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SEDAR68-AW-04

29 March 2021

Please cite this document as:
Smith, Steven G., Skyler Sagarese, Stephanie Martinez-Rivera, Kevin J. McCarthy 2021. Estimation of a Commercial Abundance Index for Gulf of Mexico Scamp & Yellowmouth Grouper Using Reef Fish Observer Data. SEDAR68-AW-04. SEDAR, North Charleston, SC. 33 pp.

SEDAR 68 Working Paper

Estimation of a Commercial Abundance Index for Gulf of Mexico Scamp & Yellowmouth Grouper Using Reef Fish Observer Data

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Final Version, March 2021

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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. 2020a). 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 for the commercial fleet using data from the reef fish observer program. Observer observations of catch included both kept and discarded fish, and thus were not directly impacted by changes in management regulations (e.g., minimum size, catch quotas, etc.). Reef fish observer data have much in common with fishery-independent surveys utilizing fishing gears, including: latitude-longitude coordinates were recorded at each specific fishing location, catches were recorded for individual species, and lengths were recorded for individual fish (Scott-Denton et al. 2011). Key differences from fishery-independent surveys were varying gear characteristics and varying levels of effort among fishing locations. Given these similarities and differences, a probability survey approach was undertaken to estimate the reef fish observer CPUE index.

Development of the methodology for the observer CPUE index entailed a number of key elements, including: (i) delineation of a spatial sample frame for the GOM; (ii) identification of valid statistical sample units with nonzero probability of capture for Scamp/Yellowmouth Grouper; (iii) identification of an appropriate effort variable; (iv) development of estimation procedures that accounted for varying gear characteristics and varying effort among sample units; and (v) specification of a stratification scheme that effectively partitioned the spatial variance of CPUE.

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 2007-2018 were used for development of an annual index of abundance for GOM Scamp and Yellowmouth Grouper. Following the SEDAR 68 Terms of Reference, the two species were combined to develop the index. 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 Scamp/Yellowmouth Grouper as well as observer observations of the two species.

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. Selection of the sample unit area (500 x 500m) was based on analyses of the spatial extent of specific fishing locations for commercial reef fishers using vertical line gears in Hawaii (Ault et al. 2018) and Puerto Rico (S.G. Smith, unpublished results). Depth at the center point of each grid cell was obtained from NOAA bathymetry data.

Index Estimation Approach

Annual CPUE and associated variance of Scamp/Yellowmouth Grouper 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

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

Sample frame mean catch and effort were respectively computed by

$$\bar{y}_{st} = \sum_h w_h \, \bar{y}_h \tag{1}$$

and

$$\bar{x}_{st} = \sum_h w_h \, \bar{x}_h \quad , \tag{2}$$

with the stratum weighting factor given by

$$w_h = \frac{N_h}{\sum_h N_h} \quad , \tag{3}$$

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,

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

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

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

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 Scamp/Yellowmouth Grouper; however, actual application required specification of many aspects of the estimation process, including delineation of the spatial sample frame relevant for Scamp/Yellowmouth Grouper (i.e., sample units with nonzero probability of capture), identification of an appropriate effort variable, 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 potential effort variables 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

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.

Valid Sample Unit for Scamp/Yellowmouth Grouper

The geo-referenced observer data were used to define the depth range where Scamp/Yellowmouth Grouper 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 Scamp/Yellowmouth Grouper sample units (500 x 500 m grid cells), i.e., sample units with a non-zero probability of catching Scamp/Yellowmouth Grouper. 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,

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

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 Scamp/Yellowmouth Grouper (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 Scamp/Yellowmouth Grouper using logistic regression. For subregions, the GOM was divided into West and East blocks separated by the Mississippi River outflow, since some reef fishes predominately occur in one subregion or the other (e.g., East for red grouper). Additional spatial analysis of Scamp/Yellowmouth Grouper occurrence was conducted to determine the southern boundary for the East subregion along Florida's Gulf Coast.

Effort Variable

Observers collected information for a variety of effort variables. These included three standard variables for hook-line gear—the number of reels (i.e., lines), number of hooks, and fishing time—which were used to create two additional variables, reel-hours and hook-hours. A sixth variable was somewhat unique: the number of 'drops' at a fishing location, i.e., the number of times the gear was deployed and retrieved.

While the ratio-of-means estimator for CPUE (eq. 4) can accommodate varying effort among sample units, it presumes a general increasing relationship between effort and catch. Two analyses were conducted to guide selection of an appropriate effort variable. First, generalized linear regression analysis was used to evaluate relationships between catch and effort for the suite of effort variables. Separate regression models were developed for occurrence (p) and catch when present (u) for each variable. Second, the average annual CV (eq. 6) of the ratio-of-means CPUE was compared for each variable. Computations of CPUE and associated CV were carried out using the depth-subregion blocking scheme developed for species association analysis as the initial stratification scheme.

Gear Designation Analysis: Reel Type

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, the selected effort variable from above 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 (described above) and reel types.

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 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, the selected effort variable from above was a continuous covariate, year-subregion-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 reel-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 focused on depth and subregion as potential stratification variables, and were carried out in two steps. First, generalized linear regression was used to analyze relationships between occurrence or catch when present and space covariates depth and subregion. For these models, reel-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 and/or subregion (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

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

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

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

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

Scamp/Yellowmouth Grouper 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 (medium and large) based on a combination of hook length and hook point-to-shaft length measurements taken by observers (**Fig 2**).

Valid Sample Unit for Scamp/Yellowmouth Grouper

Designation of the depth-subregion blocking scheme for species association analyses is illustrated in **Figs. 3** and **4**. Scamp/Yellowmouth Grouper were captured on vertical line gear within a depth range of 20 m to 150 m. Occurrence p, the proportion of sample units where at least one Scamp/Yellowmouth Grouper was captured, increased with increasing depth (**Fig. 3**). Three depth blocks were defined to distinguish low to high average occurrence: (1) 20-55 m, average $p \approx 0.05$; (2) 55-100 m, average $p \approx 0.25$; and (3) 100-150 m, average $p \approx 0.35$. As described above, East and West subregions for the GOM were divided at the Mississippi River outflow (**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 Scamp/Yellowmouth Grouper in shallow depths in the area south of 26 degrees.

Species association analysis was conducted considering Scamp/Yellowmouth Grouper 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 medium circle hooks (C_MED, **Table 1**) and large circle hooks (C_LRG, **Table 2**). For hook category C_MED, sample size constraints were satisfactory for analysis of associations between Scamp/Yellowmouth Grouper and 40 other species, of which 30 were positively associated in one or more depth-subregion block. These associated species were predominately groupers, snappers, porgies, jacks, and other reef fishes (**Table 1**). For hook category C_LRG, sample size constraints were satisfactory for analysis of associations between Scamp/Yellowmouth Grouper and 16 other species, of which 8 were positively associated in one or more depth-subregion block. Similar to hook category C_MED, the associated species were predominately groupers, snappers, porgies, jacks, 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 Scamp/Yellowmouth Grouper sample units which had a nonzero probability of capture. Valid sample units were defined as those with catches of Scamp/Yellowmouth Grouper or a positively associated species.

Effort Variable

Analyses of effort variables focused on mechanical reels, the predominant reel type, for hook categories C_MED and C_LRG. For some effort variables, there was a well-defined increasing relationship with catch (**Fig. 5A**). In other cases, there was almost no relationship with catch (**Fig. 5B**). The complete set of catch-effort relationships for the six effort variables are provided in **Appendix Figs. A1** and **A2** for C_MED and C_LRG, respectively. The precision ranks (1 best, 6 worst) of ratio-of-means CPUE estimates by effort variable are given in **Table 3**. Precision ranks were the average of the C_MED and C_LRG hook categories for each effort variable. In general, effort variables with more well-defined relationships with catch had better precision, and conversely, effort variables with less well-defined relationships with catch had worse precision. Precision was best for reels and reel-hours, worst for hooks and hook-hours, and moderate for hours and drops.

Reel-hours was selected over reels as the effort variable for the CPUE index for two reasons: (i) reel-hours (i.e., line-hours) is a widely-used effort metric in fishery science for hook-line gears; and (ii) computations of reel-hours for a given sample unit were more straightforward compared to reels in cases where observers recorded multiple fishing ‘sets’ within a 500 x 500 m grid cell.

Gear Designation Analysis: Reel Type

Regression relationships for catch dependent on reel-hours were similar for hand and mechanical reels (e.g., **Fig. 6**). 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_MED and C_LRG 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 as illustrated in **Fig. 7** to identify the maximum threshold value for effort above which mean catch remained more or less constant. For hook category C_MED, the maximum effort threshold was estimated to be 5.0 reel-hours for occurrence p and 6.5 reel-hours for catch when present u. The larger of the two values, 6.5, was selected as the maximum effort threshold, and sample unit effort observations in excess of this threshold were set equal to the threshold. For hook category C_LRG, the maximum effort threshold was estimated to be 3.5 reel-hours for occurrence and 4.0 reel-hours for catch when present. The larger of the two values, 4.0, was selected as the maximum effort threshold, and sample unit effort observations were adjusted accordingly.

Model-predicted estimates of occurrence p, catch when present u, CPUE, and relative fishing power λ are provided in **Table 4**. Hook category C_MED was selected as the standard gear. Effort for large circle hooks was converted to that of medium circle hooks, and the data were pooled for subsequent estimation of the CPUE index.

Stratification Analysis

Regression analysis indicated from two to four potential strata for depth (**Fig. 8**). The logistic regression example in **Fig. 8A** shows delineation of a 4-strata scheme for depth based on occurrence p. In contrast, the gamma pdf regression example in **Fig. 8B** shows delineation of a 2-strata depth scheme based on catch when present u. Analysis of a suite of 2-, 3-, and 4-strata depth schemes using the survey design metric n*(10%), the projected sample size to achieve a 10% CV for mean CPUE, identified a 3-strata depth scheme with intervals 20-50m, 50-75m, and 75-150m as the most effective with respect to spatial partitioning of sample variance for CPUE (**Table 5**). Our analysis also indicated that further partitioning of the survey frame into East-West subregions was not warranted. The ‘Depth only, 3-strata C’ was therefore selected for CPUE index estimation (**Table 6**).

Annual CPUE Index and Length Composition, 2007-2018

Estimates of the reef fish observer abundance index for GOM Scamp/Yellowmouth Grouper for 2007-2018 are provided in **Table 7** for the commercial vertical line fleet. The standardized index (scaled to mean CPUE for 2007-2018) time-series is graphed in **Fig. 9**, which also shows the 95% confidence intervals. The estimates suggest that Scamp/Yellowmouth Grouper abundance was relatively stable in the GOM during 2007-2018, but indicate generally lower abundance during 2010-2011 compared to other years. The CVs of the estimates ranged from 6 to 22%, with an average of 13% over the 2007-2018 time frame. Scamp/Yellowmouth Grouper population length compositions (eq. 7) are plotted by year in **Fig. 10**.

Discussion

This study developed a novel index of abundance for GOM Scamp/Yellowmouth Grouper 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 Scamp/Yellowmouth Grouper 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 Scamp/Yellowmouth Grouper stock. Aside from that fundamental question, analysis techniques were developed to account for varying gear characteristics (e.g., hook types, hook sizes, etc.) 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 index indicated a relatively stable Scamp/Yellowmouth Grouper stock in the GOM during 2007-2018, and the precision of the estimates was quite good with an average annual CV of about 13%.

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, evaluate catch-effort relationships, 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 appropriate effort variables, 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 stock-wide annual CPUE estimates for GOM Scamp/Yellowmouth Grouper.

The choice of a survey design ratio-of-means estimator for Scamp/Yellowmouth Grouper CPUE over a regression model estimator was primarily driven by the realities of the observer sampling data. Regression model CPUE estimators presume that observations are collected using a simple random sampling design. The practical consequence of this assumption for Scamp/Yellowmouth Grouper is that observations within a given depth stratum would be proportional to the stratum number of possible sample units N_h, i.e., proportional to stratum area. In other words, the proportion of stratum observations n_h/n should be more or less equal to the stratum weighting factor, $w_h=N_h/N$. The information of **Table 6** shows that this was not the case. For example, in 2010 the observer sampling proportion in shallow stratum D1 was $n_h/n=0.74$ compared to $w_h=0.56$, whereas the sampling proportion in deep stratum D3 was $n_h/n=0.04$ compared to $w_h=0.21$. A regression model estimate for year 2010 would implicitly overweight the mean CPUE in stratum D1 and underweight the mean CPUE in stratum D3 with respect to the underlying sampling assumptions, producing a biased estimate of $\overline{CPUE}_{st}$ for the GOM survey frame. Moreover, n_h/n was not consistent year to year. For example, in 2007 the observer sampling proportion in shallow stratum D1 was 0.40 compared to $w_h=0.56$, i.e., stratum D1 was undersampled in relation to the proportion of stratum area. When sampling is inconsistently disproportionate among spatial strata from year to year, fluctuations in a regression-estimated index time-series may be the result of variation in observation spatial weighting rather than actual changes in stock abundance.

In contrast, the underlying sampling assumption for a stratified survey design-based estimator for CPUE is that observations were collected using a simple random survey within each stratum rather than over the entire sample frame. By virtue of explicit spatial weighting using w_h (eqs. 1-4), disproportionate sampling among strata affects the precision (CV) but not the accuracy of estimates of $\overline{CPUE}_{st}$ for the GOM sample frame.

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Table 1. Results of Scamp/Yellowmouth Grouper species association analysis by region and depth categories for GOM vertical lines, hook size C_MED (medium circle hooks). Color coding: green, positive association; yellow, no association; blank, insufficient data for analysis.

		East GOM			West GOM		
Family/Group	**Species**	**20-55 m**	**55-100 m**	**100-150 m**	**20-55 m**	**55-100 m**	**100-150 m**
Groupers	Gag	green	green	green			
	Yellowedge Grouper			green			green
	Red Grouper	green	green				
	Graysby	green					
	Speckled Hind			green			
	Spanish Flag		green				
	Snowy Grouper			yellow			
Snappers	Red Snapper	yellow	green	green		yellow	green
	Vermilion Snapper	green	yellow	yellow		green	green
	Blackfin Snapper					green	
	Gray Snapper	green	yellow			yellow	
	Lane Snapper	yellow			green	yellow	
Grunts	White Grunt	green					
	Tomtate	yellow	yellow			yellow	
Porgies	Red Porgy	green	green	green		green	green
	Knobbed Porgy	green	green				
	Jolthead Porgy	green	yellow				
	Saucereye Porgy	green					
	Littlehead Porgy	green					
Jacks	Greater Amberjack	green	green	yellow		green	green
	Almaco Jack	green	green	yellow		green	green
	Banded Rudderfish	green	green				
	Lesser Amberjack		green	yellow			
Tilefishes	Blueline Tilefish			green			yellow
	Goldface Tilefish		yellow	yellow			
Other Reef	Gray Triggerfish	green	green		green	green	
	Creole-fish		green			green	green
	Squirrelfish	green				green	
	Spotted Moray	green					
	Short Bigeye		yellow				
Sea Basses	Bank Sea Bass		yellow				
	Tattler		yellow				yellow
Sharks	Atlantic Sharpnose Shark		yellow			green	
	Silky Shark		yellow				
Mackerels, Tunas	Blue Runner				green	yellow	
	Little Tunny		yellow	yellow		green	yellow
	Chub Mackerel		yellow				yellow
Other	Sharksucker	green	yellow				
	Blackbar Drum		yellow				
	Cubbyu		yellow				

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

		East GOM			West GOM		
Family/Group	**Species**	**20-55 m**	**55-100 m**	**100-150 m**	**20-55 m**	**55-100 m**	**100-150 m**
Groupers	Gag	green	green	yellow		yellow	yellow
	Red Grouper	yellow	green				
	Speckled Hind		yellow	yellow			
Snappers	Red Snapper	green	green	yellow		green	yellow
	Gray Snapper	green	green				
	Vermilion Snapper	yellow	yellow				
	Lane Snapper	red					
Grunts	White Grunt	yellow					
Porgies	Red Porgy	green	yellow	yellow			
	Jolthead Porgy		yellow				
Jacks	Almaco Jack		yellow			green	green
	Banded Rudderfish	green	yellow				
	Greater Amberjack		yellow	yellow		red	yellow
Other Reef	Gray Triggerfish	green	green				
Sharks	Silky Shark		yellow				
	Atlantic Sharpnose Shark		yellow				

Table 3. Average precision (CV) rank for Scamp/Yellowmouth Grouper CPUE estimates for various effort variables for two vertical line gear types: (i) mechanical reels, hook size C_MED (medium circle hooks); and (ii) mechanical reels, hook size C_LRG (large circle hooks). Corresponding graphs showing catch-effort relationships for the various effort variables are provided in **Appendix Fig. A1** for C_MED and **Appendix Fig. A2** for C_LRG. The highlighted effort variable, reel-hours, was selected for estimating CPUE.

Effort Variable	Average CV Rank
Reels	1.5
Reel-Hours	1.5
Hours	3
Drops	4
Hooks	5.5
Hook-Hours	5.5

Table 4. Effort standardization results for GOM Scamp/Yellowmouth Grouper for two hook size categories, C_MED (medium circle hooks) and C_LRG (large circle hooks). **(A)** Model-predicted estimates of occurrence p, catch when present u, CPUE (p times u), and relative fishing power λ(CPUE) considering C_MED 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_MED	0.1210	1.838	0.222	1.000
C_LRG	0.1647	1.745	0.287	1.293

(B)

Gear	λ(p)	λ(u)	λ(CPUE)
C_MED	1.000	1.000	1.000
C_LRG	1.362	0.949	1.293

Table 5. Sample size projections (n*) to achieve a 10% CV for Scamp/Yellowmouth Grouper CPUE estimates for various stratification schemes. Data were evaluated for two time periods, 2011-14 and 2015-18. The highlighted stratification was used to estimate the CPUE annual index.

Design	Description	n*(10%) 2011-14	n*(10%) 2015-18
Simple Random	1 stratum	1,390.7	1,239.5
Depth only, 2-strata A	20-75, 75-150	862.8	709.0
Depth only, 2-strata B	20-60, 60-150	979.1	867.5
Depth only, 3-strata A	20-55, 55-100, 100-150	855.8	772.0
Depth only, 3-strata B	20-55, 55-75, 75-150	834.9	707.1
Depth only, 3-strata C	20-50, 50-75, 75-150	753.1	666.9
Depth only, 3-strata D	20-45, 45-75, 75-150	846.9	729.8
Depth only, 4-strata	20-45, 45-60, 60-105, 105-150	831.9	781.5
Depth & Subregion	6-strata: Depth 3C, E & W	967.2	884.5

Table 6. (A) Strata possible sample units and associated weighting factors for the selected depth stratification scheme, and **(B)** corresponding strata sample sizes by year.

(A)

Stratum Code	Description	Possible Sample Units N_h	Weighting Factor w_h
D1	20 m ≤ depth < 50 m	380,354	0.5648
D2	50 m ≤ depth < 75 m	153,908	0.2285
D3	75 m ≤ depth ≤ 150 m	139,171	0.2067

(B)

	Strata Sample Sizes n_h		
Year	D1	D2	D3
2007	282	276	140
2008	244	165	90
2009	256	145	32
2010	597	176	31
2011	725	543	163
2012	1867	1269	502
2013	718	437	37
2014	706	308	153
2015	1311	658	282
2016	816	527	133
2017	345	323	101
2018	170	149	65

Table 7. Reef fish observer CPUE index time-series for GOM Scamp/Yellowmouth Grouper for the commercial vertical line fleet. Catch is number of fish, effort is standardized reel-hours. The relative index was scaled to mean CPUE for 2007-2018.

Year	n	Mean Catch	Mean Effort	Nominal CPUE	Relative Index	CV
2007	698	1.984	0.264	0.133	0.923	0.103
2008	499	2.333	0.335	0.144	0.998	0.178
2009	433	2.047	0.289	0.141	0.979	0.187
2010	804	1.763	0.173	0.098	0.682	0.200
2011	1431	1.898	0.164	0.087	0.602	0.130
2012	3638	1.844	0.320	0.174	1.206	0.059
2013	1192	1.682	0.260	0.154	1.072	0.220
2014	1167	1.650	0.205	0.124	0.864	0.095
2015	2251	1.690	0.278	0.164	1.142	0.074
2016	1476	1.723	0.310	0.180	1.251	0.098
2017	769	1.707	0.262	0.153	1.066	0.126
2018	384	2.094	0.366	0.175	1.215	0.123

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.

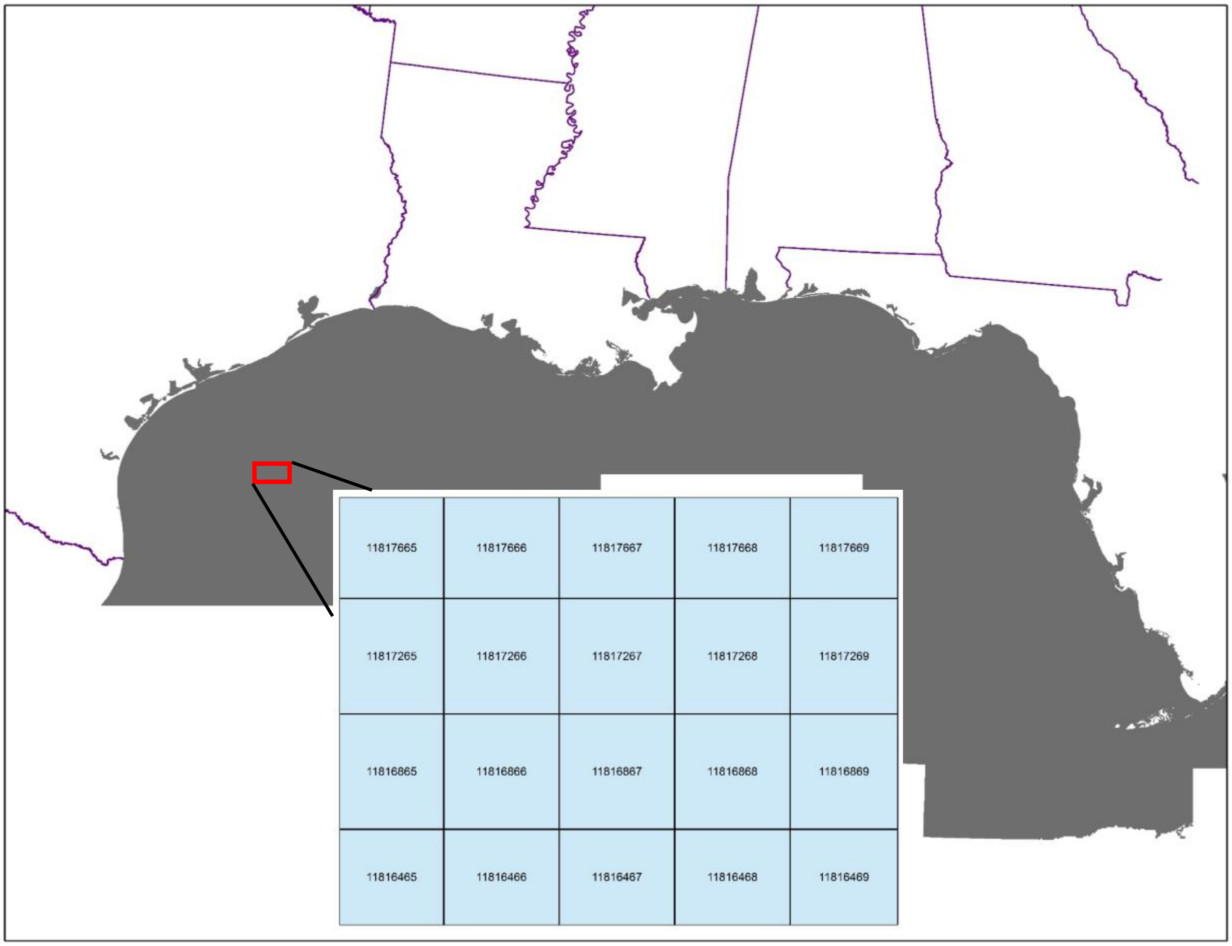
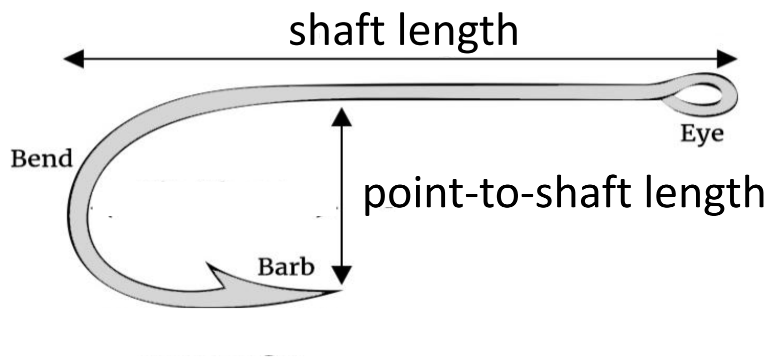


Figure 2. (A) Illustration of two hook size measurements, shaft length and point-to-shaft length, taken by onboard observers that were used to assign hook size categories. **(B)** Cumulative length-frequency distributions for Scamp/Yellowmouth Grouper for two hook size categories: (i) red line, C_MED (medium circle hooks), shaft length < 2 in.; (ii) blue line, C_LRG (large circle hooks), shaft length ≥ 2 in., point-to-shaft length ≥ 0.5 in.

(A)



(B)

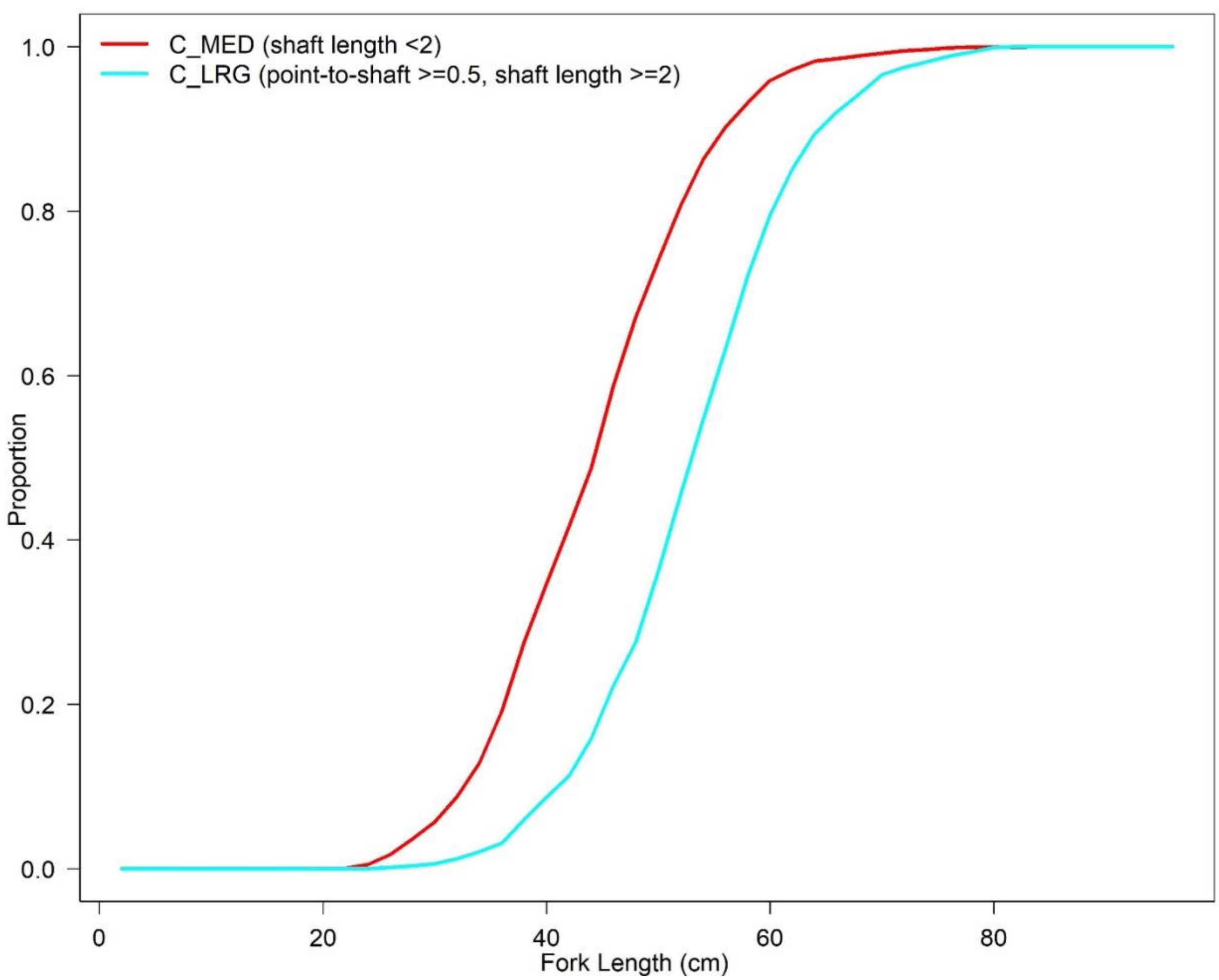


Figure 3. Logistic regression point estimates of Scamp/Yellowmouth Grouper occurrence p by depth intervals within the observed depth range of 20-150 m. Dashed lines indicate the initial depth blocking scheme for species association analysis: 20-55 m, 55-100 m, and 100-150 m.

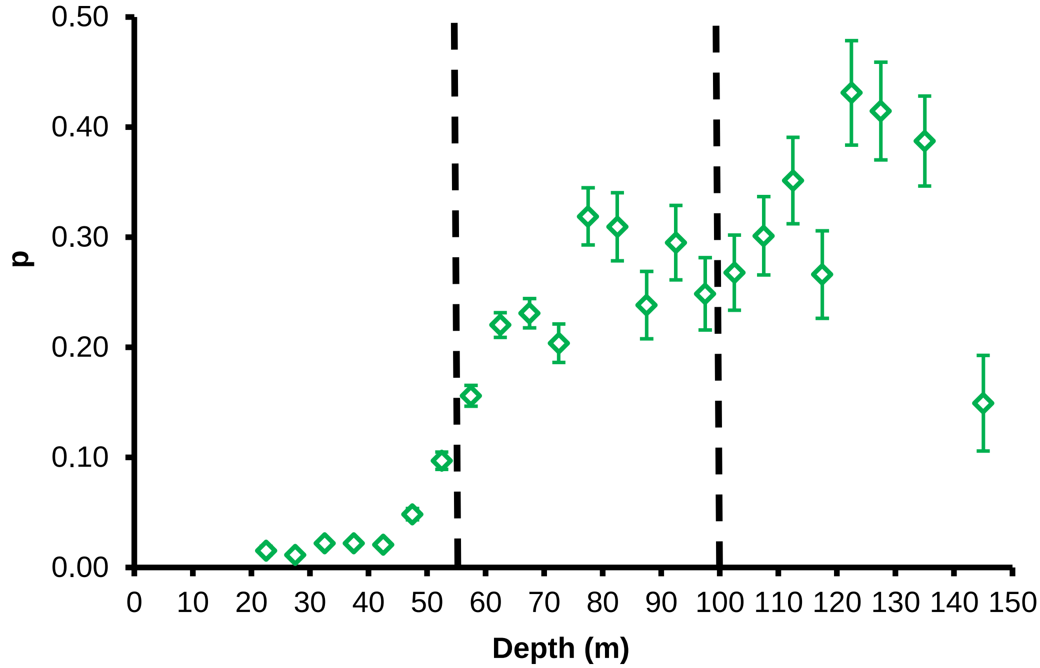


Figure 4. Map of the Scamp/Yellowmouth Grouper GOM spatial sampling frame showing the subregion-depth blocking scheme for species association analysis. Subregions are East (E) and West (W); depths are shallow (SH), medium (MD), and deep (DP), see Fig. 3. The red circle denotes the area < 26 degrees latitude in the East subregion that was excluded from the sample frame due to a combination of sparse observer coverage of vertical line trips and near-zero occurrence of Scamp/Yellowmouth Grouper in shallow depths.

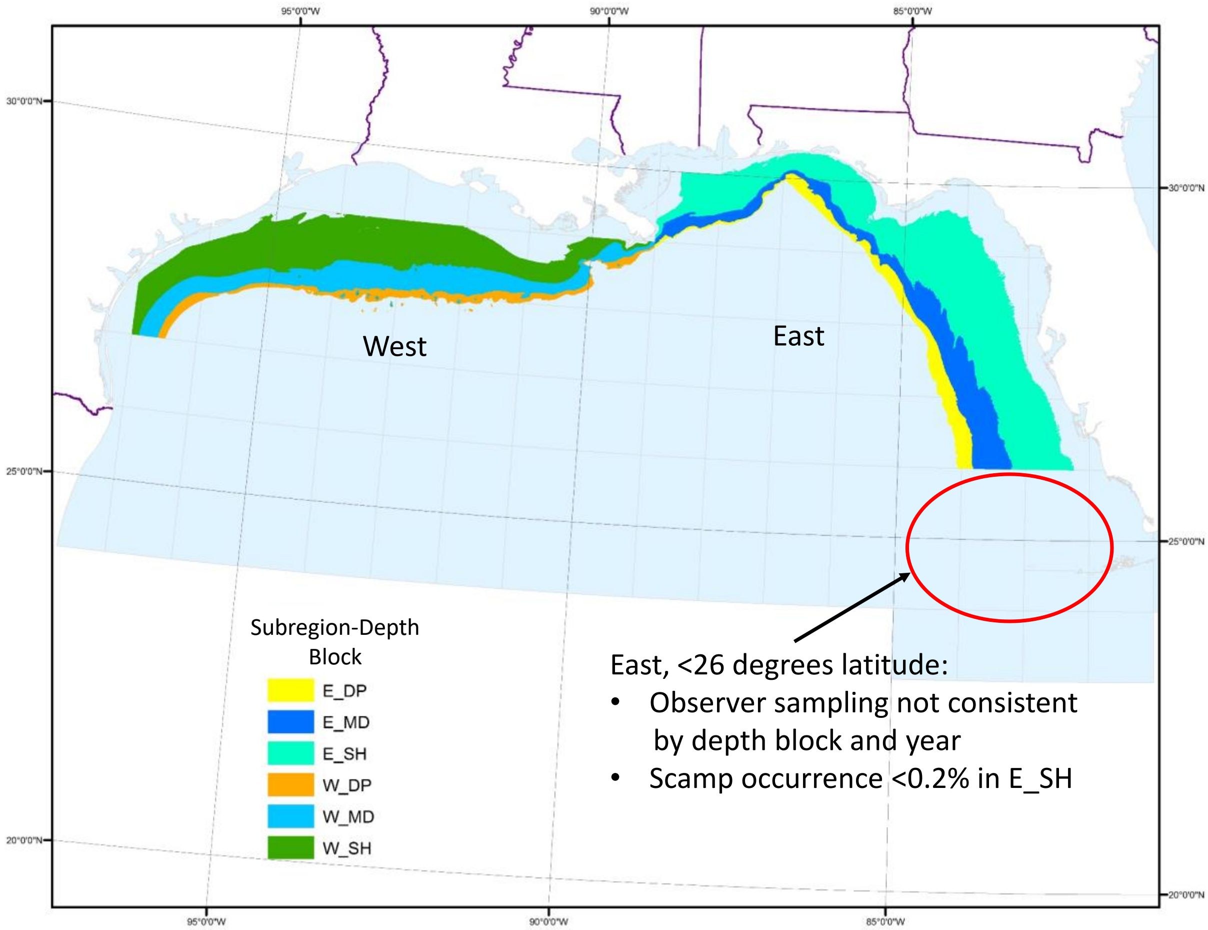


Figure 5. Generalized linear regression relationships of Scamp/Yellowmouth Grouper occurrence (left panels) and catch when present (right panels) dependent on effort for two candidate effort variables, **(A)** reel-hours and **(B)** hooks, for vertical lines with mechanical reels and medium circle hooks. Logistic regression point estimates of logit(p) (left panels) were comprised of 40 or more observations per effort interval; gamma pdf regression point estimates of catch when present u (right panels) were comprised of 15 or more observations per effort interval. The respective sample sizes (n) for logit(p) and u denoted in (A) were the same for all effort variables.

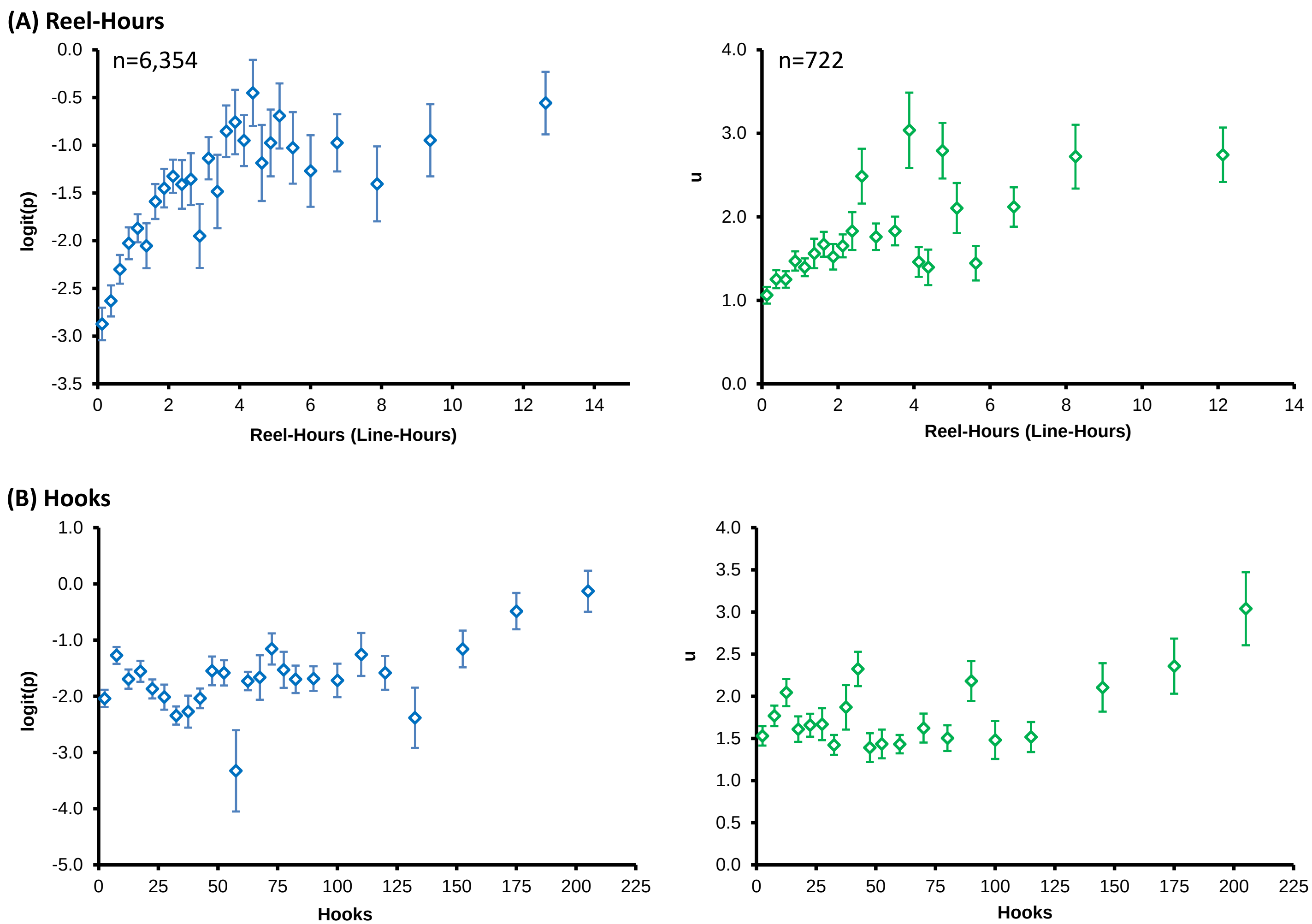
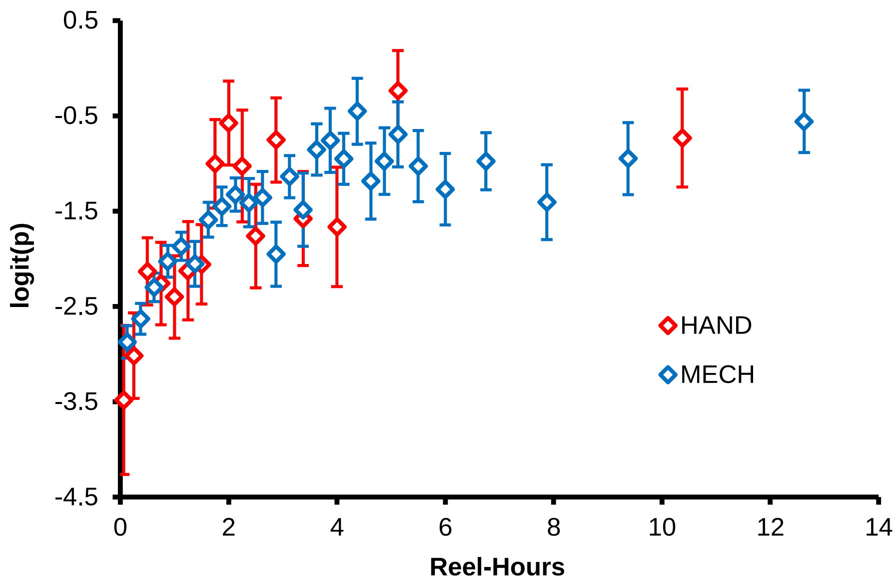


Figure 6. Scamp/Yellowmouth Grouper catch-effort relationships for vertical line hand and mechanical reels with medium circle hooks. **(A)** Logistic regression point estimates of occurrence (logit(p)) dependent on reel-hours. **(B)** Gamma pdf regression point estimates of catch when present u dependent on reel-hours.

(A)



(B)

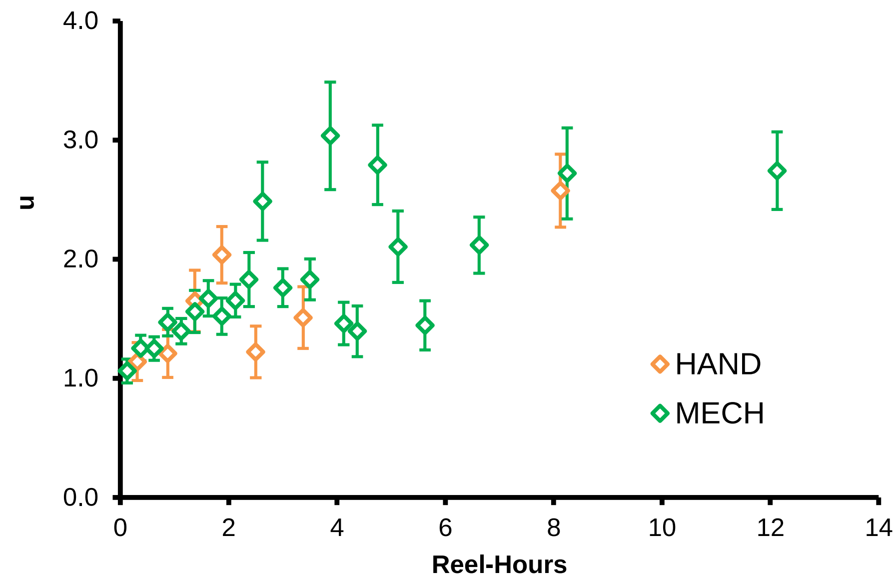
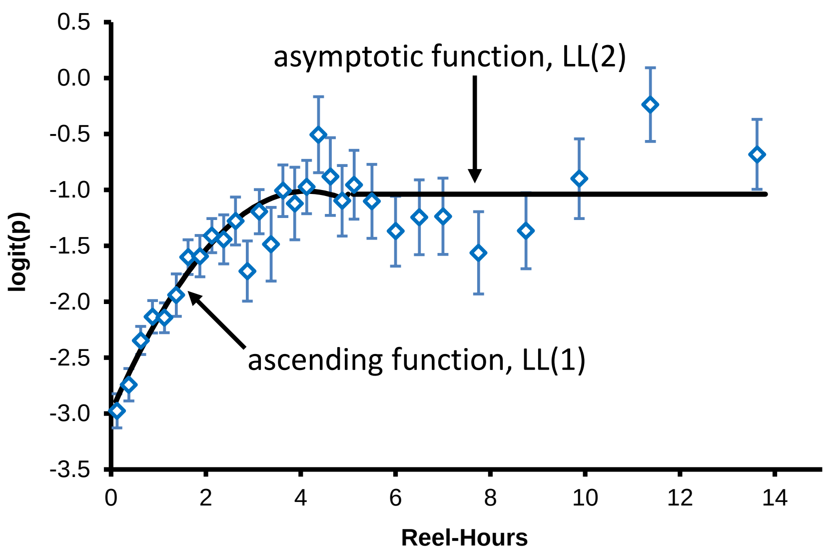


Figure 7. Illustration of procedures for identifying the maximum threshold value for effort above which mean occurrence remains more or less constant. This example is for Scamp/Yellowmouth Grouper occurrence (logit(p)) dependent on reel-hours for vertical lines with medium circle hooks. **(A)** Logistic regression point estimates of logit(p) (blue diamonds) 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 logit(p)-effort observations for the ascending and asymptotic portions of the relationship. **(B)** The fitting procedure of (A) 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 5.0 reel-hours.

(A)



(B)

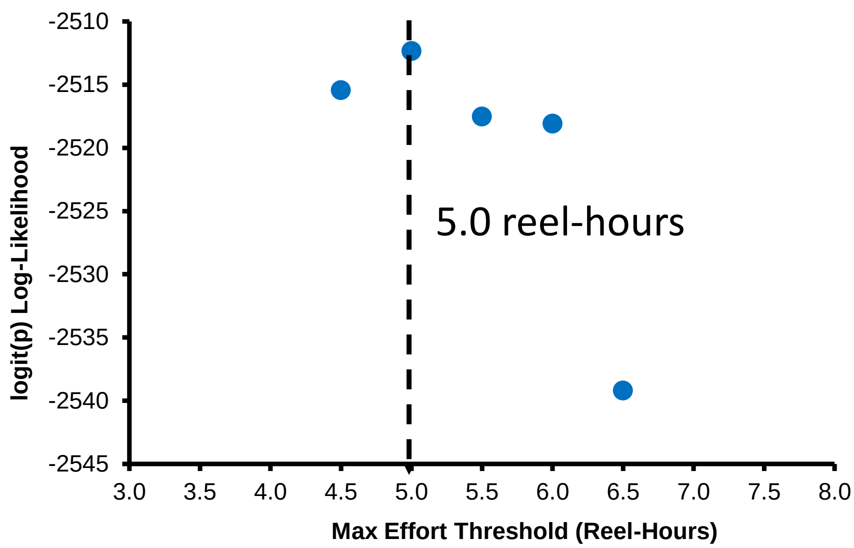
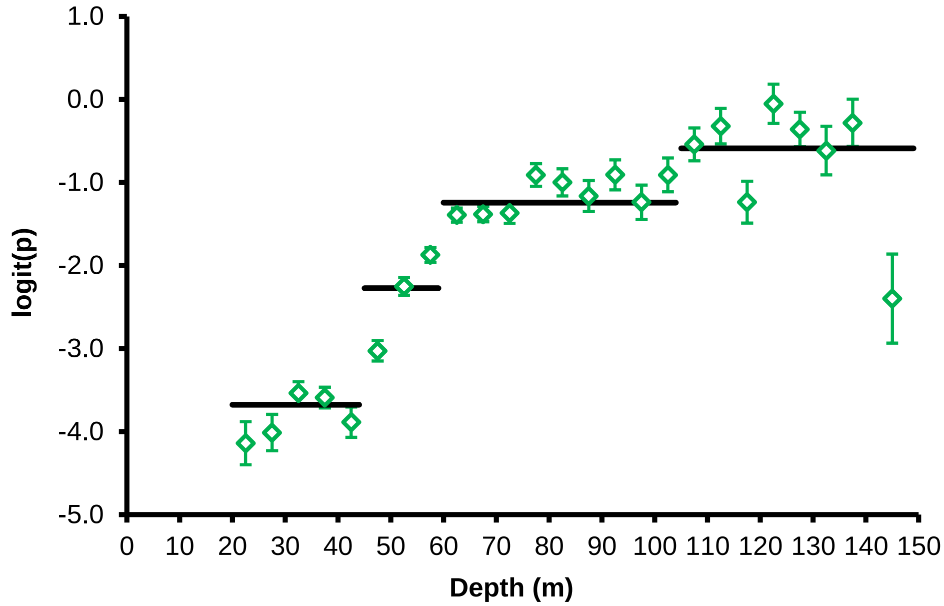


Figure 8. Generalized regression modeling for Scamp/Yellowmouth Grouper (A) occurrence (logit(p)) and (B) catch when present u as a function of depth. **(A)** Logistic regression point estimates (green diamonds with SE error bars) and associated regression functions (solid horizontal lines) for potential 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)

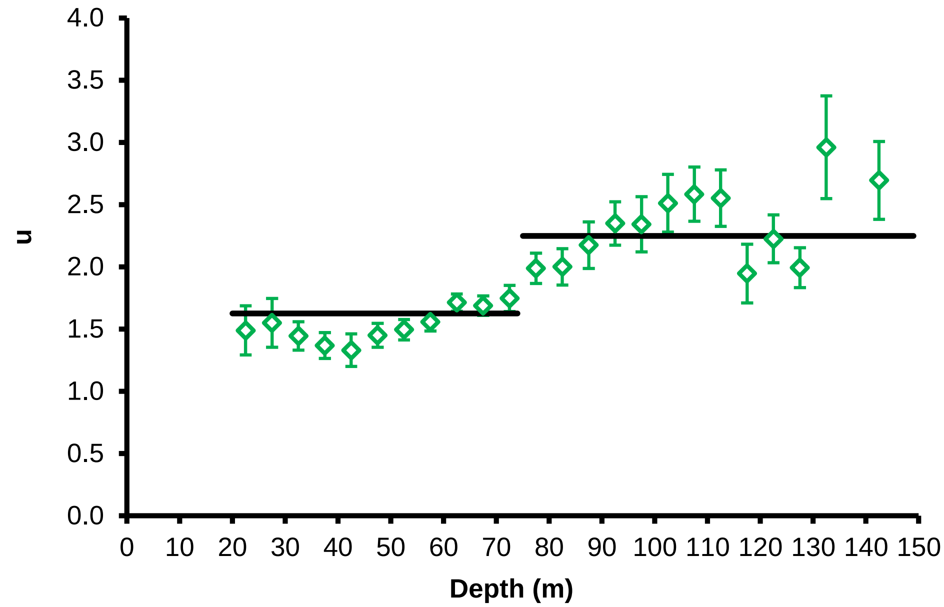


Figure 9. Time-series graph of reef fish observer standardized CPUE index (±95% CI) for GOM Scamp/Yellowmouth Grouper for the commercial vertical line fleet.

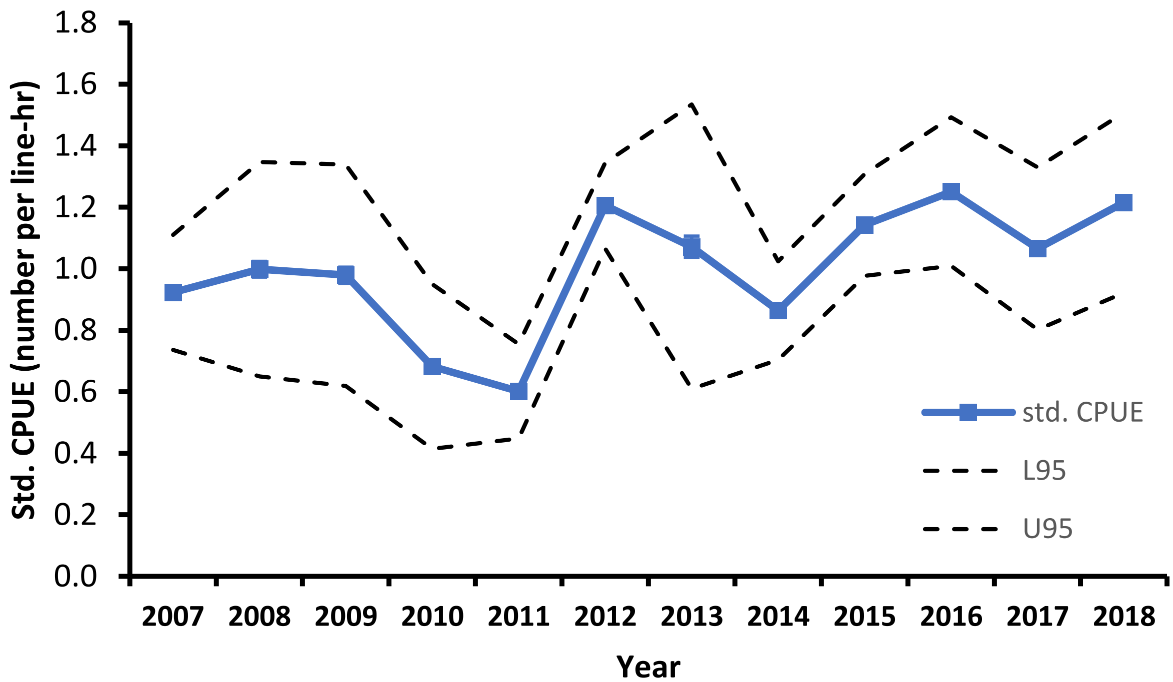
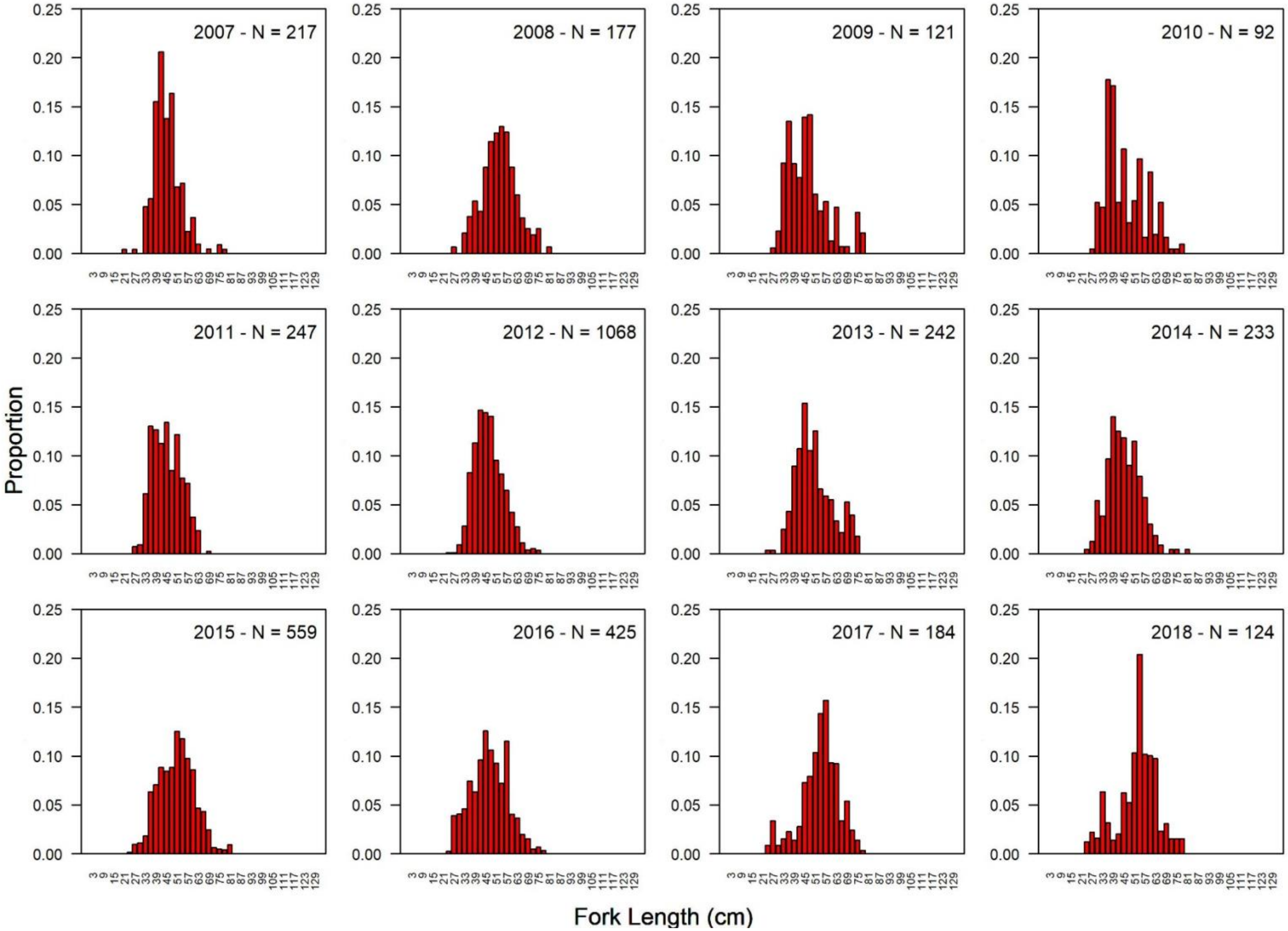


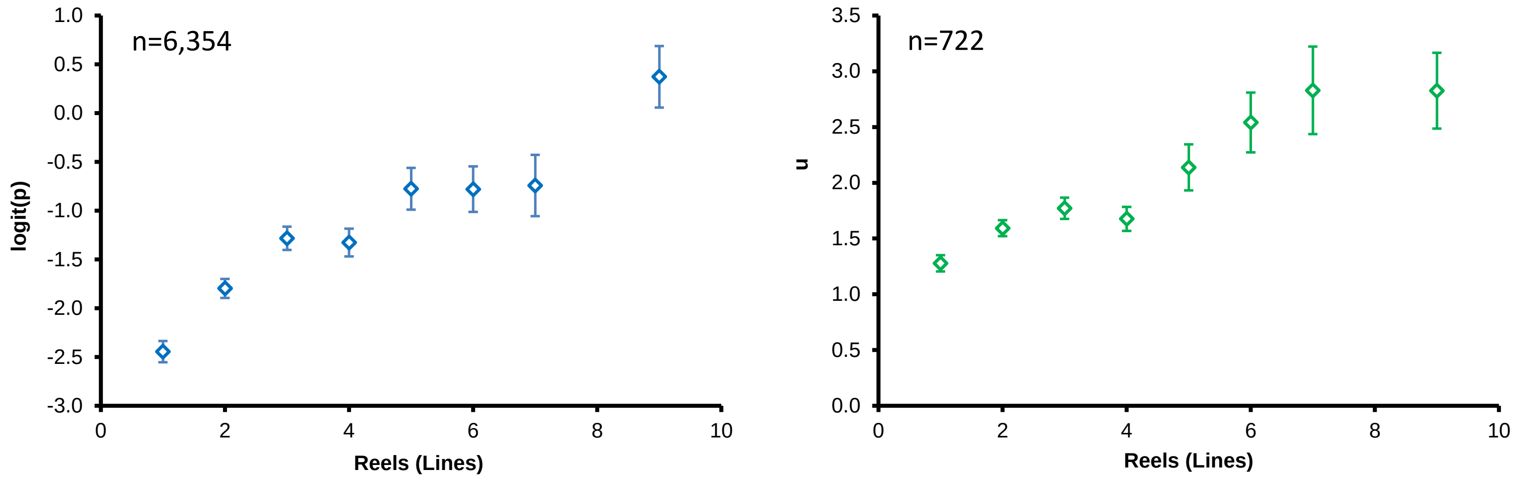
Figure 10. Annual population length compositions for GOM Scamp/Yellowmouth Grouper. N values denote the annual number of fish length observations; annual statistical sample sizes (n) are provided in **Table 7**.



Appendix

Figure A1. Evaluation of effort variables for vertical lines with mechanical reels and medium circle hooks. Generalized linear regression relationships of Scamp/Yellowmouth Grouper occurrence (left panels) and catch when present (right panels) dependent on effort for six candidate effort variables: **(A)** reels, **(B)** reel-hours, **(C)** hours, **(D)** drops, **(E)** hooks, and **(F)** hook-hours. Sample sizes denoted in (A) were the same for all effort variables. Effort variables are presented in order of precision (average annual CV) rank for CPUE estimates (best to worst).

(A) Reels: Avg. CV=23.4%, CV Rank=1



(B) Reel-Hours: Avg. CV=25.5%, CV Rank=2

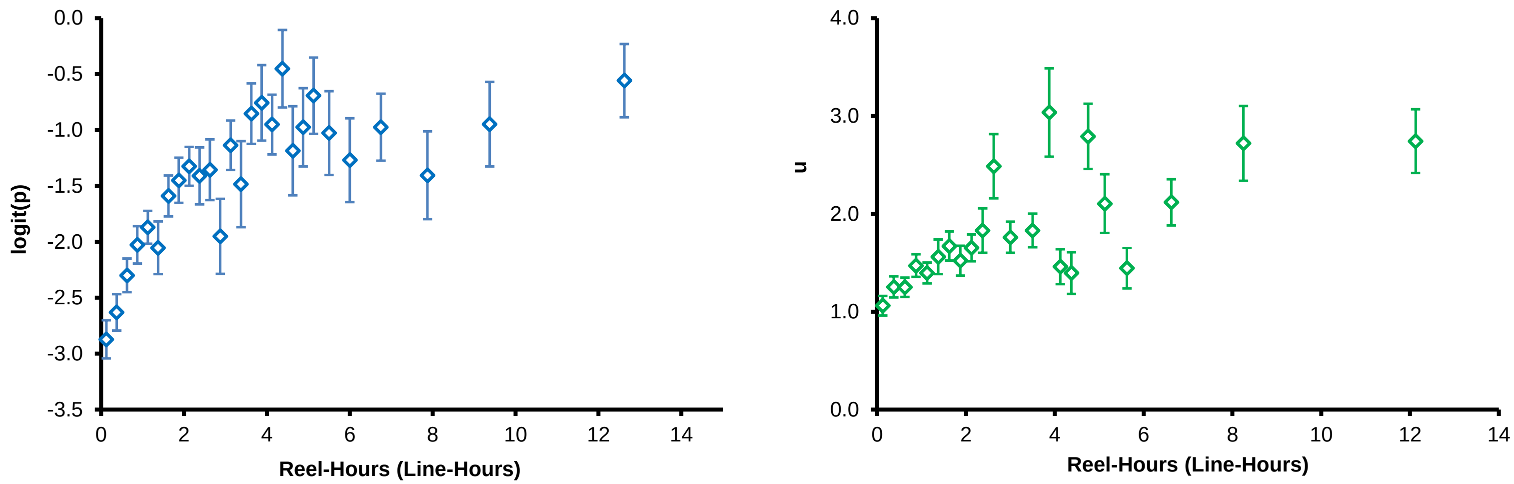
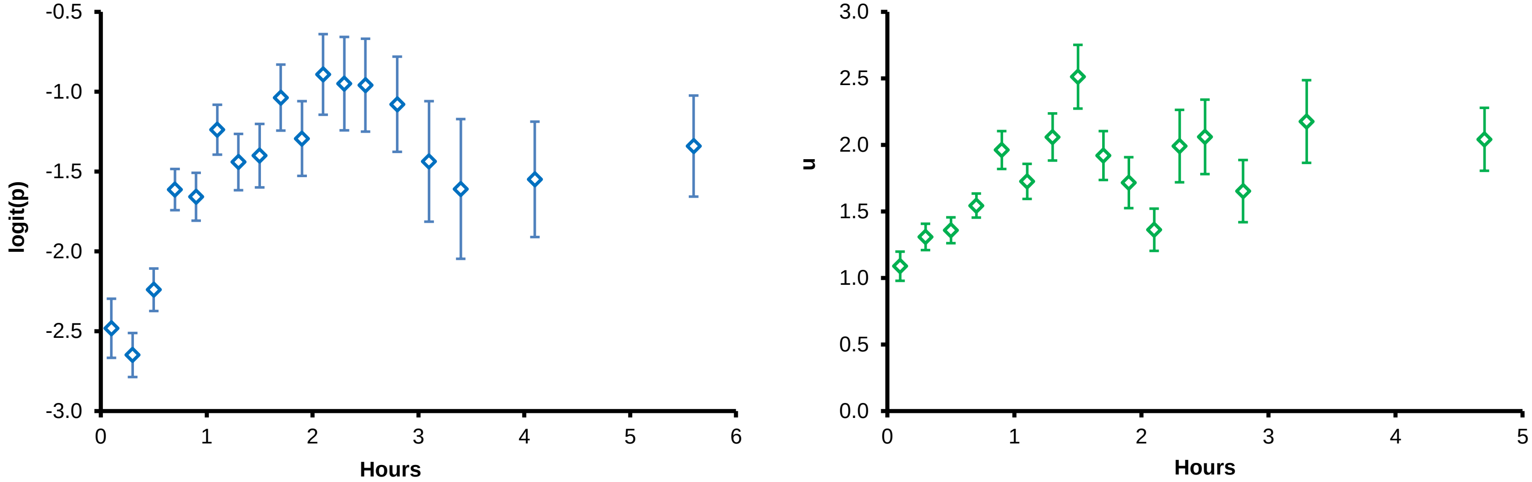


Figure A1. (cont.)

(C) Hours: Avg. CV=28.4%, CV Rank=3



(D) Drops: Avg. CV=35.5%, CV Rank=4

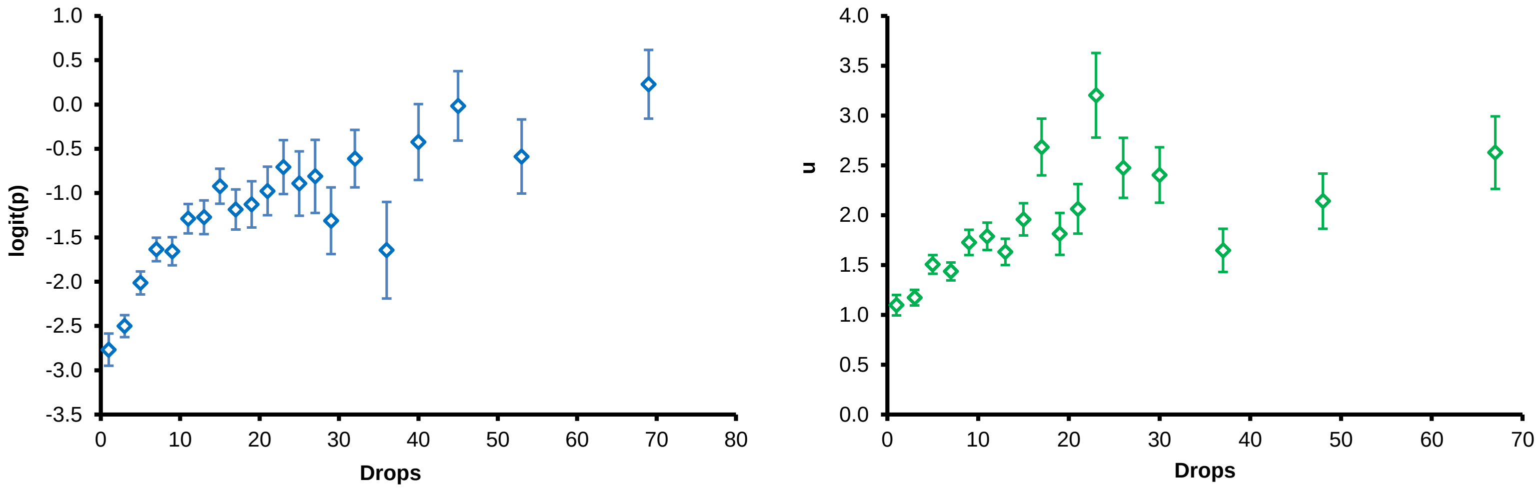
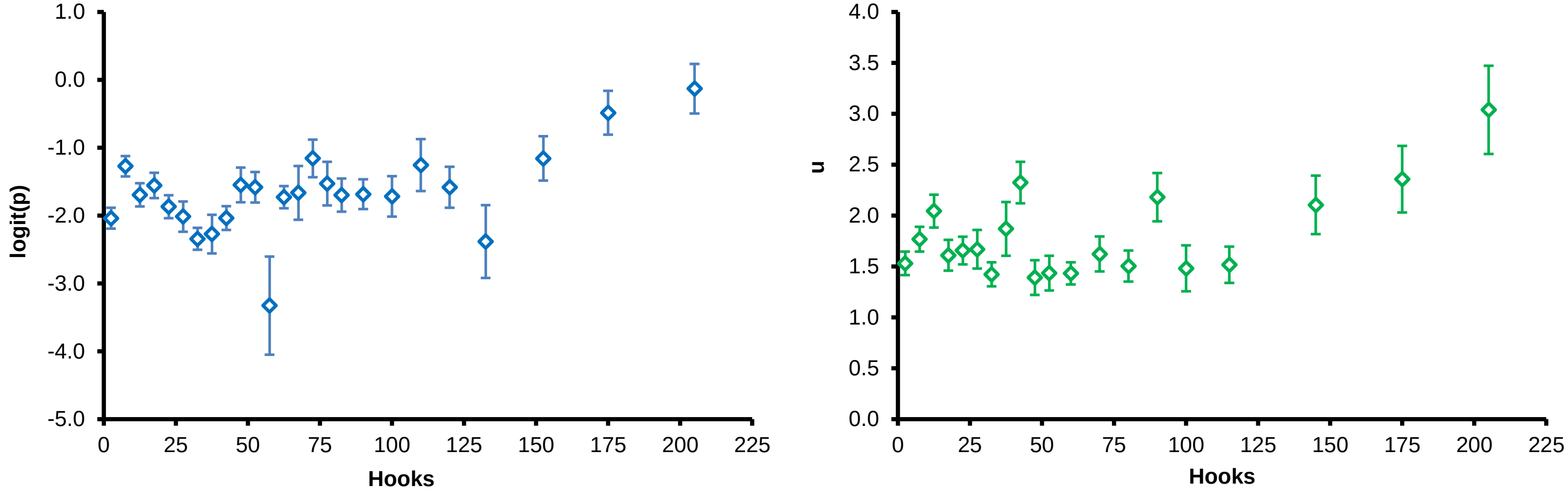


Figure A1. (cont.)

(E) Hooks: Avg. CV=181.0%, CV Rank=5



(F) Hook-Hours: Avg. CV=186.6%, CV Rank=6

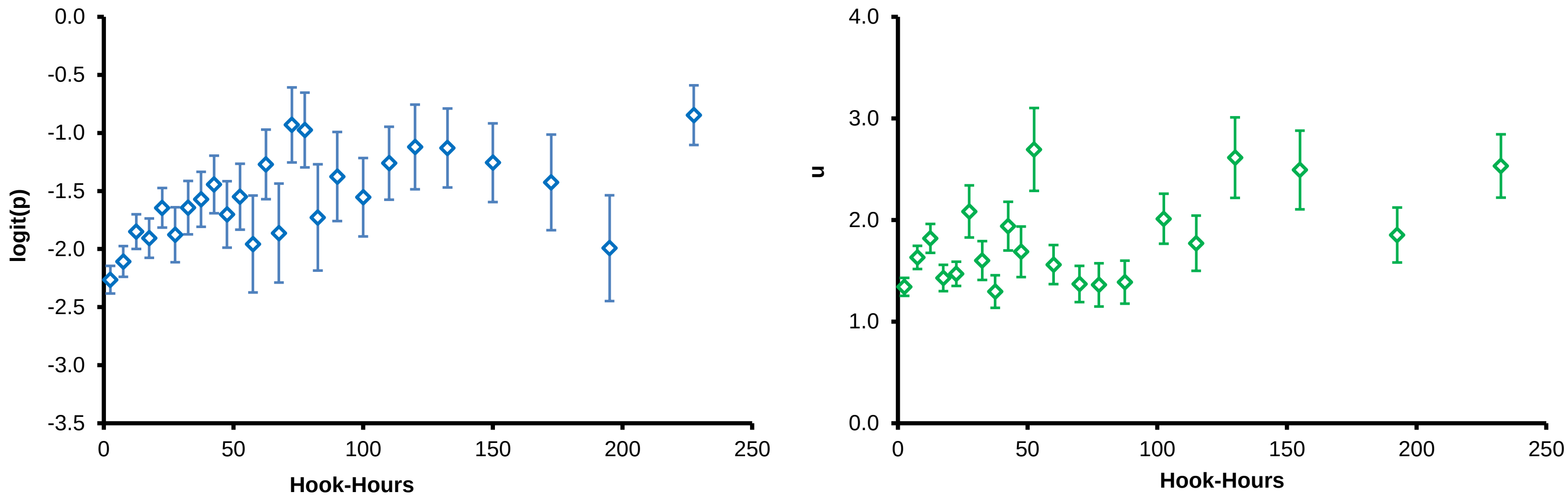


Figure A2. Evaluation of effort variables for vertical lines with mechanical reels and large circle hooks. Generalized linear regression relationships of Scamp/Yellowmouth Grouper occurrence (left panels) and catch when present (right panels) dependent on effort for six candidate effort variables: **(A)** reel-hours, **(B)** reels, **(C)** hours, **(D)** drops, **(E)** hook-hours, and **(F)** hooks. Sample sizes denoted in (A) were the same for all effort variables. Effort variables are presented in order of precision (average annual CV) rank for CPUE estimates (best to worst).

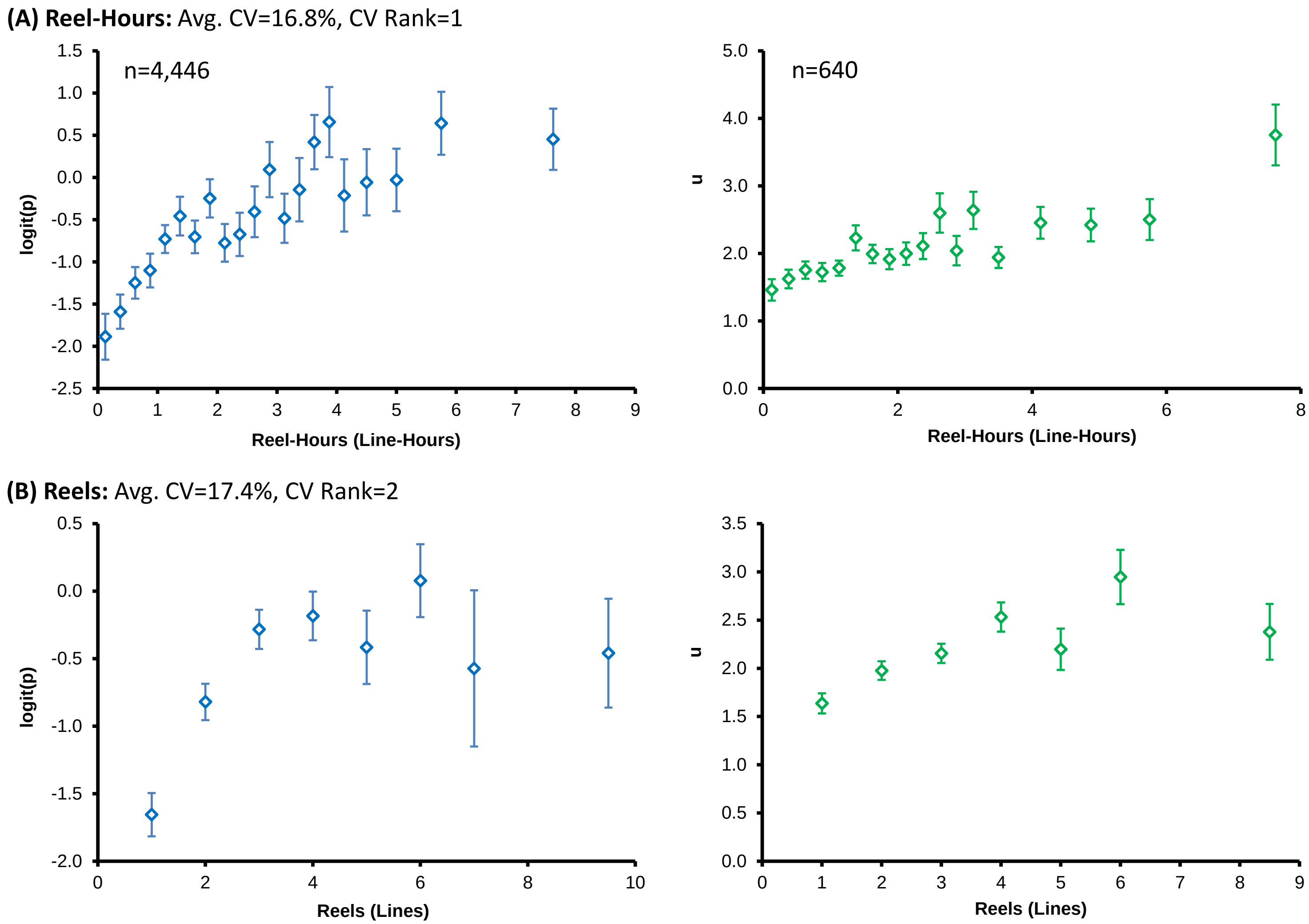
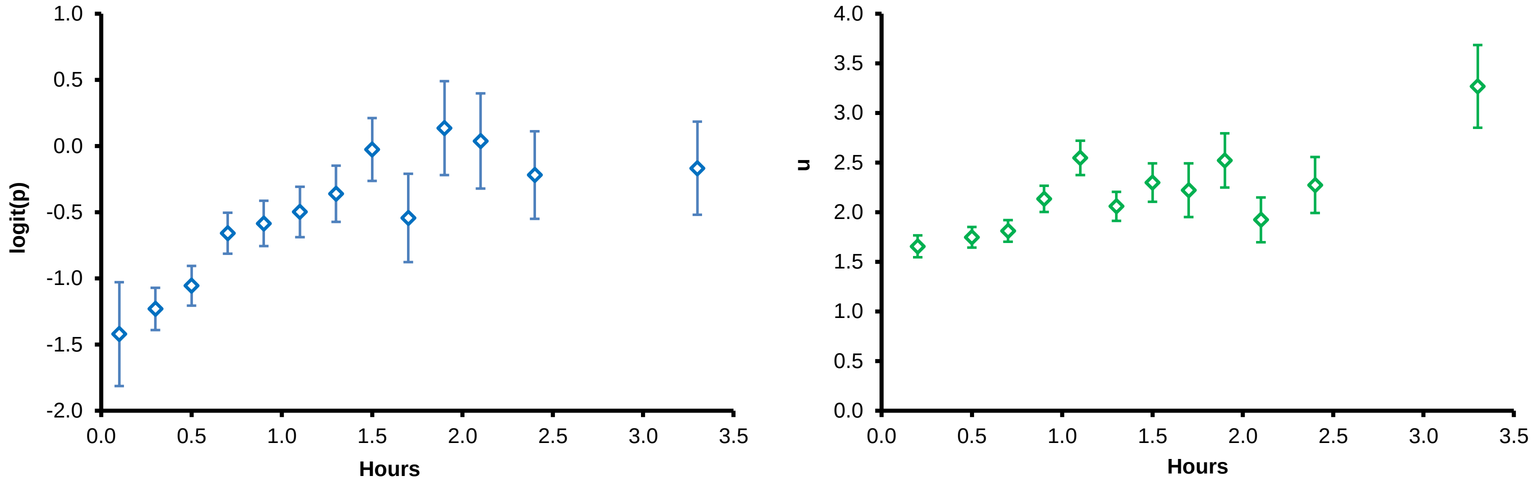


Figure A2. (cont.)

(C) Hours: Avg. CV=17.8%, CV Rank=3



(D) Drops: Avg. CV=18.0%, CV Rank=4

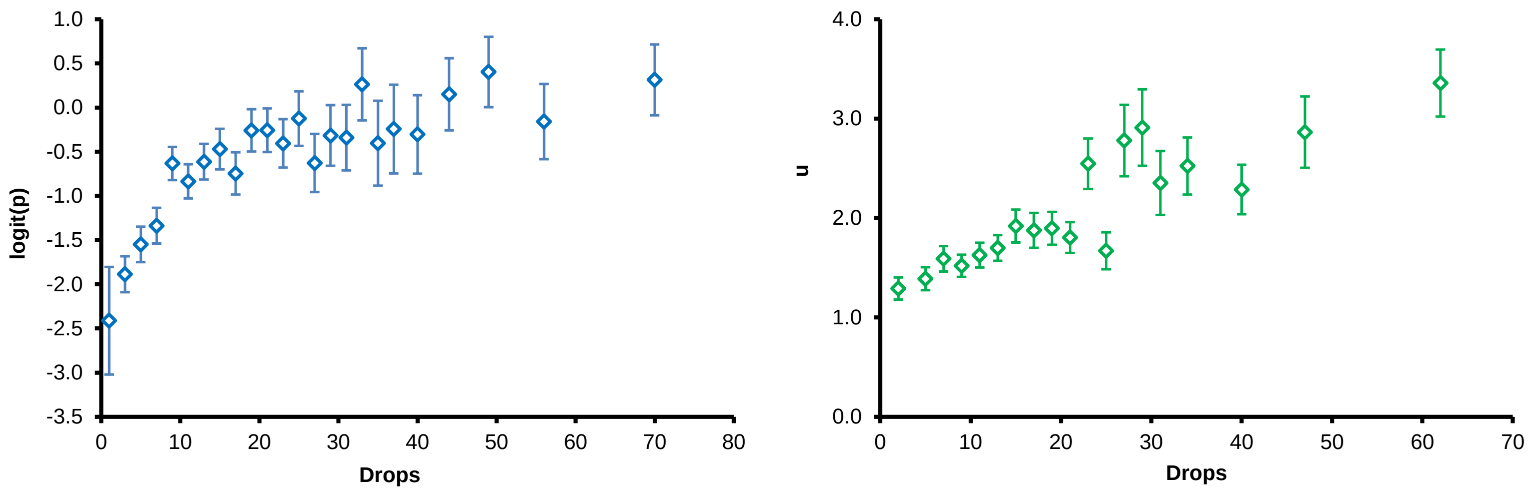
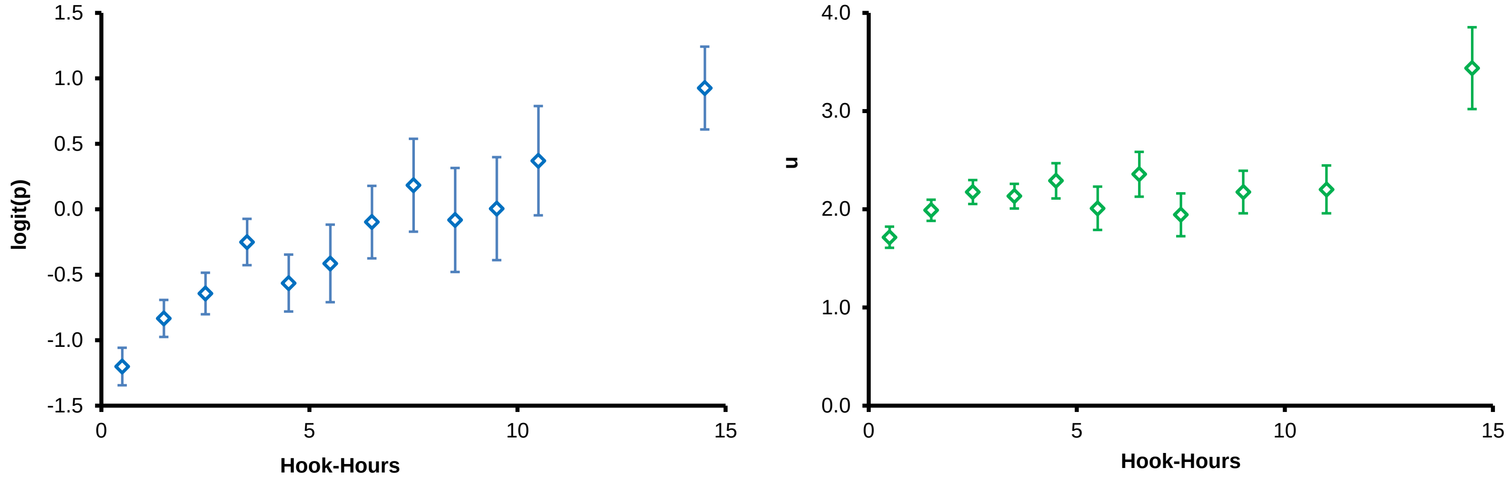


Figure A2. (cont.)

(E) Hook-Hours: Avg. CV=18.7%, CV Rank=5



(F) Hooks: Avg. CV=19.8%, CV Rank=6