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1.0 Introduction

Background

The Gulf of Mexico (GOM) shrimp trawl fishery is one of the premier commercial fisheries of the US in terms of landings, economic value, and number of participants, and has been so for many decades. Shrimp trawls, however, capture many non-target species discarded as bycatch. During the 1990s and early 2000s, devices installed on shrimp nets to limit bycatch of fishes and protected species (bycatch reduction devices, turtle excluder devices) were developed and implemented fleet-wide. In 2007, the first Individual Fishing Quota (IFQ; i.e., catch shares program) in the GOM was established for red snapper (*Lutjanus campechanus*). Bycatch of juvenile red snapper in shrimp trawls was identified as a pressing management concern, potentially impacting the sustainability of the premier catch shares species in the GOM. Implementation of the NOAA SEFSC (Southeast Fisheries Science Center) Shrimp Observer Program to collect onboard bycatch data coincided with implementation of the red snapper IFQ in 2007.

Estimates of red snapper bycatch from shrimp trawls are critical inputs for stock assessments and the subsequent determination of annual quotas. The general approach for estimating bycatch entails two catch rate expansion estimates, one to estimate total fleet effort (*f*) and one to estimate total fleet catch/bycatch (*C*). Total fleet effort is estimated using shrimp catch and effort data for a subset of vessels equipped with GPS tracklog devices (ELB, electronic logbook), assuming representativeness with shrimp fleet catch and effort,

$$\frac{C_{ELB}}{f_{ELB}} = \frac{C_{fleet}}{f_{fleet}} \quad . \tag{1.1}$$

This relationship is then used to estimate total shrimp fleet effort (tow hours),

$$\hat{f}_{fleet} = \frac{C_{fleet} \times f_{ELB}}{C_{ELB}} \quad , \tag{1.2}$$

where the respective fleet and ELB catches are obtained from reported shrimp landings. Although referred to as an ‘electronic logbook’, the ELB device only records location at specified time intervals (i.e., in essence a GPS tracklog) and does not obtain the usual gear, catch, etc., information associated with commercial fleet logbooks. Total fleet catch of non-target species (discarded as bycatch) is estimated using onboard observer catch and effort data for a subset of vessel trips, again assuming representativeness with fleet catch and effort,

$$\frac{C_{obs}}{f_{obs}} = \frac{C_{fleet}}{f_{fleet}} \quad . \tag{1.3}$$

Fleet effort from Eq.(1.2) is used to estimate total fleet bycatch,

$$\hat{C}_{fleet} = \frac{C_{obs} \times \hat{f}_{fleet}}{f_{obs}} \quad . \tag{1.4}$$

Estimation procedures employ a space-time stratification scheme within years: geographical area, depth, and season.

Prompted by concerns about the reliability of shrimp bycatch estimates for red snapper and other important commercial species, a project team was formed in 2021 to develop a cross-check procedure. This procedure entailed applying the bycatch estimation methodology to estimate the annual landings of brown shrimp, a primary target of the shrimp fleet, and then comparing the estimated landings with the reported fleet landings. The bycatch-estimated annual landings were consistently below the reported annual landings by an average of 45% (Fig. 1.1), suggesting a net systematic bias occurring somewhere in the bycatch estimation process.

The project team suspected that the bias was due to one or more of the principal data inputs for the estimation procedure: observer CPUE, fleet effort, and/or fleet landings. The origins of each input were unclear. The data processing procedures for all three major inputs were developed in the mid- to late-2000s, and then this 'legacy code' had been subsequently passed over the years from scientist to scientist who managed to make the code 'run' as new data became available. By 2021, the original developers were not available for consultation (retired, left agency, etc.). Bycatch estimation also included a fleet-wide scalar for the average nets per vessel (shrimp trawl vessels usually tow multiple nets simultaneously, typically two or four), which was used to expand observer catch rates per sampled net to total nets towed. This conversion constant was also of unclear origin. In 2021-2022, responsibility for the GOM shrimp fleet ELB and observer programs shifted from the Galveston Laboratory to the Fisheries Statistics Division (FSD) as part of a major reorganization of SEFSC. There was thus a need by FSD to gain a better understanding of the fundamental data sources and associated data processing and estimation procedures required for estimating bycatch.

Project Goal and Objectives

A reformulated and expanded project team was assembled by FSD in 2022. The project goal was to improve the methodology for estimating bycatch from shrimp trawls in the GOM. Objectives were:

1) to gain a comprehensive understanding of the fundamental data sources for estimating bycatch towards refining/modernizing data processing procedures for creating accurate analysis-ready datasets;
2) to investigate potential additional stratification variables for gear characteristics and diurnal period;
3) to cross-check the refined methodology for penaeid shrimps; and,
4) to apply the refined methodology to estimate bycatch of red snapper.

A flow diagram of key elements of data processing and estimation is provided in Fig. 1.2. Elements on the right side of the diagram are described in this report; elements on the left side are described in the companion report by Dettloff (2023). Supplemental information (procedures guides, SAS processing code, etc.) is provided in a separate folder ('Suppl_Info'), with subfolders for each report section (e.g., 'S_2.0'). Due to confidentiality issues, original source data are not provided.

Figure 1.1. Initial cross-check of the bycatch estimation procedure: observer-predicted and trip-ticket brown shrimp catch (tail wt) for 2011-2016.

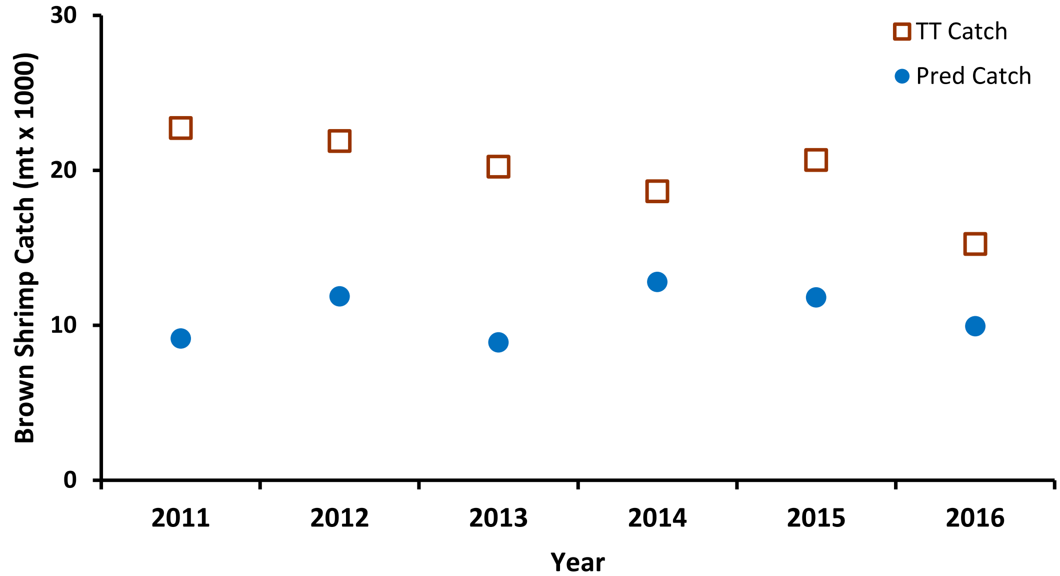
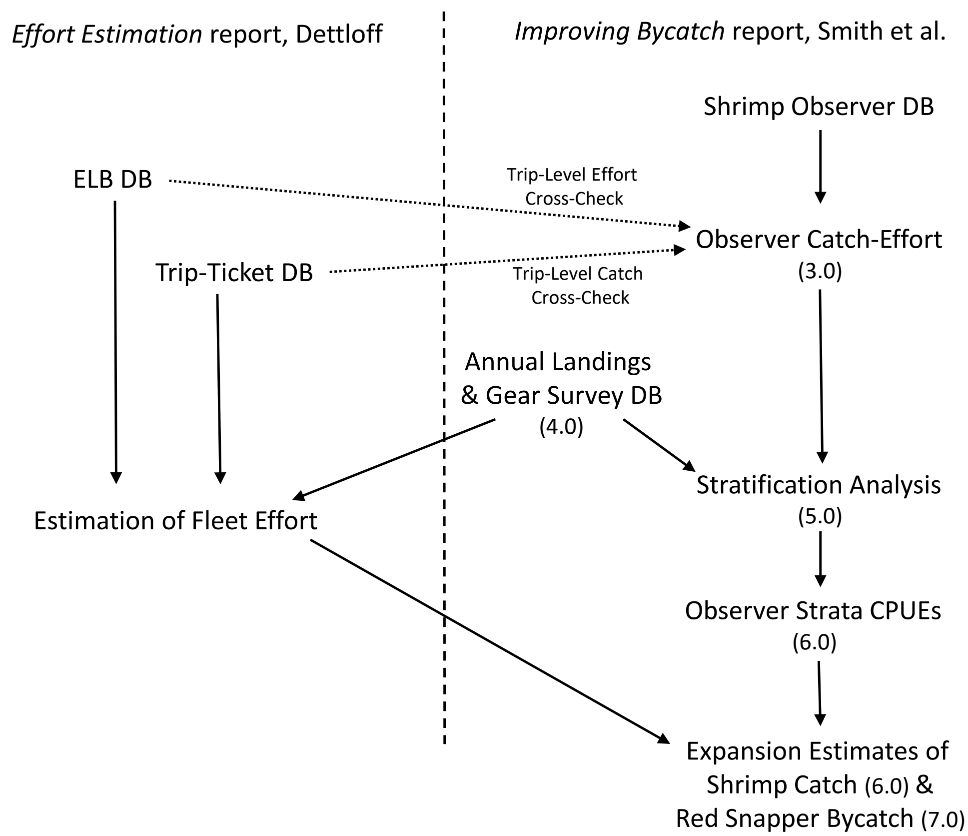


Figure 1.2. Data processing and estimation flow diagram for the Improving Bycatch Estimation project. Elements on the right side of the diagram are described in this report, with sections denoted in parentheses; elements on the left side are described in the companion report by K. Dettloff.



2.0 Methods

Study Area

The study area was the Gulf of Mexico in the southeastern USA region (Fig. 2.1), which included coastal waters of 5 states: Florida (west coast), Alabama, Mississippi, Louisiana, and Texas.

Data Sources

There were four principal data sources for bycatch estimation:

1) Trip-Ticket Landings. Catch data for the GOM shrimp trawl fleet were obtained from the trip-ticket database maintained by the Gulf States Marine Fisheries Commission (GSMFC). Trip-tickets are individual fishing trip reports filed by seafood dealers who purchase the catch from commercial fishers, and include information on catch and price by gear, species, and market category, as well as the principal fishing area for the trip (statistical reporting zones, Fig. 2.1A). Each state manages its own trip-ticket dealer reporting system (see subfolder S_2.0 in Suppl_Info for individual state trip-ticket manuals). State data are uploaded periodically (about every 3 months) to the central GSMFC trip-ticket database. The GSMFC database does not include information on trip fishing effort. The trip-ticket system was developed over a 30-year period by the various states, beginning with Florida in 1985 and concluding with Mississippi in 2012. Data processing procedures for trip-ticket data are described in Dettloff (2023).

2) ELB Units. Data for trawl fleet effort were obtained from GPS tracklog units (termed Electronic Logbooks) installed on a subset of vessels. The ELB database is maintained by NOAA SEFSC. A complete description of the ELB program and estimation of fleet effort is provided in Dettloff (2023). The original manual for ELB data processing and analysis is provided in subfolder S_2.0 in Suppl_Info.

3) Shrimp Observer Program. Data for shrimp trawl bycatch were obtained by the SEFSC Shrimp Observer Program in which scientific observers on commercial fishing vessels record detailed information on catch and effort for a subset of trips. A voluntary pilot observer program began in the 1980s, primarily testing various devices to limit the bycatch of turtles (TEDs, Turtle Excluder Devices) and fishes (BRDs, Bycatch Reduction Devices). The program became mandatory for the federally-permitted shrimp trawl fleet in 2007, coinciding with implementation of the catch shares program for red snapper. The field procedures manual for the SEFSC Shrimp Observer Program is provided in subfolder S_2.0 in Suppl_Info. Data processing for observer catch-effort data is described below in section 3.0.

4) SEFSC Annual Landings and Gear Survey. The Annual Landings and Gear (ALG) mail survey has been conducted annually since 2005 by SEFSC to collect information regarding vessel information, estimated landings, and detailed gear characteristics for all federally-permitted shrimp trawl vessels in a given year. The survey is mandatory, required as a condition for maintaining a federal shrimp fishing permit. Curiously, data from the ALG had

never been used for bycatch estimation prior to this study, even though it contained vessel-specific information on net configuration (i.e., number of trawl nets). ALG data for nets per vessel were incorporated into the revised bycatch estimation methodology, eliminating the need for a single scalar of fleet-wide average nets per vessel. Further description of ALG gear data is provided below in section 4.0.

Statistical Analysis

Bycatch estimation using observer catch rates (Eq. 1.4) was carried out using a Horvitz-Thompson ratio-of-means estimator for a stratified sample frame (Jones et al. 1995; Pollock et al. 1997; Lohr 2020), which accommodated varying levels of fishing effort among observer samples. An observer sampled trawl tow was designated as the sample unit *i*. Stratification included the legacy estimation variables depth (Fig. 2.1A), geographical area (Fig. 2.1B), and season (4-month periods or quadrimesters) to control for space-time variation in catch rates of a given species. 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 $\bar{x}$ (tow hours) in stratum *h* was computed by

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

Catch per unit effort in stratum *h* was estimated as the ratio of mean catch and mean effort,

$$\overline{CPUE}_h = \frac{\bar{y}_h}{\bar{x}_h} \quad . \tag{2.1}$$

Stratum variance of mean CPUE was estimated by

$$var[\overline{CPUE}_h] = \frac{s_h^2(y|x)}{n_h \bar{x}_h^2} \quad , \tag{2.2}$$

where sample variance $s^2(y|x)$ was computed by

$$s_h^2(y|x) = \frac{\sum_i (y_{hi} - \overline{CPUE}_h x_{hi})^2}{n_h - 1} \quad . \tag{2.3}$$

The numerator of Eq.(2.3) is sum of squared residuals of a catch dependent on effort regression passing through the origin. The slope of this relationship is mean CPUE (Eq. 2.1).

Expansion estimation of catch or bycatch *C* was carried out at the stratum level,

$$\hat{C}_h = \overline{CPUE}_h \times \hat{X}_h \quad , \tag{2.4}$$

where $\hat{X}_h$ is shrimp fleet effort. Variance of $\hat{C}_h$ was estimated using

$$var[\hat{C}_h] = var[\overline{CPUE}_h] \times \hat{X}_h^2 \quad . \tag{2.5}$$

Total catch and variance of catch were obtained by summing Eqs. (2.4) and (2.5) over all strata, respectively. Standard error of total catch was calculated as

$$SE[\hat{C}] = \sqrt{var[\hat{C}]} \quad .$$

While the ratio-of-means estimator for CPUE (Eq. 2.1) can accommodate varying effort among sample units, it presumes a general increasing relationship between effort and catch.

Generalized linear regression analysis was used to guide specification of various aspects of the estimation process described above, including evaluating relationships between catch and effort and between CPUE and potential stratification variables. Regression models were developed of the general form,

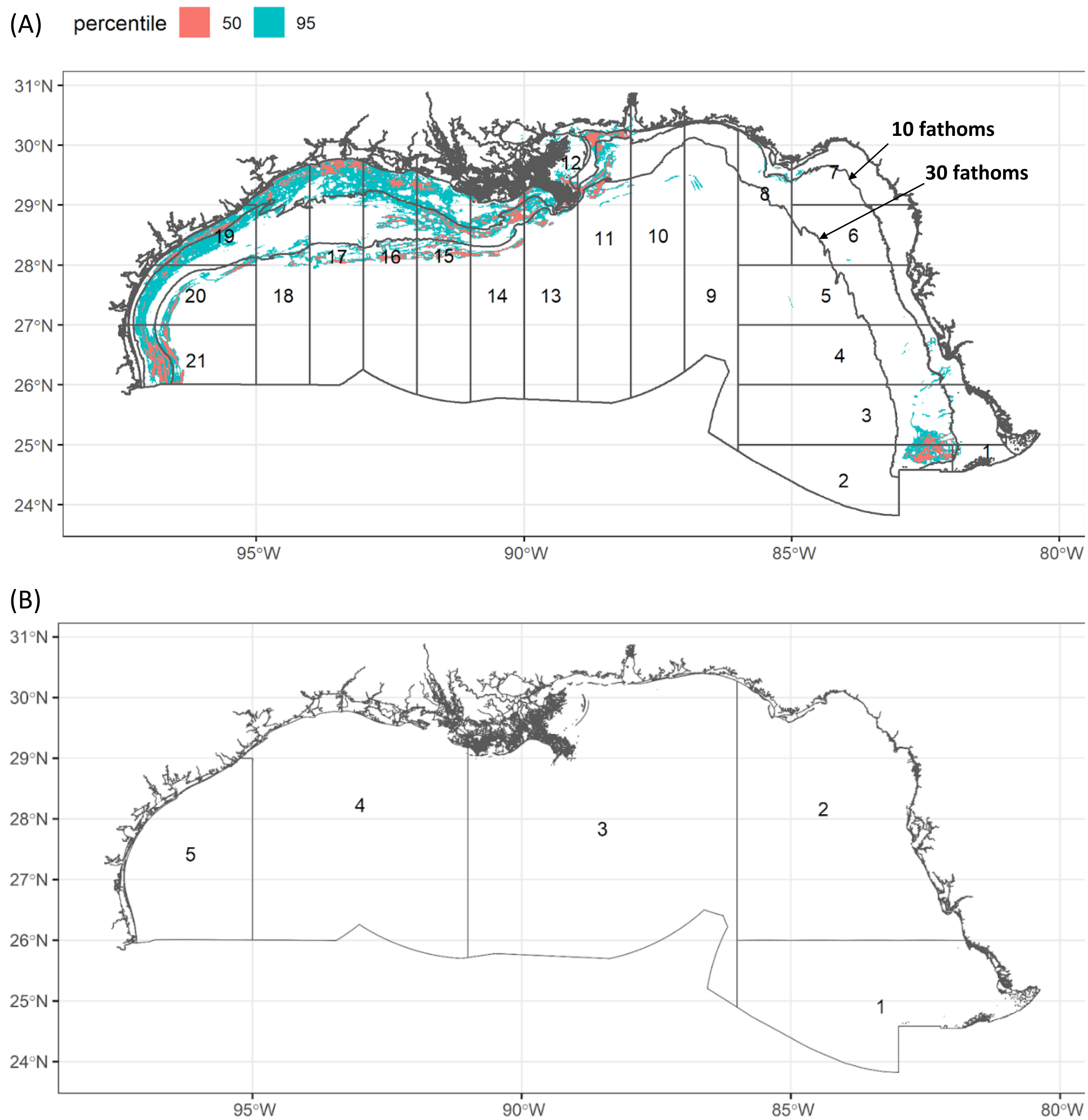
$$Catch = f(effort, addtl.covariates) + \varepsilon \quad .$$

This is the regression analogue of the ratio-of-means estimator (Eq. 2.1). In some cases catch observations had high frequencies of zero observations. A compound error pdf approach was employed for these situations, in which separate regression models were developed for occurrence (p) and catch when present (u) as functions of effort and additional covariates. Mean predictions of catch were obtained by multiplying mean predictions of p and u.

Target Species, Gears, and Fleets

Development of the bycatch estimation methodology focused on the three principal penaeid shrimp species (brown, *Farfantepenaeus aztecus*; pink, *Farfantepenaeus duorarum*; white, *Litopenaeus setiferus*) captured using otter trawl gear in offshore waters of GOM. The majority of vessels using otter trawl gear possess federal fishing permits. A smaller portion of the otter trawl fleet possess fishing permits from individual states, but these vessels are restricted to state waters (9 nautical miles from shore in Florida and Texas, 3 nm in Alabama, Mississippi, and Louisiana). State-permitted vessels mostly target shrimp species in inshore waters (e.g., coastal bays) using gears other than otter trawls (skimmer trawls, butterfly nets, roller frame trawls, etc.). Three of the four principal data sources are exclusive to the federal fleet: ELB units, shrimp observer program, and the ALG survey. Thus, estimation of penaeid catch (Eq. 2.4) and cross-checking with trip-ticket landings was restricted to the federal offshore otter trawl fleet. For application of the methodology to estimate bycatch of red snapper (*Lutjanus campechanus*), the expansion estimates of bycatch utilized offshore otter trawl effort for both federal- and state-permitted vessels (Dettloff 2023). The time period for bycatch estimation was 2014-2020, corresponding to the period where trip-ticket databases were fully in place and reliable for all the GOM states and where ELB effort data were complete.

Figure 2.1. (from Dettloff 2023) (A) GOM trip ticket statistical grid, with offshore lines delineating 10 and 30 fathom boundaries to classify three depth strata; shading shows ELB estimated shrimp trawl effort (2018-2020) classified by percentile (top 50% of effort falls in red areas, top 95% falls in combination of red and blue). (B) GOM geographical areas for bycatch estimation, comprised of statistical zones from (A): area 1, zones 1-3; area 2, zones 4-8; area 3, zones 9-14; area 4, zones 15-18; area 5, zones 19-21.



3.0 Shrimp Observer Catch-Effort Data

For the initial cross-check exercise (Fig. 1.1), the project team utilized the existing legacy code for observer data processing and estimation (Suppl_Info, subfolder S_3.0, 'Legacy SAS Code'), with minor modifications to tailor the analysis for brown shrimp. This exercise revealed that processing procedures for producing observer catch-effort data for analysis were very complex, involving numerous decisions about what data to include or exclude, accounting for various levels of subsampling of trawl catches, distinguishing usual fleet operations from specialized experimental projects (e.g., testing of bycatch reduction devices), etc. For the follow-on study, data processing procedures were refined and modernized towards improving the accuracy of observer catch-effort observations for subsequent analysis.

Refinement and Modernization of Data Processing

Fundamental refinements to legacy processing procedures (Suppl_Info, subfolder S_3.0, 'Refined SAS Code') included:

- Investigation of procedures for missing value coding and correction where possible.
- Data filtering to exclude observer data from trips that involved special projects, such as testing of bycatch reduction devices, and to include data from trips that conducted normal shrimp fishing operations.
- Imputing species weight when the subsampled catch was less than 0.1 kg.
- Modernization of processing code to make it more efficient and transparent. For example, the legacy procedure for incorporating valid zero catch observations at the species level involved hundreds of lines of code that developed a record indexing system to add zeroes via a series of do loops. This was replaced by a matrix transpose procedure that required <30 lines of code.

Cross-Checks for Observer Effort and Catch

A key concern was accuracy of observer catch and effort data. Cross-check procedures were developed to investigate catch and effort at the level of individual trips. For effort, observers recorded the start and end time of every individual trawl tow on a trip. Tow hours were summed to obtain total trip effort. Observer trips during 2014 to 2020 with an ELB unit onboard were matched to ELB trip effort estimates as a means of verifying the effort classification procedure (Dettloff 2023). Data were matched by box ID, and ELB effort data were filtered to pings falling between the first tow date and last tow date of an observer trip. Total ELB tow effort was then compared to total observer recorded effort on a trip by trip basis. This evaluation was carried out in an iterative fashion. Preliminary cross-checks between observer and ELB effort produced some extreme outliers, which in turn led to identification of various errors in the observer data regarding tow date, time, etc. Observer data processing was modified accordingly to identify and, where possible, correct effort recording errors. The resulting corrected data provided a comparison of 244 trips (*n*) from 154 vessels. Differences were approximately normally distributed around zero (Fig. 3.1), although instances where ELB boxes were presumably not recording led to some skew in the negative direction for an average percent difference of -7.7% (95% CI: -4.5%, -11.0%), determined by

$$\overline{Pct.Diff.} = \sum \frac{ELB_i - Obs_i}{Obs_i} / n \quad . \tag{3.1}$$

However, there was no evidence the median percent difference between observer recorded and ELB classified effort was significantly different from zero (p = 0.36).

Observers subsampled catches on a trip at multiple levels because it was not feasible to record catch for every tow and every net on a trip. Tows were subsampled within a trip, nets were subsampled within a tow, and species catches were subsampled within a net. For net subsampling, the total net catch was apportioned among a series of baskets, and then one basket was selected to record catch in number and weight (aggregated) by species. The ratio of sampled basket weight to total net weight (all baskets were weighed for a given net) was the basis for scaling sampled basket catch observations to catch for a sampled net. Sampled nets were then scaled by the number of nets deployed on a tow (usually 2 or 4) to obtain catch per tow, the catch observation for a sample unit *i* that pairs with an observation of tow effort. Using a trip-level application of Eq. (2.4), observer sampled tow catch rates were multiplied by total trip effort to estimate total trip catch.

Observer estimated trip catches of penaeid shrimp species were compared to reported landings from the Gulf States Marine Fisheries Commission (GulfFIN) trip ticket database for a set of matched trips during 2014-2021. For trip matching, the observer and trip ticket datasets were first joined by vessel ID. For each unique observer trip, all trip ticket trips reported by that vessel were joined to the observer trip. This allowed development of a series of conditions for matching each observer trip with the most likely trip ticket trip. The best matches were cases where the trip ticket unload date and observer reported landing date were the same. The matching procedure was extended to include trip ticket trips with unload dates 4 days after or before the observer trip landing date. Matches exceeding the 4-day cut point were excluded from the analysis, since this generally resulted in multiple trip ticket matches to a single observer trip.

As for effort, trip matching between observer and trip-ticket data was carried out in an iterative fashion. Two notable problems with trip ticket data were uncovered. First, cases were identified in which the same trip had multiple trip ticket identifiers. This issue occurred mostly with Mississippi data where their trip ticket reporting system was not properly translated into the GulfFIN database. Concatenating several fields within the GulfFIN database to create a new trip identifier field resolved this issue. The second problem involved species-specific catches for brown, pink, and white shrimp on trips where multiple species were captured. While observers recorded catch for each species separately, trip-ticket landings were commonly reported for a single species. This appeared to be a mis-reporting issue with the trip ticket landings where species-level catch may not have been properly reported if the market price was the same across all penaeids. Accordingly, the cross-matching procedure was conducted for all penaeid species combined rather than separately by each of the three shrimp species. The resulting procedure produced a total of 374 observer trips successfully matched to trip ticket trips (62% match success). There was no evidence of bias between observer and trip ticket trip catches (Fig. 3.2).

Fig. 3.1. Frequency histograms of differences in trip-level effort (tow hours) between observers and ELB units, 2014-2020. Zero differences are indicated by the red dashed lines.

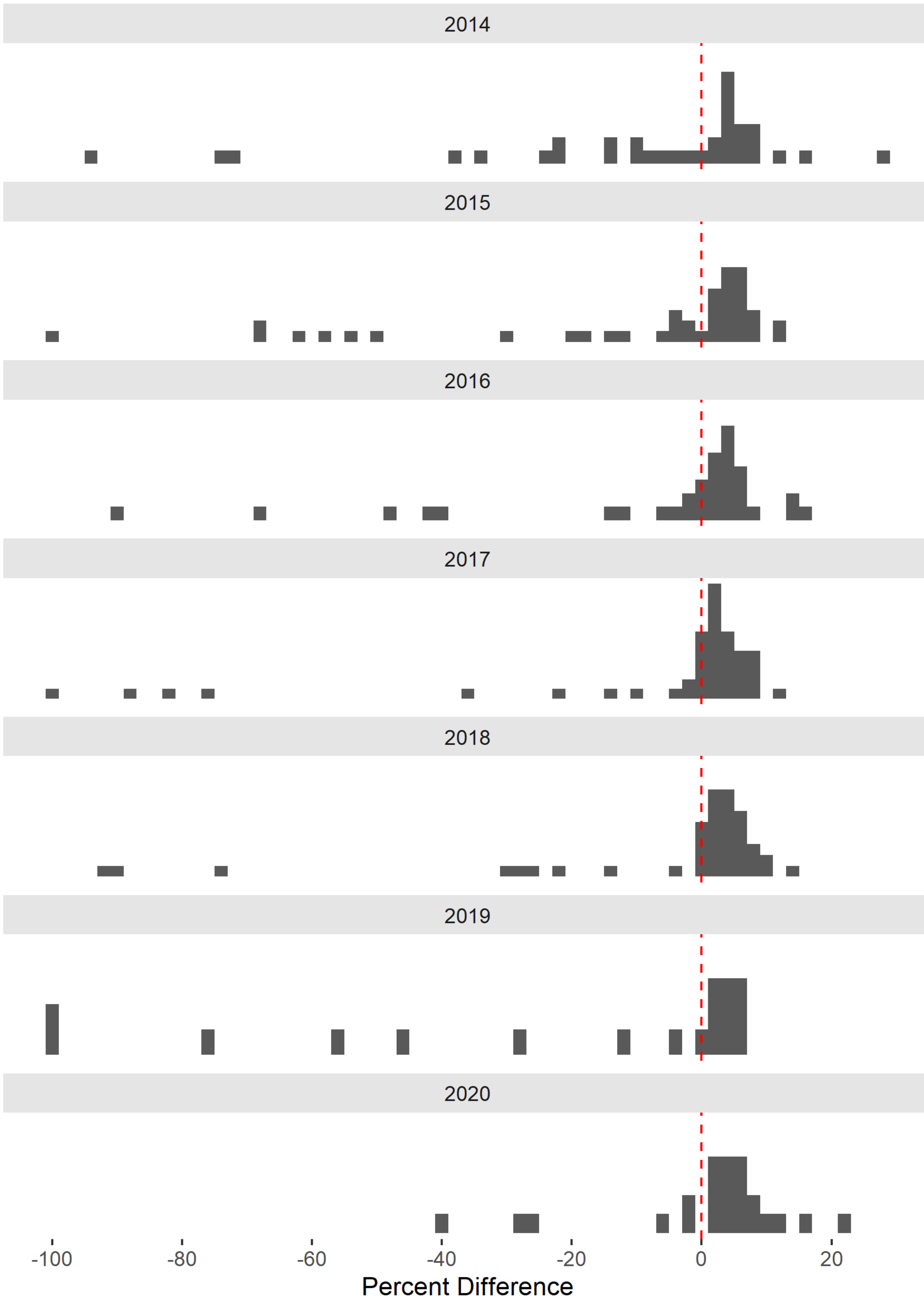
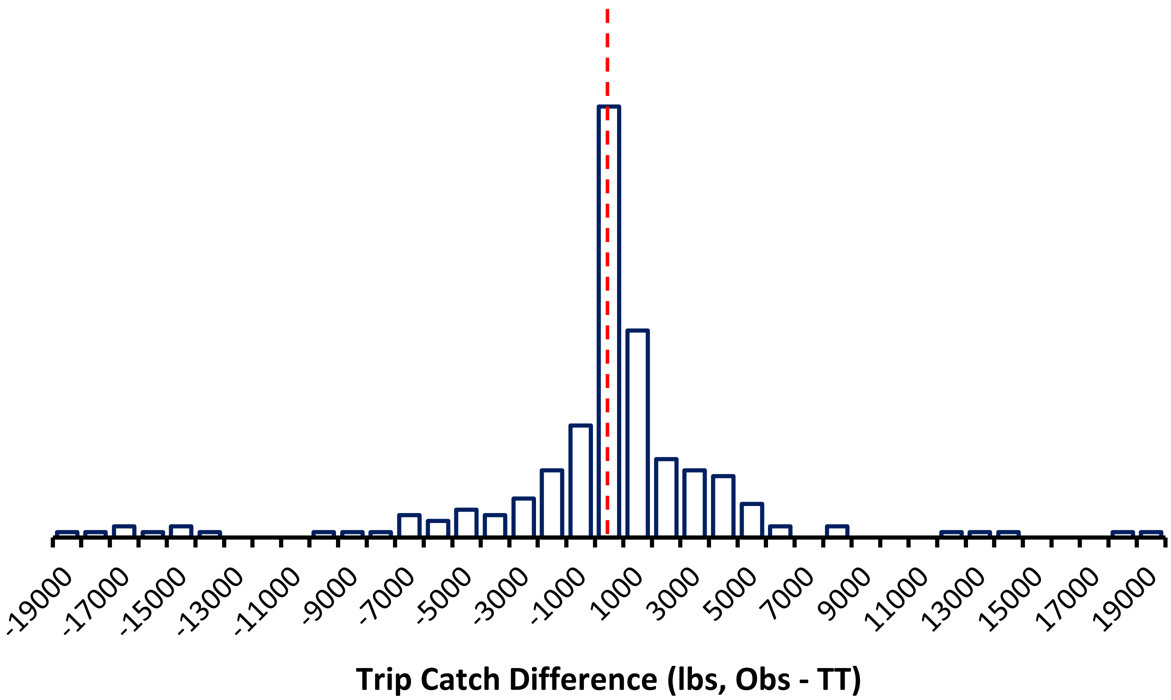


Fig. 3.2. Frequency histogram of differences in trip-level penaeid catch between observers and trip-tickets. Zero difference is indicated by the red dashed line.



4.0 Annual Landings and Gear Survey

Information on gear characteristics in the ALG survey included a main gear type (e.g. otter trawl, butterfly net, skimmer net, roller frame trawl, etc.), head rope length (HRL, a proxy for net width), and net number (i.e., the number of nets towed, typically two or four), as well as additional detailed information, such as specific net sub-types (e.g. Mongoose, 2-seam balloon, 4-seam balloon, etc.), bycatch reduction device (BRD) presence and type, mesh size, etc. Data from the ALG survey used in the analysis were limited to vessels that used otter trawl gear in a given year. Since gear type was not an explicit variable in the observer database, data on gear type from the ALG were incorporated into the observer catch-effort dataset to remove records for gears other than otter trawls (e.g., butterfly nets, roller frame trawls).

Relationships between HRL and net configuration are shown in Figs. 4.1 & 4.2, based on observer data. There was a bimodal pattern in HRL in two-net configurations and a unimodal pattern in four-net configurations (Fig. 4.1). HRL generally increased with increasing vessel length, but HRL was higher for two-net configurations compared to 4-net configurations for vessels of the same length (Fig. 4.2). In both the observer and ALG data sets, there were more vessels that used 4-net configurations than 2 (~23% of vessels in the observer dataset and ~33% in the ALG dataset).

The ALG survey provided fleet-level gear information that matched gear data collected by onboard observers, making it useful for incorporating gear characteristics into ELB effort and landings data (Fig. 1.2) and subsequently into bycatch estimation.

Figure 4.1. Distributions of head rope length (HRL) by net configuration for vessels sampled by onboard observers, 2014-2022.

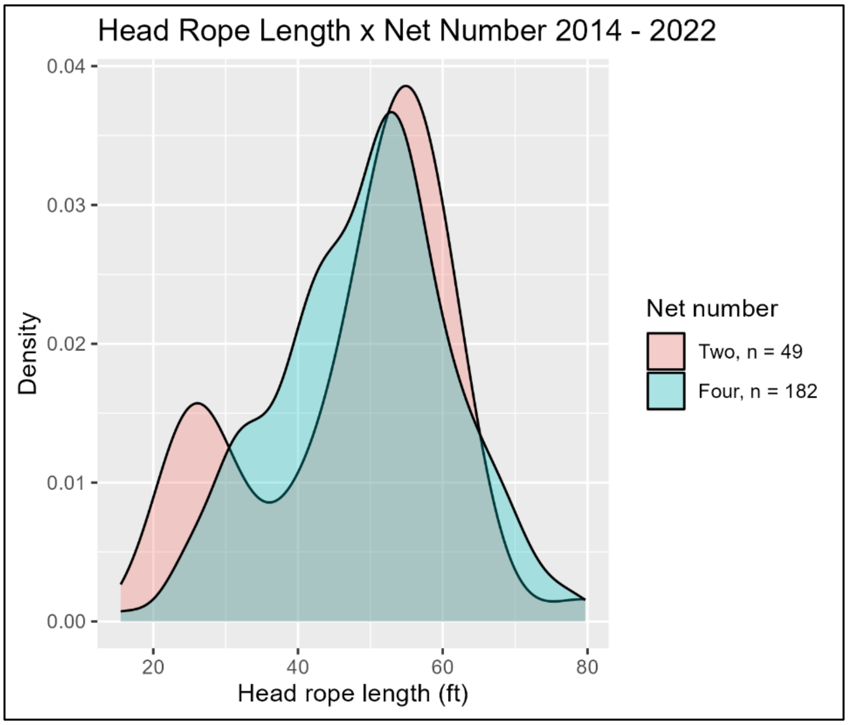
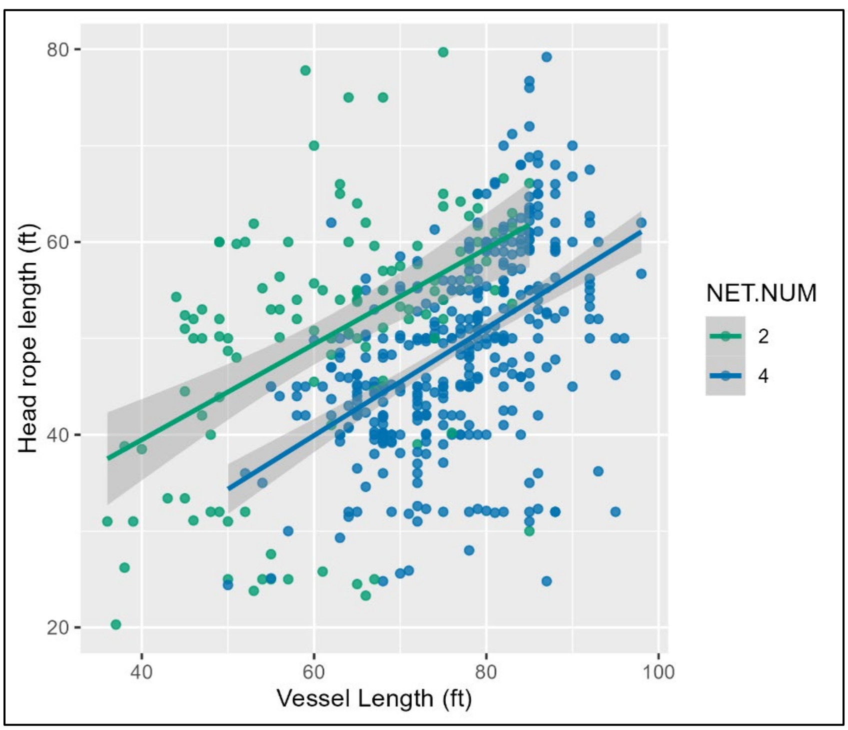


Figure 4.2. Head rope length (HRL) by vessel length and net configuration (NET.NUM). Each point represents a unique vessel.



5.0 Stratification Analysis

The legacy estimation procedures for annual bycatch from shrimp trawls accounted for space-time variation in relative abundance of target species (CPUE) via a stratification scheme based on geographical area, depth, and season. Trawl gear characteristics and diurnal period (daytime, nighttime trawling) were evaluated as potential additional stratification factors to control variation in catch rates of penaeid shrimp species. Legacy estimation also included year as a time stratification variable; however, in most years observer sampling was not adequate for all area, depth, and season combinations. Inter-annual variation within area-depth-season strata was evaluated to understand the impacts of possibly combining data across years within strata to mitigate the realities of observer space-time sampling coverage. SAS program code for data processing and analyses are provided in subfolder S_5.0 in Suppl_Info.

Trawl Net Width & Configuration

Two aspects of otter trawl gears were investigated: (1) head rope length, a proxy for trawl net width; and (2) trawl gear configuration, 2-nets vs. 4-nets. Preliminary screening analysis ruled out a third aspect, trawl mesh size, as impacting catch rates. This was likely due to the long average length of trawl tows (about 5-6 hrs) in which net clogging with biota and debris would have prevented escapement of small fish and invertebrates through the mesh. Observer-recorded information on gear characteristics were combined with shrimp species catch-effort data for individual net tows. These data were analyzed using GLM regression with the following specifications:

- response variable: catch in weight (kg) of combined penaeids (brown, white, pink)
- continuous covariate: effort (tow hrs)
- categorical space-time block covariate: combination of year-area-depth-season; area, 5 geographical regions (Fig. 1.1); depth, 3 zones, 0-10 fathoms, 10-30 fthm, >30 fthm; season, 3 quadrimesters, Jan-Apr, May-Aug, Sep-Dec.
- treatment covariates: (i) head rope length (ft); (ii) net configuration, 2-net, 4-net.

The intent of this formulation was to control for space-time variation in relative abundance and varying trawl effort, allowing for isolation of the treatment main effects (trawl width, net configuration). The observer analysis dataset was restricted to space-time blocks where both 2-net and 4-net configurations were sampled.

The two-step model-building process for the catch-effort relationship is illustrated for the 4-net configuration in Fig. 5.1A & B. In step 1, mean catch was estimated across the range of effort at specified effort intervals (≥0.25 hr), in which each interval was comprised of at least 25 observations (Fig. 5.1A). This provided insight to (i) the model form of the mean relationship between catch and effort (linear, quadratic, etc.), and (ii) an appropriate probability density function (pdf) for describing model error (approximately normal in this case). The catch-effort relationship exhibited an ascending portion from 1 to about 6 tow hrs, and then an asymptotic portion >6 tow hrs. In step 2, effort was modeled as a continuous covariate by fitting a quadratic polynomial to the full set of n=7,459 catch-effort observations (Fig. 5.1B). The asymptotic portion of the curve was accounted for by specifying a maximum threshold level, i.e., a 'plus group': effort values greater than the threshold were set to the threshold level. Catch-effort functions for 2-net and 4-net configurations were similar in form (quadratic), but catches were generally higher for 2-nets compared to 4-nets over most of the range of effort (Fig. 5.1C).

Head rope length was analyzed separately for each net configuration. There was no discernable relationship between catch and head rope length for either configuration (Fig. 5.2). For analysis of the trawl configuration main effect, head rope length was excluded as a covariate and data for the two configurations were combined. Model-predicted mean catch per net was higher for the 2-net compared to the 4-net configuration (Table 5.1), as was indicated in Fig. 5.1C; however, the overall predicted mean catch per tow (catch per net x number of nets) was higher for the 4-net configuration. Net configuration was incorporated as an important factor in subsequent analyses.

Diurnal Period

The effect of diurnal period (daytime, nighttime trawling) on shrimp CPUE was evaluated for individual shrimp species using the regression modeling formulation described above with diurnal period as the main effect treatment covariate. In contrast to considering the three penaeids as a group, species-level observations had high frequencies of zero catch observations. A compound pdf regression approach (see section 2.0) was employed for model fitting, with a logistic regression model for proportion occurrence (presence-absence observations) and a standard GLM regression for catch when present. Results of this approach are illustrated in Table 5.2 for white shrimp for a 4-net trawl configuration. Main effects predicted mean occurrence (p) was over twice as high for daytime trawls compared to nighttime, whereas the predicted mean catch when present was similar for the diurnal periods. The resulting predicted mean catch per net (p x u) was over twice as high during daytime, driven by the occurrence component of catch. Subsequent analyses incorporated diurnal period in addition to trawl configuration. A comprehensive analysis of these combined factors for the three shrimp species is presented below in section 6.0.

Inter-annual Variation

For the period 2014-2019 (pre-Covid), combinations of area, depth, season, net configuration, and diurnal period were identified where observers consistently sampled $n>15$ tows for at least 5 of the 6 years. The Horvitz-Thompson ratio-of-means procedure (section 2.2) was used to estimate annual mean CPUEs as well as the average annual CPUE for the overall time period. The results were visualized as a CPUE anomaly plot (annual CPUE minus the time period average CPUE) which highlighted the degree of inter-annual variation of CPUE. Example results of these analyses are shown for pink and brown shrimp respectively in Figs. 5.3 and 5.4.

The pink shrimp case (Fig. 5.3) shows CPUE anomaly plots over three seasons for 4-net nighttime trawls in area 1 and depth zone 2. Inter-annual variation in CPUE was fairly pronounced in each season, but the pattern among seasons was inconsistent. For example, in 2015 mean CPUE in season 2 was well below the time period average, but well above the time period average in season 3. This pattern was reversed the following year: in 2016 mean CPUE in season 2 was above the time period average, and below the time period average in season 3.

The brown shrimp example (Fig. 5.4) shows CPUE anomaly plots for 4-net nighttime trawls in two depth zones in area 3 and season 2. The most positive CPUE anomaly in depth zone 1 occurred in 2018, and the most negative anomaly occurred in depth zone 2 in the same year. For the two cases, inter-annual variation in CPUE seemed to be more related to year-to-year variation in the timing of recruitment (pink shrimp) and subsequent movement from shallower to deeper habitats (brown shrimp), and less related to year-to-year variation in the annual magnitude of recruitment. Thus, combining data across years for the same trawl configuration and diurnal period within area-depth-season strata may increase the uncertainty of CPUE estimates and subsequent expansion estimates of total catch, but should not introduce any systematic bias.

The effects of combining data across years is illustrated for season and depth strata within a given area in Fig. 5.5. Variance of mean CPUE was computed using the average annual stratum sample size to avoid inflating the precision (i.e., treating the combined years as a single survey). The average annual CPUE anomalies exhibited very clear season-depth patterns for the three shrimp species that were not obscured by using multiple years for the computations. There was general correspondence between observer sampling effort (sampled tows) and federal trawl fleet effort in area-season strata for the combined period 2014-2021 (Fig. 5.6).

Figure 5.1. Modeling of shrimp catch-effort relationship for individual nets. (A) GLM point estimates of catch at effort intervals of ≥0.25 tow hrs show an ascending relationship up to about 6 tow hrs, and then an asymptotic relationship >6 tow hrs. (B) The fitted continuous catch-effort relationship, with the asymptotic portion of the curve accounted for via a plus group. (C) Comparison of catch-effort functions for 2-net and 4-net trawl configurations.

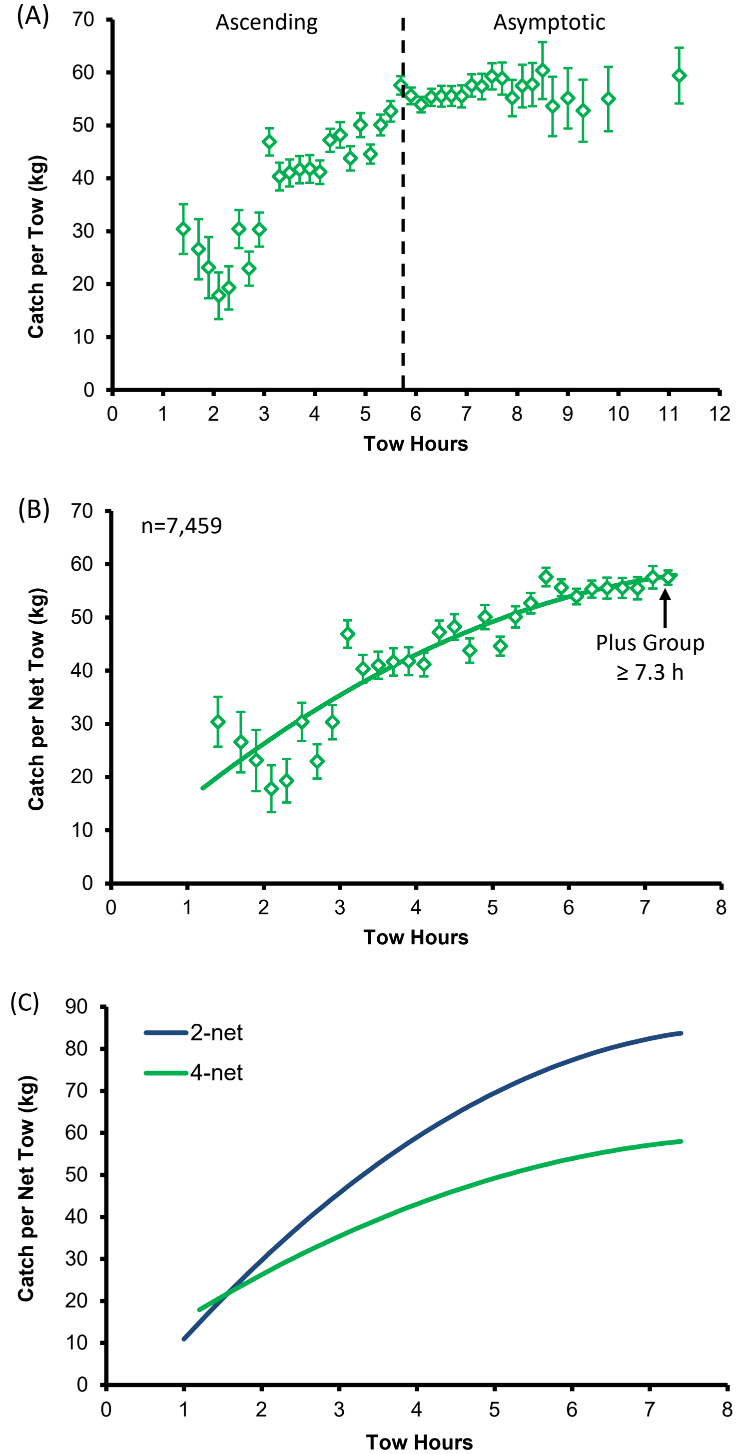
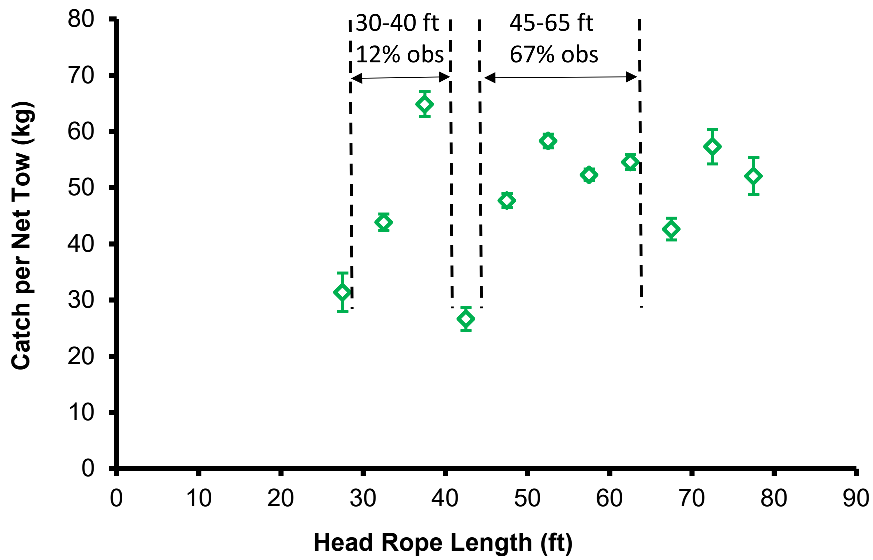


Figure 5.2. Relationship between catch per net tow and head rope length for (A) 4-net and (B) 2-net trawl configurations.

(A)



(B)

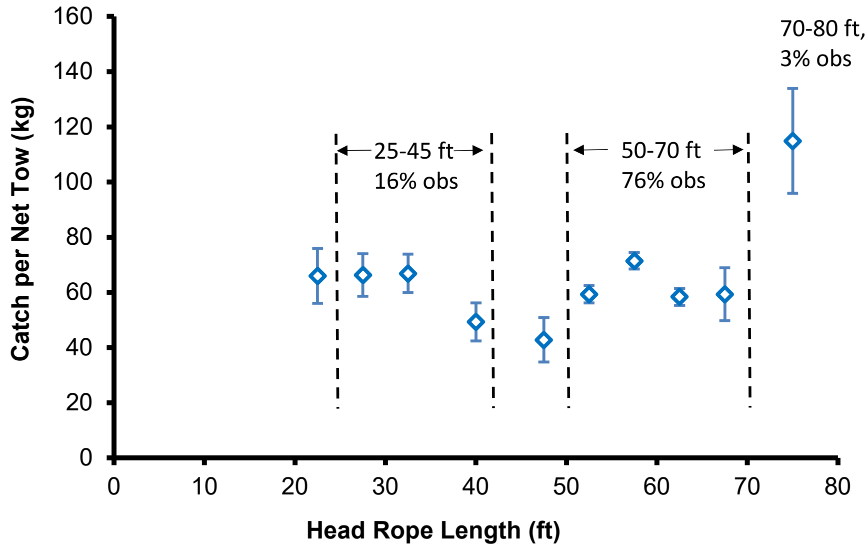


Table 5.1. Main effect GLM-predicted mean catch per net tow by trawl configuration, and the overall predicted catch per tow for nets combined (catch per net x number of nets).

Trawl Configuration	n	Catch (kg) per Net Tow Mean	SE	Catch per Tow, Nets Combined
2-net	2,086	72.9	0.86	145.8
4-net	7,498	50.8	0.60	203.1

Table 5.2. Compound pdf regression results for diurnal period main effect, illustrated for white shrimp, 4-net trawl configuration.

Diurnal	Logistic Estimates, Occurrence (p)			GLM Estimates, Catch when Present (u)			Predicted Catch (p x u)
Period	n	Mean p	SE p	n	Mean	SE	Mean
Day	1,891	0.574	0.029	3,407	35.6	0.58	20.5
Night	7,585	0.263	0.021	4,913	34.6	0.51	9.1

Figure 5.3. Plots of annual pink shrimp CPUE (±SE) anomalies from the time period average (solid horizontal line; SE, dashed lines) over three seasons in area 1 and depth zone 2 for nighttime 4-net trawls.

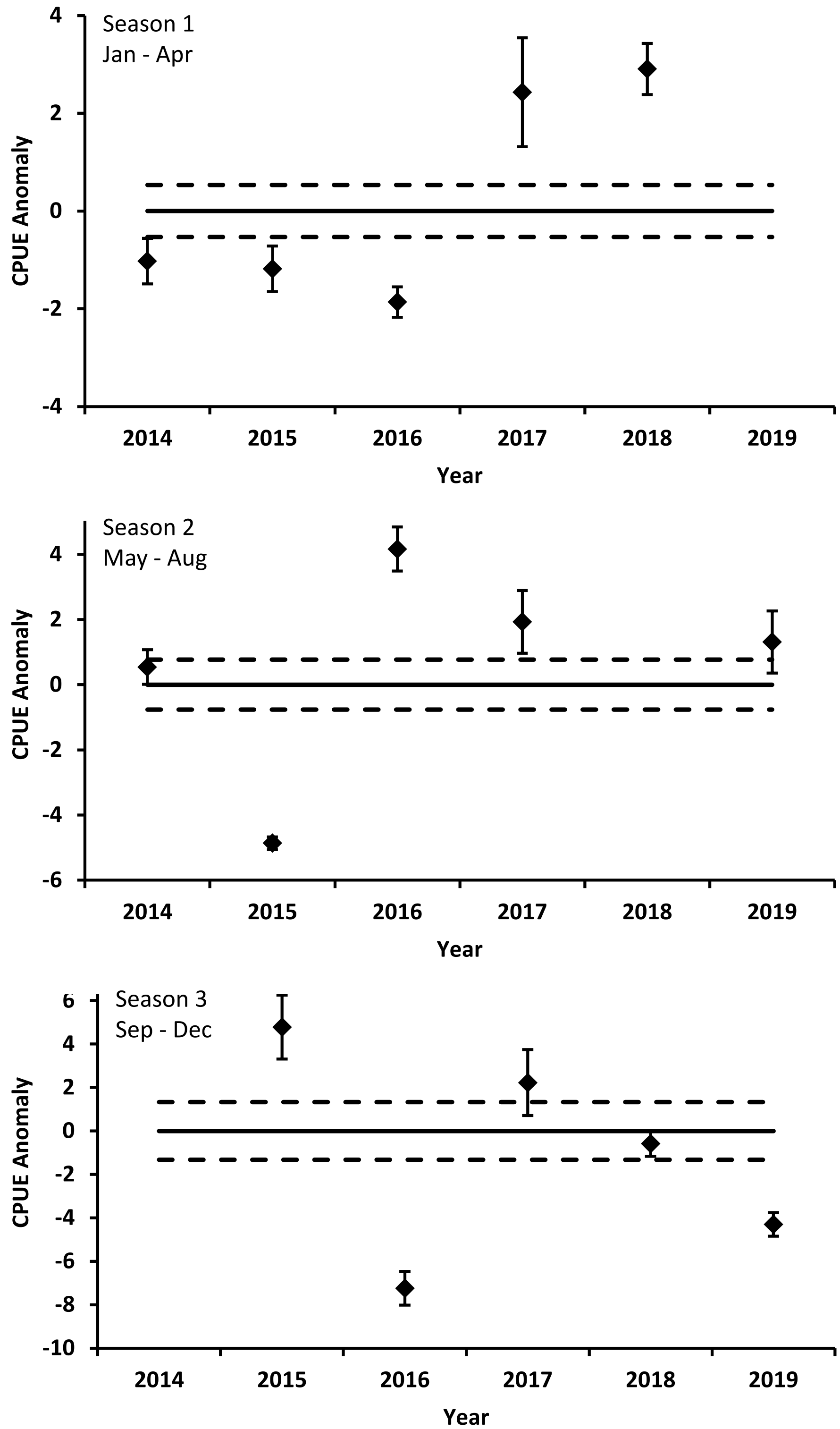


Figure 5.4. Plots of annual brown shrimp CPUE (±SE) anomalies from the time period average (solid horizontal line; SE, dashed lines) for two depth zones in area 3 and season 2 for nighttime 4-net trawls.

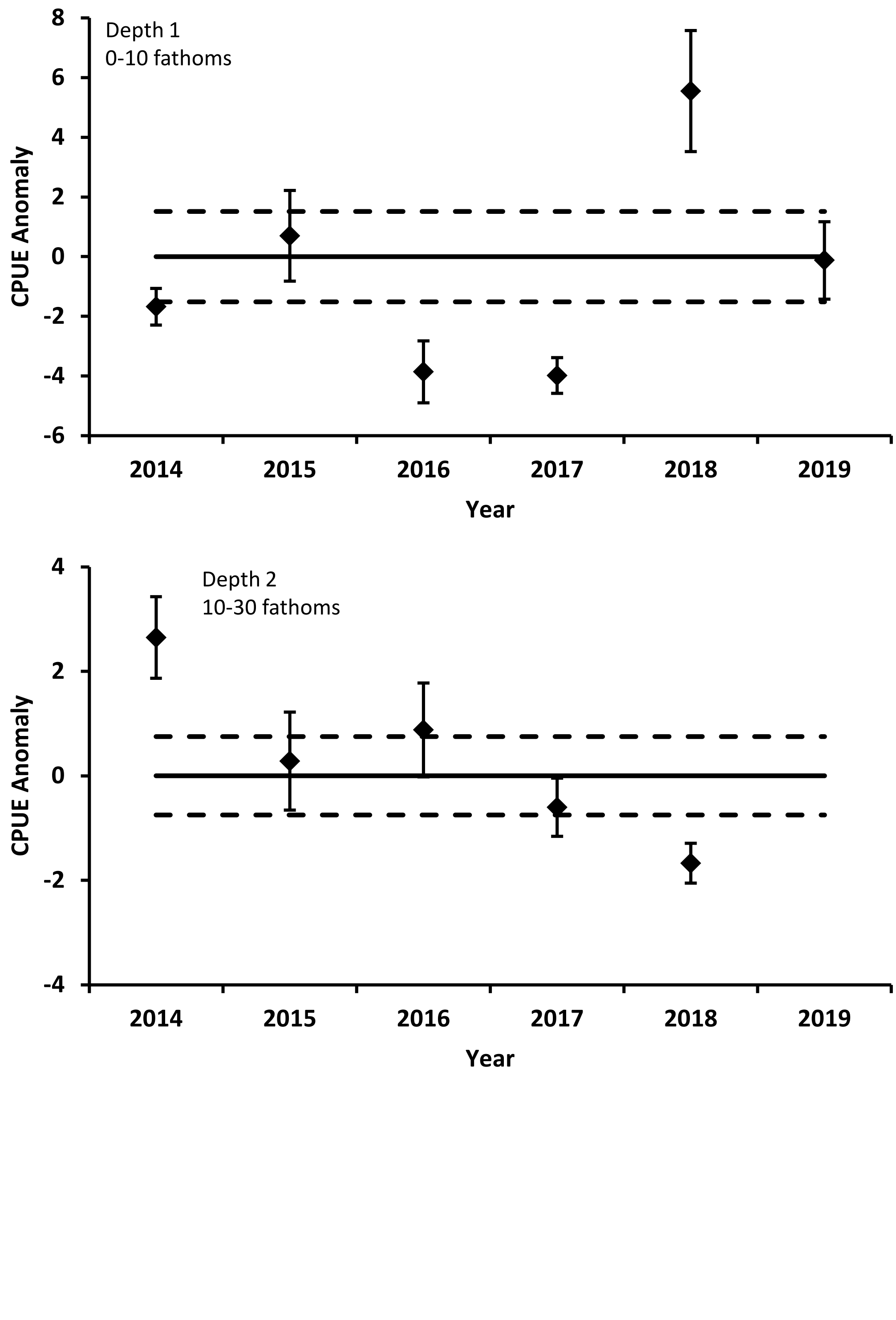


Figure 5.5. Plots of average annual depth and season CPUE (±SE) anomalies from the depth-season average (solid horizontal line; SE, dashed lines) for four cases: (A) pink shrimp, area 1, nighttime 4-net trawls; (B) brown shrimp, area 3, nighttime 4-net trawls; (C) white shrimp, area 3, daytime 4-net trawls; (D) white shrimp, area 3, nighttime 4-net trawls. Observer data for each depth and season stratum were averaged over 2014-2019.

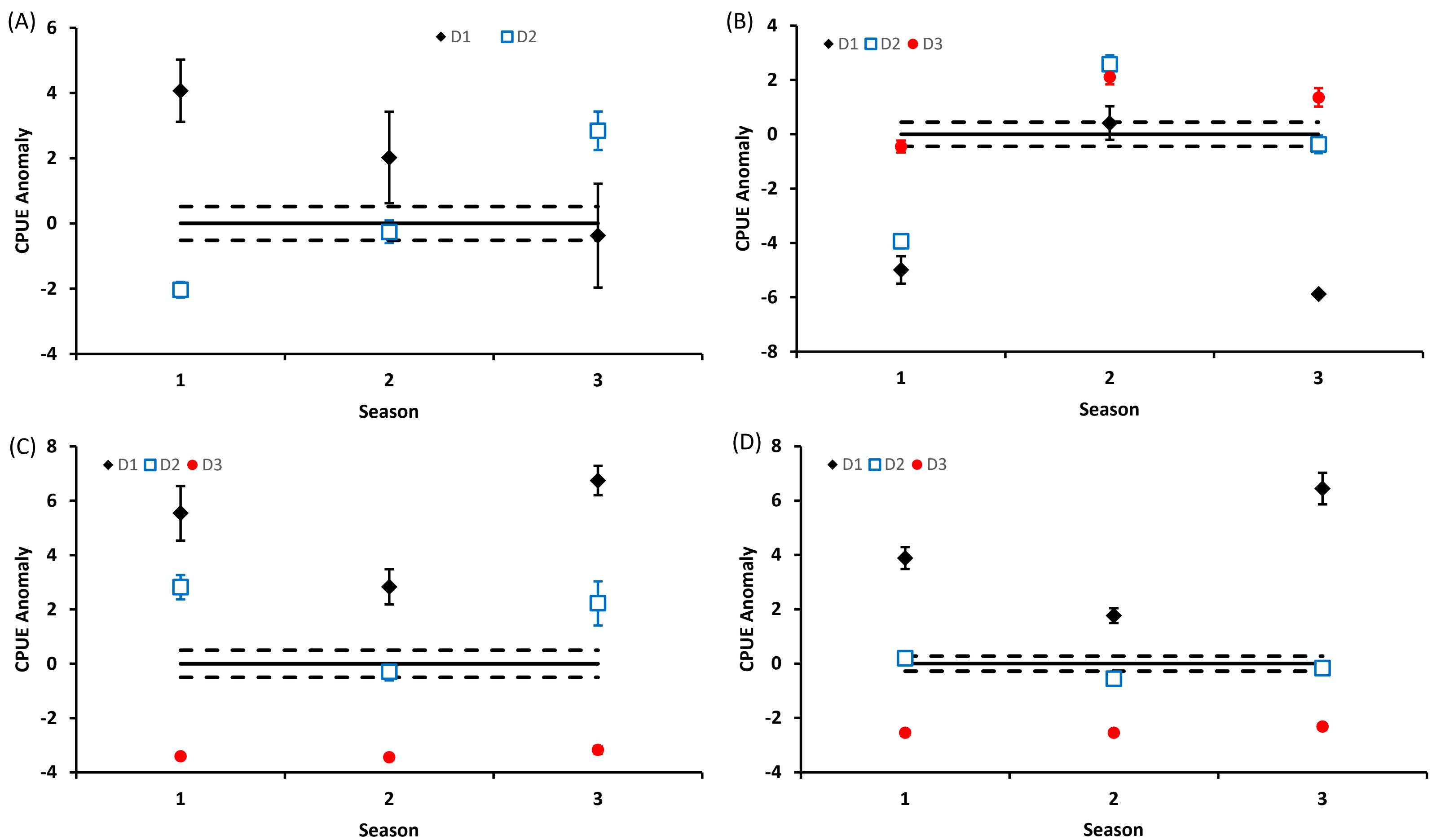
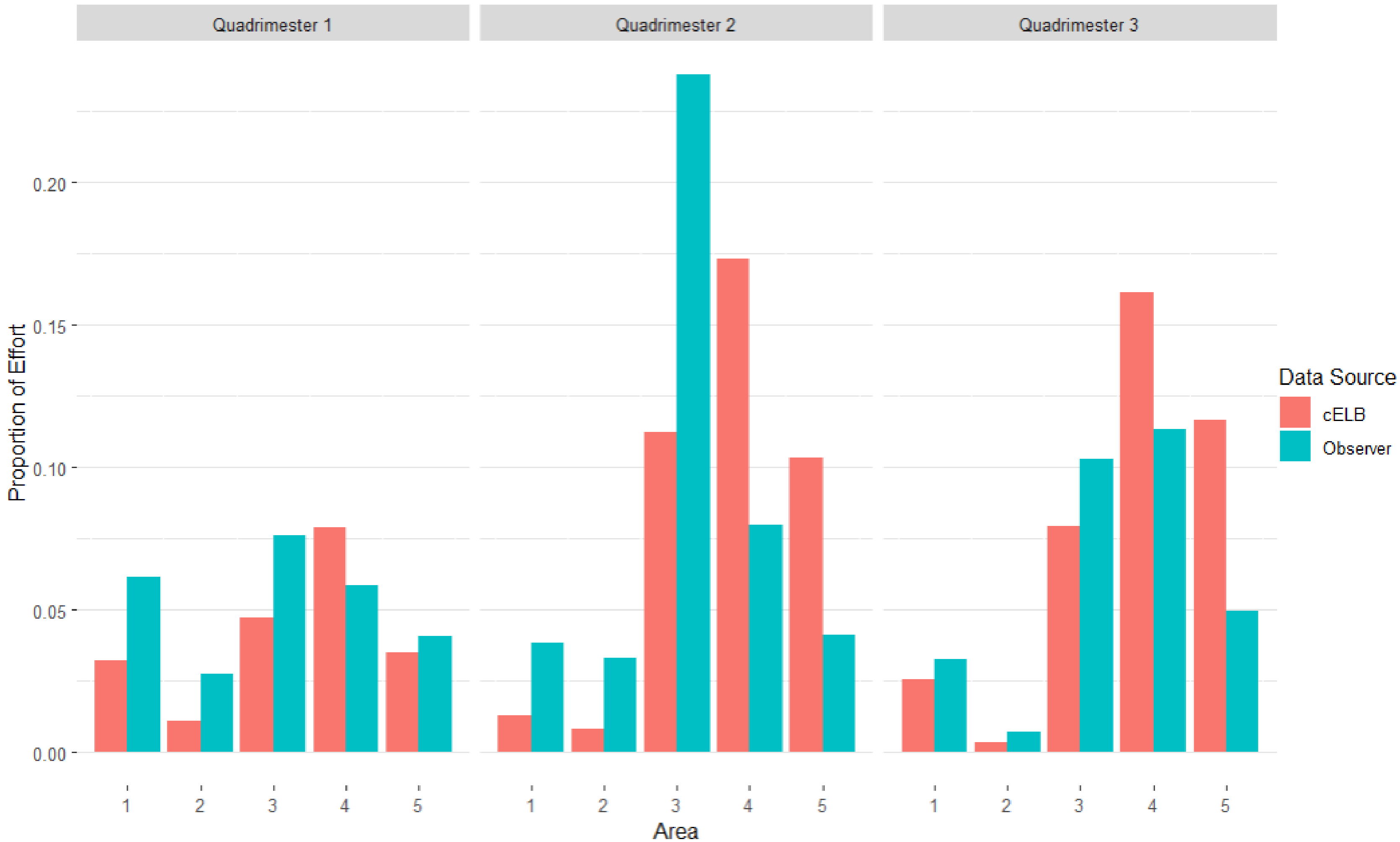


Figure 5.6. Comparison of observer sampling effort and federal trawl fleet effort by area strata and season for 2014-2021.



6.0 Observer Strata CPUEs and Expansion Estimates of Shrimp Catch

Stratification analysis (section 5.0) confirmed that accuracy and precision of observer CPUE estimates for penaeid shrimp species would be improved by using the legacy space-time strata variables area, depth, and season in the designation of strata, but that year strata could be grouped into time periods of years to mitigate observer sampling issues. This analysis also indicated the importance of accounting for trawl configuration and diurnal period to further improve estimation of mean and variance of CPUE. Combinations of trawl configuration and diurnal period were used to designate four gear types: (i) D2, daytime 2-net trawls; (ii) D4, daytime 4-net trawls; (iii) N2, nighttime 2-net trawls; and (iv) N4, nighttime 4-net trawls. Table 6.1 shows federal trawl fleet average annual effort (24-h tow-days) and observer sampled tows during 2014-2020 by area-depth-season strata and gear class. For gear N4, observer sampling of area-depth-season strata with $n \geq 10$ tows was fairly complete, except for the deep depth zone in area 1 in seasons 2 and 3 (green shading), which also had low fleet effort. Combining the seasons into a single strata would alleviate the sparse sampling in these strata-gear cells. For gears D4, N2, and D2, however, there were numerous strata-gear cells with $n<10$ observer tows (yellow shading). These cells comprised 48% of the total strata-gear cells with fleet effort > 0; however, these cells only accounted for 11% of fleet effort.

Imputation of CPUE for the missing or sparsely-sampled strata-gear cells was carried out using a classical fishery science technique: estimation of the relative fishing power among gears (Beverton and Holt 1956; Gulland 1956; Robson 1966). 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,

$$\lambda_1 = \frac{\frac{C_1}{f_1}}{\frac{C_2}{f_2}} = \frac{q_1}{q_2} \quad . \tag{6.1}$$

The effort of gear 1 can multiplied by fishing power to express the CPUE of gear 1 in terms of CPUE of gear 2,

$$\frac{C_1}{f_1\lambda_1} = \frac{C_2}{f_2} \quad . \tag{6.2}$$

In other words, fishing power can convert effort from one gear to the units of another.

Following the general ANOVA approach of Robson (1966), fishing power was evaluated for individual shrimp species with compound pdf regression analysis of observer data in which occurrence (p) or catch when present (u) was the response variable, effort was a continuous covariate, area-depth-season was a categorical space-time blocking covariate, and gear type was a categorical treatment covariate. Space-time blocks with at least 1 positive catch observation for two or more gear types were included in the analysis. For logistic regression, a further constraint was that space-time blocks with all positive catch observations were excluded.

Compound pdf regression results for the gear main effects by species are provided in Table 6.2. Plots of model-predicted catch by gear are shown for the three shrimp species in Fig. 6.1. Predicted catches were generally higher for 2-net vs. 4-net trawls within a diurnal period. Predicted catches were higher for nighttime trawls for brown and pink shrimp, and higher for daytime trawls for white shrimp.

Relative fishing power factors for converting effort from the well-sampled reference gear N4 to sparsely-sampled target gears were computed by dividing the model-predicted catch of the reference gear by the predicted catch of the target (Table 6.3). For imputation, reference gear N4 effort observations were multiplied by the fishing power factor in sparsely-sampled strata to create the respective target gear set of effort observations. Catch observations of gear N4 were then assigned as the target gear set of catch observations. Strata mean CPUEs and associated variances were estimated by species and gear using the full dataset of actual and imputed catch-effort observations (Table S_6.1, Suppl_Info, subfolder S_6.0). Estimation was carried out with the Horvitz-Thompson ratio-of-means procedure (section 2.0).

Area-depth-season strata mean CPUEs by species and gear were multiplied by the corresponding federal fleet effort (species- and gear-specific; Dettloff 2023) each year for 2014-2020 to estimate strata-species-gear annual catches. These were summed over species, gear, and strata by year to produce the total annual penaeid catch. Annual observer-predicted catches were lower than reported trip-ticket catches by an average of about 20% during the 2014-2020 time period (Fig. 6.2). Observer-predicted catches were lower compared to trip-ticket catches across all years in areas 1, 3, and 4, but were generally higher across years in area 5 (Fig. 6.3).

Table 6.1. Fleet average annual effort (24-h tow-days) and observer sampled tows during 2014-2020 by area-depth-season strata and gear class (N≡night, D≡day, 4≡4-net, 2≡2-net). Green shading denotes where pooling over seasons is required; yellow shading denotes where imputation is required; gray shading denotes cells with zero trawl effort.

			N4		D4		N2		D2	
Area	Depth (fthm)	Season	Effort	Tows	Effort	Tows	Effort	Tows	Effort	Tows
1	0-10	Jan-Apr	83.1	94	65.5	2	0.5	0	0.5	0
1	0-10	May-Aug	6.3	18	6.6	0	0.2	0	0.2	0
1	0-10	Sep-Dec	19.7	19	20.0	1	0.0	0	0.0	0
1	10-30	Jan-Apr	1118.8	565	764.7	6	7.2	0	5.3	0
1	10-30	May-Aug	463.8	329	386.6	0	12.8	0	11.1	0
1	10-30	Sep-Dec	775.9	311	642.5	0	16.6	0	13.7	0
1	>30	Jan-Apr	9.7	19	6.5	0	0.0	0	0.0	0
1	>30	May-Aug	0.3	2	0.3	0	0.0	0	0.0	0
1	>30	Sep-Dec	1.7		1.3	0	0.0	0	0.0	0
2	0-10	Jan-Apr	319.7	207	262.9	1	4.6	0	3.8	0
2	0-10	May-Aug	116.0	133	107.2	4	2.5	3	2.1	0
2	0-10	Sep-Dec	51.1	31	46.8	6	1.0	0	0.9	0
2	10-30	Jan-Apr	180.6	48	126.2	0	0.2	0	0.3	0
2	10-30	May-Aug	139.3	165	110.9	0	7.7	0	5.8	0
2	10-30	Sep-Dec	41.8	31	37.4	2	0.4	0	0.5	0
3	0-10	Jan-Apr	241.7	82	216.8	50	44.3	19	39.5	23
3	0-10	May-Aug	1035.8	287	1080.2	143	202.2	153	216.3	89
3	0-10	Sep-Dec	840.6	213	733.5	215	159.4	55	138.9	62
3	10-30	Jan-Apr	924.6	307	770.4	77	37.0	27	34.6	1
3	10-30	May-Aug	1275.8	667	1145.4	163	170.9	61	166.3	40
3	10-30	Sep-Dec	870.2	278	688.5	65	53.1	1	44.1	2
3	>30	Jan-Apr	455.7	138	370.3	107	1.9	0	2.6	4
3	>30	May-Aug	721.1	263	792.6	310	6.0	0	6.3	0
3	>30	Sep-Dec	690.5	146	635.9	152	8.6	0	8.4	0
4	0-10	Jan-Apr	849.1	106	800.5	111	276.6	29	284.2	131
4	0-10	May-Aug	2173.1	190	2245.6	145	535.8	71	597.1	125
4	0-10	Sep-Dec	2456.3	330	2119.7	204	575.2	48	519.4	46
4	10-30	Jan-Apr	1008.6	120	758.0	25	65.5	15	56.3	11
4	10-30	May-Aug	1765.4	122	1259.0	21	89.9	2	68.3	0
4	10-30	Sep-Dec	1276.7	290	931.4	12	52.5	0	36.9	0
4	>30	Jan-Apr	569.0	80	362.8	5	1.9	0	1.6	0
4	>30	May-Aug	900.7	49	669.1	7	2.0	0	1.7	0
4	>30	Sep-Dec	1005.5	144	749.0	42	4.2	0	4.2	0
5	0-10	Jan-Apr	350.2	35	379.4	52	12.3	11	14.9	134
5	0-10	May-Aug	266.5	19	291.4	15	31.2	0	36.6	0
5	0-10	Sep-Dec	341.9	31	307.2	24	21.3	2	20.7	2
5	10-30	Jan-Apr	673.1	76	466.3	7	8.4	1	6.7	1
5	10-30	May-Aug	2716.0	274	1649.0	4	120.4	3	81.5	0
5	10-30	Sep-Dec	2846.4	332	2015.7	21	26.0	0	26.2	0
5	>30	Jan-Apr	162.8	42	106.5	22	0.0	0	0.0	0
5	>30	May-Aug	587.7	47	512.4	15	0.3	0	0.3	0
5	>30	Sep-Dec	766.3	63	564.1	14	0.7	0	1.0	0

Table 6.2. Compound pdf regression results for gear main effects by species.

		Logistic Estimates, Occurrence (p)			GLM Estimates, Catch when Present (u)			Predicted Catch (p x u)
Species	Gear	n	Mean	SE	n	Mean	SE	Mean
Brown	D2	616	0.678	0.029	186	24.49	1.45	16.60
	D4	2,607	0.675	0.020	2,020	12.83	0.86	8.66
	N2	464	0.666	0.031	201	29.45	1.41	19.62
	N4	7,110	0.765	0.014	6,303	13.17	0.79	10.07
White	D2	365	0.913	0.030	592	25.41	0.90	23.20
	D4	2,916	0.858	0.016	2,043	21.58	0.61	18.53
	N2	429	0.639	0.046	395	26.53	0.99	16.95
	N4	7,782	0.606	0.026	3,722	19.26	0.55	11.67
Pink	D2	347	0.242	0.047	31	0.99	0.27	0.24
	D4	1,261	0.513	0.040	191	1.12	0.11	0.57
	N2	321	0.495	0.055	46	7.36	1.39	3.64
	N4	4,937	0.679	0.030	2,592	3.53	0.15	2.40

Figure 6.1. Plots of model-predicted mean catch by gear for brown, white, and pink shrimp.

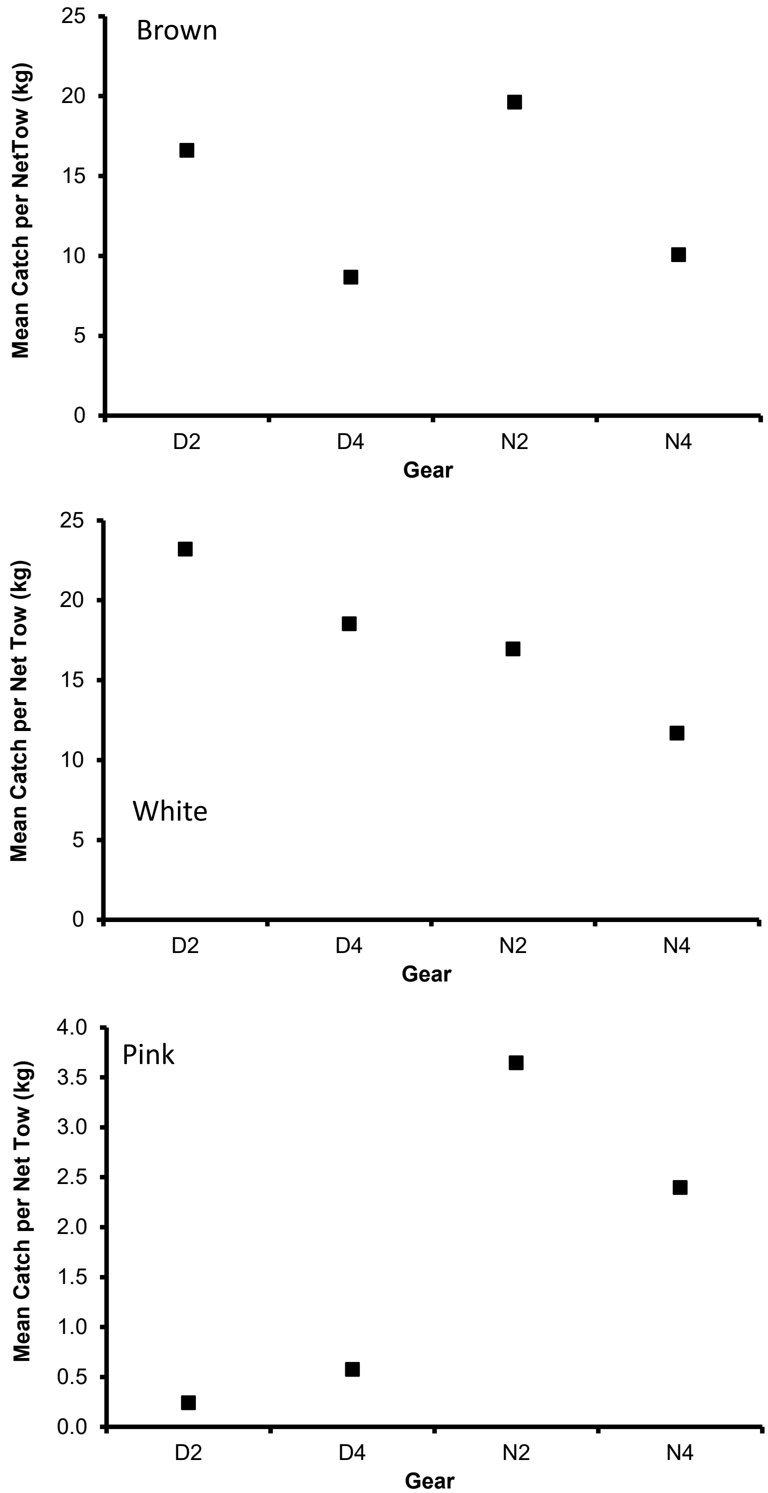


Table 6.2. Relative fishing power factors for converting effort from reference to target gears.

	Gear		Effort
Species	Reference	Target	Conversion Factor
Brown	N4	N2	0.513
	N4	D4	1.163
	N4	D2	0.607
White	N4	N2	0.688
	N4	D4	0.630
	N4	D2	0.503
Pink	N4	N2	0.658
	N4	D4	4.169
	N4	D2	9.975

Figure 6.2. Observer-predicted and trip-ticket federal fleet shrimp catch (tail wt) for 2014-2020.

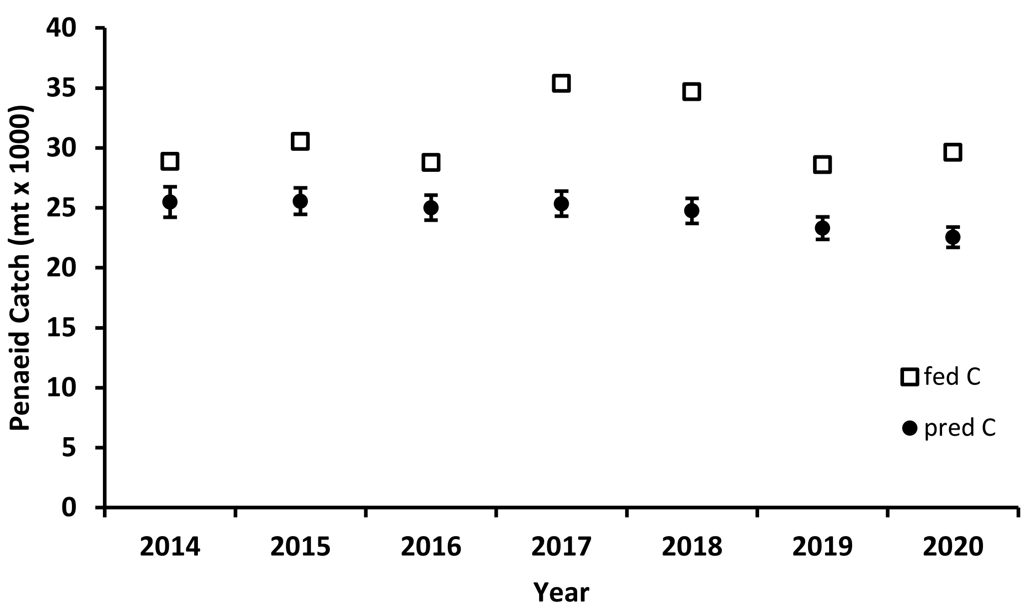


Figure 6.3. Comparison of observer-predicted and trip-ticket federal fleet shrimp catches by area and year.

7.0 Application to Red Snapper Bycatch

The methodology for estimating observer-predicted shrimp catch (section 6.0) was applied to estimate bycatch of red snapper (numbers). Compound pdf regression results for gear main effects are provided in Table 7.1. Plots of model-predicted catch by gear are shown in Fig. 7.1. Predicted catches of red snapper were generally higher for 4-net vs. 2-net trawls within a diurnal period, in contrast to shrimp species (Fig. 6.1). Predicted catches were higher for nighttime trawls for a given net configuration. Relative fishing power factors for converting effort from reference gear N4 to target gears are given in Table 7.2. Strata mean CPUEs and associated variances by gear are provided in Table S_7.1, Suppl_Info, subfolder S7.0. Area-depth-season strata mean CPUEs by gear were multiplied by the corresponding total penaeid trawl fleet effort (federal and state; Dettloff 2023) each year for 2014-2020 to estimate strata-species-gear annual catches. These were summed over gear and strata by year to produce the total annual red snapper bycatch. Bycatch estimates declined from about 9 million to 6.5 fish over the time period following declines in total trawl fleet effort (Fig. 7.2).

Table 7.1. Compound pdf regression results for gear main effects for red snapper.

		Logistic Estimates, Occurrence (p)			GLM Estimates, Catch when Present (u)			Predicted Catch (p x u)
Species	Gear	n	Mean	SE	n	Mean	SE	Mean
Red Snapper	D2	639	0.130	0.026	23	3.47	0.82	0.45
	D4	3,342	0.327	0.013	900	4.27	0.21	1.40
	N2	478	0.272	0.030	72	4.71	0.64	1.28
	N4	9,118	0.432	0.010	4,411	5.36	0.19	2.32

Figure 7.2. Plot of model-predicted mean catch by gear for red snapper.

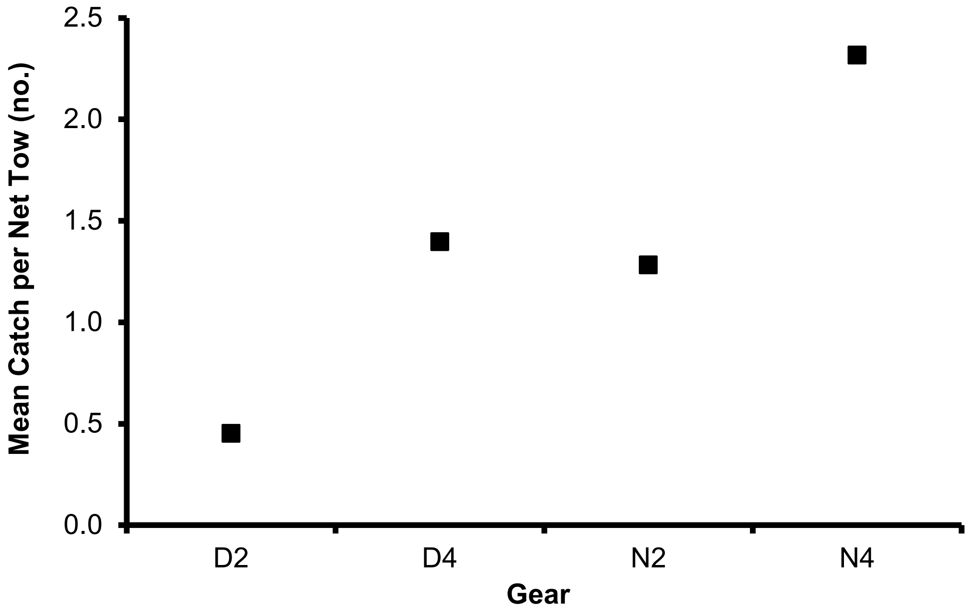
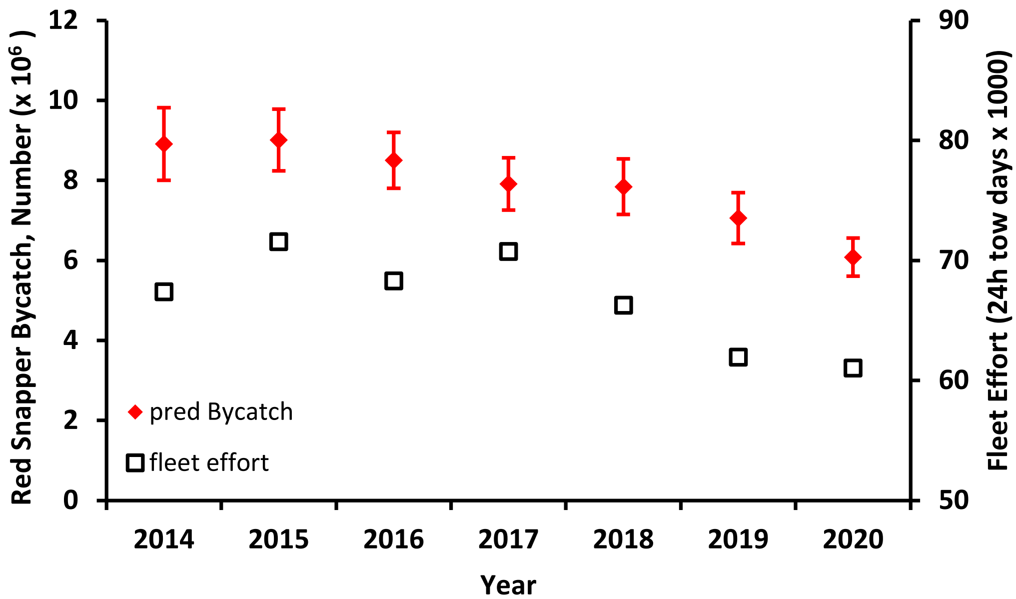


Table 7.2. Relative fishing power factors for converting effort from reference to target gears.

Species	Gear: Reference	Gear: Target	Effort Conversion Factor
Red Snapper	N4	N2	1.807
	N4	D4	1.657
	N4	D2	5.127

Figure 7.2. Observer-predicted bycatch of red snapper (number) for 2014-2020, with corresponding shrimp fleet effort (federal and state combined; secondary y-axis).



8.0 Discussion and Next Steps

Investigation of the bycatch estimation methodology back to the original data sources led to considerable refinement and modernization of data processing procedures for observer CPUE (section 3.0) and shrimp landings and effort (Dettloff 2023). The previously unused gear survey data (section 4.0) were instrumental in accounting for net configuration (2-net, 4-net) in the bycatch methodology (sections 5.0, 7.0). Our analyses also found that species-specific catch rates differed according to diurnal period (sections 5.0, 7.0). While the refined space-time-gear stratification scheme was perhaps a step forward in improving the bycatch estimation methodology, it also highlighted two key data limitations of the shrimp observer program. First, observer sampling effort did not generally cover all the fundamental area-depth-season strata in a given year, requiring pooling of data across years within strata. Second, observer sampling effort was concentrated for nighttime 4-net trawls, with sparser sampling during daytime and for 2-net trawl configurations. A fishing power imputation procedure was used to alleviate sample size issues concerning diurnal period and trawl configuration (sections 6.0, 7.0).

A cross-check showed that the revised bycatch methodology underestimated the reported annual penaeid shrimp catch by an average of 20% for the 2014-2020 time period. This may be attributed to an underestimation of fleet effort and/or an underestimation of observer catch rates (Eq. 1.4). Two aspects of fleet effort may have resulted in underestimation. First, the cross-check evaluation between trip-level observer and ELB effort (Fig. 3.1) found that the ELB units were switched off or not functioning for a portion of the matched trips, and thus were not capturing the complete trip effort. This would have led to a lower value of ELB effort (f_{ELB}) relative to ELB catch (C_{ELB}) in Eq.(1.2), resulting in an underestimate of fleet effort. The second aspect concerns the level of unreported shrimp catch. Anecdotal evidence indicates that not all of the shrimp catch is sold to licensed dealers for a variety of reasons (personal consumption by the crew, given to relatives and friends, sold directly to consumers, etc.). It is plausible that the vessels equipped with ELB units may have a higher reporting rate in the trip-ticket system compared to non-ELB vessels. This would have led to a lower value of fleet catch (C_{fleet}) relative to ELB catch (C_{ELB}) in Eq.(1.2), also resulting in an underestimate of fleet effort. For observer data, our cross-check analyses indicated that effort (Fig. 3.1) and catch (3.2) observations were unbiased at the net-, tow-, and trip-levels. Likewise, over- and under-estimation of catch rates varied among species, strata, and years (e.g., Figs. 5.3, 5.4, 6.3). The net overall effect of pooling years within strata and of imputing catch rates for sparsely sampled gears, however, may have been an underestimation of catch rates.

These outstanding underestimation issues relate to the fundamental representativeness assumptions of Eqs.(1.1) and (1.3), which can be addressed with more robust data collection/sampling methods in the future. For fleet effort, the SEFSC has been advocating for the past several years to the Gulf of Mexico Fishery Management Council to do away with the ELB units and instead equip the entire federal shrimp fleet with more standard VMS (vessel monitoring system) units as required for all other federally-permitted fishing vessels in the Southeast USA region (e.g., vessels targeting coastal reef fishes, pelagic highly migratory species, etc.). The VMS units are also essentially GPS tracklogs like the ELB units, but are mostly tamper-proof and relay information to NOAA via well-established satellite or cellular networks. Issues with observer sampling coverage can be addressed in the immediate future by refining the allocation strategy for sampling effort to include diurnal period and gear configuration along with area-depth-season strata. While the current budget for the shrimp observer program may not allow for adequate sampling of all space-time-gear strata in a single year, adjusting the allocation strategy for perhaps a 3-year time frame would be a practical short-term solution. The overall intent of the refined allocation would be to eliminate the need for strata imputation of catch rates and to minimize the effect of pooling data among years within strata.

Inferring from the cross-validation analysis of penaeid shrimp catch (Fig. 6.2), it is likely that bycatch of red snapper was also underestimated to some degree, especially if underestimation of fleet effort was the primary cause. Addressing the underestimation issues by the solutions described above will take some time. In the interim, a practical strategy for using the bycatch estimates of red snapper in stock assessments would be to consider an annual estimate as a minimum bound. Scenarios that increase the bycatch estimate by 10%, 20%, and 30% could then be addressed in the stock assessment modeling to evaluate the implications for red snapper sustainability.

Lastly, the focus of this phase of our research has been on the accuracy of bycatch estimates rather than the uncertainty (SEs). The revised bycatch estimation methodology incorporated the variance of observer catch rates, but considered fleet effort as a constant (Eq. 2.5). Accounting for variance of fleet effort would undoubtedly increase the SEs of bycatch estimates. In addition, the imputation procedure inflated the sample sizes of the sparsely sampled gears (combination of net configuration and diurnal period), also likely contributing to underestimation of the uncertainty of bycatch estimates. While the next phase of research will continue to focus on addressing accuracy problems, the research team can also work to better model the uncertainty of bycatch estimates.

Acknowledgments

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