SEAMAP Vertical Longline Survey (2012-2021): Indices of Abundance of Gulf of Mexico Red Snapper, *Lutjanus campechanus*

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SEAMAP Vertical Longline Survey (2012-2021): Indices of Abundance of Gulf of Mexico Red Snapper, *Lutjanus campechanus*

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INTRODUCTION

The NMFS began using vertical line (VL) gear in conjunction with SEAMAP reef-fish video surveys in 2010, primarily to obtain physical samples (gonads, otoliths) for supplemental life-history studies of the population segment targeted by the video survey. State partners began using similar VL sampling methods in subsequent years (Alabama: 2010, Louisiana: 2011, Florida FWRI: 2013, Texas: 2015, and Mississippi: 2016). By 2012, all state partners were using the same gear and deployment methods, with minor exceptions. By 2016, all state partners were also following a unified sampling design (GSMFC 2018). These standardized VL surveys are useful in providing physical samples; they are also valuable for the estimation of fishery-independent, relative indices of abundance (Campbell et al 2017). These indices are particularly valuable for reef-fish species like Red Snapper because, unlike some other indices, which are based on the catch from gears like trawls and bottom long-lines, the VL gear specifically targets the exploited segment of the Red Snapper population. Our goal was to use the SEAMAP vertical line survey data collected by state partners in Texas, Louisiana, Mississippi, Alabama, and Florida to estimate a gulf-wide index of abundance for Red Snapper conditioned on region, depth, and habitat type.

SAMPLING DESIGN

Before 2016, state partners employed a variety of systems to select station locations for their VL surveys. In 2015, the SEAMAP subcommittee developed a uniform sampling design that was subsequently adopted by the state partners beginning in 2016. Here we present a short history of the state-specific designs leading up to the currently employed uniform sampling design.

Alabama

In collaboration with the University of South Alabama, Alabama MRD has been using side-scan sonar to map a large portion of the shelf region with an initial emphasis on the Alabama Artificial Reef Permitting Zone (ARPZ). Each year, they randomly select 2km x 2km grid cells for mapping. In 2012, they randomly selected 12 previously mapped grid cells within the ARPZ, proportionally allocated across three depth strata (20-40m, 40-60m, and 60-100m), and then randomly selected two structure and two non-structure sites within each of the selected grid cells to sample using both ROV video and VL gear. In

2013, they increased the total number of grid cells to 18. In 2014, they increased overall effort to 24 grid cells (48 stations), included grid cells outside of the ARPZ, increased the maximum depth in their deepest depth stratum from 100m to 120m, and conducted half (n = 24) of their VL surveys along with paired ROV video surveys and half (n = 24) without paired ROV surveys. In 2015, they selected 18 grids and sampled two thirds of the stations (n = 24) with both VL and ROV and one third (n = 12) with VL only.

Louisiana

From 2011 to 2015, Louisiana sampled using a quarterly rotation across three equal width longitudinal zones. Each zone was further divided into one-minute (longitude) sections. Sites were randomly selected within these one-minute subsections with a final safety filter at the chief scientist's discretion. Sites were further divided into habitat and depth strata with the following sample allocations: 23% artificial reefs, 3% natural bottom, 74% petroleum platforms, 54% shallow (30-40m), 27% medium-depth (40-60m), and 19% deep (60-120m) (Campbell et al 2017).

Florida

In 2013, Florida's VL effort was allocated to sites that were selected from a larger group of "fishing points" provided by industry partners. These were nearly exclusively restricted to artificial reef habitats. However, beginning in 2014, Florida began to use side-scan sonar to map randomly selected grids across three statistical zones (9, 4 & 5), further divided into three depth zones (shallow: 10-37m, mid-depth: 37-110m, deep: 110-200m). They then randomly selected VL stations from habitats identified in the mapped grids including both natural and artificial reefs.

Texas

In 2015, Stations were randomly selected from a universe of known reef habitat between 10 and 40m depth and across statistical zones 17-21. These stations consisted primarily of oil and gas platforms (Campbell et al 2017).

SEAMAP uniform sampling design

In 2016 the state partners adopted the SEAMAP uniform sampling design. This design divides the GoM offshore waters between 10 and 150m depth into 150 by 150m cells. Each cell is assigned one or more habitat classifications based on multiple habitat data sources. Habitat types include unknown, known natural reef, presumed natural or artificial reef, oil/gas platforms, and artificial reefs. Sampling effort (number of stations) is allocated proportionally based on the area of each habitat type in each depth zone and the area of each depth zone in the overall region. Stations are then randomly selected based on this allocation (GSMFC 2018).

SURVEY METHODS

Survey gear and methods have been largely uniform, with only very small differences among the various state partners since 2012 (GSMFC 2018). The VL gear consists of four major parts, the mainline and reel, the backbone, the gangions (with hooks), and the weight. Reels used are typical commercial grade "bandit" type reels (e.g., Waterman Standard Electric Bottom Reel). These hold spools of approximately

500 ft of 300 to 400 lb. test, clear monofilament mainline. The mainline is connected to a detachable backbone that is 6.7m long and made of 400 lb. test clear monofilament. The mainline carries ten detachable 46 cm long gangions constructed of twisted 100 lb. monofilament placed at 61 cm intervals. Each gangion carries a single circle hook baited with Atlantic mackerel (*Scomber scombrus*). Hook size is the same for the entire backbone, but a backbone can carry 8/0, 11/0, or 15/0 size hooks. Each backbone is weighted with a 10 lb. weight (rebar, shot, anchor, etc.).

The standard survey consists of three backbones, one with each of the three hook sizes, fished from three bandit rigs simultaneously from a single vessel (GSMFC 2018). If a vessel was too small to fish three rigs simultaneously, the modified procedure was to fish two randomly selected hook sizes at the first station of the day and then rotate through the three hook sizes for the remainder of the stations for that day. In either case, the three hook sizes were rotated to different positions on the vessel throughout the day. When the survey vessel arrives at the target latitude and longitude, they use their depth sounder to locate the precise position of the reef. The vessel holds station over this position for the duration of the deployment. Gear is typically fished with the weight just off the bottom to maintain taught lines, but depth fished can be adjusted based on safety concerns and/or to avoid known hypoxic conditions. Once all three rigs are locked in at the fishing depth, they are soaked for five minutes before retrieval. After five minutes, all three rigs are reeled in simultaneously if possible. Catch was identified, weighed (kg), and measured (FL, mm). Otolith and gonads samples were collected from a random subset of fish.

INDICES OF ABUNDANCE

Data Acquisition and Processing

We acquired data from both the GSMFC SEAMAP VL database and directly from state partners. We compiled the data and conducted extensive QA/QC checks. There were two important issues uncovered during this process that we were not able to fix. First, there were a substantial number of stations from Texas in 2021 that listed more than three backbones fished. While there is likely an easy fix to this problem, we did not receive the 2021 Texas data in time to resolve it. Therefore, these data (All Texas 2021) were excluded from the analysis. The other issue was that it became evident that a substantial number of "stations" in the dataset were repeat samples occurring at the same physical locations. When these occurred on the same day, we censored the second sample, but when they occurred on different days (typically these were separated by several months if not years) we left them in the analysis. Multiple samples taken at the same location/reef should ideally not be treated as independent replicates because doing so can cause the resulting estimates of uncertainty to be anti-conservative (i.e., too narrow). The best way to model such data is to use a mixed-effects model with a random location or reef ID factor (Bolker et al 2009, Zurr et al 2009). Unfortunately, due to the limited timeline of this analysis, we were unable to explore the fit of such models. At the same time, we did not want to eliminate all repeat samples from the data set. Therefore, the uncertainty estimates resulting from our analysis should be interpreted with this in mind.

To accurately represent the fishing effort associated with each sample, we examined all fields related to lost or damaged gear and lost or damaged hooks. We compared notes, OPSCODEs, HOOKSTATUS, etc. to determine, on a hook-by-hook basis, whether individual hooks were available to catch fish. We used the count of "good" hooks (those that caught fish or were available to catch fish) on a given backbone along with the soak time for that backbone to calculate backbone-specific effort in units of hooks per hour. We then summed the effort across backbones at a station to calculate the total station-level effort. This was important because some backbones had different numbers of "good" hooks and/or different soak times. Stations with effectively zero effort (all hooks missing, lost gear, etc.) were censored.

We also created several new predictors to use in model fitting. First, we created a Zone predictor based on "Option C" from the SEDAR 74 Stock ID Report. All Texas and Louisiana stations were included in the West Zone, All Alabama stations and all Florida stations ≥ 29.0° N latitude were included in the Central Zone, and All Florida stations < 29.0° N latitude were included in the East Zone. Next, we created a coarse two-level habitat type predictor by filtering existing habitat classification fields in the various data sources. All samples identified as having occurred at artificial reefs, petroleum platforms, stand-pipes, etc. were categorized as Artificial Reef habitat type, and all samples identified as having occurred at natural bottom or natural reef were categorized as Natural Bottom habitat type. Samples identified as having occurred on unknown or unstructured habitats were censored from the data set (n = 48). Next, we created a three-level Depth factor using the SEAMAP depth strata (Shallow = 10-20m, Mid-depth = 20-40m, and Deep = 40-150m). Finally, we created three binomial Hook-size indicator variables for each of the hook sizes used in the survey. This was used to account for the fact that not all three hook sizes were fished at all sites (e.g., when only two backbones were fished off smaller vessels). These were based on the number of "good" hooks of each size fished at a station. For example, the 8/0 Hook-size indicator was equal to 1 if eight or more "good" hooks of this size were fished at the station and equal to 0 if seven or fewer "good" hooks were fished at the station.

Because of the lack of standardization of gear and deployment methods existing before 2012, we did not include any data from earlier years in our analysis. Unfortunately, data from Mississippi were not acquired in time to include in the current analysis. However, we now have those data in hand, and can integrate them into the analysis later if desired.

Sample coverage

While our goal was to develop an index of abundance conditioned on region, depth, and habitat type, the data did not include sufficient representation in each orthogonal combination of these variables for a synoptic examination (Tables 1-3, Figures 1-7). Coverage was very limited for several categories. Sample sizes were insufficient for accurate estimation of relative abundance on Deep Artificial reefs and on both Shallow and Mid-depth Natural reefs in the West and Central Zones. Conversely, sample sizes were too small for Shallow and Mid-depth Artificial reefs and Deep Natural reefs in the East Zone. Additionally, samples in the West Zone were dominated by those from Louisiana, particularly in the early and late years. Similarly, samples in the Central Zone were dominated by those from Alabama during the early and late years. Due to the lack of balanced sample coverage across the factors of interest, we constructed several models, each including different sets of predictors, to try to provide informative indices of abundance across various segments of the population. It is important to keep in mind that the estimates from these models are greatly influenced by the various biases in sample coverage, which should be considered when interpreting the various indices. We considered attempting to use a weighted model that would account for some of these biases. Unfortunately, there was not enough information available across the various combinations of the factors of interest to construct a defensible or comprehensive weighting scheme. Additionally, there is no weighting scheme that can account for orthogonal combinations of predictors that are simply lacking sufficient sample coverage to provide estimates of the response variable.

Model fitting and results

The unconditional distribution of the response variable (RScount = number of Red Snapper caught per station) had a low mean (3.23), a high variance (24.75) and a high proportion of zeros (53%, Figure 8). When conditioned on year, these patterns remained evident, suggesting that a negative binomial GLM, or negative binomial GLM with additional zero inflation, would likely provide the best fit to the data.

We anticipated that the imbalances and incomplete coverage in the dataset would limit the complexity of models that could be fit to the data. Therefore, our strategy was to start simple and then add complexity by incorporating additional factors of interest. We started with a simple conditional model of Red Snapper count as a function of Year (as a categorical predictor) and the three hook-size indicator variables with an offset for effort.

$$RScount \sim Year + HS8 + HS11 + HS15 + \text{offset}(\log(HookHours))$$

We fit GLMs with three different distributions (Poisson, negative binomial type 1, and negative binomial type 2) using this same conditional formula. We also fit three corresponding zero-inflation mixture models with the zero-inflation parameter conditioned on the Year factor. The best fitting model according to AIC was the negative binomial type 1 GLM with zero-inflation (Table 4). We calculated randomized quantile (RQ) residuals from our model (Dunn & Smyth 1996; Gelman & Hill 2006, Hartig 2022) and assessed model fit using a quantile-quantile plot along with plots of residuals against fitted values and against the Year predictor. All plots indicated an acceptable model fit (Figures 8 & 9). Plots of residuals against predictors that were not in the model (i.e., Zone, Depth, and Habitat) suggested that their inclusion might improve model fit (Figure 9). All the predictors (Year and all three hook-size indicators) had a significant effect on the response variable based on "leave-one-out" likelihood ratio tests (LRT, all p-values < 0.001). This model resulted in a single gulf-wide index of abundance (Table 5, Figure 10). This index is naïve in that it incorporates all the site selection biases inherent in the data set (e.g., more artificial reef than natural reef samples; more samples from AL and LA than other areas, particularly in the early and late years; more deep natural reefs and shallow artificial reefs in the West and Central zones; more shallow natural reefs and deep artificial reefs in the East, etc.).

To build a more comprehensive picture of Red Snapper relative abundance, we wanted to take some of these other potential predictors into account by including them in the models. We began by fitting conditional models of Red Snapper count as a function of Year, Habitat, the Year:Habitat interaction, and the three hook-size indicators with an offset for effort.

$$RScount \sim Year + Habitat + Year{:}Habitat + HS8 + HS11 + HS15 + \text{offset}(\log(HookHours))$$

Again, we fit the same six GLMs as described above. Based on AIC, the best fitting of these models was again the type 1 negative binomial model with zero inflation (Table 6). Diagnostic plots as described above indicated an acceptable model fit (Figures 11 & 12). Based on LRTs, the Year:Habitat interaction and all three hook-size indicators were significant predictors of Red Snapper catch (all p-values < 0.0001). The indices from this model are conditional on year and habitat type but are averaged over all other potential predictors and therefore suffer from the same potential sampling design biases as the more naïve model above. The difference is that this model considers the differences in catch between the two major habitat types sampled, artificial and natural reefs (Table 7, Figure 13).

We repeated the above for models including Year, Depth, and the Year:Depth interaction (Tables 8 & 9, Figures 14-16) as well as for Year, Zone, and the Year:Zone interaction (Tables 10 & 11, Figures 17-19).

$$RScount \sim Year + Depth + Year{:}Depth + HS8 + HS11 + HS15 + \text{offset}(\log(HookHours))$$

$$RScount \sim Year + Zone + Year{:}Zone + HS8 + HS11 + HS15 + \text{offset}(\log(HookHours))$$

Since there were no samples collected in the East Zone in the early (2012) and late (2019-2021) parts of the time series, the only way to fit the Year + Zone + Year:Zone model was to censor these early and late years from the dataset. As an alternative, we also fit three separate models, one for each Zone (West, Central, and East) using the full time series available for each Zone. All three models were type 1 negative binomial models with zero-inflation with Red Snapper count conditioned on Year, the three hook-size indicators, and an offset for effort and with the zero-inflation component conditioned on Year. We present the fitted values and uncertainties from the three models on the same plot for comparison (Table 12, Figures 20 & 21).

We attempted to further generalize the resulting indices by fitting models to more than two predictors at once including Year, Depth, Habitat; Year, Depth, Zone; and Year, Habitat, Zone. In all three cases, even for severely restricted subsets of the data, we ran into model convergence issues. There were simply not enough non-zero responses in some cells for the models to converge reliably.

All model fitting was conducted in the R environment for statistical computing (R Core Team 2022) and utilized the glmmTMB package (Brooks et al 2017). We used the DHARMa package (Hartig 2022) to calculate randomized quantile (RQ) residuals.

We have plotted the length frequency distributions for all of the fish included in the analysis both pooled and broken down by hook-size, Zone, and both hook-size and Zone (Figures 22-25).

DISCUSSION

During the early years of sampling (2012-2015), spatial coverage was severely limited and there was a general lack of standardization among the sampling designs employed by the various state partners. This has resulted in what are likely to be severely biased samples (e.g., most early surveys are concentrated in the Alabama Reef Permit Zone and the area in Louisiana directly south of the Mississippi delta known as “Rig City” and all East samples from 2013 and all Texas samples from 2015 occurred on artificial habitats). Even during years with the most complete spatial coverage (2016-2018) certain combinations of Zone, Habitat, and Depth are simply not well represented (e.g., Mid-depth artificial reefs in the East Zone, Shallow and Mid-depth natural reefs in the Central and West Zones). Low sample numbers in particular categories are likely a function of low availability of stations that fit those categories. In this sense, they are not particularly problematic in terms of introducing bias. They are, however, a barrier to the use of models as estimation tools. This issue is exacerbated by the high proportion of zeros in the data set. Small sample sizes in particular orthogonal combinations of predictors, combined with a high proportion of zero responses results in a high likelihood that all the samples for a particular combination of factor levels are zeros. This makes the variance estimation necessary for model fitting impossible.

With the above caveats in mind, the overall “naïve” index, with CPUE modelled on Year, reflects a consistent and relatively strong downward trend over the time series (even ignoring the anomalously high estimate for 2012). This appears to be at least qualitatively similar in the early part of the time series (pre-2016) as in the later part (post 2016). The “by habitat” indices appear to be divergent in the early years (pre-2016) with higher CPUE on artificial reefs than on natural reefs, and more convergent in later years (post 2016) when the difference between the two habitats disappears. Based on previous analyses of similar data sets (Campbell et al 2017), we expected a much more consistent difference between the two habitat types with artificial reefs outperforming natural reefs. The “by Depth” indices exhibit patterns that reflect the overall pattern in the Year-only index, namely a generally consistent decline in CPUE across the series. In general, it appears the Shallow index has somewhat lower CPUE across the time series with a more prominent and earlier onset decline than the other two depth strata. The Mid-depth stratum has the highest overall CPUE with some indication of a decline in the later years. The Deep stratum exhibits moderate CPUE with some suggestion of a late decline. The “by Zone” indices again reflect the overall pattern of steady decline in CPUE across the time series seen in the Year-only index, at least for the West and Central Zones. The Central Zone exhibits the most drastic decline, with a slower and less consistent decline in the West Zone. The East zone, while exhibiting the lowest CPUE by far, does not appear to be declining. If anything, there may be a suggestion of a decline between 2013 and 2014 with a slight increase from 2014 onwards, although the increase is quite small relative to the overall uncertainty in the index.

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Table 1: Number of VL stations in the West Zone across years, depth strata, and habitat types.

	Artificial			Natural		
Year	*Shallow*	*Mid-depth*	*Deep*	*Shallow*	*Mid-depth*	*Deep*
2012	14	56	22	0	1	5
2013	94	205	101	0	7	15
2014	19	41	39	0	0	2
2015	38	66	40	0	0	5
2016	33	33	2	7	13	26
2017	34	34	4	0	10	75
2018	31	33	5	0	0	66
2019	29	38	3	0	8	43
2020	11	11	0	0	0	0
2021	22	16	2	0	0	29

Table 2: Number of VL stations in the Central Zone across years, depth strata, and habitat types.

	Artificial			Natural		
Year	*Shallow*	*Mid-depth*	*Deep*	*Shallow*	*Mid-depth*	*Deep*
2012	14	56	22	0	1	5
2013	94	205	101	0	7	15
2014	19	41	39	0	0	2
2015	38	66	40	0	0	5
2016	33	33	2	7	13	26
2017	34	34	4	0	10	75
2018	31	33	5	0	0	66
2019	29	38	3	0	8	43
2020	11	11	0	0	0	0
2021	22	16	2	0	0	29

Table 3: Number of VL stations in the East Zone across years, depth strata, and habitat types

	Artificial			Natural		
Year	*Shallow*	*Mid-depth*	*Deep*	*Shallow*	*Mid-depth*	*Deep*
2012	14	56	22	0	1	5
2013	94	205	101	0	7	15
2014	19	41	39	0	0	2
2015	38	66	40	0	0	5
2016	33	33	2	7	13	26
2017	34	34	4	0	10	75
2018	31	33	5	0	0	66
2019	29	38	3	0	8	43
2020	11	11	0	0	0	0
2021	22	16	2	0	0	29

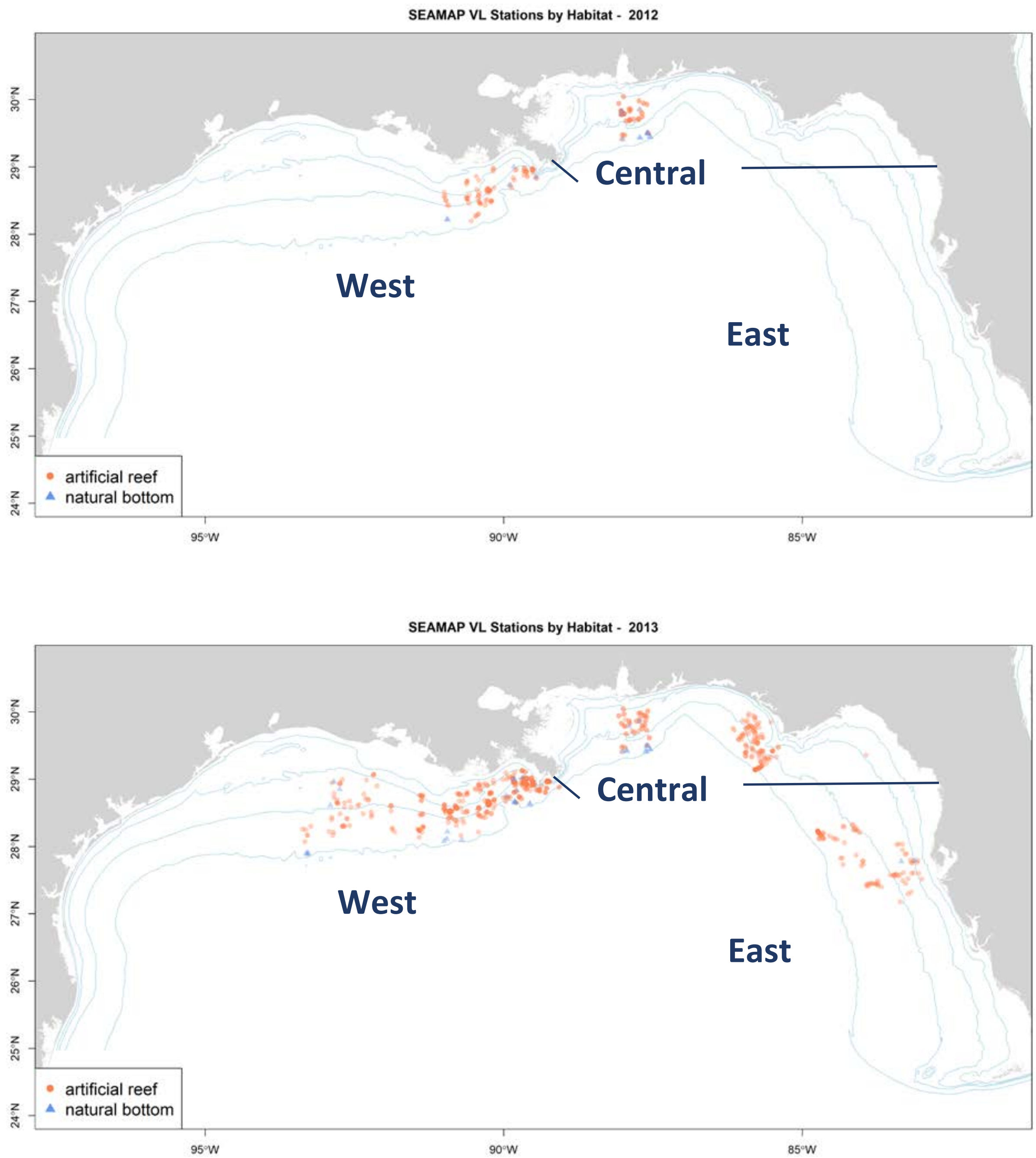
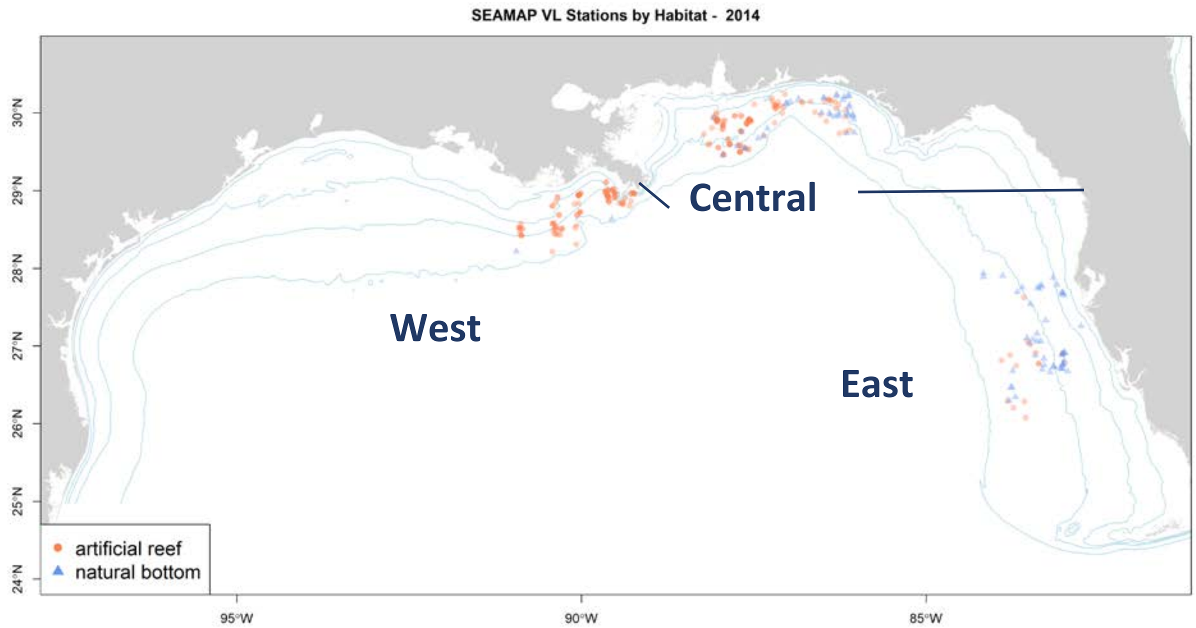


Figure 1: Maps of VL stations conducted in 2012 (top) and 2013 (bottom). Orange circles represent artificial reefs, while light-blue triangles represent natural bottom. Zones (West, Central, and East) are as described in "Option C" from the SEDAR 74 Stock ID Report. Isobath lines represent the limits of the SEAMAP depth strata (10, 20, 40, and 150 m).



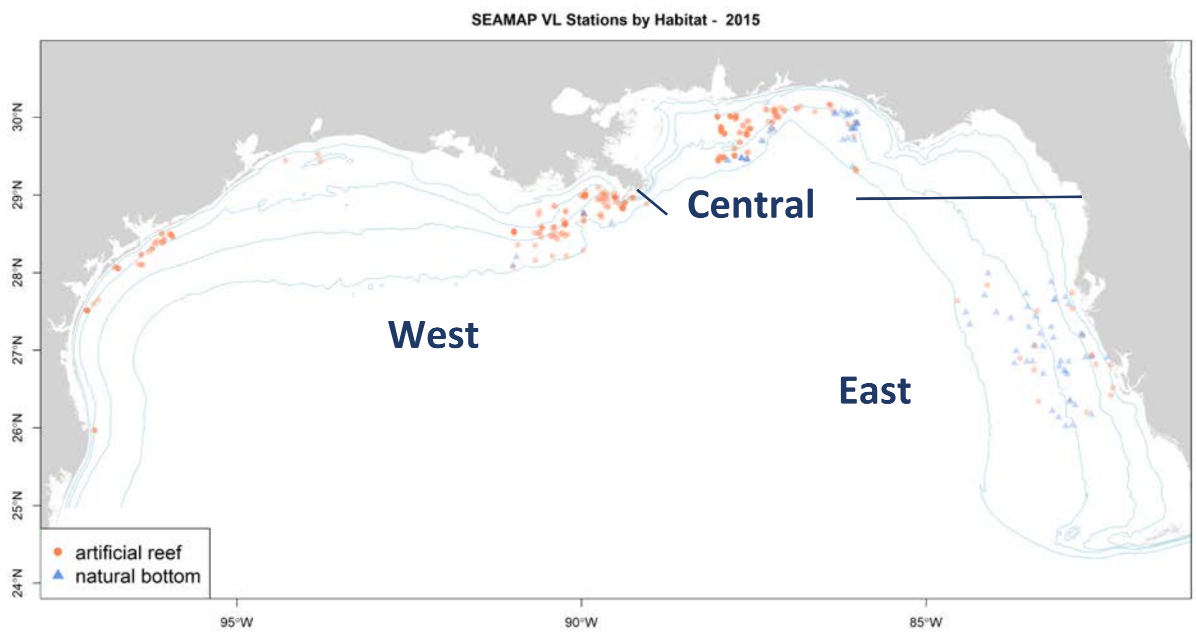
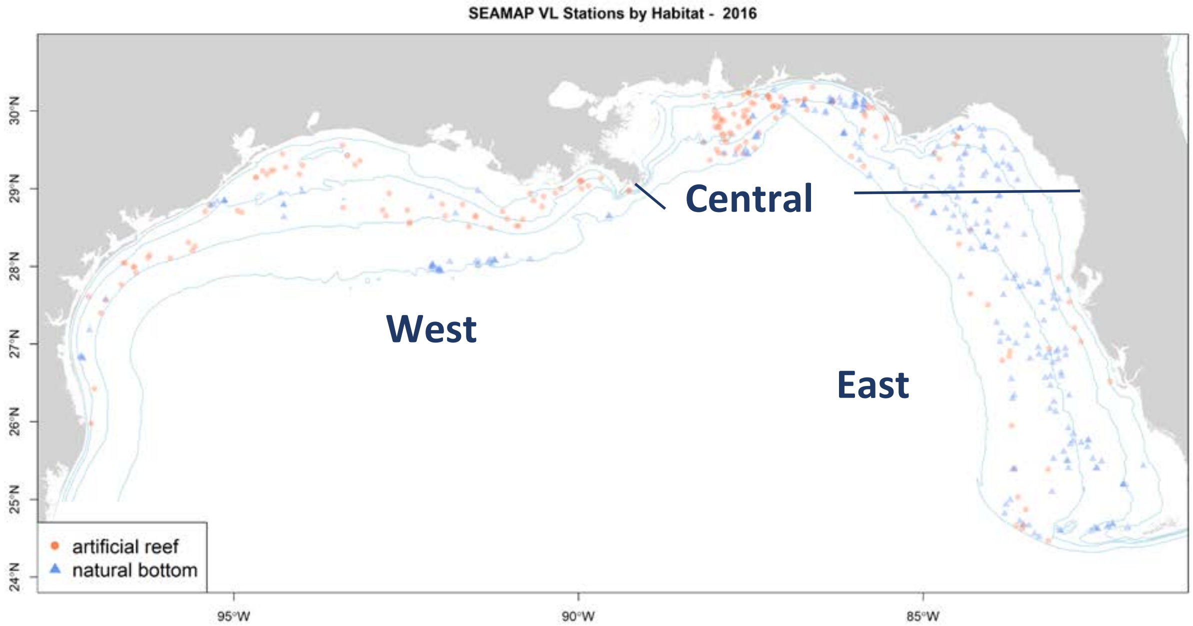


Figure 2: Maps of VL stations conducted in 2014 (top) and 2015 (bottom). Orange circles represent artificial reefs, while light-blue triangles represent natural bottom. Zones (West, Central, and East) are as described in "Option C" from the SEDAR 74 Stock ID Report. Isobath lines represent the limits of the SEAMAP depth strata (10, 20, 40, and 150 m).



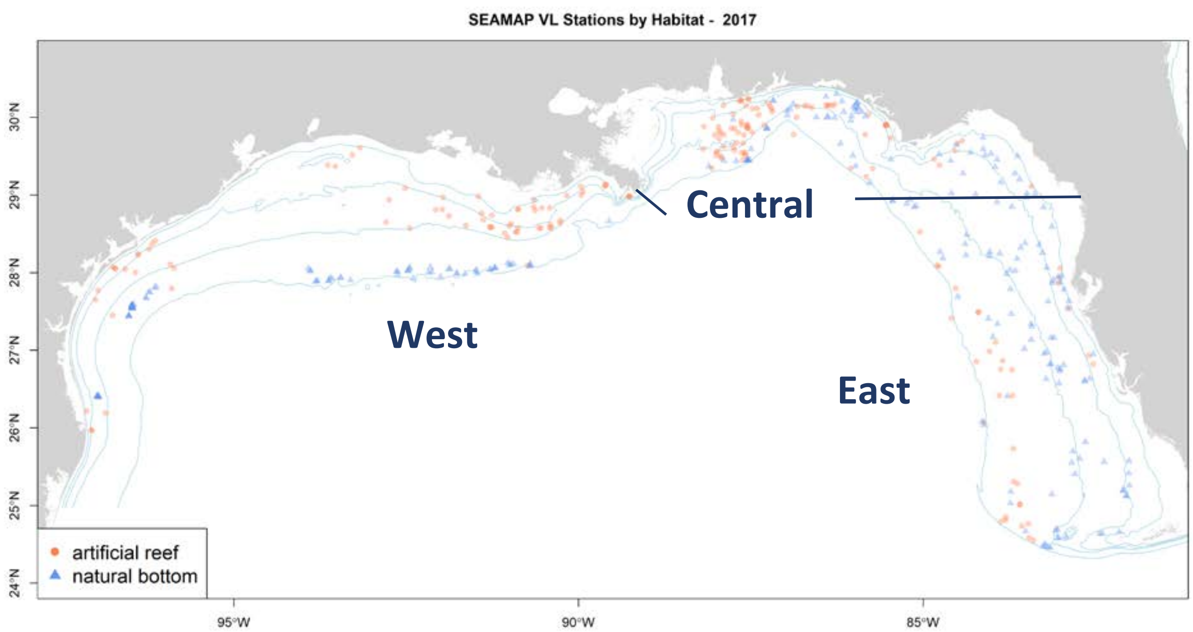
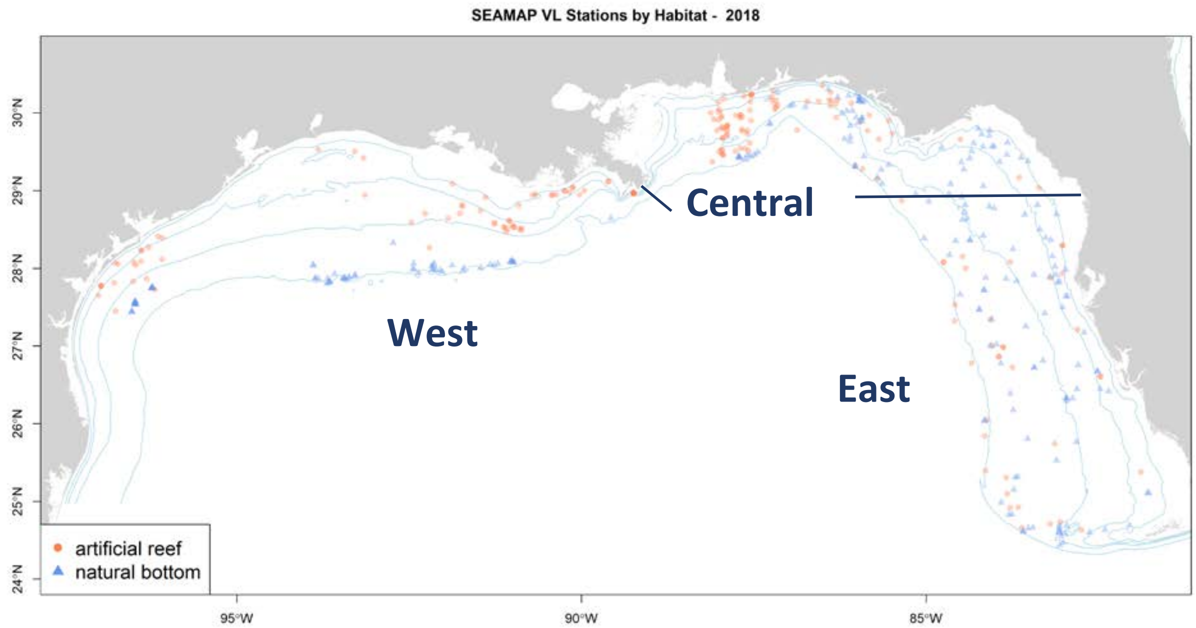


Figure 3: Maps of VL stations conducted in 2016 (top) and 2017 (bottom). Orange circles represent artificial reefs, while light-blue triangles represent natural bottom. Zones (West, Central, and East) are as described in "Option C" from the SEDAR 74 Stock ID Report. Isobath lines represent the limits of the SEAMAP depth strata (10, 20, 40, and 150 m).



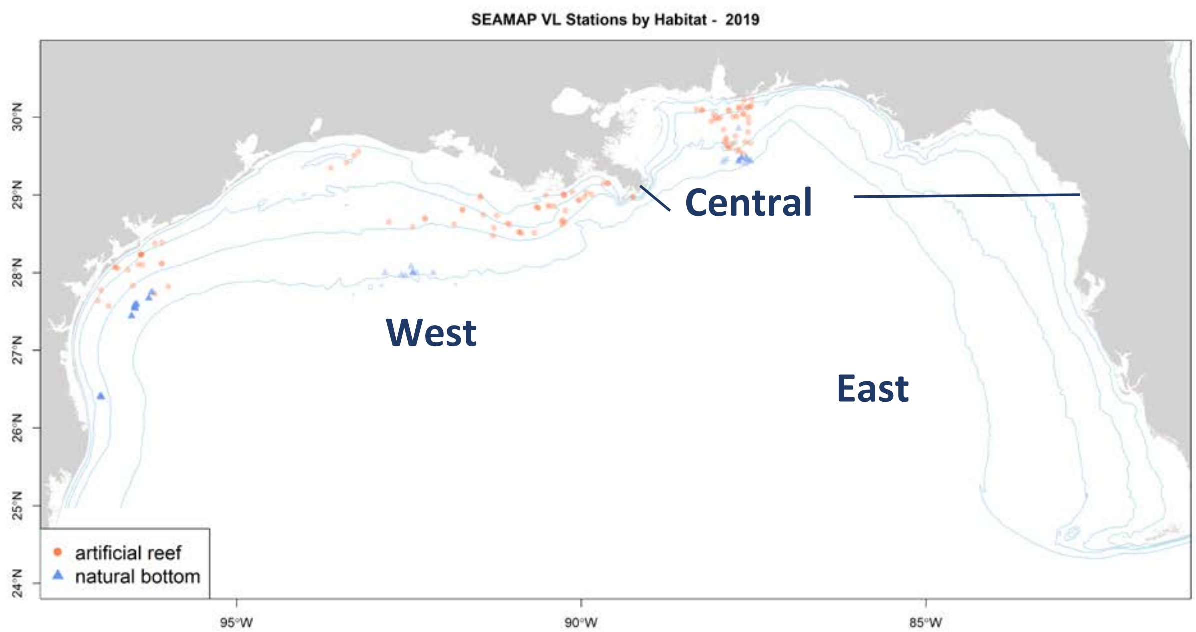
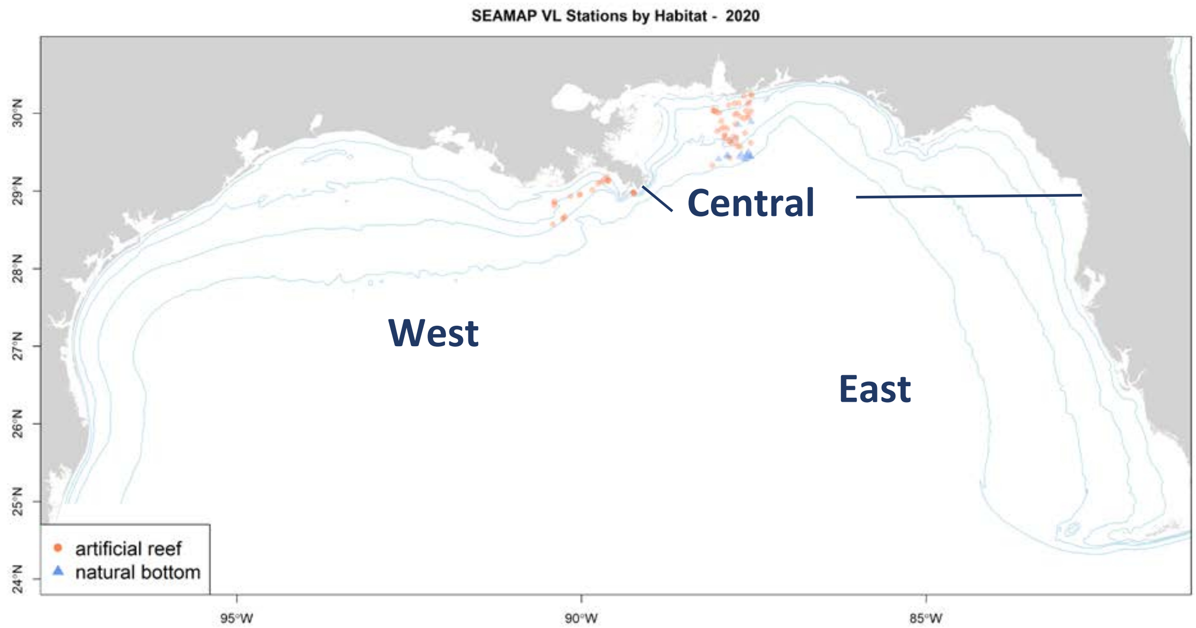


Figure 4: Maps of VL stations conducted in 2018 (top) and 2019 (bottom). Orange circles represent artificial reefs, while light-blue triangles represent natural bottom. Zones (West, Central, and East) are as described in "Option C" from the SEDAR 74 Stock ID Report. Isobath lines represent the limits of the SEAMAP depth strata (10, 20, 40, and 150 m).



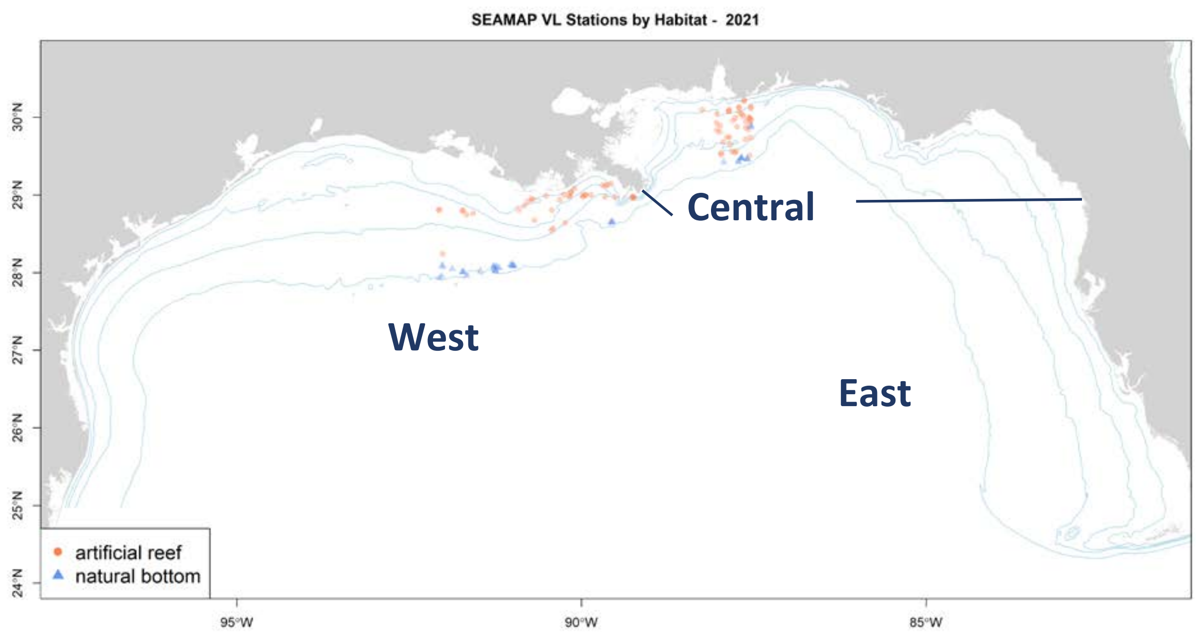


Figure 5: Maps of VL stations conducted in 2020 (top) and 2021 (bottom). Orange circles represent artificial reefs, while light-blue triangles represent natural bottom. Zones (West, Central, and East) are as described in “Option C” from the SEDAR 74 Stock ID Report. Isobath lines represent the limits of the SEAMAP depth strata (10, 20, 40, and 150 m).

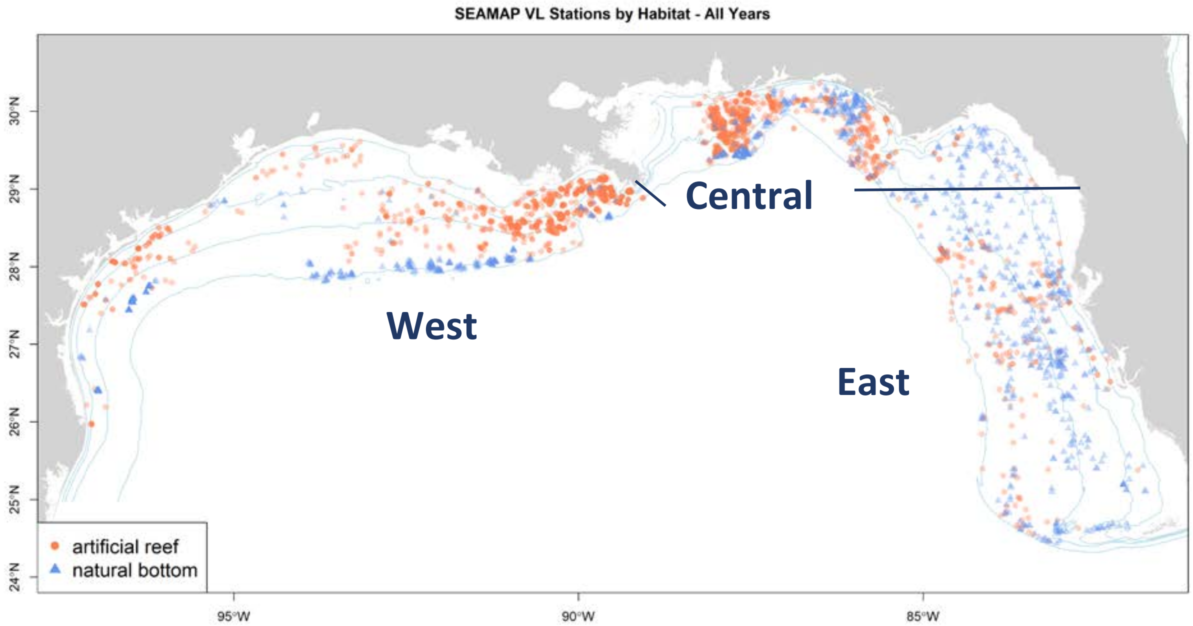


Figure 6: Top: Maps of VL stations conducted from 2012-2021. Orange circles represent artificial reefs, while light-blue triangles represent natural bottom. Zones (West, Central, and East) are as described in "Option C" from the SEDAR 74 Stock ID Report.

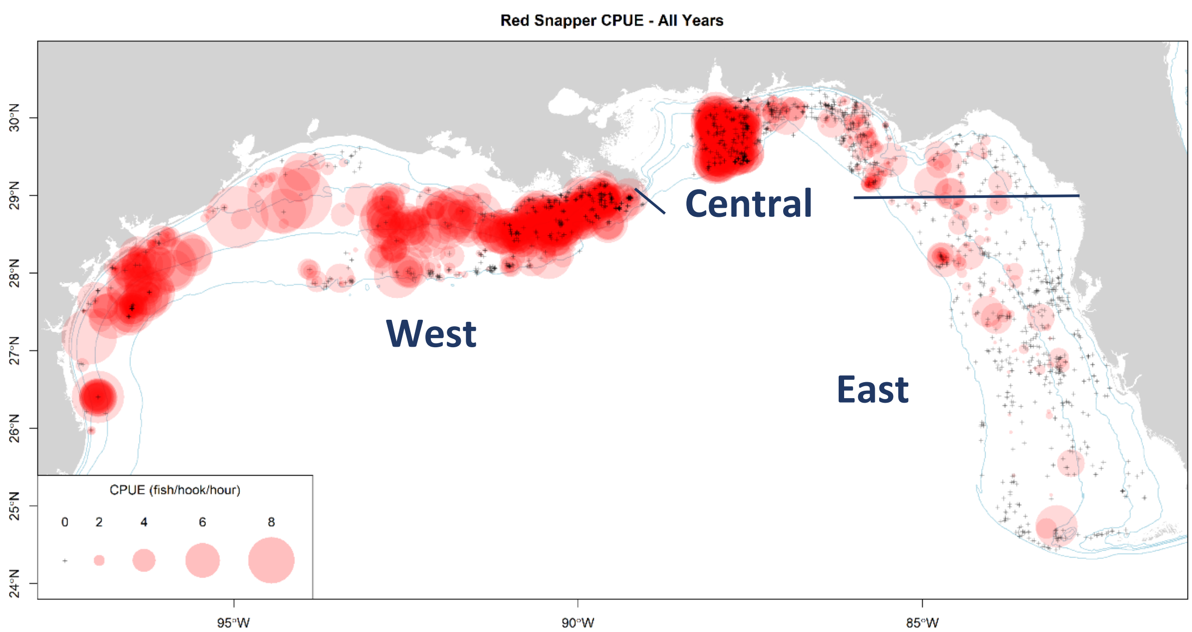


Figure 7: Bubble plot of vertical line CPUE of Red Snapper at stations sampled from 2012-2021. Zero-catch samples are plotted as black "+" symbols.

Table 4: Comparison of ΔAIC among six competing initial models. The conditional formula for all models was Red Snapper catch as a function of the Year factor and the three hook-size indicator variables. The zero-inflation component was conditioned on the Year factor.

Model	ΔAIC	df
Negative binomial 1 - zero-inflation	0	24
Negative binomial 2 - zero-inflation	160	24
Negative binomial 1	221	14
Negative binomial 2	387	14
Poisson - zero-inflation	2397	23
Poisson	10574	13

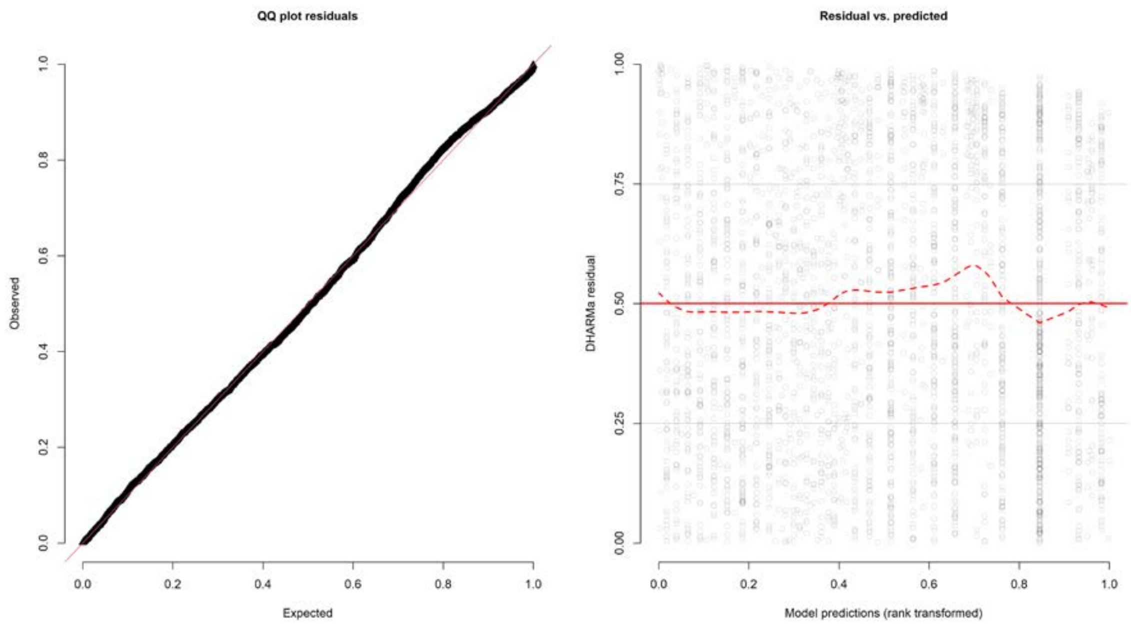


Figure 8: Quantile-Quantile plot (left) and Residual vs. Predicted values (right) from a type 1 negative binomial GLM with zero-inflation. Response modeled as a function of the Year factor and the three hook-size indicators. Zero-inflation modeled as a function of the Year factor. Residuals are randomized quantile residuals.

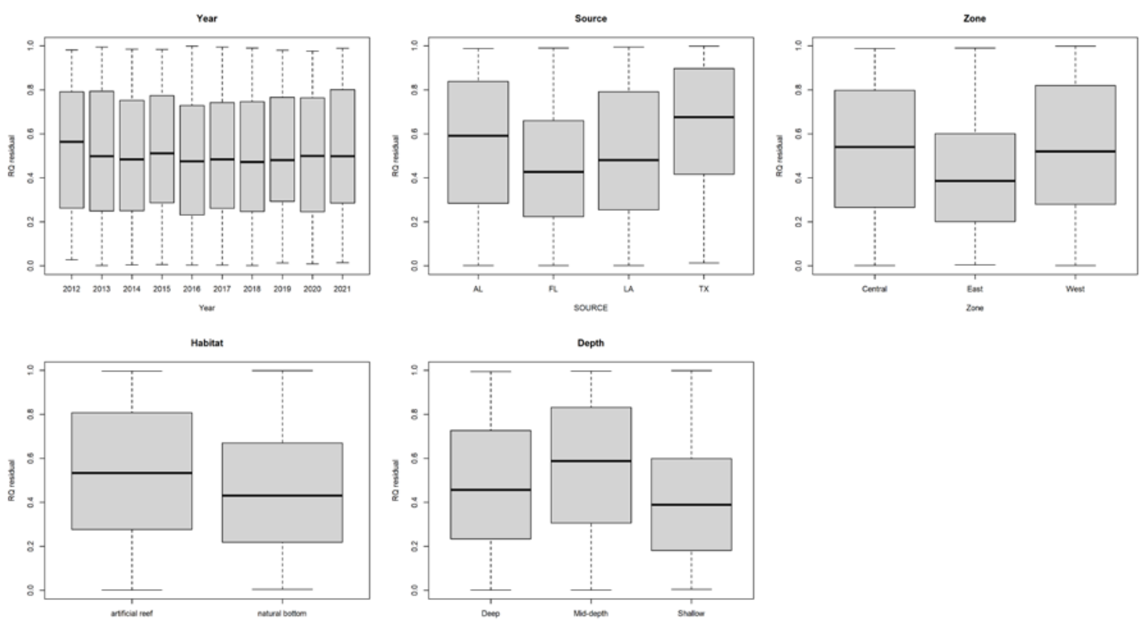


Figure 9: Plots of randomized quantile residuals against predictors that were (year) and were not (Source, Zone, Habitat, Depth) included in the model. From a type 1 negative binomial GLM with zero-inflation. Response modeled as a function of the Year factor and the three hook-size indicators. Zero-inflation modeled as a function of the Year factor.

Table 5: Model predictions from type 1 negative binomial GLM with zero-inflation. The conditional formula for the model was Red Snapper catch as a function of the Year factor and the three hook-size indicator variables. The zero-inflation component was conditioned on the Year factor. Fit, SE, CV, LL, and UL (resp.) are the model fitted values, standard errors, coefficient of variation (SE/Fit), and approximate lower and upper limits of a 95% confidence interval, all on the response scale. Fit, LL, and UL (stand.) are standardized values (divided by the mean of the fitted values).

Year	Fit (resp.)	SE (resp.)	CV (resp.)	LL (resp.)	UL (resp.)	Fit (stand.)	LL (stand.)	UL (stand.)
2012	3.251	0.263	0.081	2.724	3.778	1.764	1.479	2.050
2013	1.999	0.108	0.054	1.783	2.216	1.085	0.968	1.203
2014	2.104	0.169	0.080	1.766	2.442	1.142	0.958	1.325
2015	1.974	0.149	0.075	1.676	2.272	1.071	0.910	1.233
2016	1.603	0.153	0.096	1.296	1.909	0.870	0.703	1.036
2017	1.725	0.145	0.084	1.434	2.015	0.936	0.778	1.094
2018	1.395	0.123	0.088	1.150	1.641	0.757	0.624	0.890
2019	1.782	0.174	0.098	1.434	2.131	0.967	0.778	1.156
2020	1.271	0.201	0.158	0.869	1.673	0.690	0.472	0.908
2021	1.322	0.177	0.134	0.967	1.676	0.717	0.525	0.910

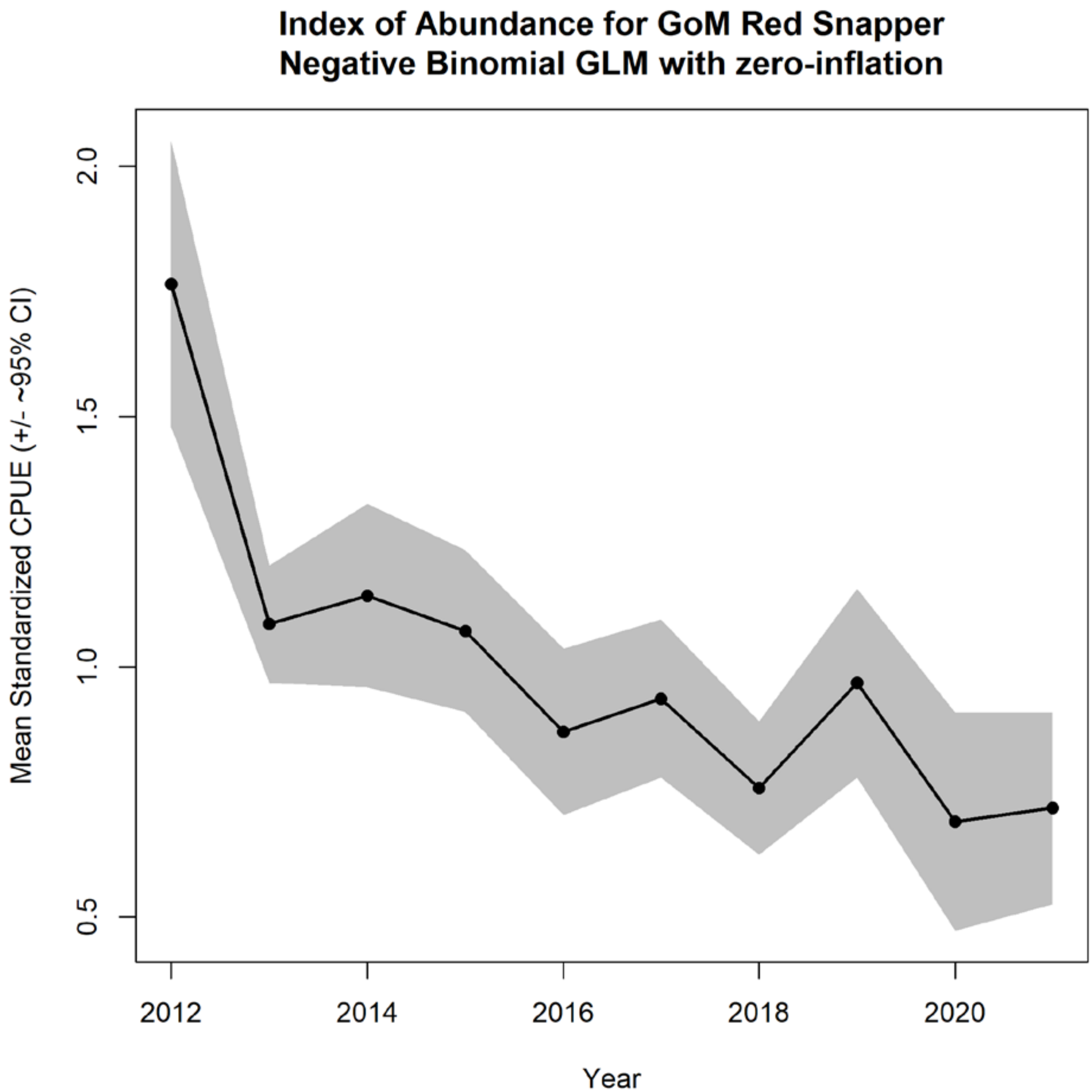


Figure 10: Standardized index of abundance based on model predictions from type 1 negative binomial GLM with zero-inflation. The conditional formula for the model was Red Snapper catch as a function of the Year factor and the three hook-size indicator variables. The zero-inflation component was conditioned on the Year factor.

Table 6: Comparison of ΔAIC among six competing initial models. The conditional formula for all models was Red Snapper catch as a function of Year, Habitat, the Year:Habitat interaction, and the three hook-size indicator variables. The zero-inflation component was conditioned on Year, Habitat, and the Year:Habitat interaction.

Model	ΔAIC	df
Negative binomial 1 - zero-inflation	0	44
Negative binomial 2 - zero-inflation	120	44
Negative binomial 1	237	24
Negative binomial 2	422	24
Poisson - zero-inflation	2173	43
Poisson	9912	23

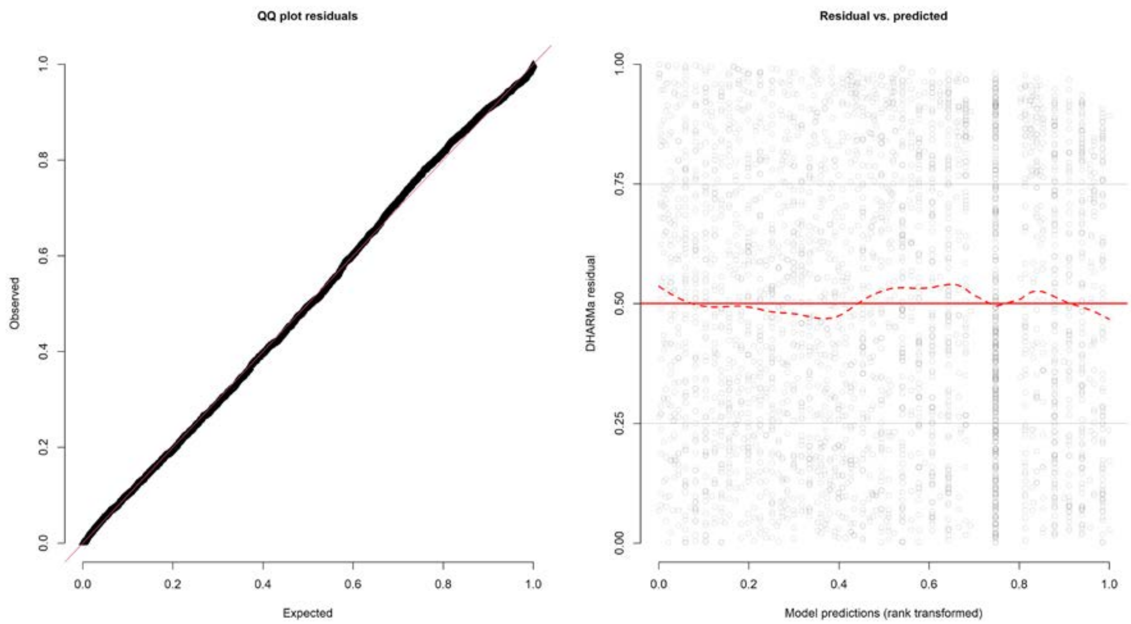


Figure 11: Quantile-Quantile plot (left) and Residual vs. Predicted values (right) from a type 1 negative binomial GLM with zero-inflation. Response modeled as a function of Year, Habitat, the Year:Habitat interaction, and the three hook-size indicators. Zero-inflation modeled as a function of Year, Habitat and the Year:Habitat interaction. Residuals are randomized quantile residuals.

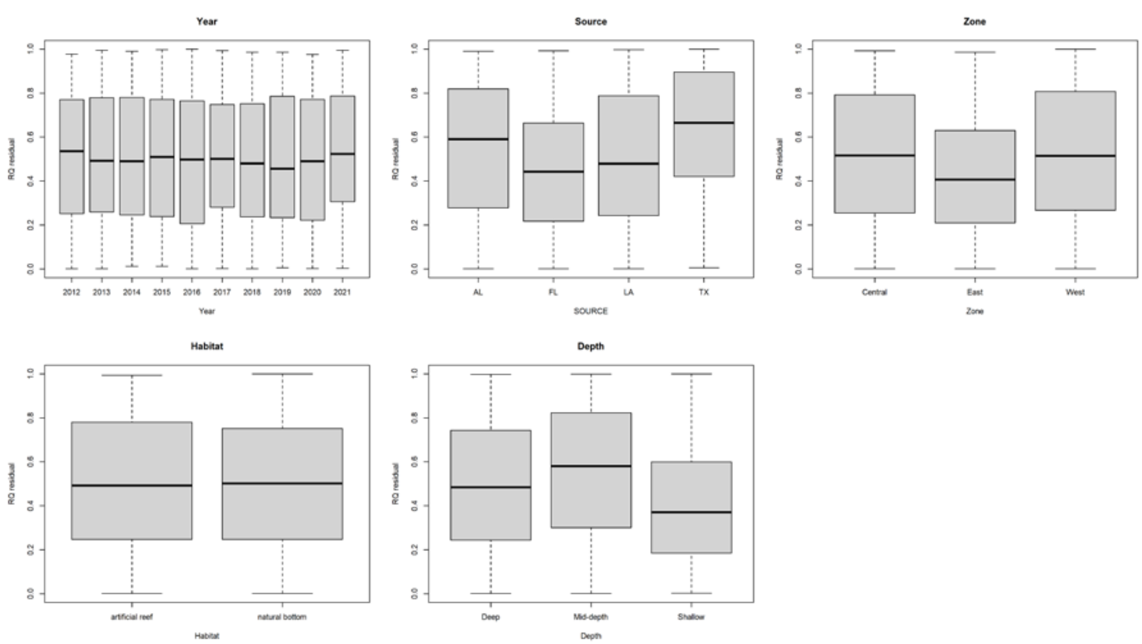


Figure 12. Plots of randomized quantile residuals against predictors that were (Year, Habitat) and were not (Source, Zone, Depth) included in the model. From a type 1 negative binomial GLM with zero-inflation. Response as a function of Year, Habitat, the Year:Habitat interaction and the three hook-size indicators. Zero-inflation modeled as a function of Year, Habitat, and the Year:Habitat interaction.

Table 7: Model predictions from type 1 negative binomial GLM with zero-inflation. The conditional formula for the model was Red Snapper catch as a function of Year, Habitat, the Year:Habitat interaction, and the three hook-size indicator variables. The zero-inflation component was conditioned on Year, Habitat, and the Year:Habitat interaction. Fit, SE, CV, LL, and UL (resp.) are the model fitted values, standard errors, coefficient of variation (SE/Fit), and approximate lower and upper limits of a 95% confidence interval, all on the response scale. Fit, LL, and UL (stand.) are standardized values (divided by the mean of the fitted values).

Year	Habitat	Fit (resp.)	SE (resp.)	CV (resp.)	LL (resp.)	UL (resp.)	Fit (stand.)	LL (stand.)	UL (stand.)
2012	artificial reef	3.443	0.276	0.080	2.892	3.994	2.249	1.889	2.609
2013	artificial reef	1.919	0.106	0.055	1.707	2.131	1.253	1.115	1.392
2014	artificial reef	2.361	0.191	0.081	1.979	2.743	1.542	1.293	1.792
2015	artificial reef	2.291	0.169	0.074	1.953	2.629	1.496	1.275	1.717
2016	artificial reef	2.361	0.251	0.106	1.859	2.863	1.542	1.214	1.870
2017	artificial reef	1.522	0.171	0.113	1.179	1.865	0.994	0.770	1.218
2018	artificial reef	1.718	0.189	0.110	1.340	2.096	1.122	0.876	1.369
2019	artificial reef	1.629	0.196	0.120	1.236	2.021	1.064	0.808	1.320
2020	artificial reef	1.258	0.218	0.174	0.821	1.695	0.822	0.537	1.107
2021	artificial reef	1.568	0.228	0.145	1.112	2.024	1.024	0.727	1.322
2012	natural bottom	1.089	0.455	0.418	0.178	1.999	0.711	0.116	1.306
2013	natural bottom	1.350	0.404	0.299	0.542	2.158	0.882	0.354	1.409
2014	natural bottom	0.643	0.173	0.269	0.297	0.988	0.420	0.194	0.646
2015	natural bottom	0.335	0.094	0.279	0.148	0.523	0.219	0.097	0.341
2016	natural bottom	0.705	0.122	0.173	0.461	0.949	0.461	0.301	0.620
2017	natural bottom	1.565	0.190	0.121	1.186	1.945	1.022	0.774	1.271
2018	natural bottom	0.851	0.116	0.136	0.619	1.083	0.556	0.404	0.707
2019	natural bottom	2.024	0.324	0.160	1.376	2.672	1.322	0.899	1.745
2020	natural bottom	1.239	0.441	0.356	0.357	2.121	0.809	0.233	1.385
2021	natural bottom	0.749	0.225	0.300	0.300	1.198	0.489	0.196	0.783

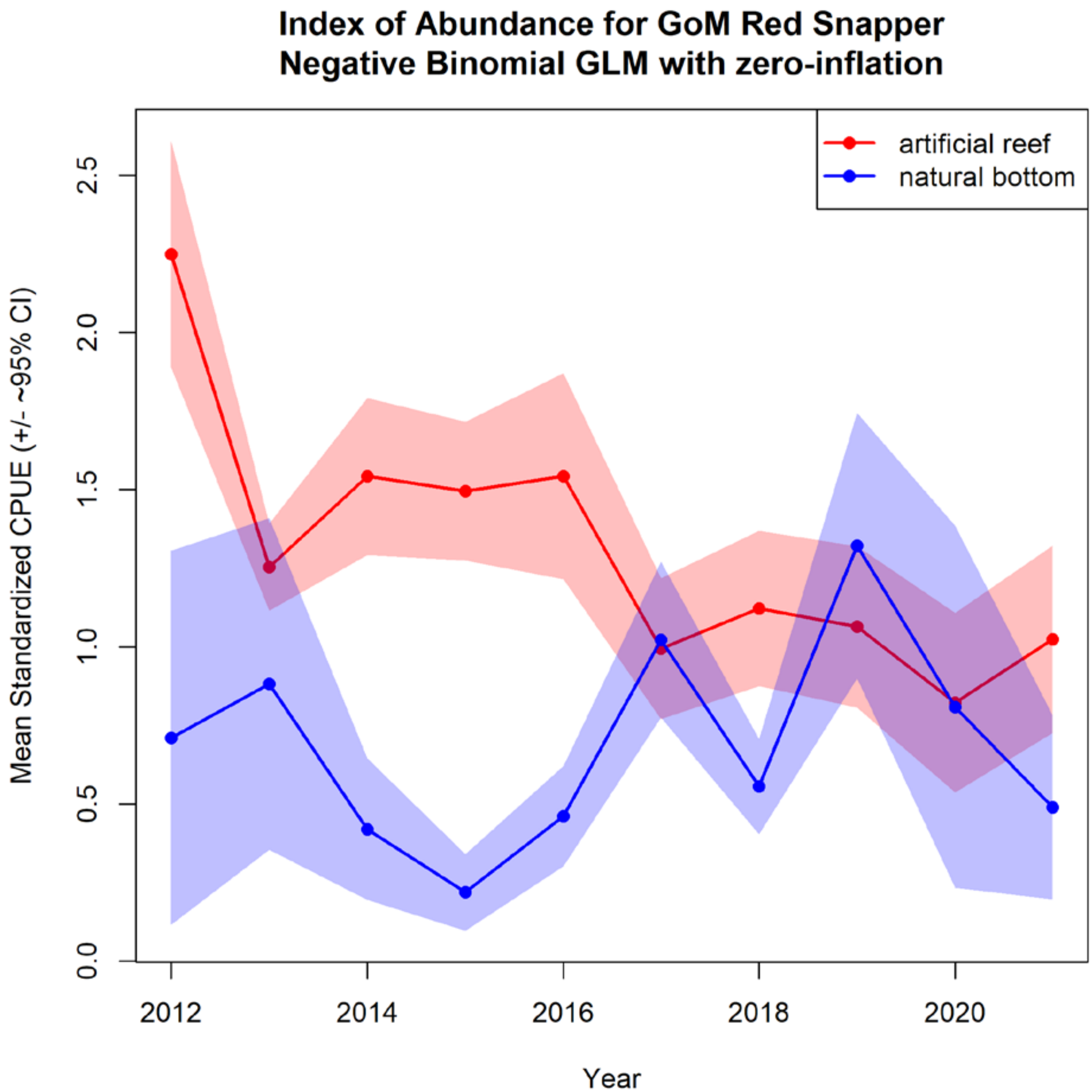


Figure 13: Standardized index of abundance based on model predictions from type 1 negative binomial GLM with zero-inflation. The conditional formula for the model was Red Snapper catch as a function of Year, Habitat, the Year:Habitat interaction, and the three hook-size indicator variables. The zero-inflation component was conditioned on Year, Habitat, and the Year:Habitat interaction.

Table 8: Comparison of ΔAIC among six competing initial models. The conditional formula for all models was Red Snapper catch as a function of Year, Depth, the Year:Depth interaction, and the three hook-size indicator variables. The zero-inflation component was conditioned on Year, Depth, and the Year:Depth interaction.

Model	ΔAIC	df
Negative binomial 1 - zero-inflation	0	64
Negative binomial 2 - zero-inflation	185	64
Negative binomial 1	200	34
Negative binomial 2	442	34
Poisson - zero-inflation	2189	63
Poisson	9558	33

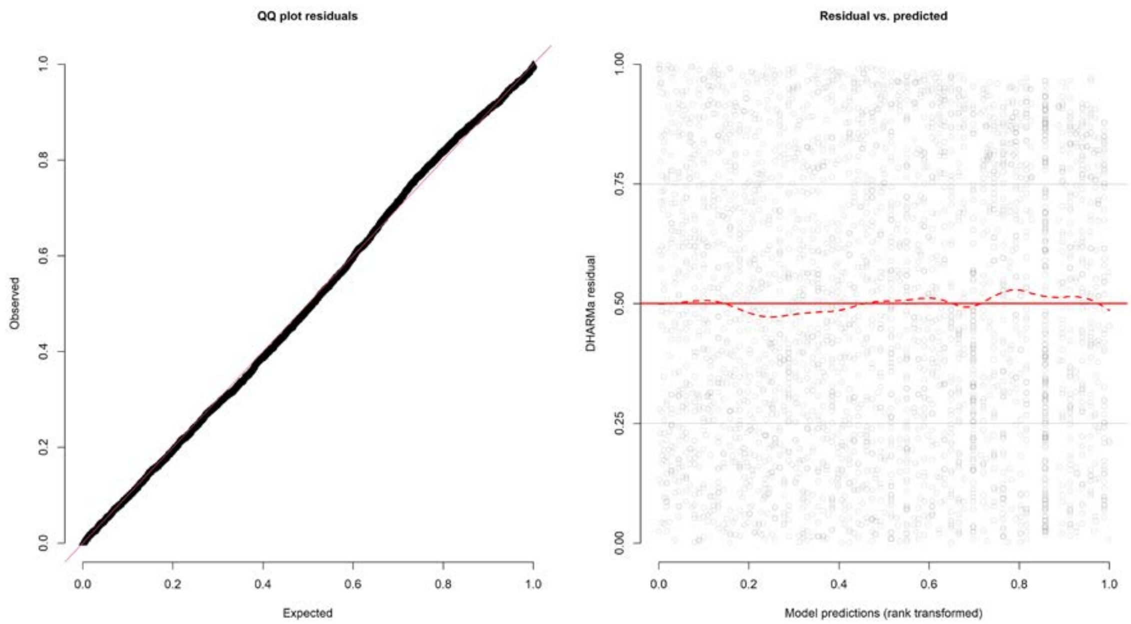


Figure 14: Quantile-Quantile plot (left) and Residual vs. Predicted values (right) from a type 1 negative binomial GLM with zero-inflation. Response modeled as a function of Year, Depth, the Year: Depth interaction, and the three hook-size indicators. Zero-inflation modeled as a function of Year, Depth and the Year: Depth interaction. Residuals are randomized quantile residuals.

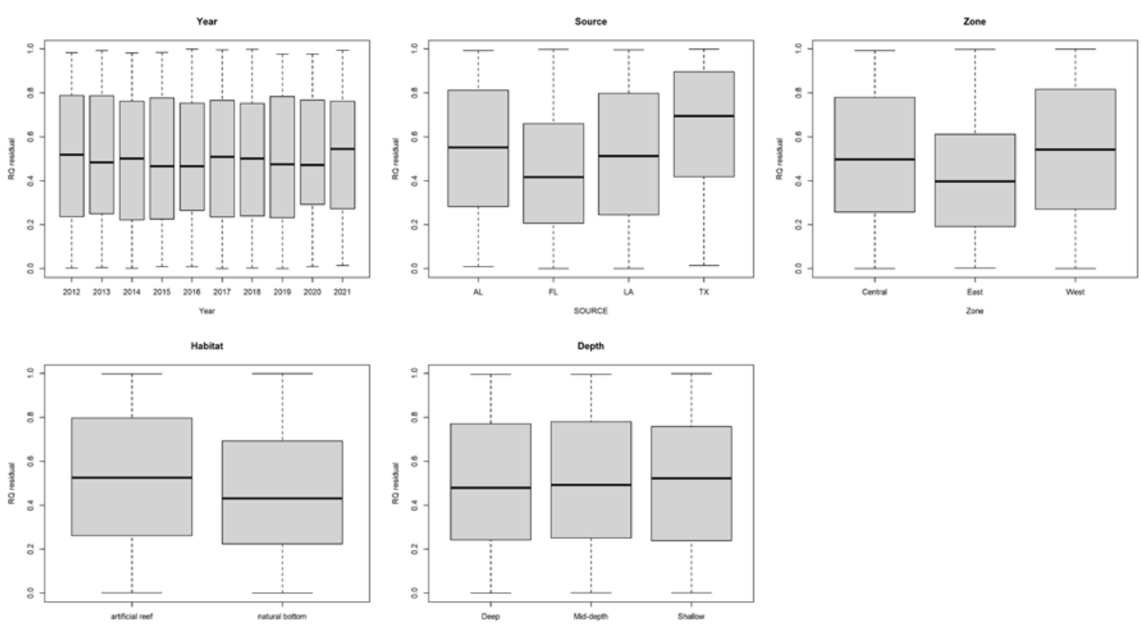


Figure 15. Plots of randomized quantile residuals against predictors that were (Year, Depth) and were not (Source, Zone, Habitat) included in the model. From a type 1 negative binomial GLM with zero-inflation. Response as a function of Year, Depth, the Year: Depth interaction and the three hook-size indicators. Zero-inflation modeled as a function of Year, Depth, and the Year: Depth interaction.

Table 9: Model predictions from type 1 negative binomial GLM with zero-inflation. The conditional formula for the model was Red Snapper catch as a function of Year, Depth, the Year: Depth interaction, and the three hook-size indicator variables. The zero-inflation component was conditioned on Year, Depth, and the Year: Depth interaction. Fit, SE, CV, LL, and UL (resp.) are the model fitted values, standard errors, coefficient of variation (SE/Fit), and approximate lower and upper limits of a 95% confidence interval, all on the response scale. Fit, LL, and UL (stand.) are standardized values (divided by the mean of the fitted values).

Year	Depth	Fit (resp.)	SE (resp.)	CV (resp.)	LL (resp.)	UL (resp.)	Fit (stand.)	LL (stand.)	UL (stand.)
2012	Mid-depth	3.671	0.341	0.093	2.989	4.354	2.134	1.737	2.530
2013	Mid-depth	2.385	0.157	0.066	2.070	2.700	1.386	1.203	1.569
2014	Mid-depth	2.597	0.259	0.100	2.079	3.115	1.509	1.208	1.810
2015	Mid-depth	2.162	0.215	0.100	1.731	2.593	1.257	1.006	1.507
2016	Mid-depth	2.450	0.275	0.112	1.899	3.001	1.424	1.104	1.744
2017	Mid-depth	2.770	0.297	0.107	2.177	3.363	1.610	1.265	1.954
2018	Mid-depth	2.318	0.258	0.111	1.801	2.834	1.347	1.047	1.647
2019	Mid-depth	2.494	0.303	0.121	1.888	3.100	1.449	1.097	1.801
2020	Mid-depth	1.563	0.285	0.182	0.993	2.133	0.908	0.577	1.240
2021	Mid-depth	2.116	0.319	0.151	1.477	2.754	1.230	0.858	1.601
2012	Deep	2.315	0.420	0.181	1.476	3.155	1.346	0.858	1.834
2013	Deep	1.822	0.180	0.099	1.461	2.183	1.059	0.849	1.268
2014	Deep	1.717	0.238	0.138	1.242	2.193	0.998	0.722	1.274
2015	Deep	1.758	0.230	0.131	1.298	2.218	1.022	0.754	1.289
2016	Deep	0.768	0.157	0.204	0.454	1.081	0.446	0.264	0.628
2017	Deep	1.628	0.204	0.125	1.221	2.035	0.946	0.709	1.183
2018	Deep	1.113	0.145	0.130	0.823	1.403	0.647	0.478	0.816
2019	Deep	1.730	0.298	0.172	1.134	2.326	1.006	0.659	1.352
2020	Deep	1.271	0.453	0.357	0.365	2.177	0.739	0.212	1.265
2021	Deep	0.964	0.255	0.265	0.453	1.475	0.560	0.263	0.857
2012	Shallow	3.159	0.843	0.267	1.473	4.845	1.836	0.856	2.816
2013	Shallow	1.190	0.189	0.159	0.812	1.568	0.692	0.472	0.911
2014	Shallow	1.184	0.331	0.279	0.523	1.846	0.688	0.304	1.073
2015	Shallow	1.887	0.364	0.193	1.160	2.615	1.097	0.674	1.520
2016	Shallow	1.381	0.298	0.216	0.785	1.977	0.803	0.456	1.149
2017	Shallow	0.545	0.141	0.258	0.264	0.827	0.317	0.153	0.480
2018	Shallow	0.771	0.225	0.292	0.321	1.220	0.448	0.186	0.709
2019	Shallow	0.680	0.188	0.277	0.303	1.057	0.395	0.176	0.614
2020	Shallow	0.611	0.273	0.447	0.065	1.157	0.355	0.038	0.672
2021	Shallow	0.601	0.239	0.398	0.123	1.079	0.349	0.071	0.627

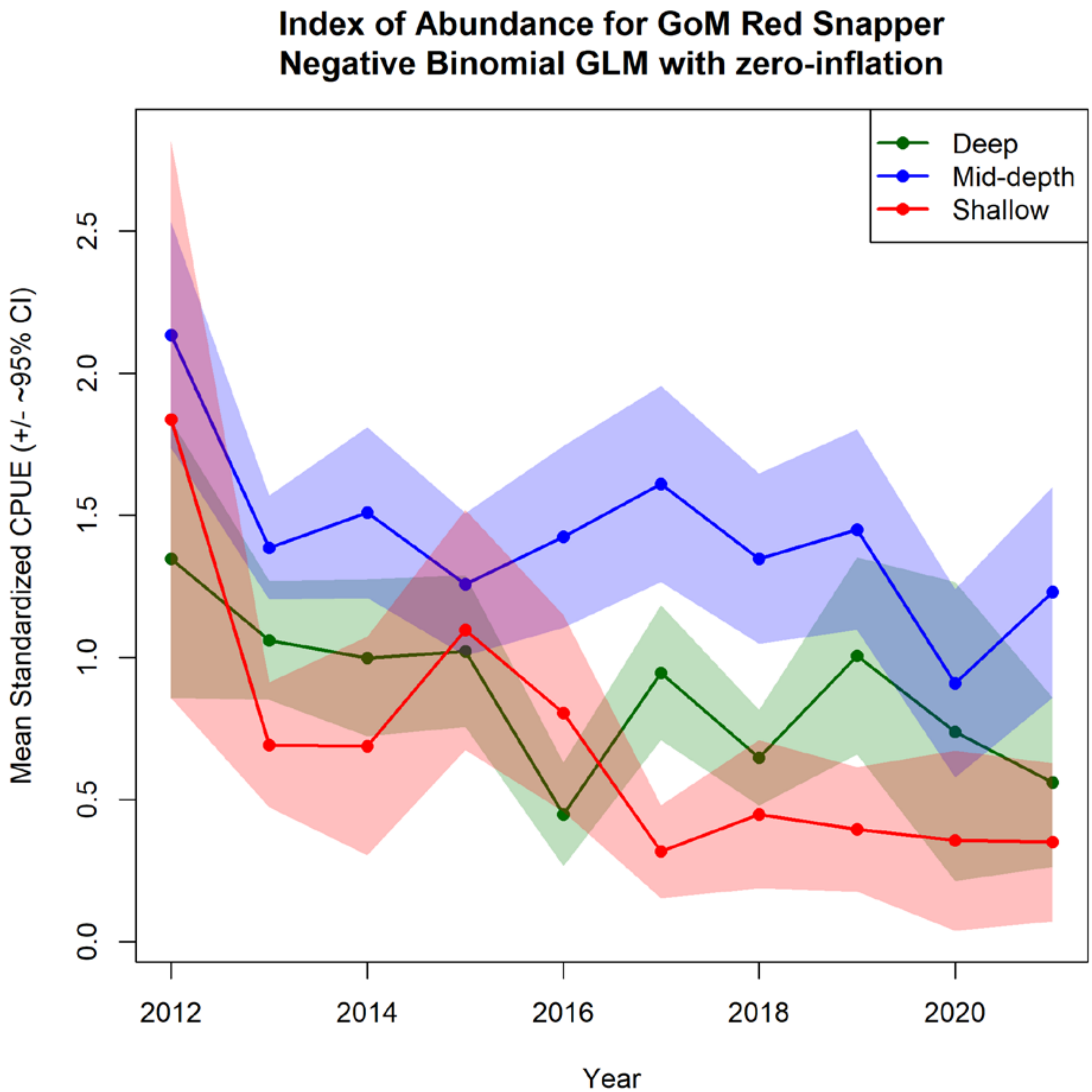


Figure 16: Standardized index of abundance based on model predictions from type 1 negative binomial GLM with zero-inflation. The conditional formula for the model was Red Snapper catch as a function of Year, Depth, the Year:Depth interaction, and the three hook-size indicator variables. The zero-inflation component was conditioned on Year, Depth, and the Year:Depth interaction.

Table 10: Comparison of ΔAIC among six competing initial models. The conditional formula for all models was Red Snapper catch as a function of Year, Zone, the Year: Zone interaction, and the three hook-size indicator variables. The zero-inflation component was conditioned on Year, Zone, and the Year: Zone interaction.

Model	ΔAIC	df
Negative binomial 1 - zero-inflation	0	40
Negative binomial 2 - zero-inflation	47	40
Negative binomial 1	183	22
Negative binomial 2	313	22
Poisson - zero-inflation	1615	39
Poisson	7390	21

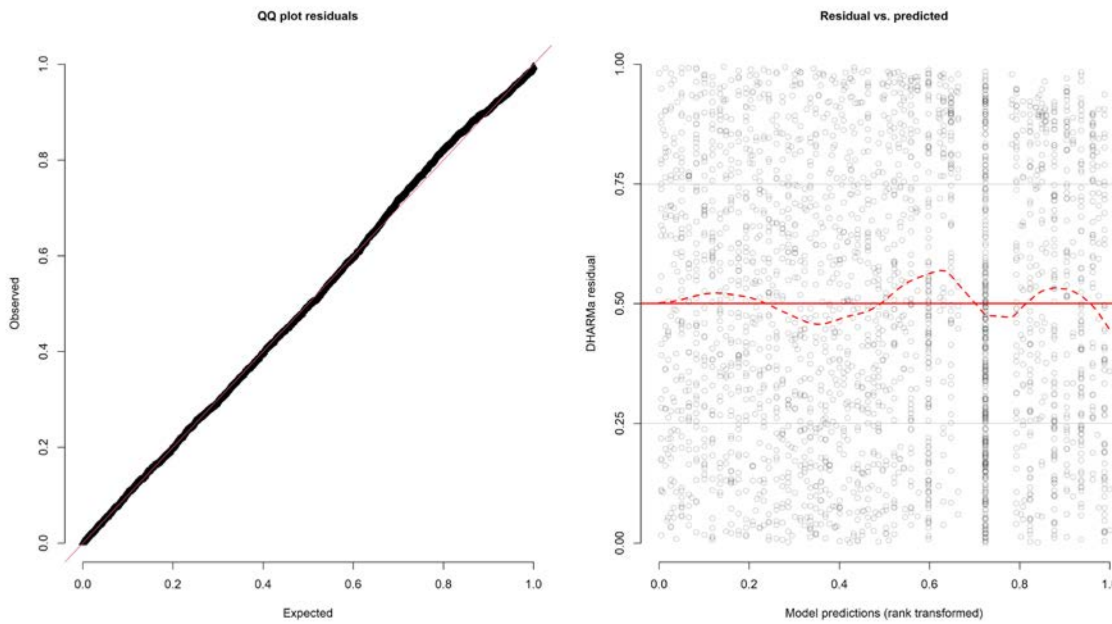


Figure 17: Quantile-Quantile plot (left) and Residual vs. Predicted values (right) from a type 1 negative binomial GLM with zero-inflation. Response modeled as a function of Year, Zone, the Year: Zone interaction, and the three hook-size indicators. Zero-inflation modeled as a function of Year, Zone and the Year: Zone interaction. Residuals are randomized quantile residuals.

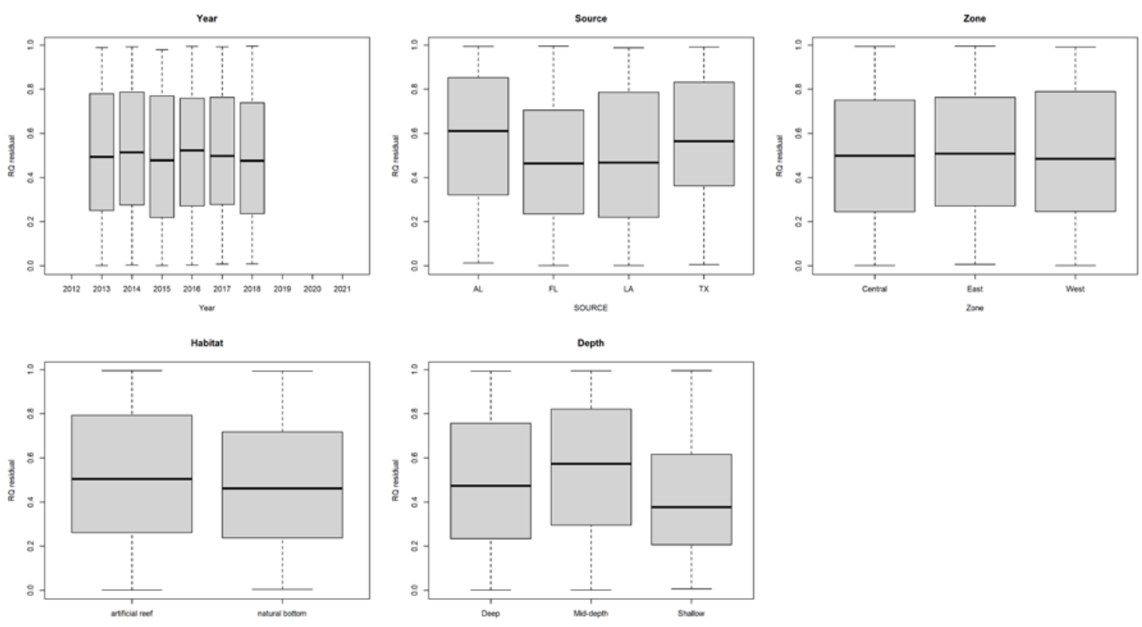


Figure 18. Plots of randomized quantile residuals against predictors that were (Year, Zone) and were not (Source, Depth, Habitat) included in the model. From a type 1 negative binomial GLM with zero-inflation. Response as a function of Year, Zone, the Year: Zone interaction and the three hook-size indicators. Zero-inflation modeled as a function of Year, Zone, and the Year: Zone interaction.

Table 11: Model predictions from type 1 negative binomial GLM with zero-inflation. The conditional formula for the model was Red Snapper catch as a function of Year, Zone, the Year: Zone interaction, and the three hook-size indicator variables. The zero-inflation component was conditioned on Year, Zone, and the Year: Zone interaction. Fit, SE, CV, LL, and UL (resp.) are the model fitted values, standard errors, coefficient of variation (SE/Fit), and approximate lower and upper limits of a 95% confidence interval, all on the response scale. Fit, LL, and UL (stand.) are standardized values (divided by the mean of the fitted values).

Year	Zone	Fit (resp.)	SE (resp.)	CV (resp.)	LL (resp.)	UL (resp.)	Fit (stand.)	LL (stand.)	UL (stand.)
2013	Central	2.397	0.239	0.100	1.919	2.875	1.700	1.361	2.039
2014	Central	2.501	0.281	0.112	1.939	3.063	1.774	1.375	2.172
2015	Central	1.777	0.230	0.129	1.318	2.236	1.260	0.934	1.586
2016	Central	0.970	0.153	0.158	0.663	1.276	0.688	0.470	0.905
2017	Central	1.094	0.172	0.157	0.749	1.438	0.776	0.531	1.020
2018	Central	1.279	0.179	0.140	0.922	1.637	0.907	0.654	1.161
2013	East	0.782	0.186	0.237	0.411	1.153	0.554	0.291	0.818
2014	East	0.170	0.128	0.752	-0.086	0.426	0.121	-0.061	0.302
2015	East	0.196	0.075	0.381	0.047	0.345	0.139	0.033	0.245
2016	East	0.337	0.118	0.349	0.102	0.572	0.239	0.072	0.406
2017	East	0.354	0.109	0.307	0.137	0.571	0.251	0.097	0.405
2018	East	0.573	0.172	0.300	0.229	0.917	0.406	0.162	0.650
2013	West	1.747	0.114	0.065	1.520	1.975	1.239	1.078	1.400
2014	West	1.955	0.215	0.110	1.525	2.386	1.387	1.081	1.692
2015	West	2.391	0.208	0.087	1.975	2.806	1.695	1.400	1.990
2016	West	2.953	0.337	0.114	2.278	3.627	2.094	1.615	2.572
2017	West	2.430	0.230	0.095	1.971	2.889	1.723	1.397	2.049
2018	West	1.479	0.176	0.119	1.127	1.832	1.049	0.799	1.299

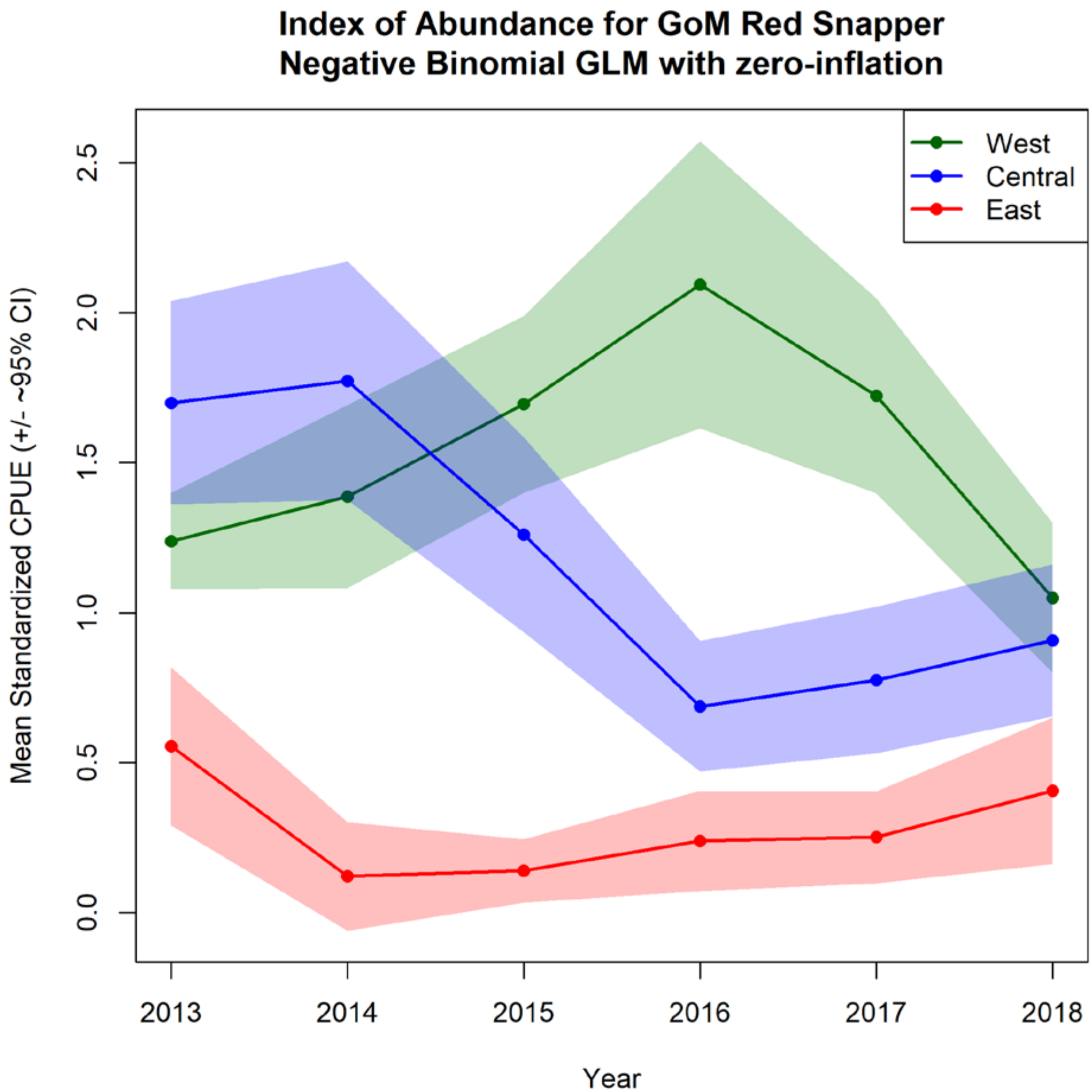


Figure 19: Standardized index of abundance based on model predictions from type 1 negative binomial GLM with zero-inflation. The conditional formula for the model was Red Snapper catch as a function of Year, Zone, the Year: Zone interaction, and the three hook-size indicator variables. The zero-inflation component was conditioned on Year, Zone, and the Year: Zone interaction.

Table 12: Model predictions from three independent type 1 negative binomial GLMs with zero-inflation, one for each Zone (West, Central, and East). The conditional formula for each model was Red Snapper catch as a function of Year and the three hook-size indicator variables. The zero-inflation components were conditioned on Year. Fit, SE, CV, LL, and UL (resp.) are the model fitted values, standard errors, coefficient of variation (SE/Fit), and approximate lower and upper limits of a 95% confidence interval, all on the response scale. Fit, LL, and UL (stand.) are standardized values (divided by the mean of the fitted values for that particular model).

Year	Zone	Fit (resp.)	SE (resp.)	CV (resp.)	LL (resp.)	UL (resp.)	Fit (stand.)	LL (stand.)	UL (stand.)
2012	West	2.221	0.273	0.123	1.675	2.767	1.205	0.909	1.502
2013	West	1.702	0.111	0.065	1.481	1.924	0.924	0.804	1.044
2014	West	1.908	0.209	0.109	1.490	2.326	1.035	0.809	1.262
2015	West	2.208	0.196	0.089	1.816	2.600	1.198	0.985	1.411
2016	West	2.437	0.293	0.120	1.851	3.023	1.322	1.004	1.641
2017	West	2.037	0.202	0.099	1.633	2.440	1.105	0.886	1.324
2018	West	1.457	0.174	0.119	1.109	1.804	0.791	0.602	0.979
2019	West	2.141	0.220	0.103	1.702	2.580	1.162	0.924	1.400
2020	West	1.181	0.349	0.296	0.483	1.879	0.641	0.262	1.020
2021	West	1.137	0.215	0.189	0.707	1.566	0.617	0.384	0.850

Year	Zone	Fit (resp.)	SE (resp.)	CV (resp.)	LL (resp.)	UL (resp.)	Fit (stand.)	LL (stand.)	UL (stand.)
2012	Central	4.277	0.403	0.094	3.472	5.083	2.155	1.749	2.561
2013	Central	3.011	0.280	0.093	2.451	3.571	1.517	1.235	1.800
2014	Central	2.872	0.309	0.107	2.255	3.489	1.447	1.136	1.758
2015	Central	2.042	0.253	0.124	1.536	2.548	1.029	0.774	1.284
2016	Central	1.246	0.191	0.153	0.865	1.627	0.628	0.436	0.820
2017	Central	1.329	0.203	0.153	0.922	1.735	0.670	0.465	0.874
2018	Central	1.576	0.212	0.134	1.153	1.999	0.794	0.581	1.007
2019	Central	0.874	0.194	0.222	0.487	1.262	0.441	0.245	0.636
2020	Central	1.222	0.216	0.177	0.790	1.653	0.616	0.398	0.833
2021	Central	1.396	0.248	0.178	0.899	1.893	0.703	0.453	0.954

Year	Zone	Fit (resp.)	SE (resp.)	CV (resp.)	LL (resp.)	UL (resp.)	Fit (stand.)	LL (stand.)	UL (stand.)
2013	East	0.40	0.15	0.37	0.10	0.70	2.06	0.53	3.58
2014	East	0.09	0.07	0.79	-0.05	0.22	0.44	-0.26	1.14
2015	East	0.09	0.04	0.47	0.01	0.18	0.48	0.03	0.93
2016	East	0.17	0.08	0.49	0.00	0.33	0.86	0.02	1.71
2017	East	0.16	0.08	0.47	0.01	0.31	0.83	0.05	1.61
2018	East	0.26	0.12	0.47	0.02	0.50	1.33	0.09	2.56

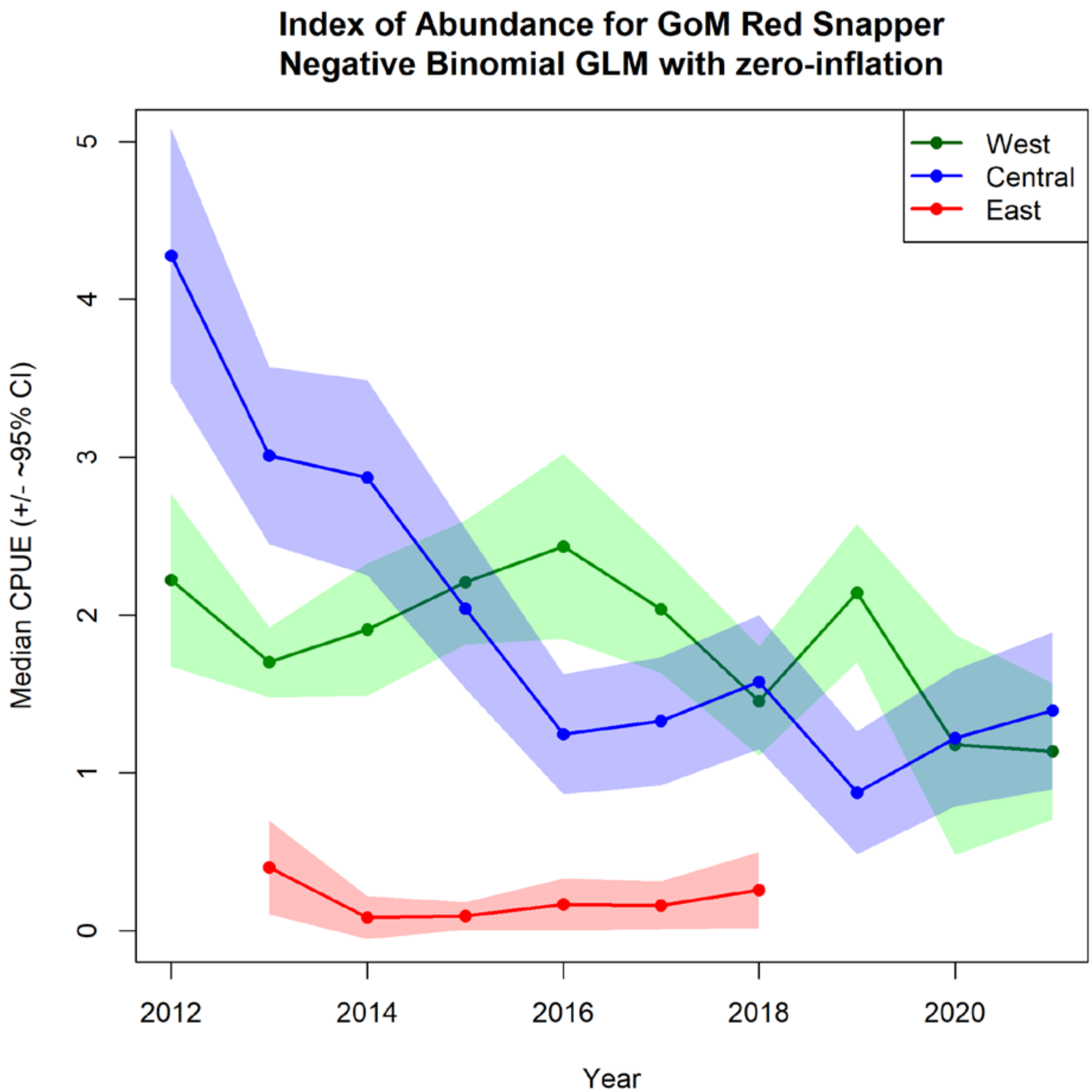


Figure 20: Median CPUE index of abundance (not standardized) based on model predictions from three independent type 1 negative binomial GLMs with zero-inflation, one for each Zone (West, Central, East). The conditional formula for each model was Red Snapper catch as a function of Year and the three hook-size indicator variables. The zero-inflation components were also conditioned on Year.

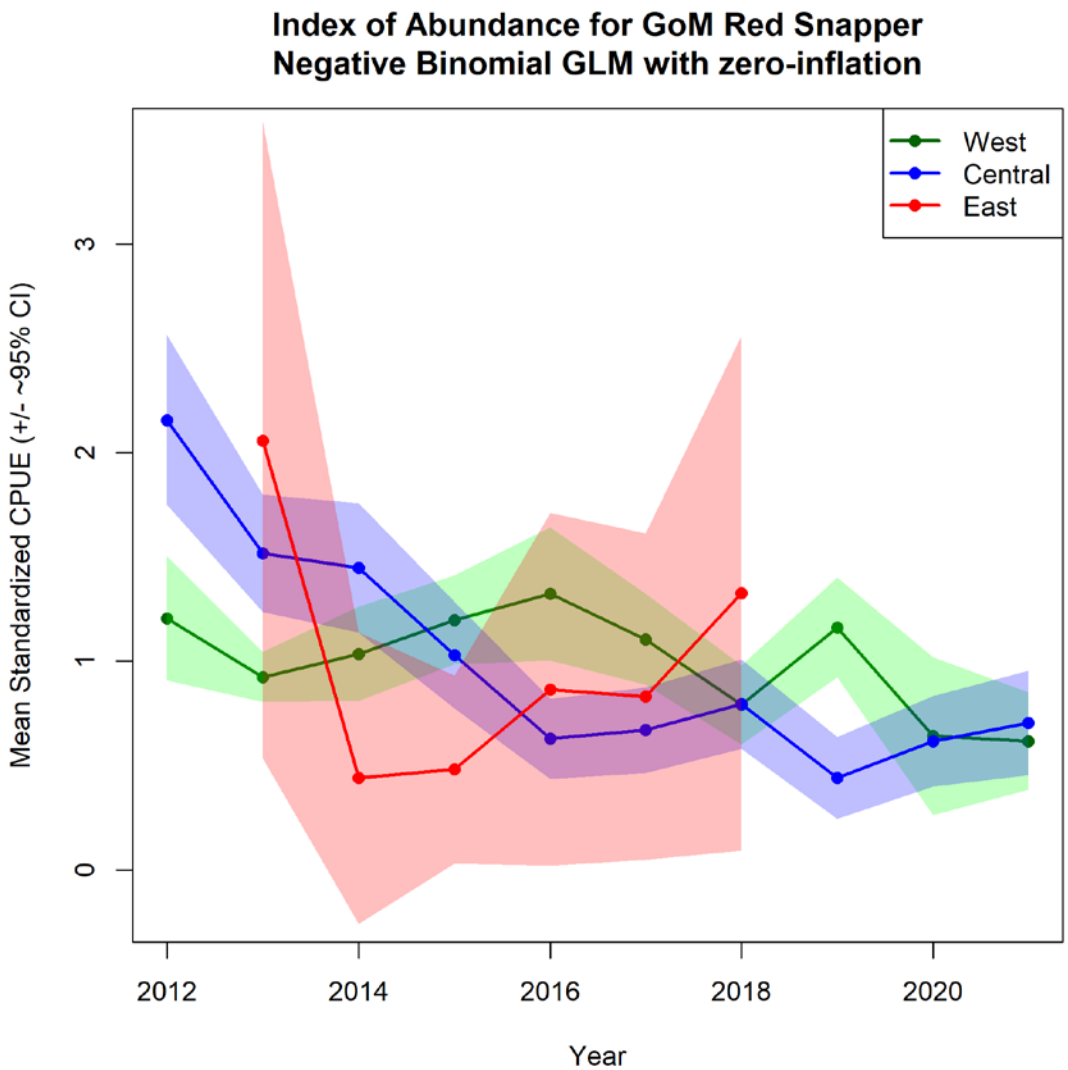


Figure 21: Standardized indices of abundance based on model predictions from three independent type 1 negative binomial GLMs with zero-inflation. Standardization is based on the mean prediction from each model, so the mean of each index is 1. The conditional formula for each model was Red Snapper catch as a function of Year and the three hook-size indicator variables. The zero-inflation components were conditioned on Year.

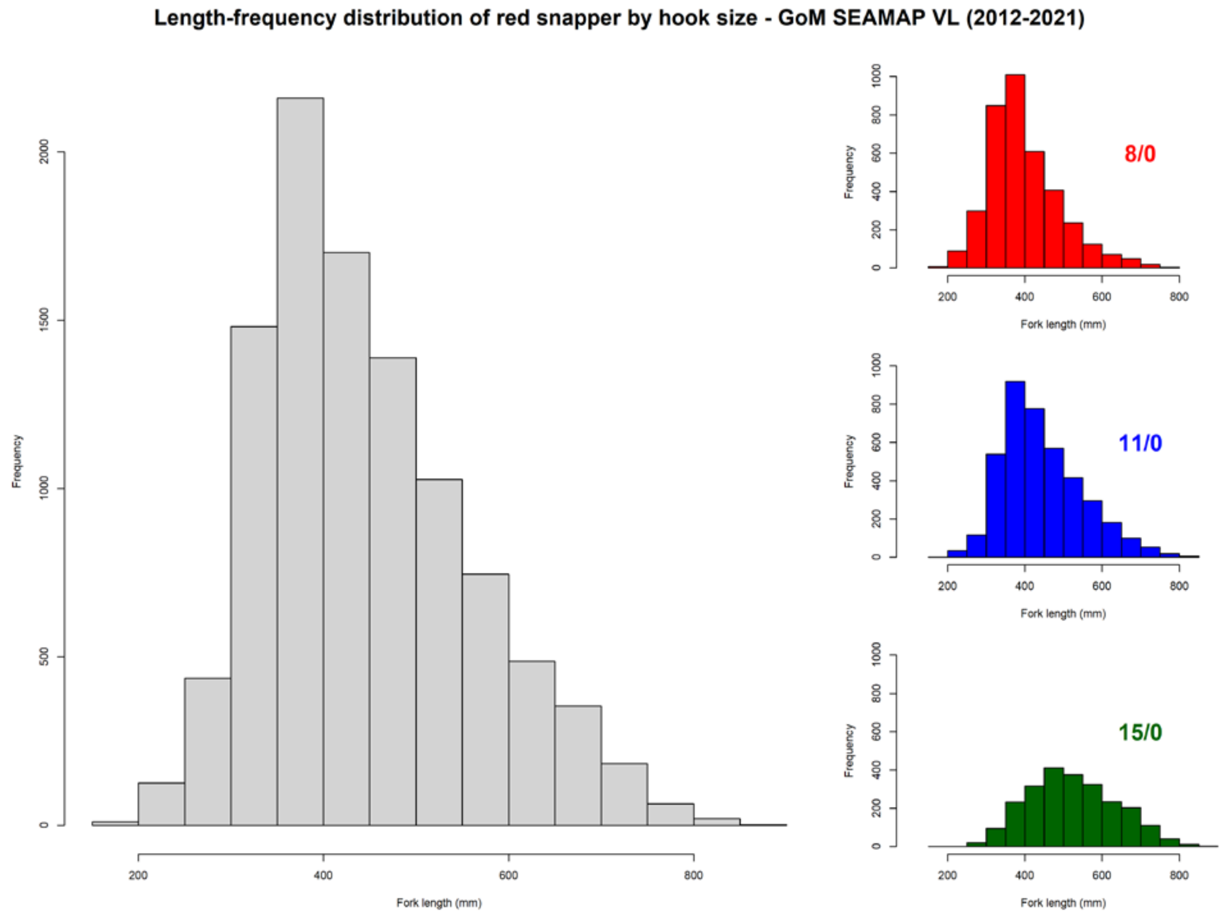


Figure 22: Length-frequency distribution for all fish used in the analysis with separate distributions for fish captured on the three hook sizes. Lengths measured in mm FL.

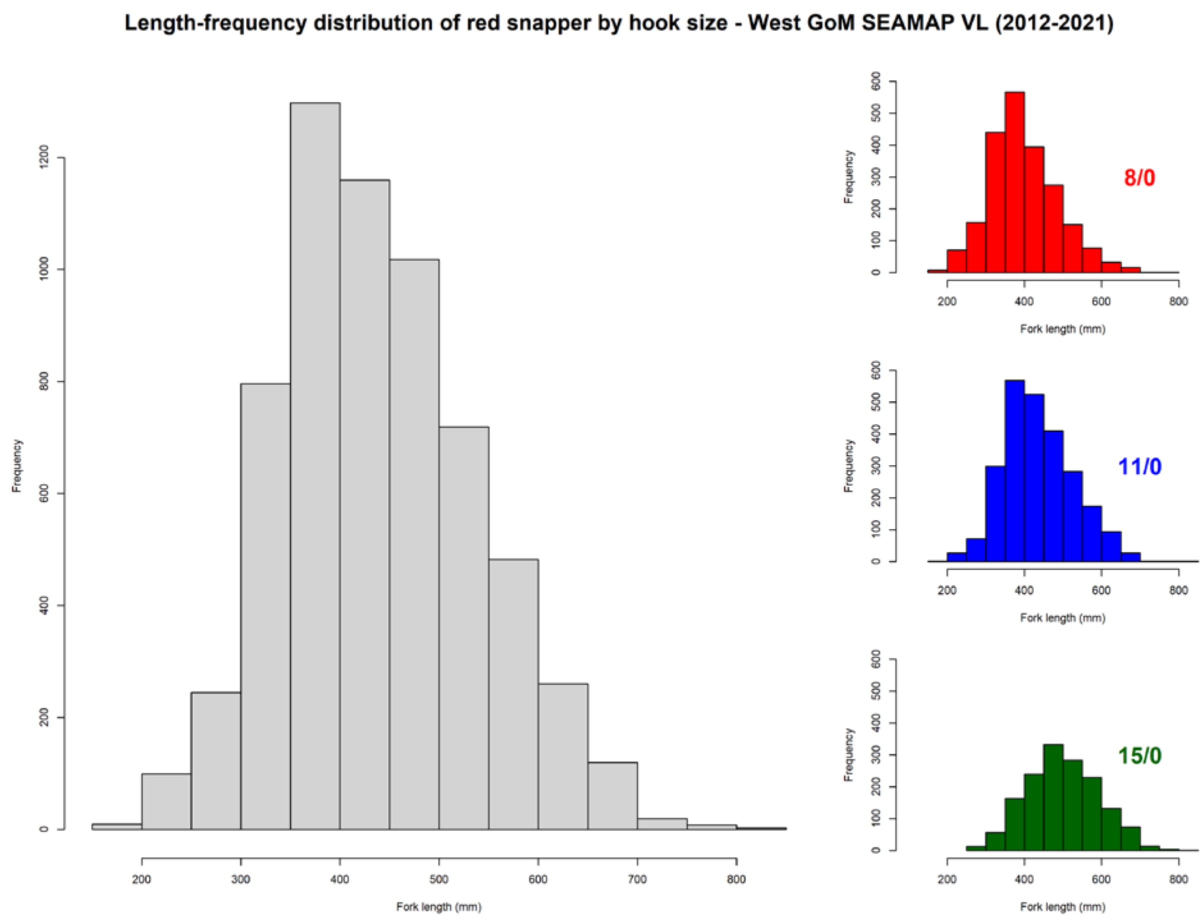


Figure 23 Length-frequency distribution for all West Zone fish used in the analysis with separate distributions for fish captured on the three hook sizes. Lengths measured in mm FL.

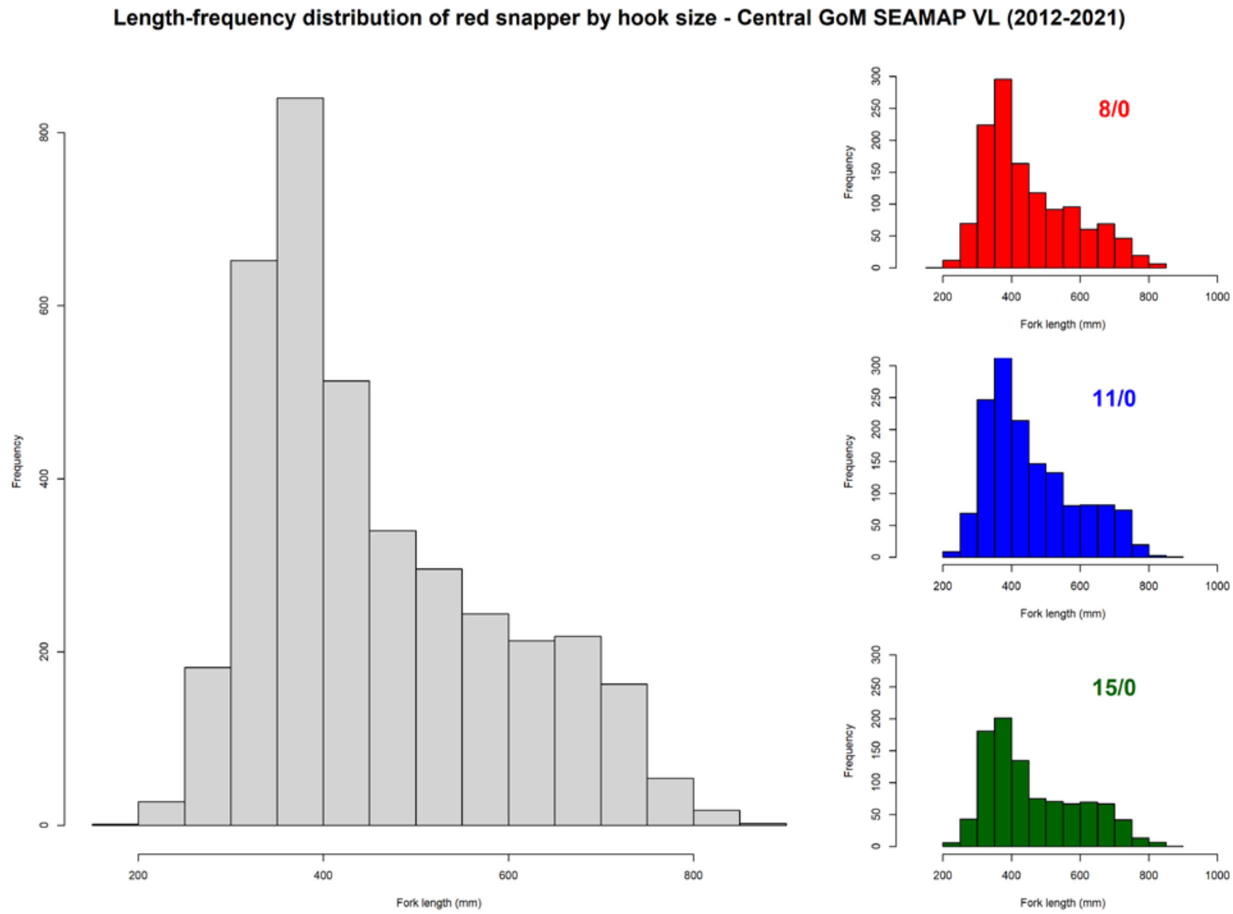


Figure 24: Length-frequency distribution for all Central Zone fish used in the analysis with separate distributions for fish captured on the three hook sizes. Lengths measured in mm FL.

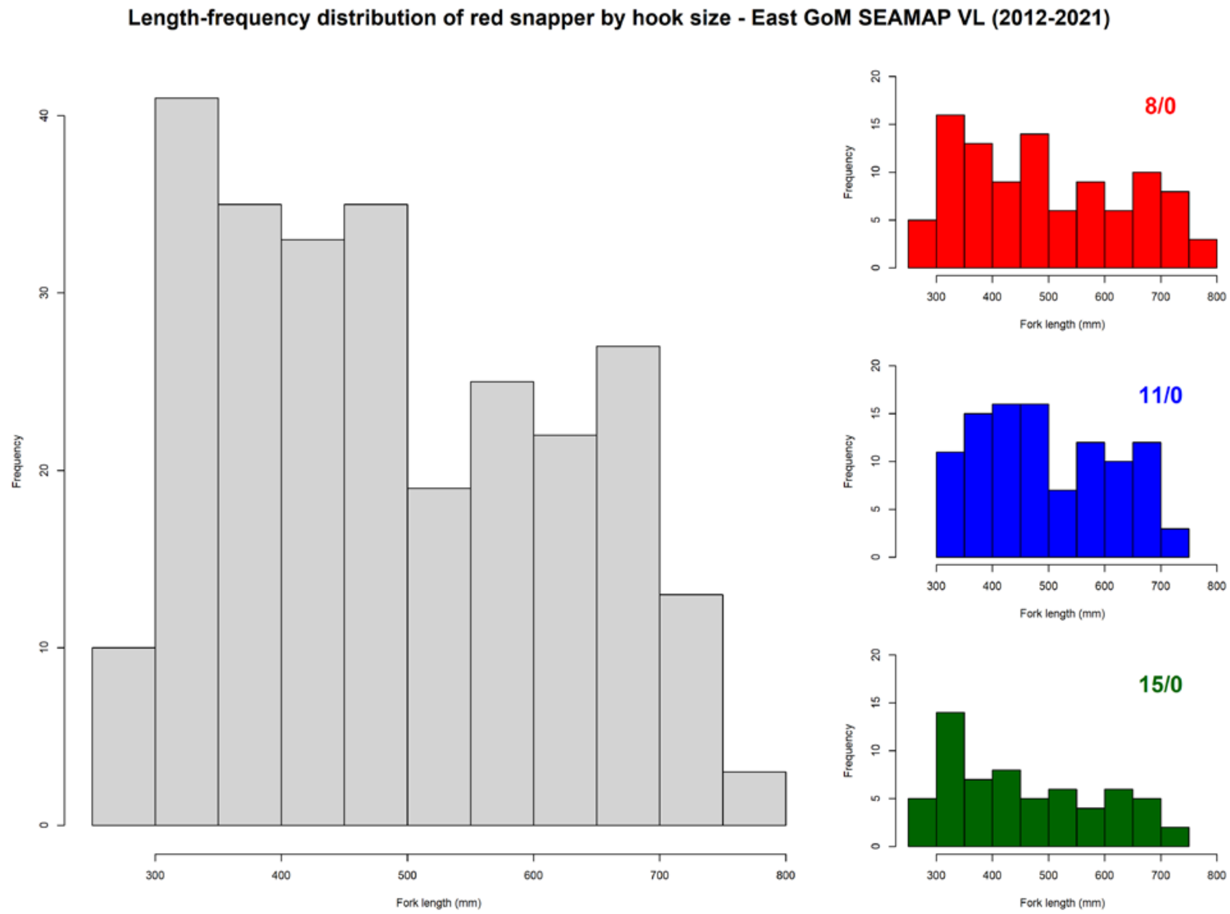


Figure 25: Length-frequency distribution for all East Zone fish used in the analysis with separate distributions for fish captured on the three hook sizes. Lengths measured in mm FL.