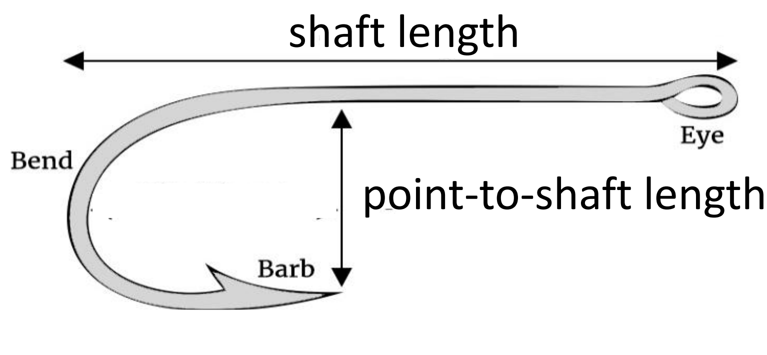


Figure 2. (A) Illustration of two hook size measurements, shaft length and point-to-shaft length, taken by onboard observers that were used to evaluate hook size categories. **(B)** Cumulative length-frequency distributions for Red Snapper for two hook size categories: (i) red line, C_SM (small circle hooks), 0.7 in ≤ shaft length < 1.7 in; (ii) blue line, C_LG (large circle hooks), shaft length ≥ 1.7 in.

(A)



(B)

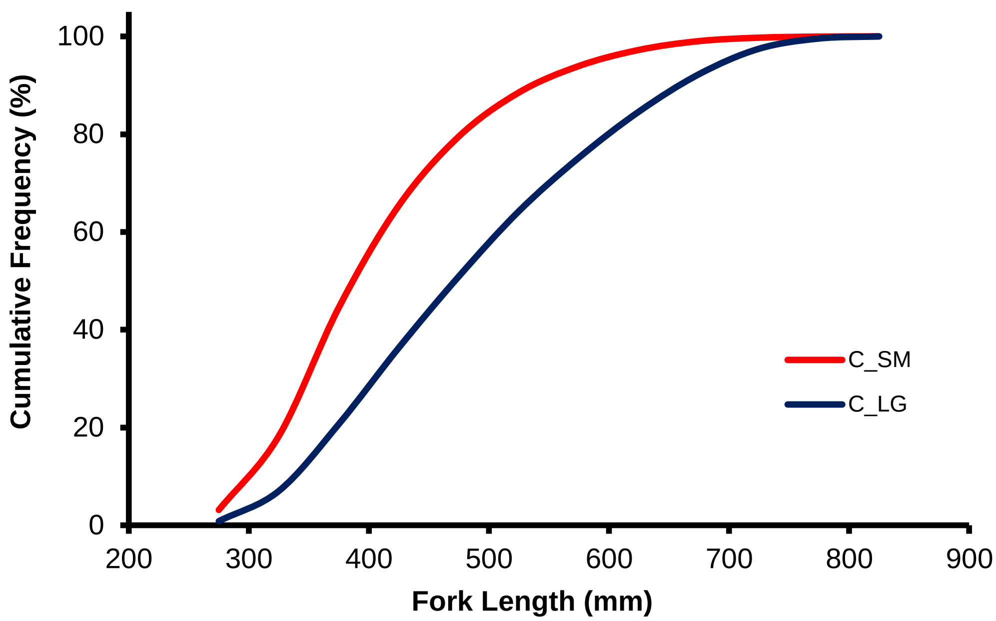


Figure 3. Logistic regression point estimates of Red Snapper occurrence p by depth intervals within the observed depth range of 10-160 m. Dashed lines indicate the initial depth blocking scheme for species association analysis: 10-25 m, 25-85 m, 85-140 m, and 140-160 m. The deepest category (140-160 m) was subsequently excluded from analysis due to insufficient sample sizes within GOM geographic zones (East, Central, West).

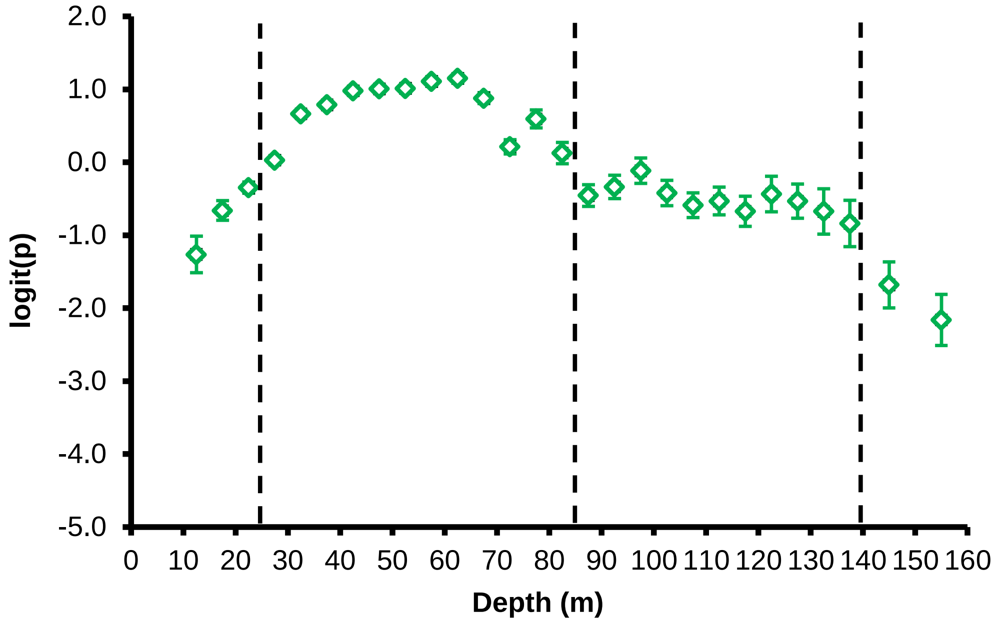


Figure 4. Map of Red Snapper GOM spatial sampling frame showing the subregion-depth blocking scheme for species association analysis. The frame included commercial logbook 1-degree grids reporting catches of Red Snapper. Subregions were denoted by statistical zones: East, 4-6; Central, 7-12; and West, 13-21 (W). Depths were assigned to 3 categories: shallow, 10-25m (red shading); mid-depth, 25-85m (yellow shading); and deep, 85-140m (blue shading). Statistical zones 1-3 (below 26 degrees latitude) in the East subregion were excluded from the sample frame due to a combination of sparse observer coverage of vertical line trips and near-zero occurrence of Red Snapper in shallow depths.

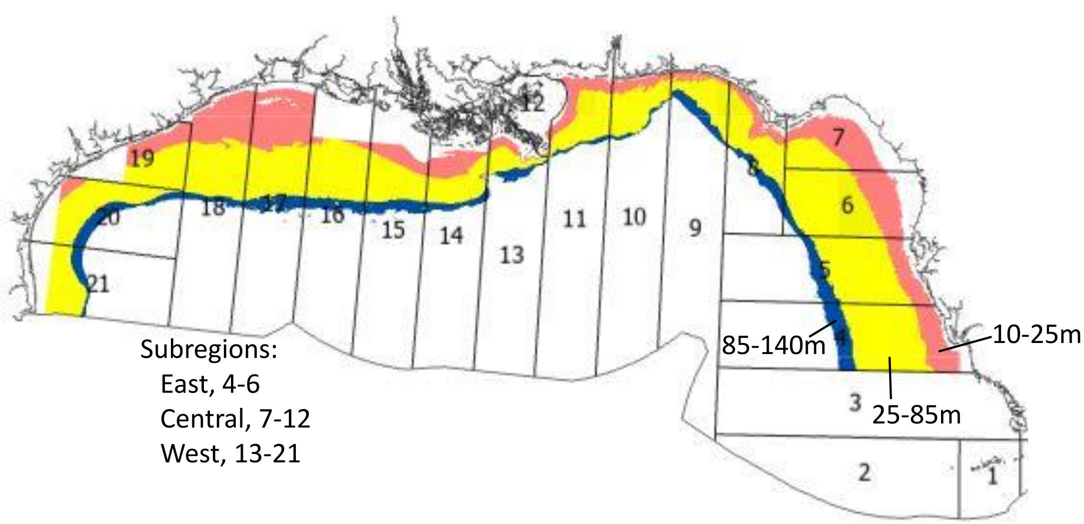


Figure 5. Illustration of procedure for identifying the maximum threshold value for effort above which mean catch remains more or less constant. This example is for Red Snapper catch (y) dependent on reel-hours for vertical lines with small circle hooks. Maximum likelihood regression point estimates of log(y+1) (green diamonds) with normal error pdf show two distinct relationships, an initial increasing relationship between occurrence and effort that transitions to an asymptotic relationship in which catch remains constant over a wide range of effort. Separate continuous functions were fit to the log(y+1)-effort observations for the ascending and asymptotic portions of the relationship. The fitting procedure was repeated for different effort values for the transition between the two functions. The total log-likelihood (LL) is the sum of the log-likelihoods for the separate functions, LL=LL(1) + LL(2). The transition value that maximized the total log-likelihood was selected as the maximum effort threshold. In this case, the maximum threshold was 3.0 reel-hours.

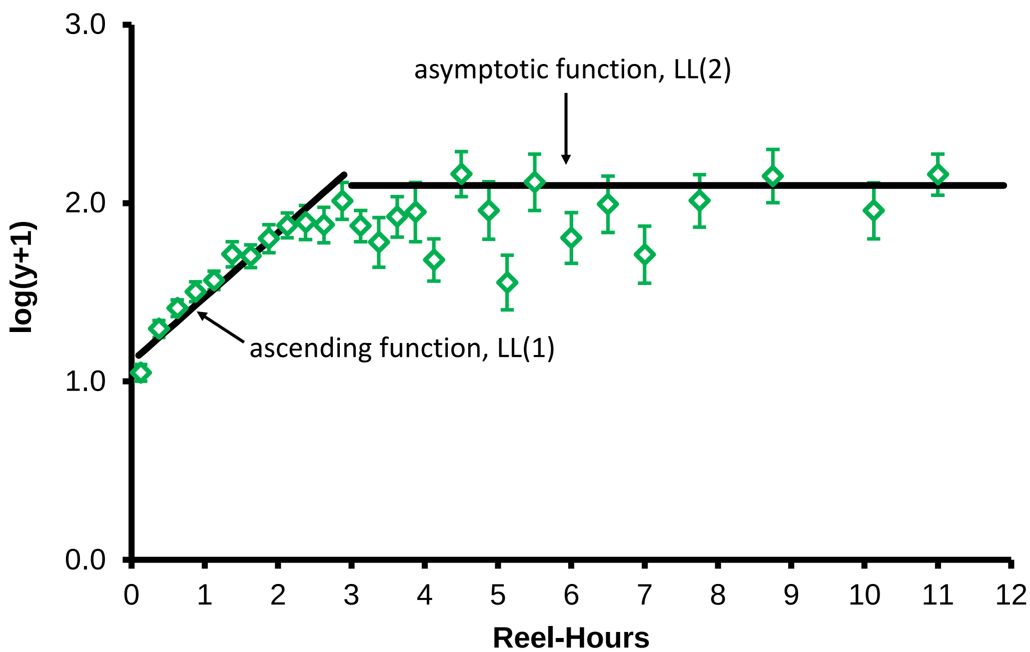
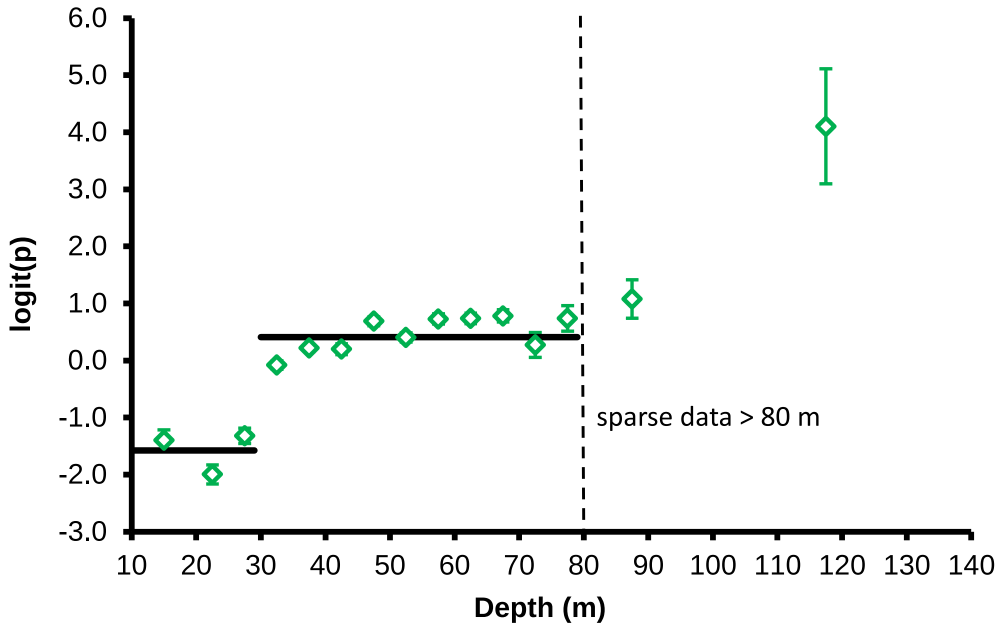


Figure 6. Generalized regression modeling for Scamp/Yellowmouth Grouper (A) occurrence (logit(p)) and (B) catch when present u as a function of depth. **(A)** Logistic regression point estimates (green diamonds with SE error bars) and associated regression functions (solid horizontal lines) for potential depth strata. **(B)** Gamma pdf regression point estimates of catch when present (green diamonds with SE error bars) and associated regression functions (solid horizontal lines) for potential depth strata.

(A)



(B)

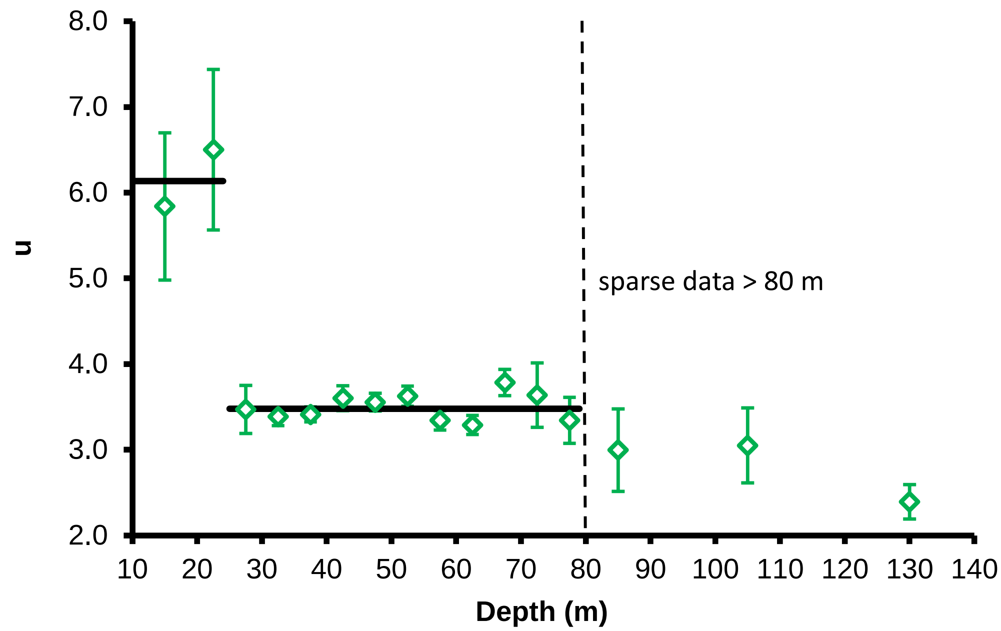


Figure 7. Time-series graph of reef fish observer standardized CPUE index (±95% CI) for Eastern GOM Red Snapper for the commercial vertical line fleet.

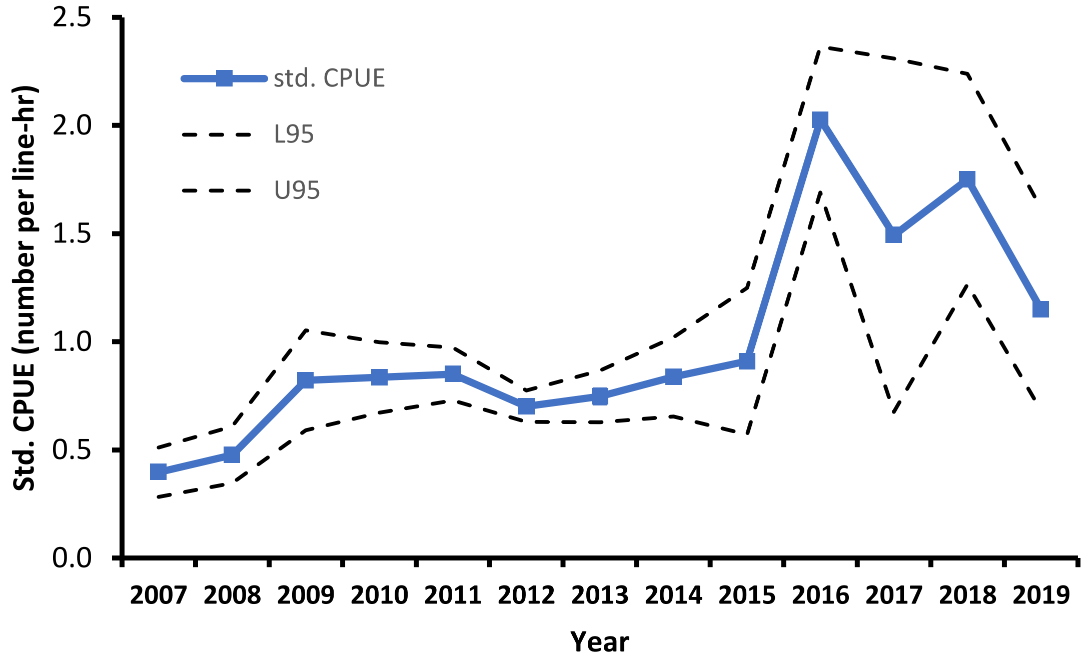


Figure 8. Time-series graph of reef fish observer standardized CPUE index (±95% CI) for Central GOM Red Snapper for the commercial vertical line fleet.

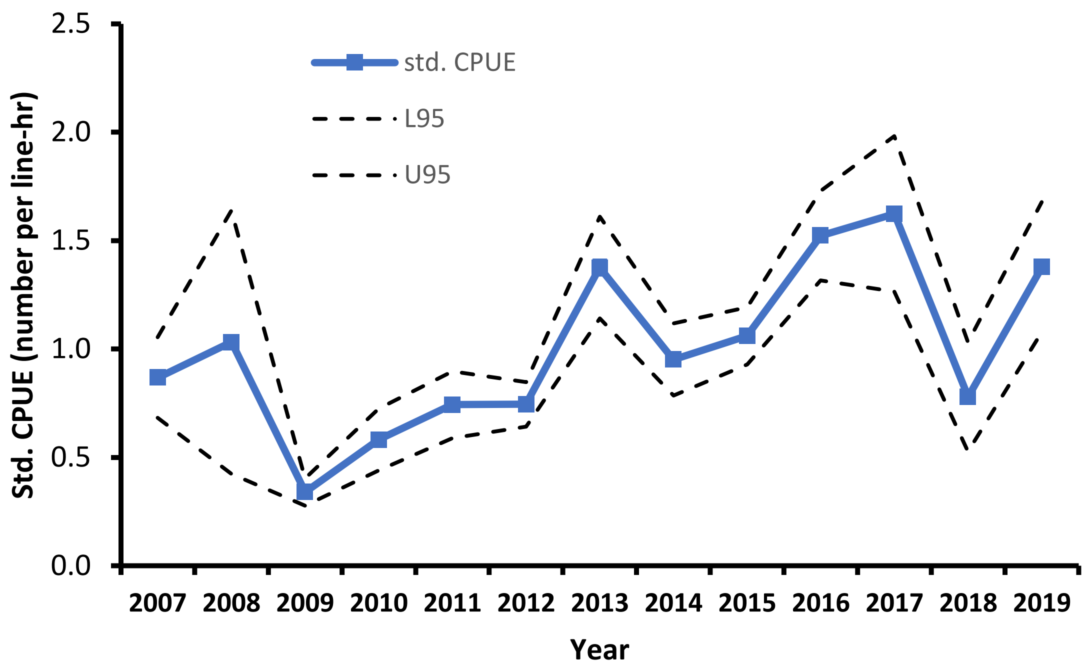


Figure 9. Time-series graph of reef fish observer standardized CPUE index (±95% CI) for Western GOM Red Snapper for the commercial vertical line fleet.