Estimates of otter trawl bycatch of smalltooth sawfish and giant manta ray in federal shrimp fisheries in the Southeast USA

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SFD Contribution xxxx

Background

On April 26, 2021, the Southeast Regional Office (SERO) completed a biological opinion on the effects of the implementation of the sea turtle conservation regulations applicable to shrimp trawling and the authorization of southeast U.S. shrimp fisheries in federal waters on threatened and endangered species and designated critical habitat, in accordance with Section 7 of the ESA. The biological opinion was the result of an intra-agency consultation; SERO was both the action agency under our authorities to conserve sea turtles under the ESA and to manage federal shrimp fishing under the Magnuson-Stevens Act (16 U.S.C. §1801 et seq.) and the consulting agency.

On June 2, 2023, SERO's Sustainable Fisheries Division (SFD) (serving as the action agency) requested the Protected Resources Division (PRD) (serving as the consulting agency) reinitiate the subject consultation. Regulations at 50 C.F.R. § 402.16 require reinitiation of formal Section 7 consultation under the ESA if discretionary involvement or control over the action has been retained (or is authorized by law) and: (1) the amount or extent of the incidental take is exceeded; (2) new information reveals effects of the agency action that may affect listed species or critical habitat in a manner or to an extent not previously considered; (3) the agency action is subsequently modified in a manner that causes an effect to the listed species or critical habitat that was not previously considered; or (4) if a new species is listed or critical habitat designated that may be affected by the identified action. The subject fisheries have exceeded the anticipated incidental takes of giant manta ray (i.e., trigger #1) and SERO has received new smalltooth sawfish and giant manta ray bycatch and species information, which may trigger #2. In their reinitiation request, SFD summarized the last biological opinion on the subject action, documented why reinitiation is required, and outlined how SFD and PRD would need to work together to prepare a complete reinitiation package.

In March 2024, SERO requested data and analyses to support the reinitiation of ESA Section 7 consultation on the Southeast U.S. shrimp fisheries in federal waters under the Magnuson-Stevens Act to address bycatch of giant manta ray and smalltooth sawfish and compliance with the terms and conditions of the 2021 biological opinion's incidental take statement.

Specifically, SERO requested the following:
1) Updated bycatch estimates for giant manta ray and smalltooth sawfish.
a. Previous bycatch estimates for these species considered data through 2019; please update estimates through 2022. Estimates will also be needed for 2023, when available.
b. To the extent practicable, please generate model-based and design-based estimates of total annual bycatch in conjunction with the best currently available shrimp effort estimates, using BycatchEstimator (https://ebabcock.github.io/BycatchEstimator/) or similar approaches to consider the appropriate underlying statistical distribution for zero inflated data and characterize uncertainty in resultant estimates.
c. To the extent practicable, please consider the underlying distribution of the species in the generation of bycatch estimates.
d. To the extent practicable, please generate spatiotemporally-explicit bycatch estimates to allow for the identification of seasons and/or areas with the greatest bycatch risk.

2) To the extent practicable, please assess the precision of the current sawfish bycatch estimate to potential future scenarios of increased observer effort. For example, how would increased levels (i.e., 1.1x, 1.25x, 1.5x, 2x, 5x, etc.) of observer effort reduce uncertainty (e.g., coefficient of

variation) of sawfish bycatch estimates in the fishery?

This report, to the extent practical, provides data and analysis to meet these two requests. A third request was to provide a population viability analysis (PVA) update for smalltooth sawfish evaluating the population's ability to recover in the context of ongoing bycatch as estimated in in this report and a significant mortality event in 2024. A separate report will provide that model.

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Abstract

The southeast shrimp trawl observer data were used, along with total effort data, to estimate bycatch of smalltooth sawfish and giant manta rays in the Gulf of America (formerly Gulf of Mexico) and US South Atlantic region. Gulf sawfish were estimated for 2015 to 2023 and giant manta rays from 2019 to 2023. South Atlantic sawfish were estimated from 2009 to 2022 and giant manta rays from 2019 to 2022. Due to the limited geographical range of smalltooth sawfish, only statistical zones 1-4 in the Gulf and 28 to 30 in the South Atlantic were included in the analysis. All specimens caught were included in the analysis, so these estimates are total bycatch, not bycatch mortality. Ratio estimators, with and without pooling across 2- and 4-year time intervals, and Bayesian generalized linear models using the negative binomial distribution estimated similar total bycatch across the time series, but differed in how much they averaged across the year-to-year variability caused by the low observer coverage rate. Estimates for smalltooth sawfish in the Gulf ranged from 30 animals (CI: 6-74) in 2013 to 123 animals (CI: 47-258) in 2020 and ranged from 22 animals (CI: 1-81) in 2013 to 58 animals (CI: 8-190) in 2016 in the South Atlantic. Mean model-based bycatch estimates for giant manta ray in the Gulf ranged from 385 animals (CI: 144-781) in 2021 to 863 animals (CI: 357-1643) in 2023 and ranged from 477 animals (CI: 67-1707) in 2022 to 1245 animals (CI: 205-4611) in 2019 in the South Atlantic. The credible intervals from the model are narrower than those estimated by Carlson (2020) based on a bootstrapped ratio estimator, but the intervals overlap for overlapping years.

Introduction

Smalltooth sawfish and giant manta rays are rarely observed in shrimp trawls in the U.S. Gulf of America (formerly Gulf of Mexico, hereafter Gulf) and South Atlantic regions. Yet, observer coverage for shrimp fisheries is also very low, particularly in the South Atlantic. In the Shrimp Trawl Observer data, sawfish are recorded in very small numbers, primarily in shrimp statistical zones 1 through 4 in the Gulf, and zones 28 and 29 in the US South Atlantic region (Figure 1). Giant manta rays are less rarely observed and more widely distributed (Figure 1). They were not identified to species in the US observer data until 2019.

Total bycatch has been estimated for these species in the shrimp trawl fisheries (Carlson 2020). However, there is a need to update the estimates so that bycatch can be monitored and to provide estimates of the potential uncertainties in the estimates. In the Gulf, total effort is estimated within each stratum (combination of year, season, statistical zone, and depth zone) from a model based on the landings and other data sources, so that there is a mean and

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standard error of total fishing hours per stratum. For the South Atlantic, no estimates of hours or sets are available, although there is data on the number of trips landing shrimp in each region. The uncertainty in the estimates of total effort increases uncertainty in the estimates of total bycatch (Babcock et al. 2018).

The objective of this paper is to estimate the total bycatch per year of smalltooth sawfish and giant manta rays in the federal shrimp trawl fishery in the Gulf of America (formerly Gulf of Mexico) and South Atlantic, using both design-based and model-based estimation methods to estimate both the best estimate of total bycatch and its uncertainty.

Methods

Data sources

Bycatch data were provided by the Shrimp Trawl Observer Program, which is coordinated by the NOAA SEFSC (Scott-Denton et al. 2012). Set was used as the sample unit to conserve resolution of Statistical Zone (StatZone) in the observer data, rather than trip, because a vessel can conduct fishing sets in multiple StatZones per trip. Season (1: Jan-Apr, 2: May-Aug, 3: Sep-Dec) and year were assigned based on the date of the observed set. Depth zone (1: <10 fathoms and 2: ≥10 fathoms) was assigned based on the recorded depth of the set. When depth was not recorded for the set in the observer dataset, approximate depth was added by matching the recorded starting latitude and longitude in the observer set with bathymetry information extracted from the ETOPO 2022 15 Arc-Second Global Relief Model (NOAA National Centers for Environmental Information 2022), and the depth zone was assigned based on the approximate depth. StatZone was recorded by observers for each set. Effort for each set (hours fished) was recorded by the observer, and CPUE was calculated as the catch of a given species divided by the hours fished in that set.

For the Gulf, estimates of total effort were provided for years 2008–2023 based on a revised methodology that also uses electronic logbook (ELB) data (Atkinson et al. 2025) (K. Dettloff, personal communication, 2025). Estimates of effort and standard error per strata were provided as fishing days and were converted to fishing hours (hours=fishing days * 24).

For the South Atlantic, the state trip ticket reports were used to estimate total effort in number of trips, beginning in 2009 (D. Gloeckner, personal communication, 2024). Consistent with Babcock et al. (2018), effort was measured in number of trips for the south Atlantic, rather than fishing hours as was done in the Gulf, because fishing hours were not reported consistently in the trip ticket data used to calculate total effort. The potential stratification variables in the South Atlantic included year, season, and depth zone, as defined above, as well as a trip code variable that indicates whether the vessel was targeting rock shrimp. For the observer data, ordinary vs rock shrimp sets are indicated by a code in the trip ID number (GA for ordinary shrimp trawls vs. GW for rock shrimp). For the South Atlantic effort data, we used all trips that recorded their gear as “shrimp trawl” or “trawl, otter, bottom, shrimp,” and counted those that recorded their target species as rock shrimp as "GW,” and all others as "GA”. The observer data was aggregated to the trip level for the analysis, where the StatZone, dpz and season were allocated to whatever level was associated with the majority of the sets in the trip.

Estimates of bycatch were made separately for the Gulf and South Atlantic regions due to the difference in effort estimation and different levels of observer coverage (see observer coverage levels shown in the results). The South Atlantic estimates should be considered preliminary and highly uncertain, because of the very low observed effort levels and the fact that the effort data have not been checked and validated to the same level as Gulf data.

The spatial area and time period included in the analysis was different for each species. Due to the limited geographical range of smalltooth sawfish, only statistical zones 1-4 in the Gulf and 28 to 30 in the South Atlantic were included in the analysis (Figure 1). Sawfish are known to occur south of StatZone 28 on the east Florida coast, but there was very little recorded shrimp trawl effort south of StatZone 28 (Figure 1c). Giant manta rays were not recorded to species as part of the observer protocol until 2019, so the analysis for Gulf manta rays was limited to 2019-2023. Due to lack of observed coverage (only one observed trip), 2023 was not included in either analysis in the South Atlantic. Although observers record sightings and bycatch of protected species in unsampled nets, only on-station captures were considered (i.e. sightings and captures in unsampled nets were excluded) which excluded one non-station giant manta ray sighting, and two non-station captures of smalltooth sawfish. Therefore, estimated bycatch rates presented below are per fully observed “on station” fishing hour, and these are the bycatch rates that are expanded to the total effort to estimate total bycatch.

For giant manta rays, a species distribution model (SDM) was available, and it is possible that including the predicted probabilities of Giant Manta presence from the SDM as a predictor variable in the statistical models would improve precision of bycatch estimates (Farmer et al. 2022). The previous analysis by Carlson (2020) used the same giant manta ray SDM but only had access to manta ray probabilities averaged across each StatZone in each month of the year. Because both manta rays and shrimp trawl effort are concentrated in a small part of each StatZone, this average did not capture which StatZones and months had higher encounter rates between shrimp trawls and manta rays. For this analysis, an average probability of manta encounter was calculated for each StatZone and month, using a refined method that focused on areas within each StatZone where the manta SDM and shrimp fishery overlapped, for use as a potential predictor variable in the bycatch estimation models. Manta ray probabilities from the SDM predicted on a fine scale prediction grid were provided by the author (N. Farmer, personal communication, 2024), along with average shrimp fishing effort by month, in hours fished, projected in the same grid. This fine-scale spatial distribution of the shrimp fishery effort, from the electronic logbook program, was only available for the years 2018 and 2019, and these two years were averaged together to produce a single map of the effort distribution in each month. Giant manta ray encounter probability was calculated as the weighted average, across the fine-scale pixels in each StatZone and month, of the SDM manta probability of presence, weighted by average shrimp trawl effort in the same pixel (Appendix 1, Figure A1-1, A1-2). Thus, the estimated manta ray encounter probability was higher in months and

StatZones with more spatial overlap between the shrimp trawl distribution and manta ray SDM. This encounter probability was only included in the bycatch estimation models for South Atlantic manta rays because the manta ray probability variable did not improve predictive skill of the model for the Gulf in a preliminary analysis (Appendix 2, Table A2-1, Figure A2-1). See Woods (2024) and Appendix 1 and 2 for details.

Analysis methods
To determine whether the data were suitable for the proposed methods of estimating total bycatch, we produced graphical summaries of the data distribution, including: (1) comparing the distribution of effort (in hours and sets for the Gulf, and trips for the South Atlantic) between the observer data and the total effort data across potential levels of categorical variables including years, StatZones, dpzs and seasons, and for the South Atlantic, TripCode; (2) comparing the distribution of presence and absence observations of each species across levels of the categorical variables; and (3) histograms of effort for presence and absence observations.

We estimated total bycatch with several design-based, model-based frequentist, and model-based Bayesian methods. Design-based estimates were calculated using stratified ratio estimators (Rao 2000): where the total bycatch in each year is:

$$\hat{C} = \sum_i \left(\frac{\underline{c_i}}{\underline{e_i}}\right) E_i$$

Where *i* refers to the strata, E_i is total effort in the strata, $\underline{e_i}$ is the mean of effort and $\underline{c_i}$ is the mean of bycatch across observed sets in the strata. The variance of the estimate is:

$$V(\hat{C}) = \sum_i E_i^2 \frac{(1-f_i)}{n_i} \left(s_{c,i}^2 + \left(\frac{\underline{c_i}}{\underline{e_i}}\right)^2 s_{e,i}^2 - 2\left(\frac{\underline{c_i}}{\underline{e_i}}\right) s_{ce,i} \right)$$

Where f_i is the fraction of sample units (i.e. trips or sets) sampled, n_i is the number of sample units in the stratum, and s_c^2, s_e^2 and s_{ce} are the variance of catch, variance of effort and covariance of catch and effort, respectively, across observed sets or trips in the stratum.

Unpooled ratio estimators were used to calculate total bycatch for only those strata with observations of the bycatch species. Only year and StatZone were included as stratification variables in the Gulf and year, StatZone and tripcode for the South Atlantic because the small sample size made dividing by dpz or season impractical. This method is most consistent with methods previously used for sawfish (Carlson 2020). Because both species were rare and many years had zero observed catches, we also produced a ratio estimator pooled across several years. For sawfish, a four-year pooling variable was used (i.e. 2008-2011, 2012-2015, 2016-2019, and 2020-2023). Because giant manta rays were observed in every year in the Gulf, no pooling was used. A two-year pool was used for South Atlantic mantas (i.e. 2019-2020, 2021-2022). The number of years pooled was chosen based on the total years of data available for each species and the frequency of zero observation years that could create empty bins. When year was pooled, the estimated total bycatch in each year was estimated by allocating the total catch in the StatZone to years based on the total effort in the year and StatZone. For methodological details and simulation testing, along with the code, see the GitHub and associated papers (Babcock et al. 2022, Babcock et al. 2023, Babcock 2024).

Model based estimators were calculated in a two-step process. First, we chose the best combination of predictor variables using the Bayesian Information Criteria (BIC) and Akaike Information Criterion (AIC) in a frequentist context. Both AIC and BIC weigh the tradeoff between model complexity and model fit to find the model that best predicts the y data. BIC favors simpler models than AIC because it has a stronger penalty on complexity. Models with a BIC within 10 units of the best model were considered plausible for further consideration. Because the bycatch species were recorded as integer counts with a possibility of over-dispersion, we used a negative binomial likelihood (negative binomial 2) and checked for the adequacy of the fit using quantile residuals (Hartig 2022). For the Gulf, the most complex model considered for the log mean catch of sawfish was:

(1) $log\ log\ (\mu)\ = intercept + FourYear + StatZone + dpz + season + offset(log(hours)$

With an estimated dispersion parameter (ϕ) such that the residual variance is $\sigma^2\ = \mu + \mu^2/\phi$. For the South Atlantic, the potential predictor variables were FourYear, StatZone and TripCode. There was no offset in the South Atlantic because each observation was one trip and trips were the unit of effort. For mantas in the Gulf, Year was used as a categorical variable instead of FourYear. For South Atlantic manta rays, Tripcode was included, and the weighted probability of encounter for each StatZone and month, based on the SDM (Farmer et al. 2022), was also considered as a numerical variable with an estimated slope.

For the Gulf, because the total effort data used in the expansion was estimated from a model, with uncertainty, we used a Bayesian method to calculate the total bycatch following the methods of Babcock et al. (2018). Bayesian models were fitted using the same negative binomial 2 likelihood and the predictor variables considered plausible by the BIC model selection. The Bayesian information criteria WAIC and LOOIC were used to compare the models (Vehtari et al. 2017). Within the Bayesian models, the total effort for each stratum (combination of year, season, depth zone and StatZone) was drawn from a random normal distribution with the mean and standard error provided for the strata. The total bycatch in each stratum was calculated as the predicted catch per hour (i.e. with an offset of 0) from the model times the random draw of effort, and the total bycatch was summed across strata within each year. The model was fitted using a Hamiltonian Markov Chain Monte Carlo (MCMC) algorithm (Carpenter et al. 2017), and the mean, median, and 95% credible intervals of each year’s total bycatch estimate were calculated across converged MCMC draws. The priors were weakly informative, and were normal(0,10) for the intercept or normal(0,1) for the other regression coefficients and half-normal(0,1) for the negative binomial dispersion coefficient ϕ. Model convergence was evaluated using the Gelman-Rubin Rhat diagnostic (should be near 1), and the effective sample size (neff, should be greater than 300) (Gelman et al. 2013). Prior predictive simulations were used to ensure that the priors were sufficiently informative to allow the data to inform the posterior distributions (McElreath 2020). Posterior predictive simulations and quantile residuals were used to ensure that the distribution of the data and the simulated data from the model were consistent.

For the South Atlantic, because the effort data was trip by trip, not aggregated, it was not necessary to simulate the effort distribution. However, Bayesian models were applied to several plausible models to get WAIC and LOOIC values and estimate the variances using MCMC. The fitted Bayesian model was used to predict the bycatch in each trip from the full trip data set, and these predictions were summed across MCMC draws to estimate total bycatch in each year.

The design-based estimators and frequentist models were estimated using the *bycatchEstimator* R library (Babcock 2022, Babcock et al. 2022, Babcock et al. 2023, Babcock 2024), and the Bayesian analysis was conducted using the *rstan* package (Stan Development Team 2024). The code to run the STAN models is available on GitHub (Babcock 2025).

Results

Detailed model results are given in Tables 1-3 and Figures 2-7 for sawfish, and Tables 4-6 and Figures 8-12 for manta. The estimates of total bycatch per year are given in Table 3 and Figure 7 for sawfish, and Table 6 and Figure 12 for manta. A comparison between the bycatch estimates of Carlson (2000) and the current bycatch estimates is given in Table 7 and Figure 13.

Gulf Sawfish

For zones 1 to 4, observer coverage was low (overall 1.4% of fishing hours). Sampling effort was particularly low in 2020, due to Covid, and this is reflected in the large standard error of the mean CPUE in that year (Figure 2a). Effort in zones 1-4 dipped in the mid-2010s, but increased with a peak before Covid before declining in recent years (Figure 2b). Despite low observer coverage, there were at least some sampled sets in each level of StatZone, year and dpz, allowing for estimation of the effects of the factors on bycatch in the linear models (Figure 3a). The observed sawfish (19 total, Table 3) were found in sets that were typical in terms of hours fished (Figure 4a).

The four-year pooling variable helped reduce the high variability in bycatch estimates seen in the unpooled ratio estimator, smoothing the estimates across years (Figure 5a). The best frequentist GLM according to the BIC was the model with FourYear as the only predictor variable, implying that none of the other variables (dpz, season, StatZone) greatly improved the model. However, models within 10 units of the best model, implying some support from the data, included some with either StatZone or dpz (Table 1a). AIC preferred models that included StatZone. In the Bayesian models, WAIC and LOOIC preferred the model FourYear and StatZone (Table 1b). All Bayesian models had adequate MCMC convergence diagnostics (Table 2a). Diagnostic plots are presented in Appendix 3, Figures A3-1 and A3-2. For comparison, Figure 7a shows the estimates and 95% intervals for the best model (FourYear+StatZone) and for the ratio estimator with FourYear as pooling variable, showing that the model estimates are consistent with the estimates of the ratio estimator. The corresponding values are given in Table 3a.

South Atlantic Sawfish

For the South Atlantic StatZones 28–30 from 2009 to 2022, observer coverage was even lower than in the Gulf (overall 0.7% of trips). Although sampling effort was lower in 2020 due to Covid, there happened to be no sawfish catch that year, so the estimate of total sawfish bycatch was not inflated as in the Gulf (Figure 2c). Effort in zones 28 to 30 decreased during the 2009-2022 period (Figure 2d). Despite low observer coverage, there were at least some sampled sets in each level of StatZone, year and TripCode, allowing for estimation of the effects of the factors on bycatch in the linear models (Figure 3b).

Because no sawfish were observed in the South Atlantic until 2016, the ratio estimator estimated zero bycatch from 2009–2015 (Figure 5b). The observer coverage rate ranged from 0.25% to 1.2% of trips across 2009–2022 (4–24 trips per year), and only 4 sawfish were observed in the entire time series (Table 3), meaning that only 2.6% of observed trips encountered a sawfish. Thus, with these low observer coverage rate, the probability that the observers would happen to see a sawfish bycatch event was low in each year, and the year-specific ratio estimator was unable to provide accurate estimates of bycatch. The four-year pooling variable smoothed estimates from 2016-2022. The best model according to both AIC and BIC included FourYear, TripCode, and season (Table 1c), however WAIC and LOOIC both preferred the model with only FourYear and season (Table 1d). All models had adequate convergence diagnostics for all parameters (Table 2b). Diagnostic plots are presented in Appendix 3, Figures A3-3 and A3-4.

All the Bayesian models had similar wide credible intervals in the estimate (Figure 6b). Based on WAIC and LOOIC, the model with the FourYear variable and season was considered best. Figure 7b compares the estimates and 95% intervals for the preferred model (FourYear+season) and the ratio estimator with the FourYear smoothing variable, showing that the intervals overlap in years with data. The corresponding values are given in Table 3b.

Gulf Giant Manta Ray

Observer coverage was similarly low for the Gulf zones 1 to 21 (overall 1.06% of fishing hours) from 2019 to 2023. Effort slightly decreased over the 2019-2023 period (Figure 8b). There were at least some sampled sets in each level of StatZone, year, season and dpz, allowing for estimation of effects of those factors on bycatch in the linear models (Figure 9a). The observed manta were found in sets that were typical in terms of hours fished (Figure 4b).

There was less year-to-year variability but relatively high uncertainty in the bycatch estimates from the ratio estimators for manta (Figure 10a). The best model according to the BIC was the model including Year only followed by Year + dpz; however, there was a difference between BIC and AIC, which preferred a more complex model that included dpz, StatZone, and Year due to the reduced penalty for additional parameters in AIC (Table 4a). Because StatZone was expected to be important for Gulf manta rays, we ran Bayesian models with StatZone as well as Year and dpz. The WAIC and LOOIC preferred the models that included Year, StatZone and dpz (Table 4b). However, the simpler model with Year and StatZone also performed well, so we chose it as the best model. All models had adequate convergence diagnostics (Table 5a). Diagnostic plots are presented in Appendix 3, Figures A3-5 and A3-6.

The models indicated a general increase in bycatch of manta rays from 2019-2023 (Figure 11a), reflecting the increase in CPUE in the observer data. For comparison, Figure 12a shows the estimates and 95% intervals for the Year+StatZone model and for the unpooled ratio estimator. Year to year estimates of bycatch were comparable, with exception to some difference in the initial year (2019). The corresponding bycatch estimates and variances are given in Table 6a.

South Atlantic Manta

For the South Atlantic StatZones 28-33 from 2019 to 2022, observer coverage was extremely low (overall 0.01% of trips). As in the Gulf, effort in zones 28 to 33 decreased during the 2019-2022 period (Figure 8d). No manta rays were caught on GW-coded observer trips, but there were sampled sets in each level of StatZone, year and TripCode, allowing for estimation of the effects of the factors on bycatch in the linear models (Figure 9b). As in the Gulf, the ratio estimator found very high uncertainty in the bycatch level (Figure 10b). The two-year pooling variable helped smooth across years slightly.

The best model according to both AIC and BIC was the model with the manta encounter probability variable and TwoYear (Table 4c). The WAIC preferred the model with the encounter probability variable, but LOOIC slightly preferred the model without (Table 4d). The effect of manta ray encounter probability on bycatch was positive, as expected. Unlike in the Gulf, StatZone was not an important factor in estimating manta ray bycatch in the South Atlantic. All models had adequate convergence diagnostics for all parameters (Table 5b). Diagnostic plots are presented in Appendix 3, Figures A3-7 and A3-8. The manta ray models for the South Atlantic had very wide credible intervals in the estimates (Figure 11b). Based on WAIC and LOOIC, we considered the model with encounter probability and TwoYear as best. Figure 12b compares the estimates and 95% intervals for the best model and for the pooled ratio estimator, showing that the intervals overlap in years with data, but the confidence intervals are very wide for both methods. The corresponding values are given in Table 6b.

Discussion

Because sawfish and manta rays are relatively rare, and sample sizes in the observer program are low, bycatch events are rarely observed. However, since the total fishing effort is up to 100 times the observed effort, rare bycatch may still amount to a large number of individual animals caught in the fishery. Due to the rarity of both sawfish and manta rays as observed bycatch, and the low level of observer coverage, it is not possible to produce precise estimates of the total bycatch. In particular, simple ratio estimators, even with some degree of pooling, provide very wide confidence intervals, with potential catches from zero to several hundred in years when a sawfish or manta happened to be observed, with estimates of zero in the years with no observed bycatch. The four-year pooling variable was useful for smoothing some interannual variation in sawfish bycatch estimates while maintaining the simplicity of the ratio estimator method. The model-based estimator smooths out the year-to-year variation and provides an estimate for each year. The model-based numbers are probably the best estimate of catches in each year for scientific purposes, such as for stock assessment and management strategy evaluation. However, the model is not able to estimate year-to-year variation in bycatch due to the low sample size and rarity of both species. Thus, if there was a change in bycatch rate due to, for example, fishers actively avoiding bycatch, the model would not pick this up at the current observer coverage level, particularly in the South Atlantic.

The precision of the models could potentially be improved by adding independent information about the distribution of the two species. Including a variable based on a species distribution model for manta (Farmer et al. 2022) did not improve model predictions for the Gulf in a preliminary study (Appendix 2), although it did improve the predictions for the South Atlantic. This may be because the SDM was parameterized with more data in the South Atlantic portion of the range (Farmer et al. 2022) than in the Gulf, therefore the SDM may not have adequately captured months and locations with higher manta encounter probability in the Gulf. SDMs based on larger data sets could potentially improve estimates for both models. However, higher observer coverage levels are critically important to provide precise annual estimates of bycatch.

The previous estimates of bycatch for giant manta rays and sawfish, by Carlson (2020), were made with a bootstrapped ratio estimator. Those estimates had wide confidence intervals but overlapped with the results for our model in comparable years. For example, the most recent years with a positive catch in Carlson's (2000) analysis were 0- 1477 for sawfish in the South Atlantic in 2018, 0-5187 for sawfish in Gulf in 2019, 0-6299 for manta rays in South Atlantic in 2019, and around 140 for manta rays in Gulf in 2019. The credible intervals for our model estimators overlap with these intervals, but are narrower, implying that the model is able to improve precision (Table 7, Figure 14). The ratio estimator with pooling across FourYear time blocks similarly served to smooth over some of the year -to-year variation in bycatch estimates.

The model-based estimators produce the best estimates that can be made with the current levels of observer coverage. However, the credible intervals remain wide. In addition, both design-based and model-based estimates make the assumption that the observed effort is representative of the total fishery. If, for example, fishers change their behavior to avoid bycatch when observers are present, then the estimates might not be accurate. Another source of uncertainty, particularly in the Gulf, is the model-based estimates of total effort, which include uncertainty. A precise and accurate estimate of total bycatch would require higher observer coverage, particularly in the StatZones where sawfish or mantas are caught, and potentially more precise total effort estimates in each stratum.

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Tables and Figures

Table 1. Information criteria for model selection. Smaller deltaAIC and deltaBIC values are better models. A "+" or a number indicates the variable is included.

(a) Top models by BIC for Gulf sawfish.

dpz	season	StatZone	Four Year	AICc	df	logLik	BIC	delta BIC	delta AIC	weight
			+	254.57	5	-122.28	287.61	0.00	0.92	0.97
+			+	255.22	6	-121.60	294.87	7.26	1.57	0.03
		+	+	253.79	8	-118.88	306.65	19.04	0.14	0.00
+		+	+	253.65	9	-117.81	313.11	25.51	0.00	0.00

(b) WAIC and LOOIC for Gulf sawfish.

Model	WAIC	LOOIC
FourYear	1.79	1.66
FourYear+dpz	1.91	1.81
FourYear+StatZone	0	0

(c) Top models according to BIC for South Atlantic sawfish.

dpz	Season	StatZone	TripCode	Four Year	AICc	df	logLik	BIC	delta BIC	delta AIC	weight
	+		+	+	18.55	8	-0.78	41.97	0.00	0.00	0.95
	+	+	+	+	19.04	10	1.24	48.03	6.06	0.49	0.05
				+	40.22	5	-14.91	55.07	13.11	21.67	0.00
	+			+	34.98	7	-10.11	55.57	13.61	16.70	0.00

(d) WAIC and LOOIC for South Atlantic sawfish

Model	WAIC	LOOIC
FourYear	1.13	1.07
FourYear+season	0	0
FourYear+season+TripCode	1.01	1.04

Table 2. Estimates for intercept (b0), other regression coefficients (b) and the scale parameter (phi) and convergence diagnostics for sawfish, top Bayesian models.

(a) Gulf

Model	Parameter	mean	sd	Q2.5	Q50	Q97.5	n_eff	Rhat
y~FourYear	b0	-7.29	0.39	-8.09	-7.27	-6.58	1531.9	1
	b[1]	0.04	0.57	-1.11	0.05	1.12	1935.71	1
	b[2]	-0.18	0.54	-1.23	-0.18	0.87	2007.24	1
	b[3]	-0.08	0.51	-1.11	-0.08	0.92	1691.05	1
	phi	0.52	0.53	0.02	0.33	1.91	3325.2	1
y~FourYear+StatZone	b0	-7.24	0.67	-8.59	-7.21	-6	1767.02	1
	b[1]	0	0.56	-1.1	0.02	1.08	3681.16	1
	b[2]	-0.18	0.56	-1.28	-0.18	0.92	3556.38	1
	b[3]	0.01	0.5	-0.98	0.01	0.99	3822.86	1
	b[4]	0.12	0.61	-1	0.1	1.35	1959.31	1
	b[5]	-1.04	0.7	-2.48	-1.03	0.29	2327.43	1
	b[6]	-0.36	0.74	-1.85	-0.32	1.05	3281.37	1
	phi	0.53	0.52	0.03	0.35	1.88	4616.28	1
y~FourYear+dpz	b0	-6.89	0.57	-8.09	-6.87	-5.82	2426.69	1
	b[1]	0.08	0.54	-0.98	0.09	1.12	3259.2	1
	b[2]	-0.25	0.55	-1.33	-0.23	0.78	3277.14	1
	b[3]	-0.04	0.51	-1.05	-0.04	0.96	3265.33	1
	b[4]	-0.5	0.54	-1.5	-0.52	0.61	2485.19	1
	phi	0.52	0.51	0.02	0.34	1.87	4320.23	1

(b) South Atlantic

Model	Parameter	mean	sd	Q2.5	Q50	Q97.5	n_eff	Rhat
y~FourYear	b0	-4.18	0.72	-5.71	-4.14	-2.86	2832.25	1
	b[1]	-0.55	0.85	-2.32	-0.54	1.08	4016.2	1
	b[2]	0.63	0.8	-0.95	0.65	2.16	3684.99	1
	b[3]	0.8	0.8	-0.76	0.8	2.39	3633.32	1
	phi	0.88	0.61	0.08	0.76	2.31	4089.46	1
y~FourYear+season	b0	-4.68	0.95	-6.57	-4.67	-2.88	1849.72	1
	b[1]	-0.61	0.86	-2.36	-0.6	1.04	3895.47	1
	b[2]	0.59	0.78	-0.91	0.59	2.11	3343.98	1
	b[3]	0.94	0.79	-0.63	0.94	2.45	3094.46	1
	b[4]	1.03	0.82	-0.5	1.02	2.62	2315.6	1
	b[5]	-0.7	0.86	-2.36	-0.69	0.96	2899.59	1
	phi	0.94	0.61	0.11	0.83	2.38	4568.89	1
y~FourYear+season+	b0	-4.73	0.97	-6.74	-4.7	-2.87	2369.8	1

Model	Parameter	mean	sd	Q2.5	Q50	Q97.5	n_eff	Rhat
TripCode	b[1]	-0.59	0.84	-2.23	-0.57	0.98	3648.43	1
	b[2]	0.59	0.79	-0.96	0.58	2.12	3392.1	1
	b[3]	0.91	0.82	-0.73	0.91	2.51	3752.82	1
	b[4]	1.05	0.81	-0.54	1.06	2.67	2985.76	1
	b[5]	-0.72	0.85	-2.4	-0.71	0.89	3453.53	1
	b[6]	0.04	0.81	-1.56	0.05	1.56	3833.09	1
	phi	0.92	0.61	0.1	0.81	2.38	4325.23	1

Table 3. Estimated total bycatch of sawfish for best models (Gulf: FourYear+StatZone; SATL: FourYear+season), and ratio estimator with pooling by StatZone.

(a) Gulf

							Model				Ratio	
Year	Total effort	Obs effort	Sawfish sets	Sawfish obs	CPUE	CPUE SE	mean	SE	lci	uci	mean	SE
2008	114577	1530	0	0	0	0	82.4	41.3	28.0	185.0	89.0	39.3
2009	124076	2214	4	4	0.002	0.001	90.6	38.2	33.0	185.0	96.4	42.5
2010	59281	1817	1	1	0.001	0.001	47.1	20.4	18.0	95.0	46.1	20.3
2011	64569	874	0	0	0	0	50.6	20.9	19.0	101.0	50.2	22.1
2012	90840	1241	0	0	0	0	69.9	37.2	19.0	157.1	72.2	43.8
2013	38114	900	2	3	0.003	0.002	29.8	16.6	6.0	74.0	30.3	18.4
2014	127328	1044	0	0	0	0	93.6	45.3	29.0	202.0	101.2	61.4
2015	104785	1847	1	1	0.001	0.001	84.6	40.8	25.0	181.0	83.3	50.5
2016	112832	2528	0	0	0	0	75.5	34.7	23.0	154.1	66.9	33.2
2017	144260	1655	2	2	0.001	0.001	93.2	43.2	32.0	196.0	85.5	42.4
2018	170242	1624	0	0	0	0	100.4	47.0	31.0	215.0	100.9	50.0
2019	152279	940	2	2	0.002	0.001	93.0	43.4	28.0	191.0	90.3	44.8
2020	183346	449	1	1	0.003	0.003	122.9	54.5	47.0	258.0	121.9	49.3
2021	153137	2839	1	1	0	0	109.1	42.1	44.0	208.0	101.8	41.2
2022	123524	3875	4	4	0.001	0.001	84.7	34.3	33.0	165.0	82.1	33.2
2023	80805	1860	0	0	0	0	48.4	20.2	19.0	96.0	53.7	21.7

(b) South Atlantic

							Model				Ratio	
Year	Total trips	Obs trips	Sawfish trips	Sawfish obs	CPUE	CPUE SE	mean	SE	lci	uci	mean	SE
2009	2091	24	0	0	0	0	39.5	27.0	7.0	113.1	0.0	0.0
2010	2546	8	0	0	0	0	48.2	32.7	9.0	129.0	0.0	0.0

2011	2822	19	0	0	0	0	53.3	36.4	10.0	151.0	0.0	0.0
2012	2575	17	0	0	0	0	32.6	32.1	3.0	119.0	0.0	0.0
2013	1720	8	0	0	0	0	21.6	21.5	1.0	77.0	0.0	0.0
2014	2082	11	0	0	0	0	25.9	25.4	1.0	90.0	0.0	0.0
2015	1741	7	0	0	0	0	21.8	21.7	1.0	81.0	0.0	0.0
2016	1726	19	1	1	0.053	0.053	58.0	46.7	8.0	190.2	95.9	66.6
2017	1447	8	0	0	0	0	50.6	40.1	7.0	164.1	80.4	55.9
2018	1139	5	1	1	0.2	0.2	42.9	33.8	6.0	133.0	63.3	44.0
2019	1499	4	0	0	0	0	51.4	41.6	7.0	166.1	83.3	57.9
2020	1204	6	0	0	0	0	64.8	55.7	7.0	209.0	92.6	63.9
2021	1002	11	0	0	0	0	53.9	46.4	6.0	182.0	77.1	53.2
2022	752	9	2	2	0.222	0.147	39.1	34.1	4.0	125.1	57.8	39.9

Table 4. Information criteria for model selection for giant manta rays. A "+" or a number indicates the variable is included.

(a) Top models by BIC for Gulf manta.

dpz	season	StatZone	Year	AICc	df	logLik	BIC	delta BIC	delta AIC	weight
			+	385.30	6	-186.65	429.85	0.00	45.99	0.88
+			+	381.86	7	-183.92	433.83	3.98	42.54	0.12
	+		+	386.28	8	-185.14	445.68	15.83	46.96	0.00
+	+		+	381.81	9	-181.90	448.62	18.77	42.48	0.00
		+	+	342.34	26	-145.11	535.28	105.44	2.91	0.00
+		+	+	339.43	27	-142.65	539.79	109.95	0.00	0.00
	+	+	+	345.11	28	-144.49	552.89	123.04	5.67	0.00
+	+	+	+	341.82	29	-141.84	557.01	127.17	2.37	0.00

(b) WAIC and LOOIC for Gulf manta.

Model	WAIC	LOOIC
Year	66.64	69.63
Year+dpz	64.52	65.36
Year+StatZone	4.10	3.81
Year+StatZone+dpz	0.00	0.00

(c) Top models according to BIC for South Atlantic manta.

dpz	Season	StatZone	Weight Prob	Two Year	AICc	df	logLik	BIC	delta BIC	delta AIC	weight
			13.20	+	39.23	4	-15.31	47.68	0.00	0.00	0.84
+			12.80	+	41.41	5	-15.24	51.80	4.12	1.86	0.11
				+	47.93	3	-20.78	54.36	6.68	8.94	0.03
	+		14.90	+	43.65	6	-15.17	55.91	8.23	3.71	0.01
+				+	48.80	4	-20.10	57.25	9.57	9.57	0.01
+	+		14.42	+	45.97	7	-15.10	60.03	12.36	5.57	0.00
	+			+	50.88	5	-19.98	61.27	13.59	11.33	0.00
+	+			+	51.75	6	-19.22	64.02	16.34	11.81	0.00
		+	21.07	+	48.22	9	-13.63	65.63	17.95	6.64	0.00

(d) WAIC and LOOIC for South Atlantic manta

Model	WAIC	LOOIC
TwoYear	0.95	0.00
TwoYear+weightprob	0.00	0.02

Table 5. Parameter estimates for regression coefficients (b) and the scale parameter (phi) and convergence diagnostics for manta, for two models.

(a) Gulf

Model	Parameter	mean	sd	Q2.5.	Q50.	Q97.5	n_eff	Rhat
y~Year	b0	-8.17	0.41	-8.97	-8.16	-7.4	1230.83	1
	b[1]	-0.02	0.61	-1.26	-0.02	1.12	2596.89	1
	b[2]	-0.2	0.54	-1.3	-0.2	0.83	1929.74	1
	b[3]	0.43	0.5	-0.55	0.43	1.41	1588.16	1
	b[4]	0.88	0.52	-0.13	0.88	1.88	1582.65	1
	phi	0.04	0.09	0	0.02	0.18	1277.24	1
y~Year+StatZone	b0	-9.28	0.53	-10.33	-9.27	-8.26	2588.88	1
	b[1]	0.1	0.61	-1.12	0.11	1.23	5421.13	1
	b[2]	-0.13	0.53	-1.21	-0.12	0.91	4548.53	1
	b[3]	0.42	0.49	-0.53	0.42	1.39	3857.96	1
	b[4]	1.28	0.5	0.27	1.29	2.27	3996.32	1
	b[5]	-0.66	0.82	-2.32	-0.64	0.89	6891.69	1

b[6]	-0.52	0.85	-2.25	-0.49	1.07	8506.55	1
b[7]	-0.09	0.96	-1.97	-0.08	1.75	8628.24	1
b[8]	-0.09	0.95	-1.95	-0.09	1.71	7289.68	1
b[9]	-0.04	0.98	-1.96	-0.03	1.87	9181.01	1
b[10]	-0.16	0.93	-2	-0.14	1.62	8202.75	1
b[11]	-0.11	0.96	-2.09	-0.09	1.78	7756.5	1
b[12]	-0.01	1.03	-2.04	0	1.96	9552.9	1
b[13]	-0.07	0.97	-1.99	-0.07	1.87	9233.08	1
b[14]	0.15	0.61	-1.08	0.16	1.3	5565.34	1
b[15]	1.71	0.65	0.35	1.72	2.97	6378.21	1
b[16]	3.03	0.46	2.15	3.03	3.95	4088.83	1
b[17]	0.04	0.75	-1.48	0.06	1.42	8293.86	1
b[18]	0.09	0.76	-1.47	0.11	1.53	7127.25	1
b[19]	-0.57	0.79	-2.23	-0.55	0.96	7499.47	1
b[20]	-0.53	0.84	-2.32	-0.5	1.02	7239.9	1
b[21]	-0.53	0.81	-2.17	-0.5	0.98	8132.94	1
b[22]	-0.6	0.81	-2.23	-0.58	0.9	7134.18	1
b[23]	-0.41	0.86	-2.14	-0.39	1.18	8637.07	1
b[24]	-0.69	0.81	-2.36	-0.66	0.83	6911.16	1
phi	0.26	0.31	0.03	0.15	1.2	3576.72	1

(b) South Atlantic

Model	Parameter	mean	sd	Q2.5	Q50	Q97.5	n_eff	Rhat
y~TwoYear	b0	-1.71	0.91	-3.14	-1.81	0.25	1140.28	1
	b[1]	-0.44	0.79	-1.94	-0.45	1.2	2395.05	1
	phi	0.09	0.1	0.01	0.06	0.36	1543.21	1
y~TwoYear+WP	b0	-2.38	1.01	-4.16	-2.44	-0.17	1799.98	1
	b[1]	-0.46	0.78	-1.97	-0.47	1.08	2507.75	1
	b[2]	0.95	1.01	-1	0.95	2.96	1868.4	1
	phi	0.14	0.17	0.01	0.08	0.65	2142.24	1

Table 6. Estimated total bycatch of manta for best Bayesian model (Gulf: Year+StatZone, SATL: TwoYear+weightprob), and ratio estimate.

(c) Gulf

							Model				Ratio	
Year	Total effort	Obs effort	Manta sets	Manta obs	CPUE	CPUE SE	mean	SE	lci	Uci	mean	SE
2019	1614152	11314	2	2	<0.001	<0.001	406.3	167.2	163.0	844.2	194.6	136.9
2020	1697810	9661	3	3	<0.001	<0.001	442.7	241.0	107.0	1034.3	481.1	272.8
2021	1656717	21251	5	5	<0.001	<0.001	384.6	166.4	144.0	780.5	344.6	154.7
2022	1097645	18718	6	9	<0.001	<0.001	460.7	161.6	202.0	807.1	445.9	224.3
2023	886550	11151	9	9	0.001	<0.001	863.4	333.8	357.0	1643.0	1046.3	386.3

(d) South Atlantic

							Model				Ratio	
Year	Total trips	Obs trips	Manta trips	Manta obs	CPUE	CPUE SE	mean	SE	lci	uci	mean	SE
2019	5872	20	1	6	0.3	0.30	1244.8	1811.3	204.8	4611.2	1214.9	1213.4
2020	5615	9	0	0	0	0	1194.5	1734.2	196.9	4406.7	1161.7	1160.3
2021	4339	30	3	3	0.1	0.056	629.9	1635.7	89.2	2252.7	309.9	174.0
2022	3276	12	0	0	0	0	477.0	1244.4	67.4	1707.4	234.0	131.4

Table 7. Comparison of bootstrap (Carlson 2020) and model results.

Species	Region	Year	Model mean	SE	LCL	UCL	Bootstrap mean	LCL	UCL
Sawfish	SATL	2016	58.0	46.7	8.0	190.2	207.9	0	3876.5
		2018	42.9	33.8	6.0	133.0	129.2	0	1477
Sawfish	Gulf	2009	90.6	38.2	33.0	185.0	96.8	0	351.6
		2010	47.1	20.4	18.0	95.0	21.8	0	NA
		2012	69.9	37.2	19.0	157.1	77.1	0	NA
		2013	29.8	16.6	6.0	74.0	118.8	0	308.7
		2015	84.6	40.8	25.0	181.0	36.3	0	NA
		2017	93.2	43.2	32.0	196.0	289.9	0	4640.8
		2019	93.0	43.4	28.0	191.0	90.3	0	5186.8
Manta	SATL	2019	1244.8	1811.3	204.8	4611.2	1538.7	0	6298.6
Manta	Gulf	2019	406.3	167.2	163.0	844.2	1538.7	0	6298.6

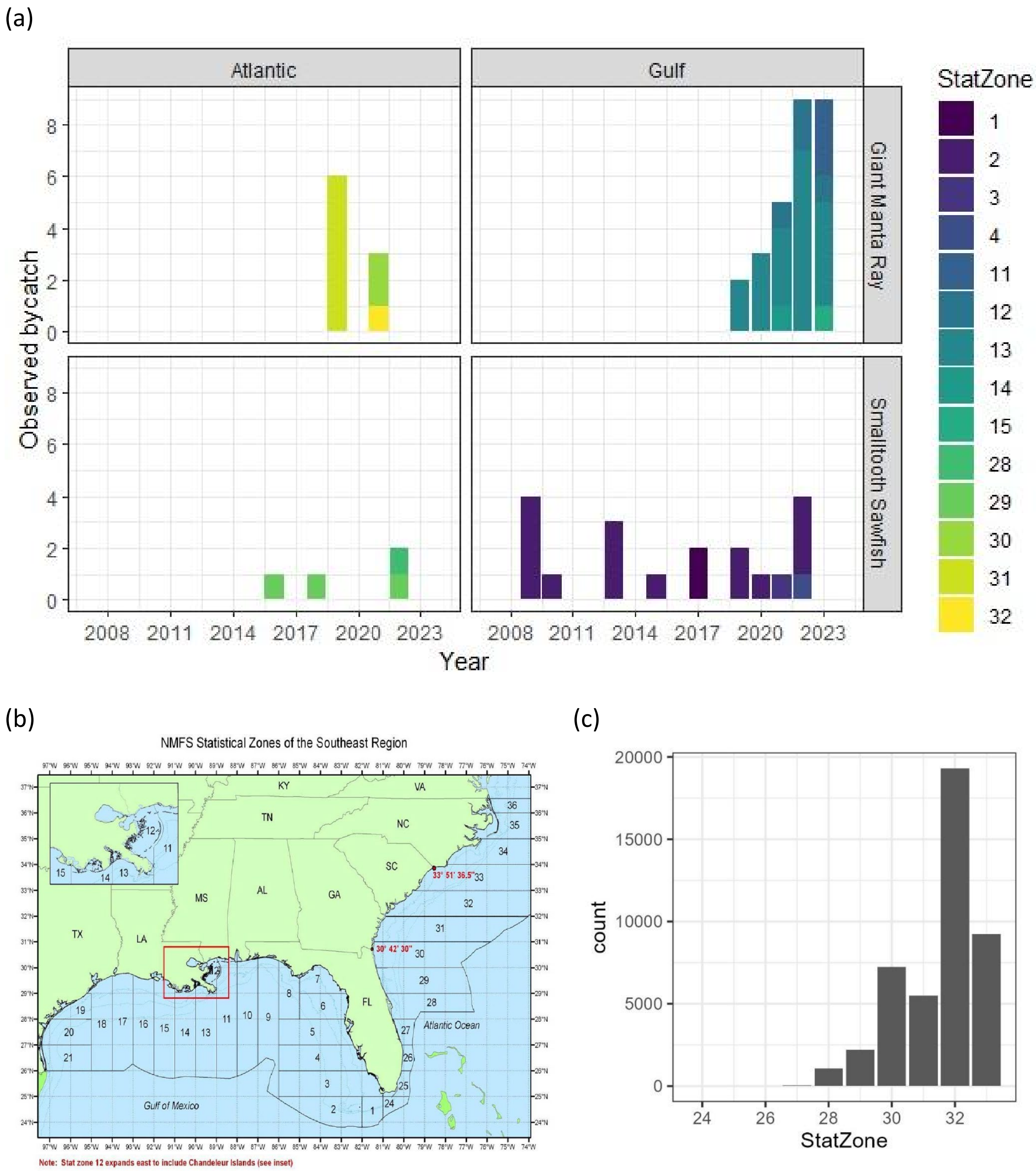


Figure 1. Observed catches of sawfish and manta by year and shrimp statistical zone (**a**), a map of the shrimp statistical zones (**b**) from National Marine Fisheries Service (2020), and (**c**) reported shrimp trips from 2015 to 2022 in the South Atlantic.

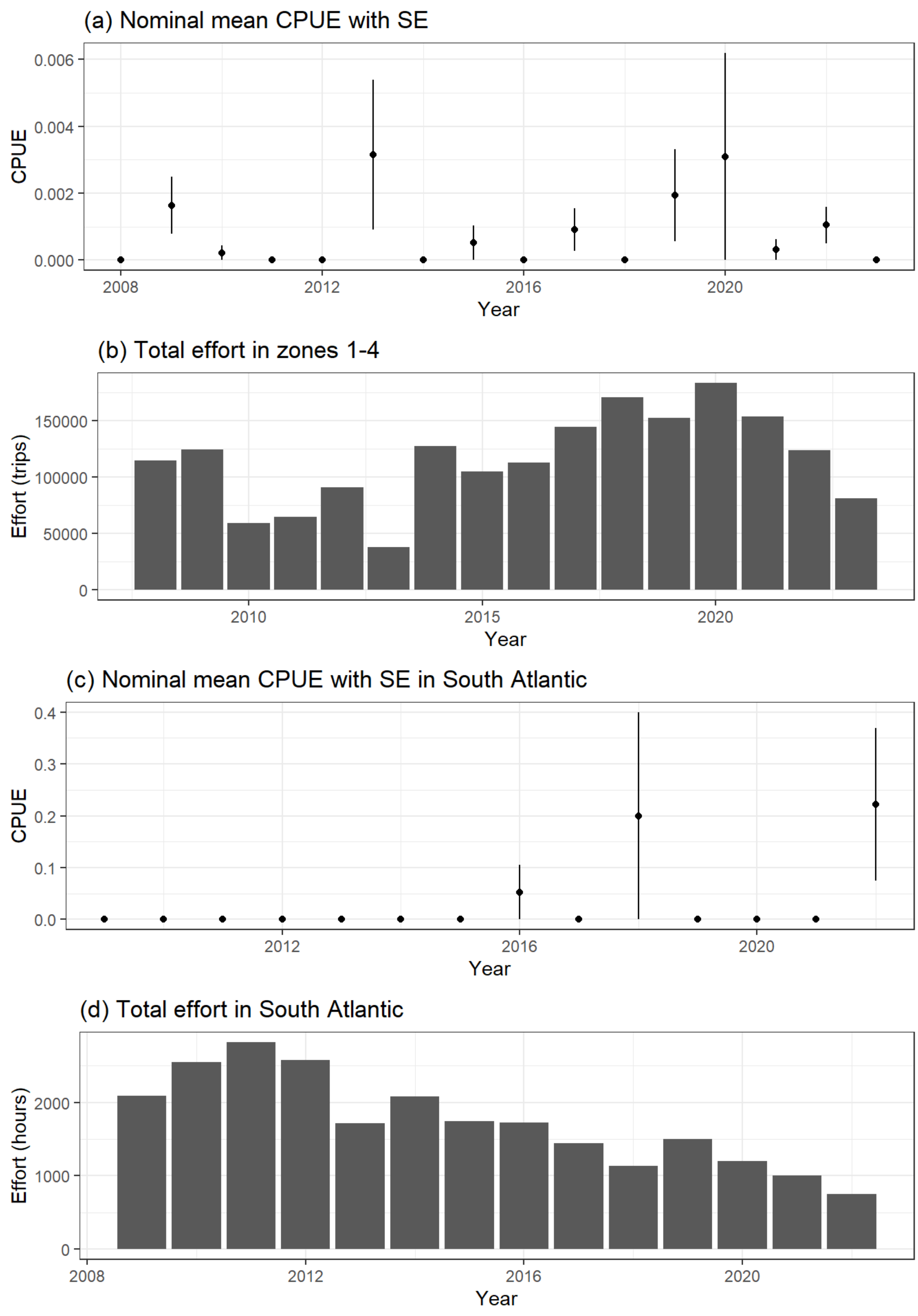
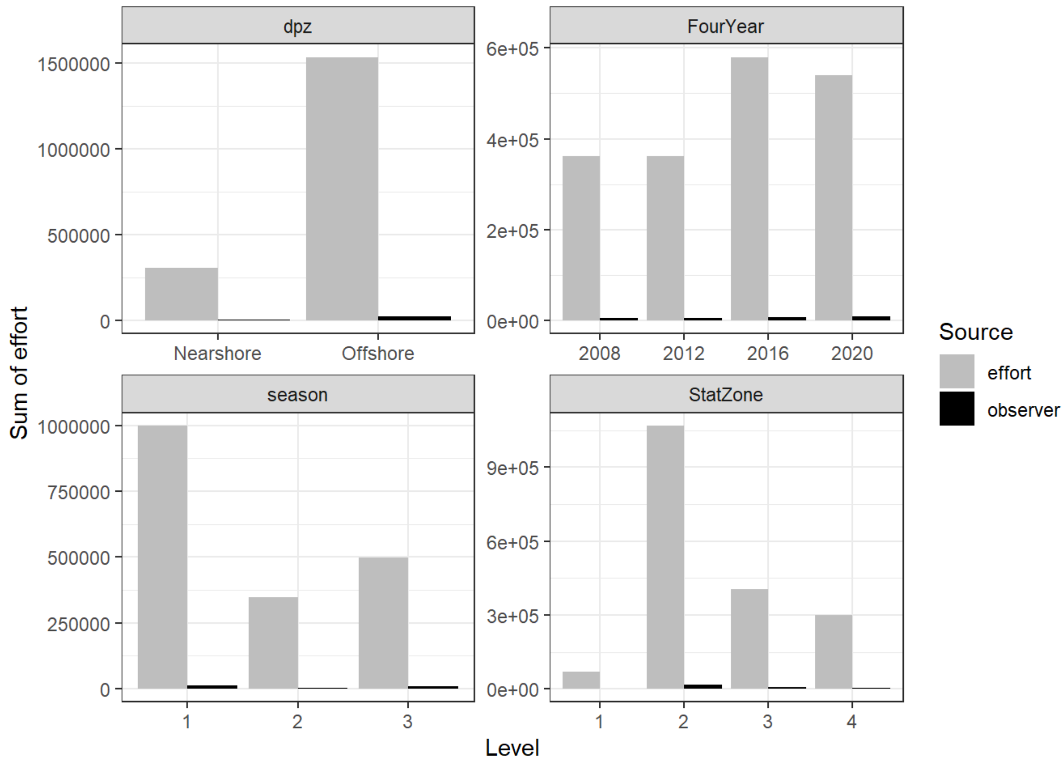


Figure 2. Gulf sawfish nominal CPUE with standard error (**a**), and total effort (**b**), and the same in the South Atlantic region (**c, d**).

(a) In Gulf StatZones 1-4 for sawfish



(b) In the South Atlantic zones 28:30 for sawfish

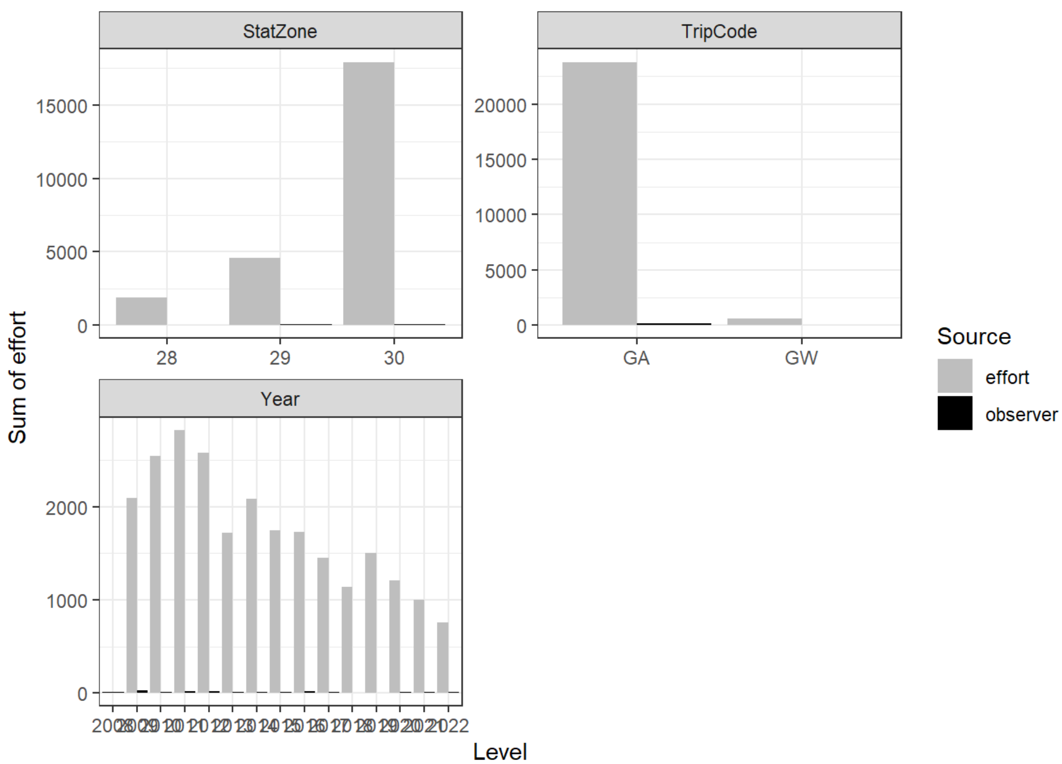
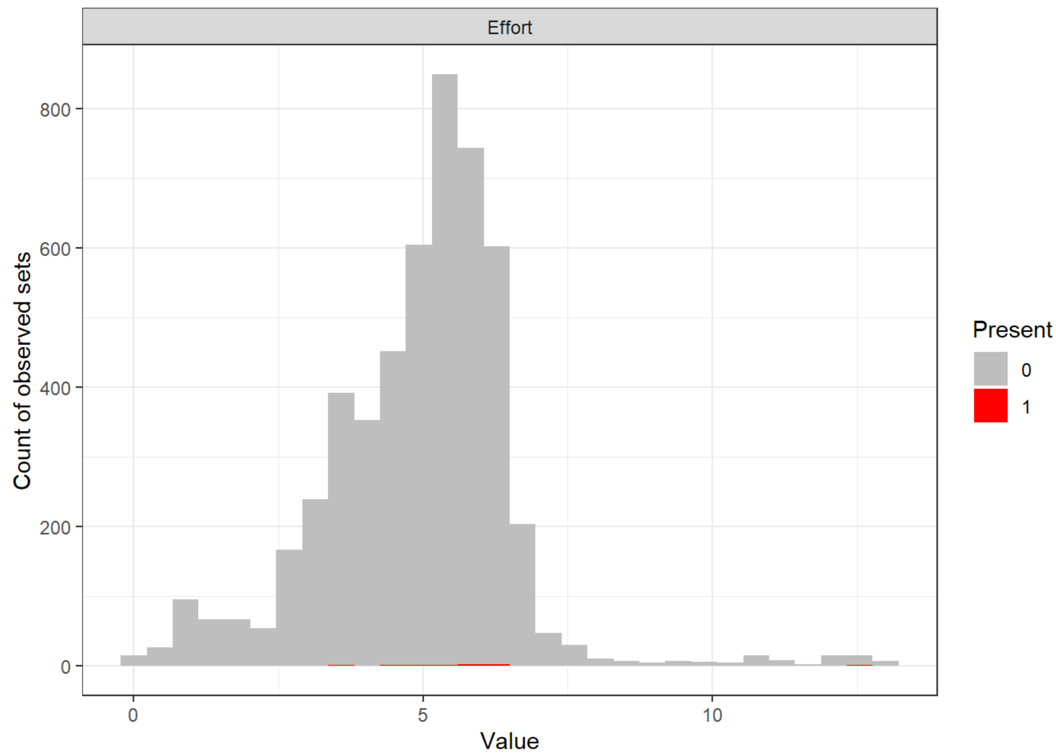


Figure 3. Observer coverage for the StatZones included for sawfish by factor variables.

(a)



(b)

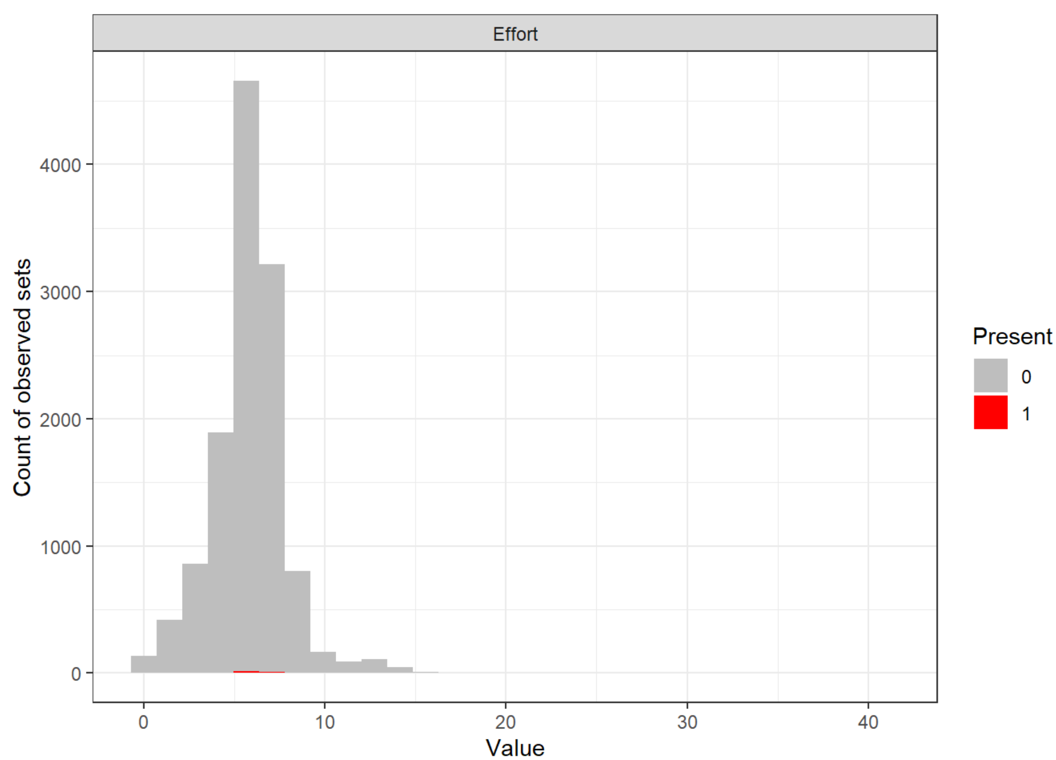
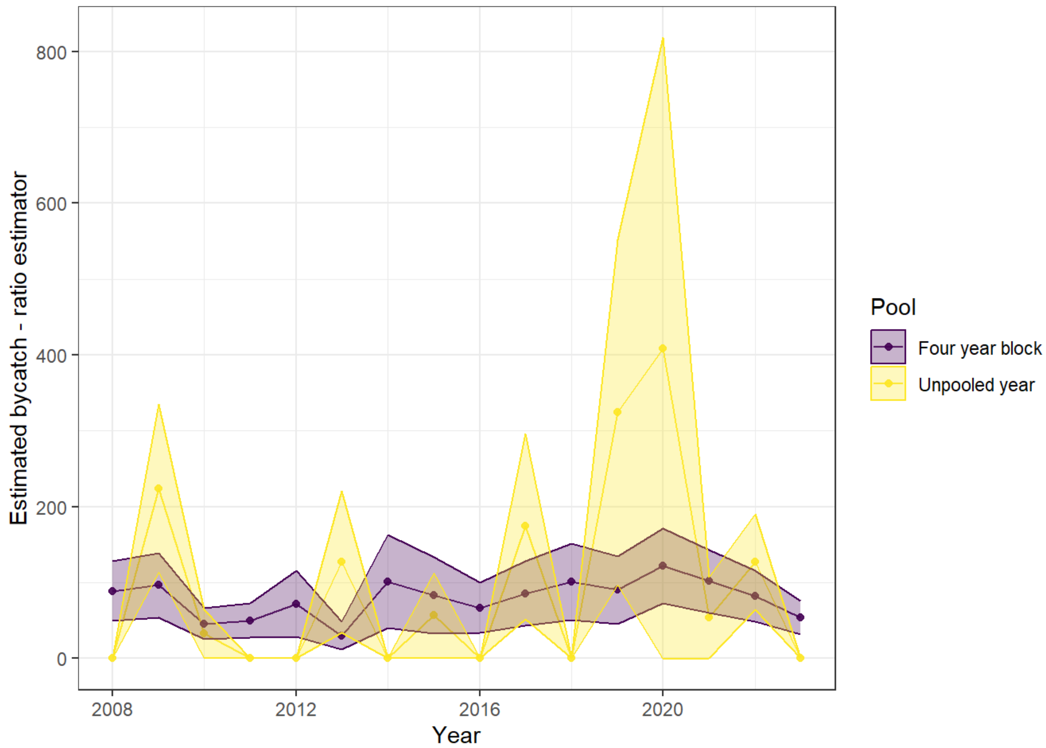


Figure 4. Hours per set in observed sets in Zones 1-4 by presence and absence of sawfish (**a**) and hours per set in observed Gulf sets by presence and absence of manta (**b**).

(a) Gulf



(b) South Atlantic

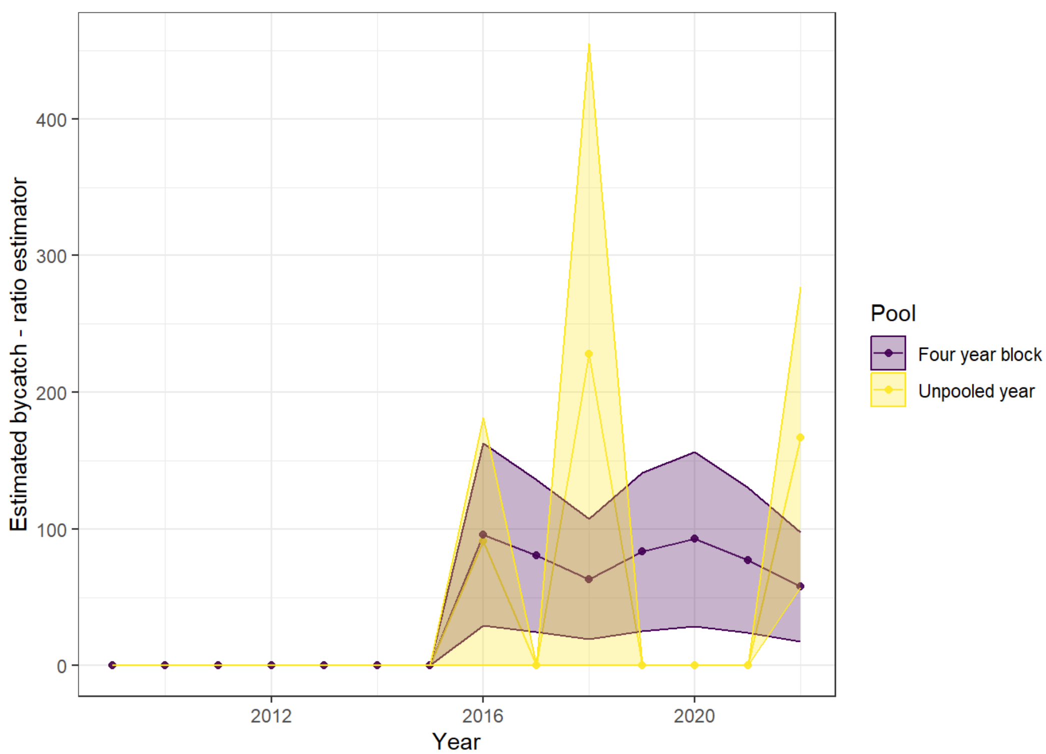
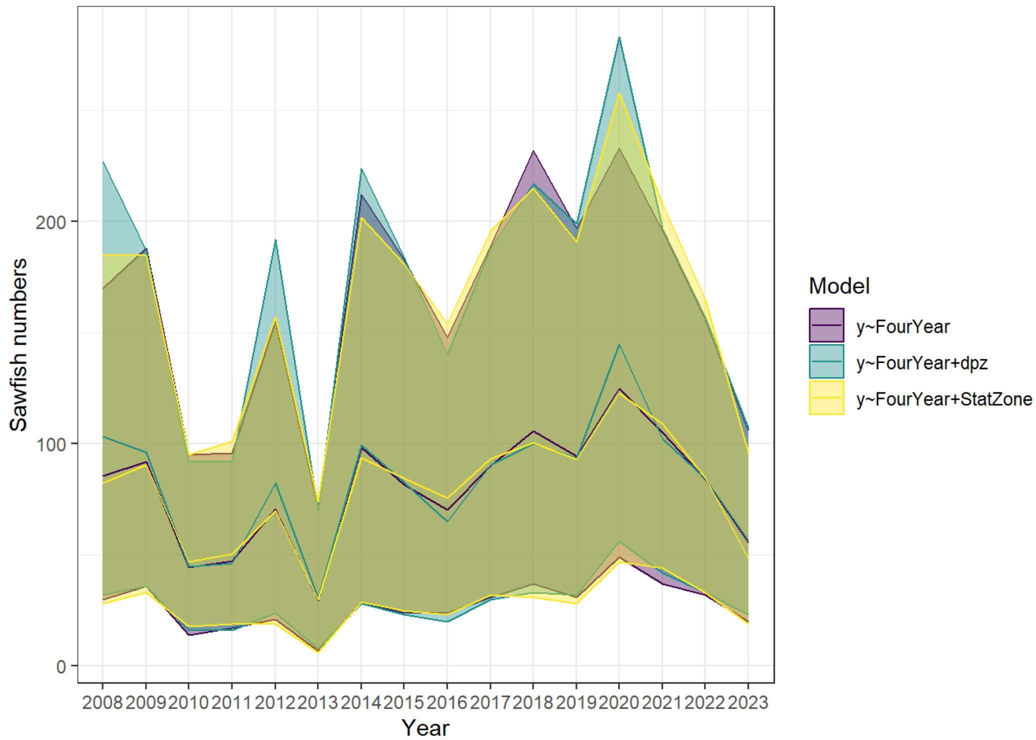


Figure 5. Pooled and unpooled ratio estimates for sawfish plus and minus one standard error.

(a) Gulf



(b) South Atlantic

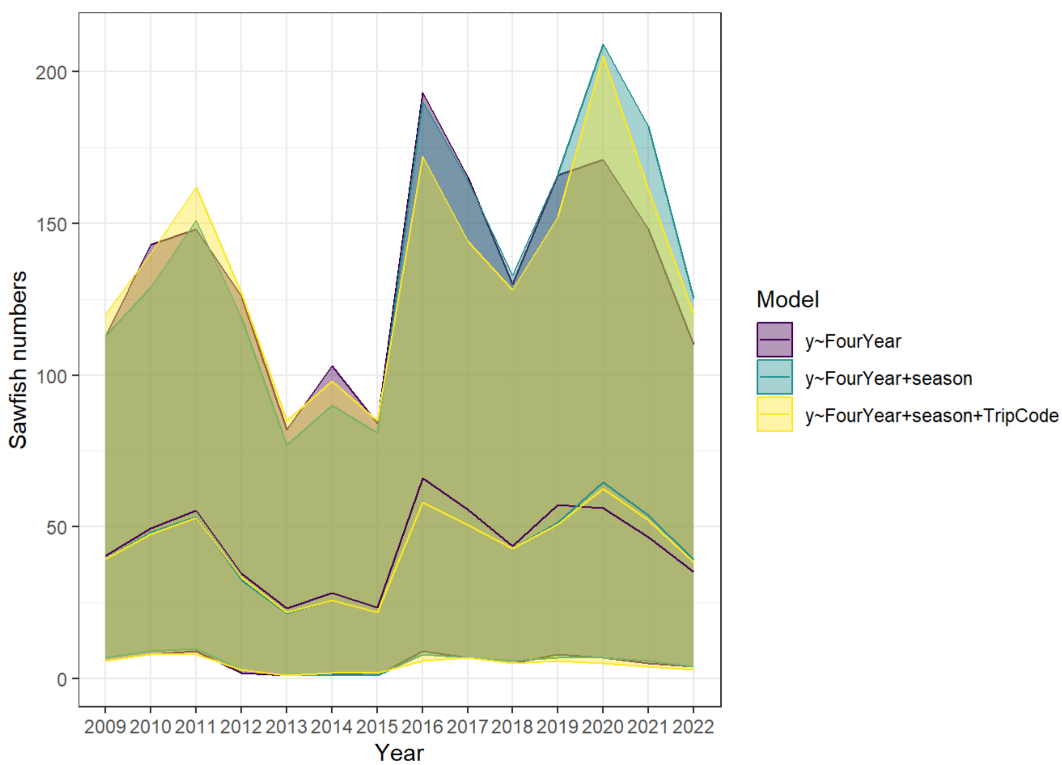
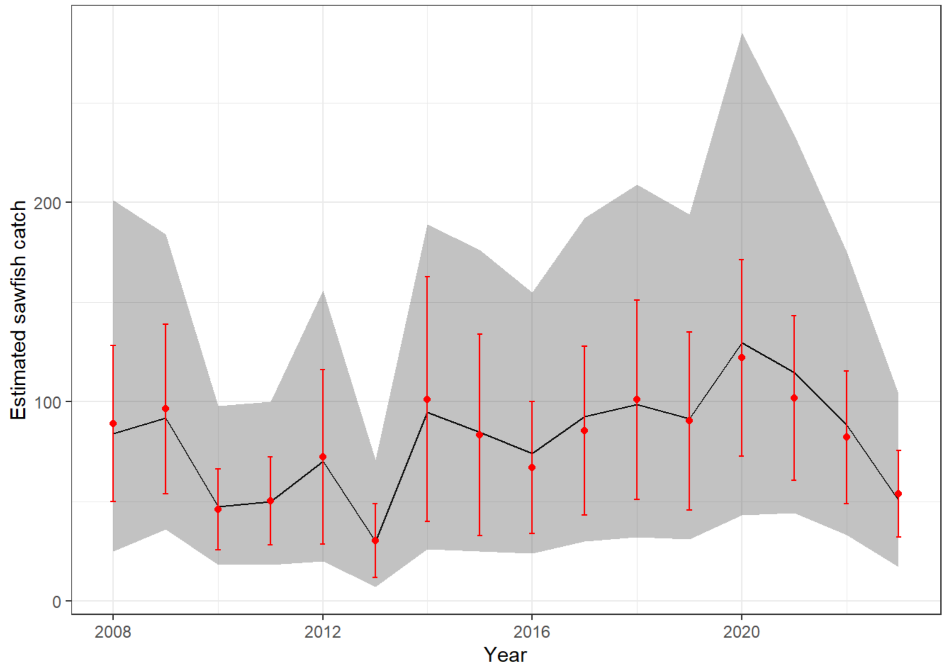


Figure 6. Model based estimates for sawfish, with 95% Bayesian credible intervals.

(a) Gulf



(b) South Atlantic

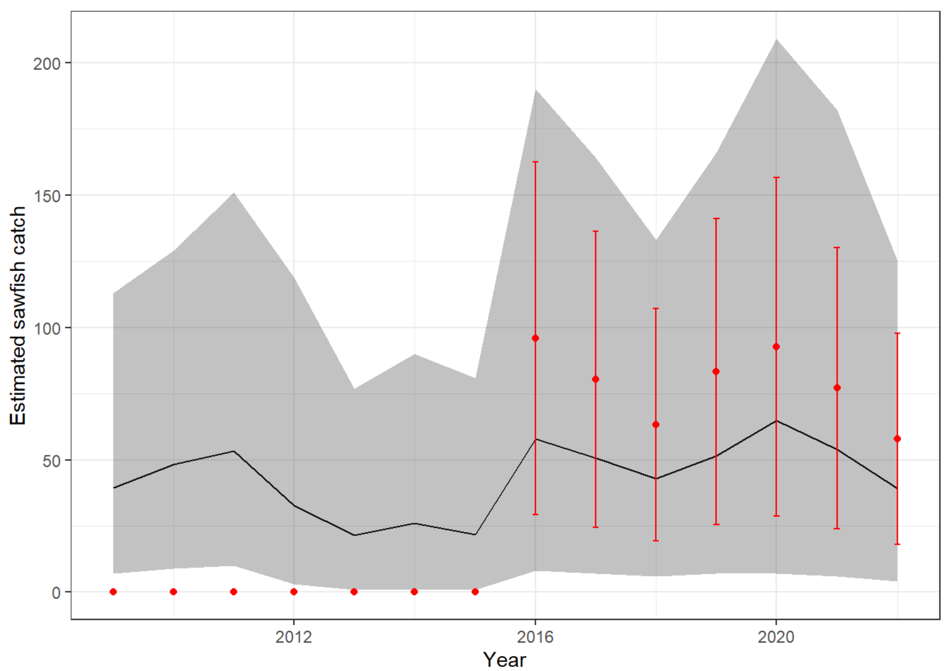


Figure 7. Best Bayesian model compared (line and shading of 95% C.I.) to pooled ratio estimate (Red confidence intervals are 2 standard errors) for sawfish. Best model includes FourYear and StatZone.

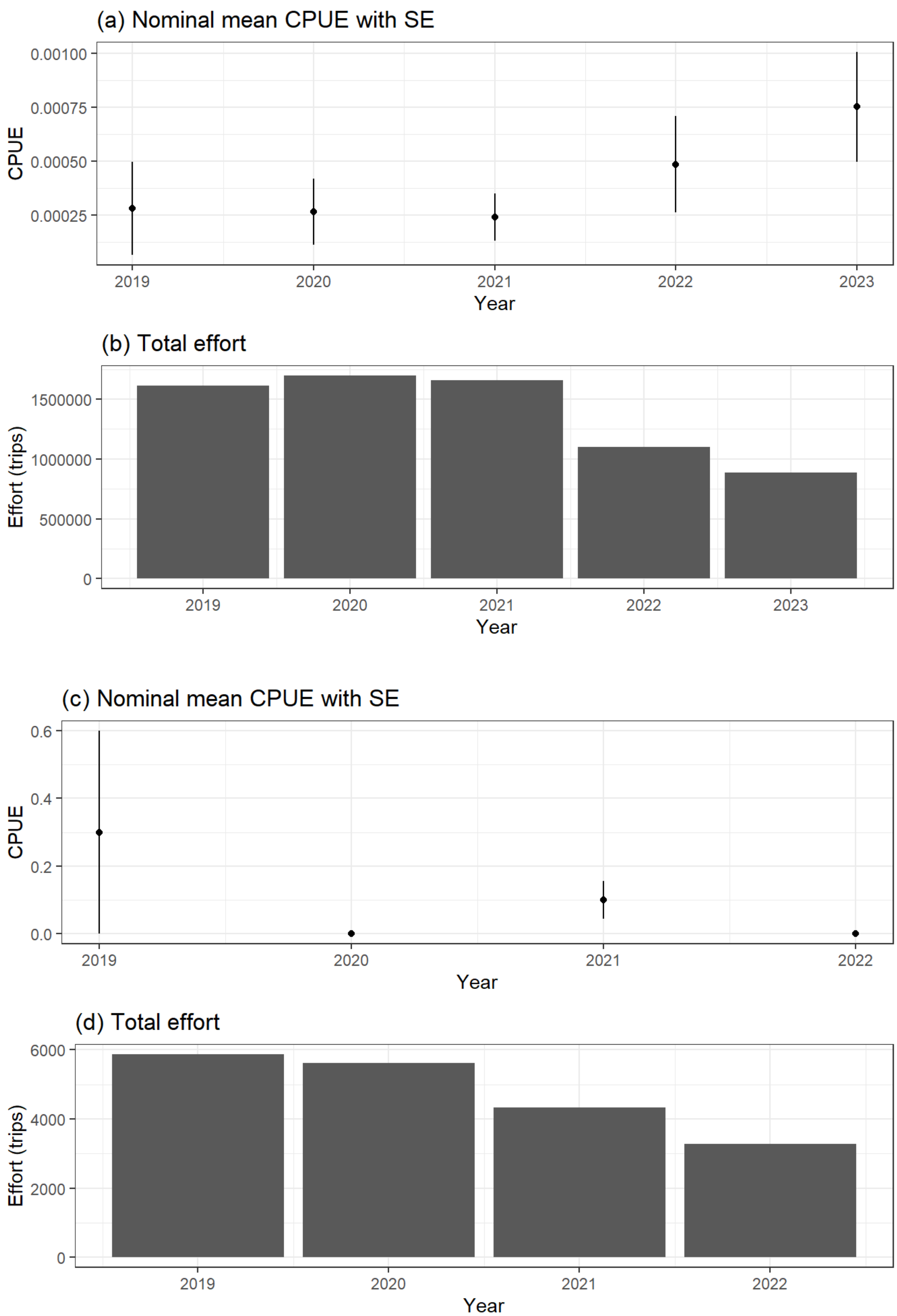
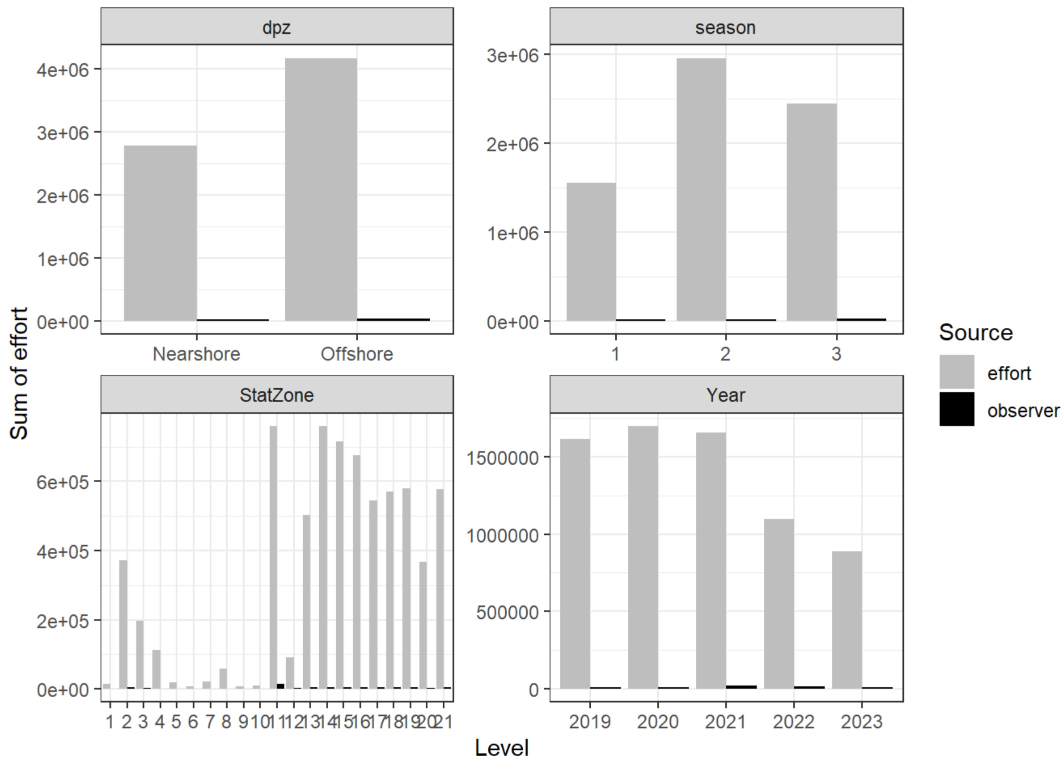


Figure 8. Gulf manta nominal CPUE with standard error (**a**), and total effort (**b**), and the same in the South Atlantic region (**c, d**).

(a) In Gulf StatZones 1-21 for manta



(b) In the South Atlantic StatZones 28-33 for manta

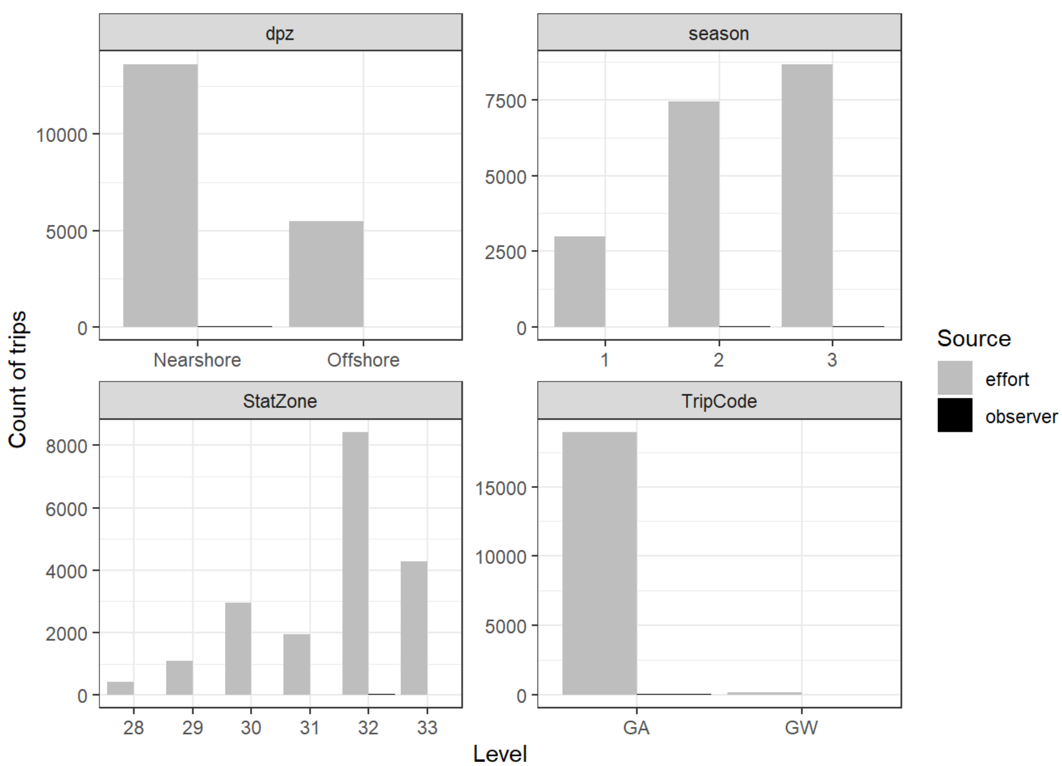
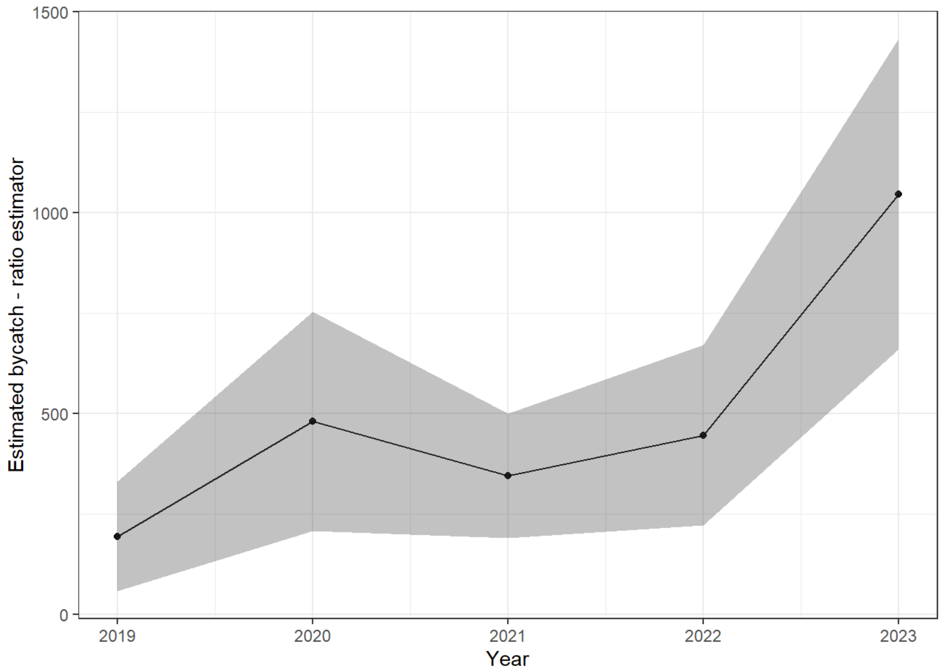


Figure 9. Observer coverage for the StatZones included for manta by factor variables.

(a) Gulf



(b) South Atlantic

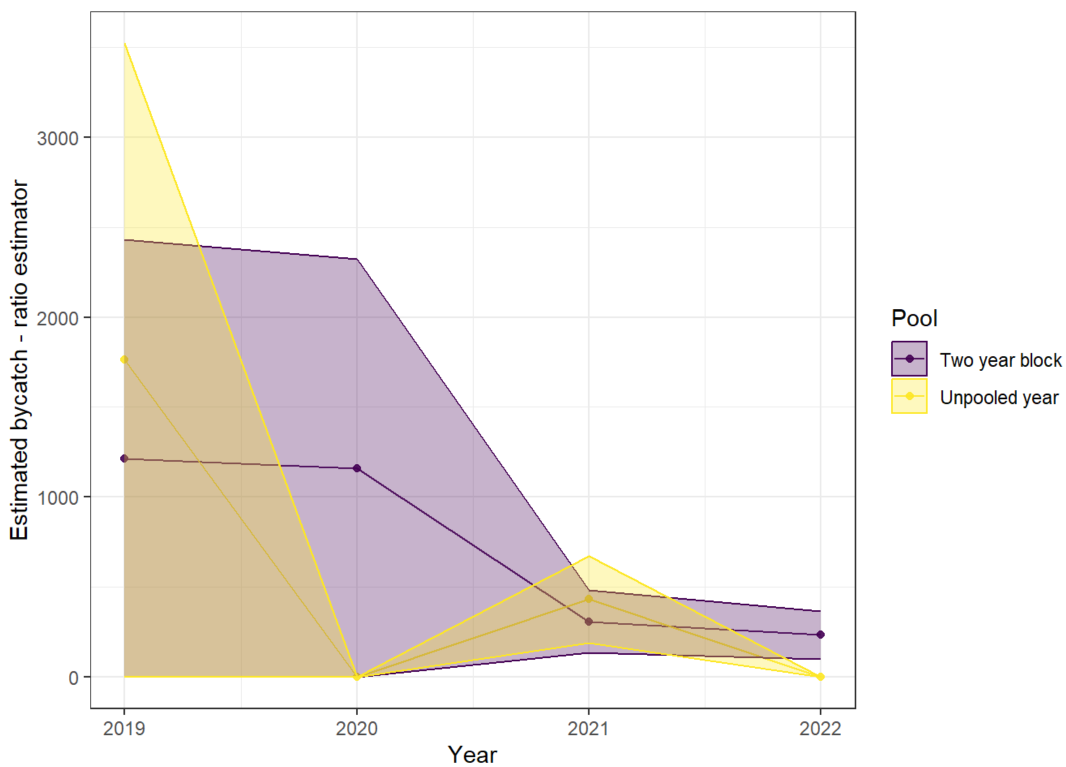
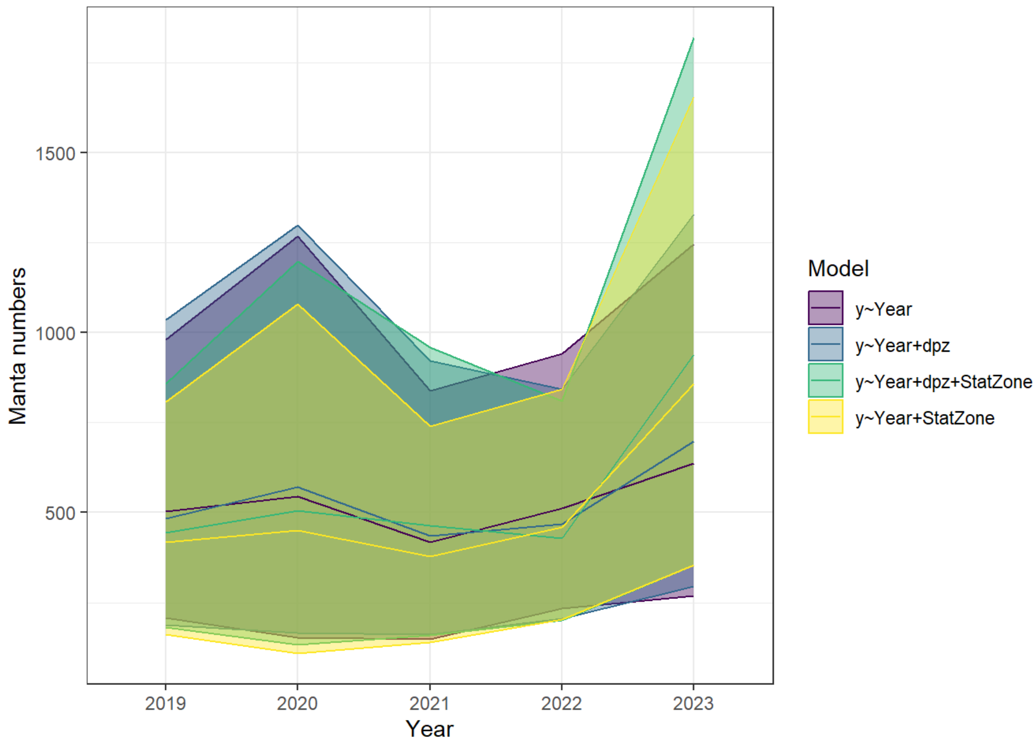


Figure 10. Pooled and unpooled ratio estimates for manta plus and minus one standard error. Pooling was not used for Gulf mantas.

(a) Gulf



(b) South Atlantic

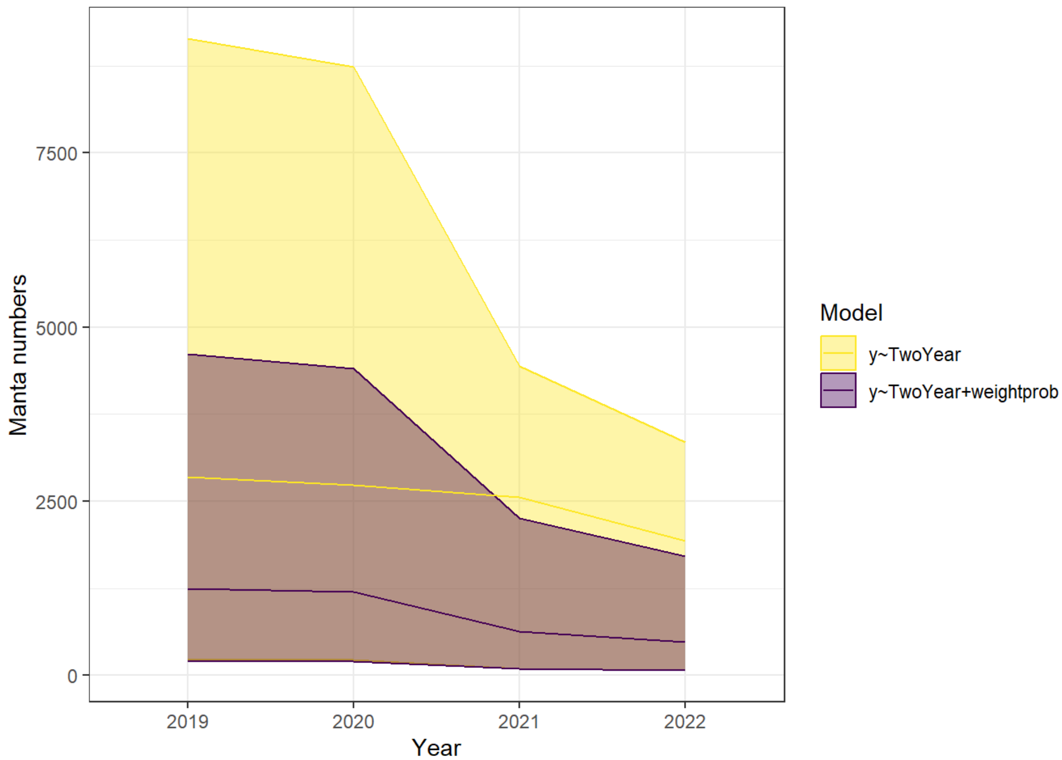
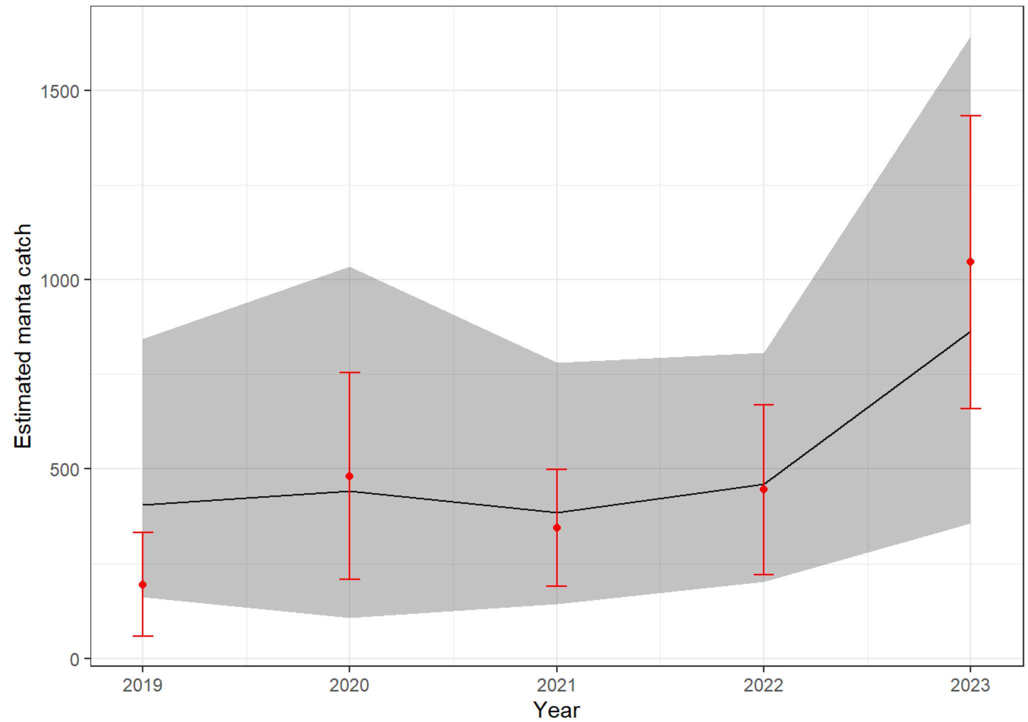


Figure 11. Model based estimates for manta, with 95% Bayesian credible intervals.

(a) Gulf



(b) South Atlantic

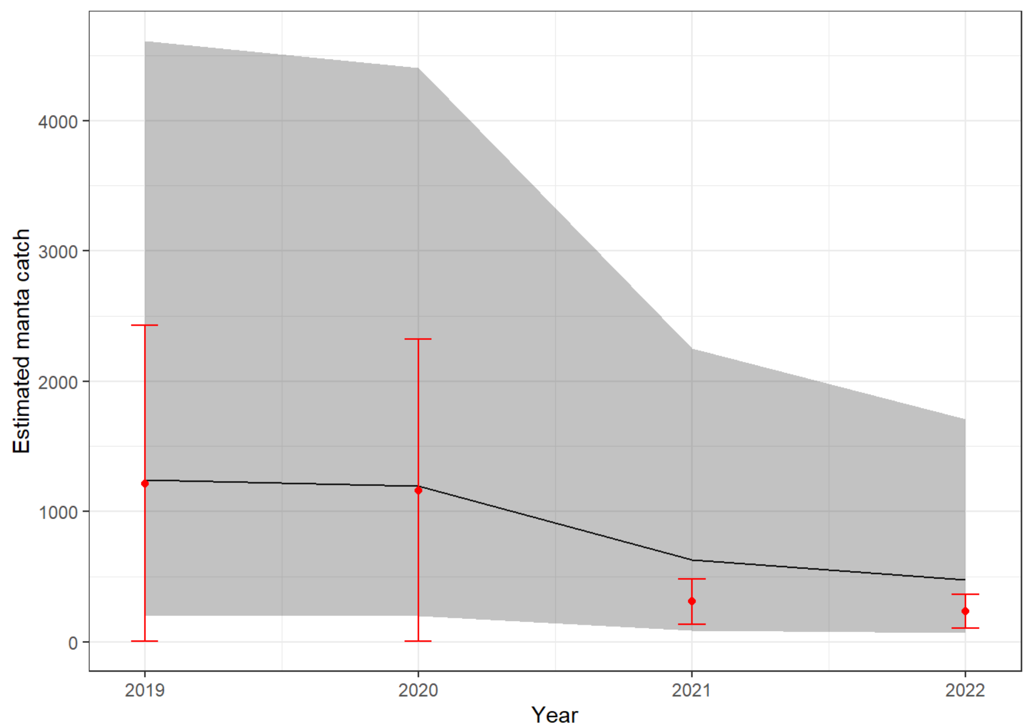
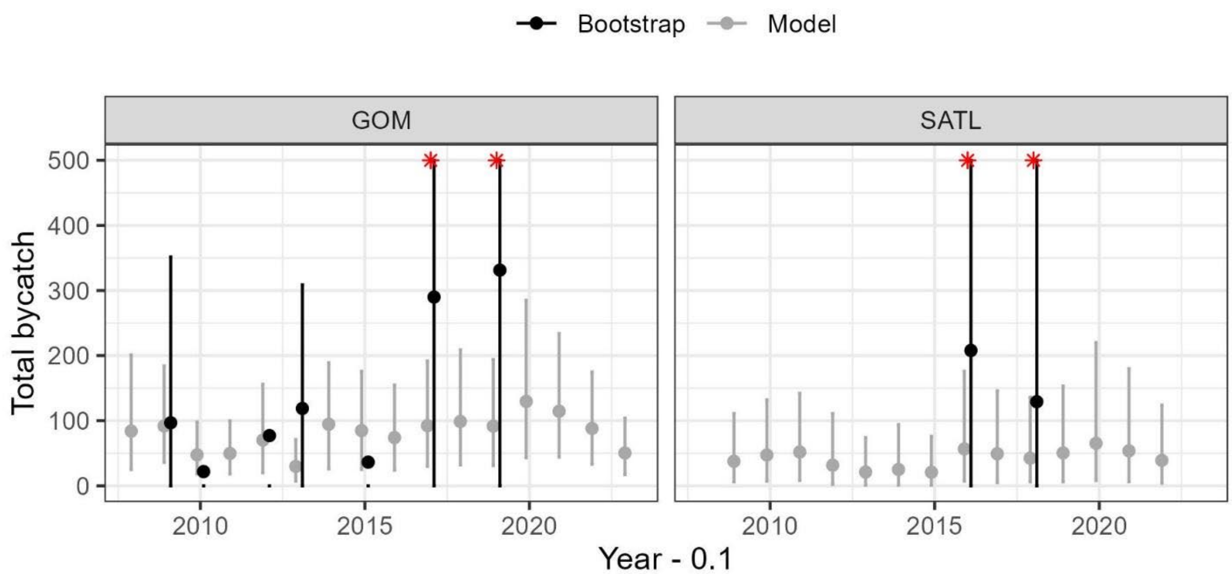


Figure 12. Best Bayesian model compared (line and shading of 95% C.I.) to ratio estimate (Red confidence intervals are two standard errors) for manta.

(a) Sawfish



(b) Manta

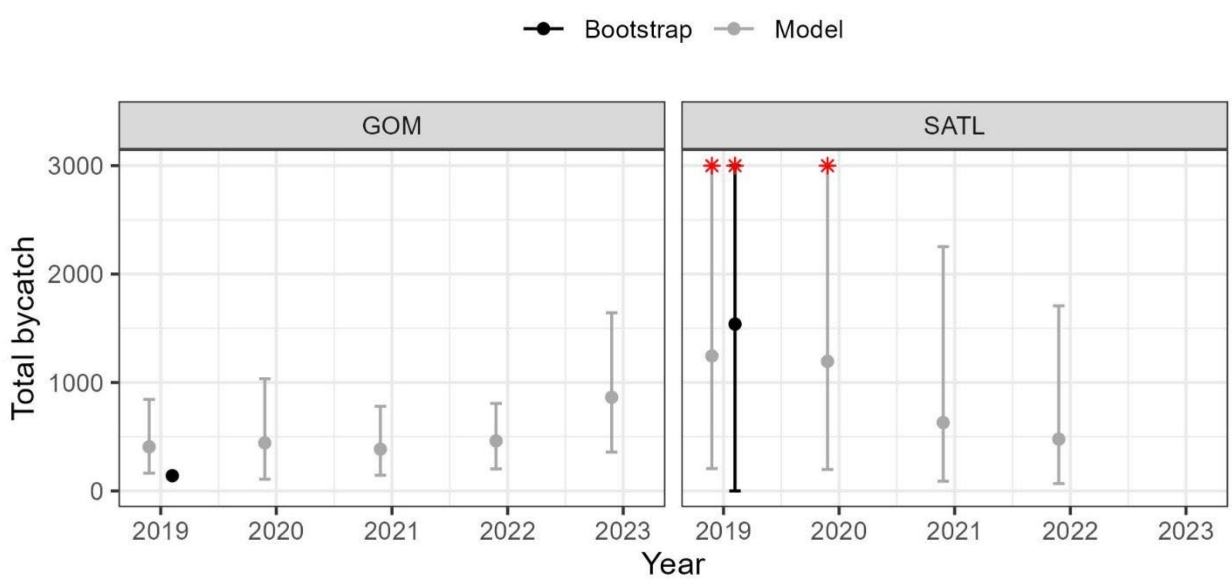


Figure 13. Comparison of Carlson (2020) bootstrapped unpooled ratio estimator means with 95% confidence intervals and best Bayesian model estimates from this analysis with 95% credible interval for Gulf and SATL sawfish (**a**) and manta rays (**b**). An asterisk (*) indicates that the upper bound of the interval was greater than 500 (for sawfish) or 3000 (for manta); see numbers in Table 7.

Appendix 1. Manta Encounter Probability analysis from Woods (2024)

The calculations of Woods (2024) for the probability of manta encounter and the bycatch model selection results are reproduced here. Both shrimp trawling effort (Figure A1, first row) and manta probability of presence (Figure A1, second row) are concentrated in shallower waters within each StatZone. Thus, multiplying these two distributions together (Figure A1, bottom row) gives high encounter probabilities in the shallow coastal zones in the north central Gulf and West of the Dry Tortugas. The weighted average encounter probability (Figure A2), varied across months in each StatZone. For the Gulf, the StatZones where manta bycatch was recorded (Zones 12, 13 and 14) had manta encounter probabilities not much different from other zones. However, in the South Atlantic, the few manta encounters were associated with high manta encounter probability.

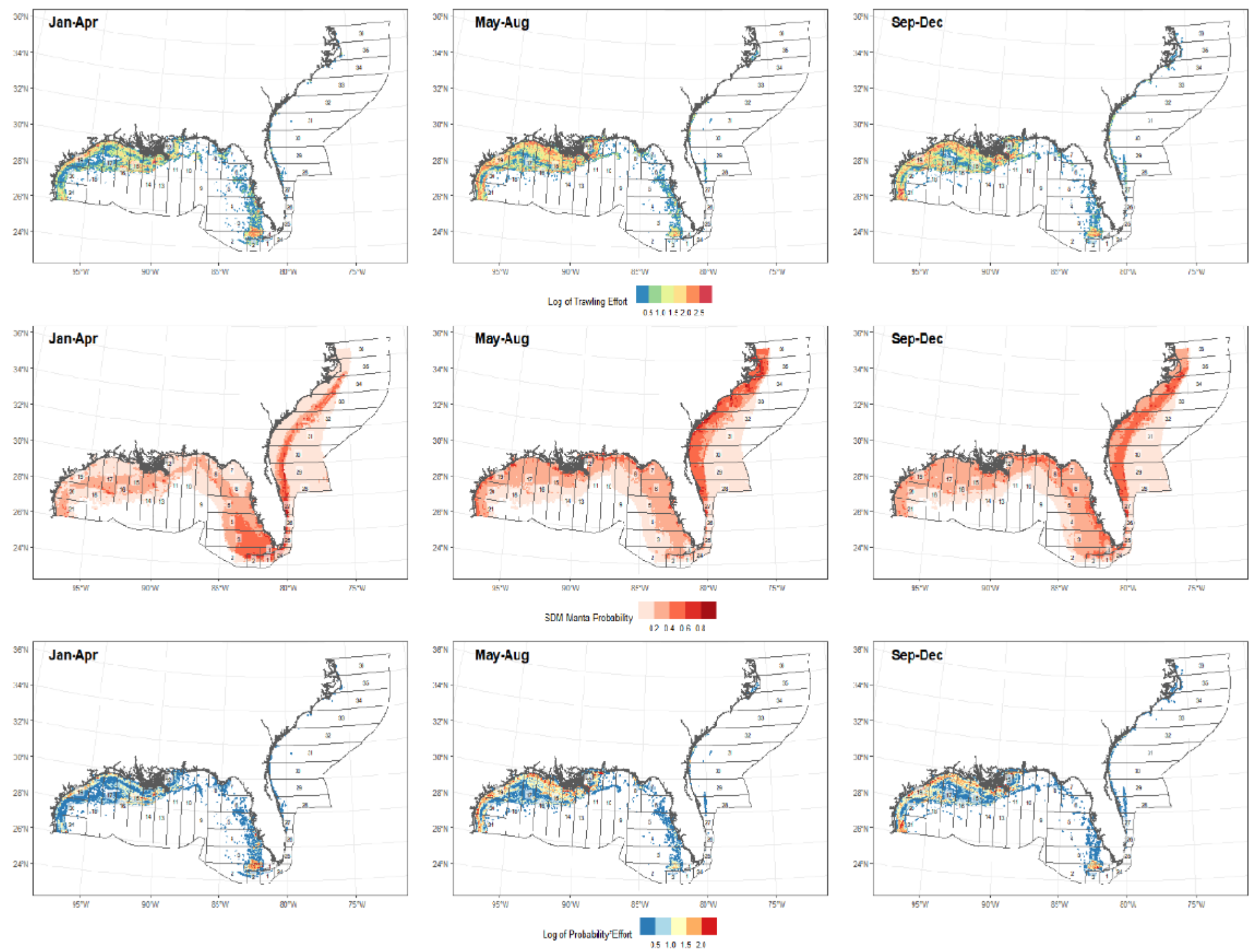


Figure A1-1. Shrimp trawling effort (top row), SDM manta probability (middle row, Farmer et al. 2022), and the product of effort and manta probability (bottom row) averaged over months in each season (reprinted from Woods, 2024).

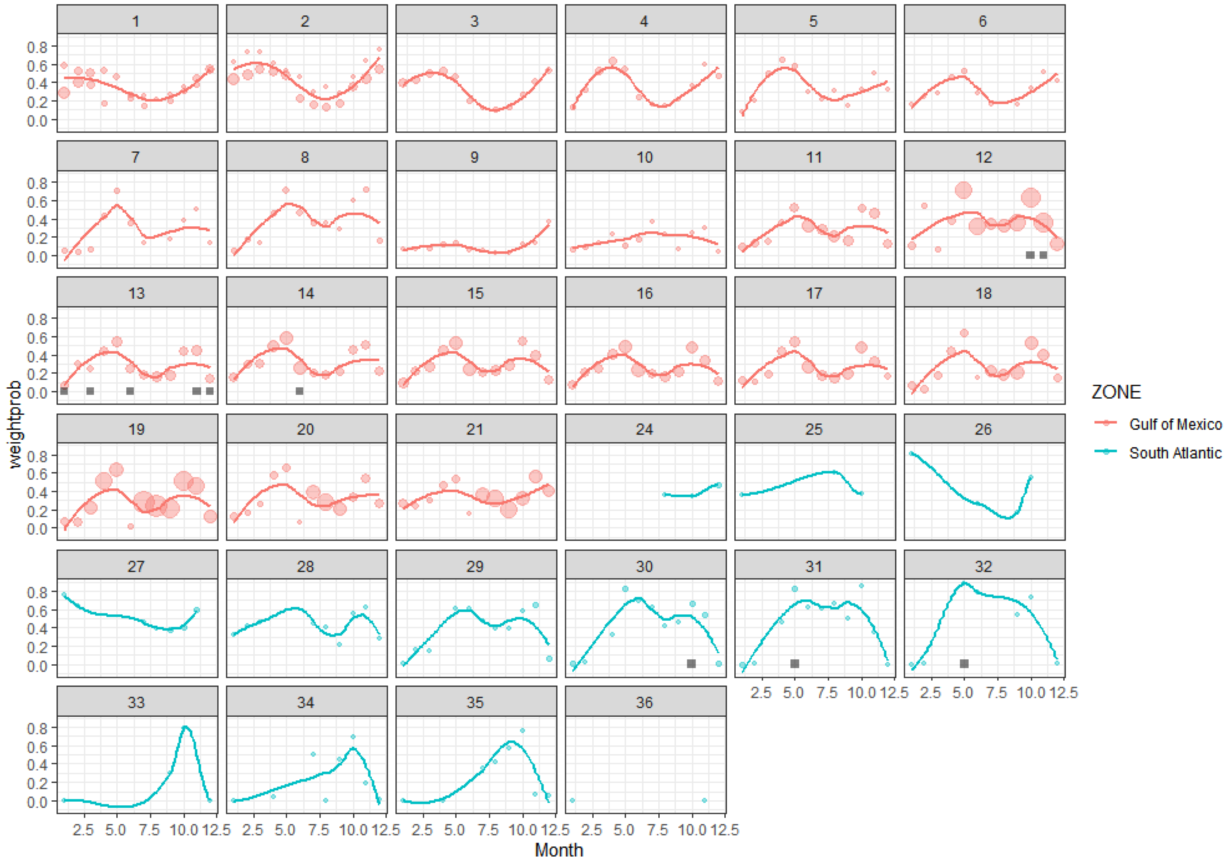


Figure A1-2. Manta encounter probability (weightprob) by month (x axis) and StatZone (panel). Size of the dot is proportional to shrimp trawl effort, and the line is smooth to show the pattern (reprinted from Woods, 2024). Manta catches in the observer data are indicated with a black square.

Appendix 2 – Comparison of models with weighted manta probability variable for estimates of giant manta ray bycatch for the Gulf and South Atlantic.

To compare the predictive skill of the weighted probability covariate derived from a species distribution model of giant manta ray in the Gulf and South Atlantic, we conducted model runs of the 2019-2002 time period with and without the weighted probability variable. Inclusion of this variable did not improve model predictive skill for Gulf mantas but was effective for South Atlantic mantas, as measured by AIC and BIC (Table A2-1).

Table A2-1. Information criteria for model selection. A "+" or a number indicates the variable is included.

(a) Top models by BIC for Gulf manta.

dpz	season	StatZone	Weight Prob	Two Year	AIC	BIC	df	logLik	deltaBIC	weight	deltaAIC
				+	261.4	283.2	3	-127.7	0.0	0.91	25.3
+				+	259.4	288.4	4	-125.7	5.2	0.07	23.3
			-2.40	+	261.6	290.5	4	-126.8	7.4	0.02	25.5
		+		+	238.6	405.1	23	-96.3	122.0	0.00	2.5
+		+		+	236.1	409.9	24	-94.1	126.7	0.00	0.0
		+	-1.67	+	239.7	413.5	24	-95.8	130.3	0.00	3.6
+		+	-1.48	+	237.4	418.4	25	-93.7	135.2	0.00	1.3
	+	+		+	240.1	421.1	25	-95.0	137.9	0.00	4.0
+	+	+		+	236.6	424.9	26	-92.3	141.7	0.00	0.5
	+	+	-0.79	+	241.9	430.2	26	-95.0	147.0	0.00	5.8
+	+	+	-0.80	+	238.4	433.9	27	-92.2	150.8	0.00	2.3

(b) WAIC and LOOIC for Gulf manta.

Model	waic	looic
y~TwoYear	46.35	47.62
y~TwoYear+weightprob	46.81	48.86
y~TwoYear+StatZone	0	0

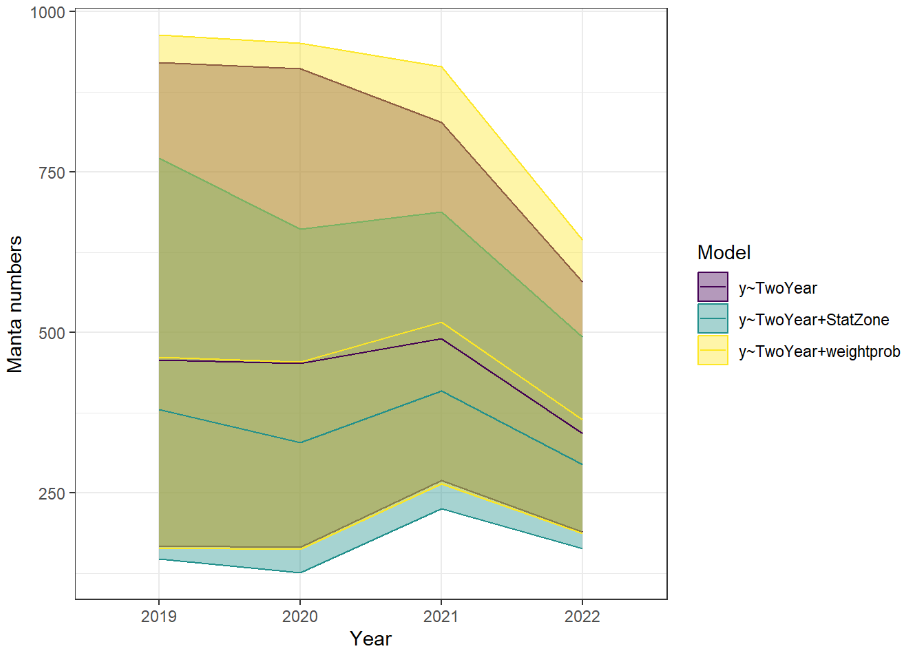
(c) Top models according to BIC for South Atlantic manta.

dpz	season	StatZone	Weight Prob	TwoYear	AIC	BIC	df	logLik	deltaBIC	weight	deltaAIC
			+	13.20	38.6	47.7	4	-15.3	0.0	0.8	0.0
+			+	12.80	40.5	51.8	5	-15.2	4.1	0.1	1.9
			+		47.6	54.4	3	-20.8	6.7	0.0	9.0
	+		+	14.90	42.3	55.9	6	-15.2	8.2	0.0	3.7
+			+		48.2	57.2	4	-20.1	9.6	0.0	9.6
+	+		+	14.42	44.2	60.0	7	-15.1	12.4	0.0	5.6
		+	+	21.07	45.3	65.6	9	-13.6	18.0	0.0	6.7
+		+	+	21.07	47.3	69.9	10	-13.6	22.2	0.0	8.7

(d) WAIC and LOOIC South Atlantic manta

Model	waic	looic
y~TwoYear	0.95	0.00
y~TwoYear+weightprob	0.00	0.02

(a)


1000
750
500
250
Manta numbers
2019
2020
2021
2022
Year
Model
y~TwoYear
y~TwoYear+StatZone
y~TwoYear+weightprob

(b)

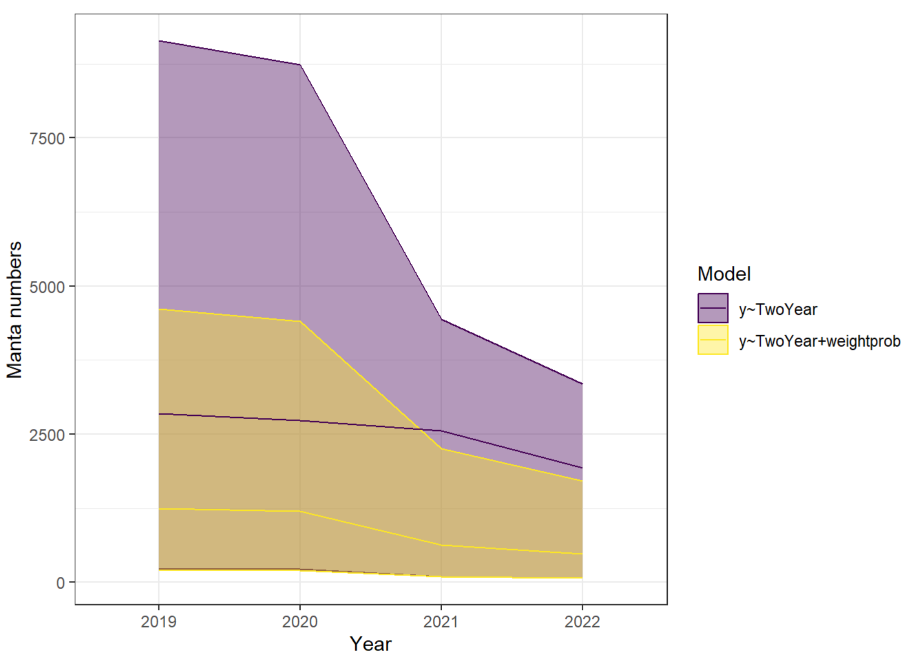

7500
5000
2500
0
Manta numbers
2019
2020
2021
2022
Year
Model
y~TwoYear
y~TwoYear+weightprob

Figure A2-1. Model-based estimates of manta ray bycatch using the weighted probability variable and monthly effort data for (**a**) the Gulf of America (formerly Gulf of Mexico) and the (**b**) South Atlantic.

Appendix 3. Diagnostic figures for Bayesian models

The Negative Binomial model adequately modeled the distribution of the data for the Gulf sawfish (Figure A3-1). The posteriors were only slightly narrower than the priors, particularly for the dispersion parameter, indicating that the data were not very information about the model parameters (Figure A3-2). However, the prior predictive simulations show that the priors allowed for a very wide distribution of the data, and the posterior predictive simulations were narrower, indicating that the data did inform the estimates, and the priors were not unduly restrictive. Similar patterns were seen for South Atlantic sawfish (Figure A3-3, A3-4), Gulf manta (Figure A3-5, A3-6), and South Atlantic manta (Figure A3-7, A3-8).

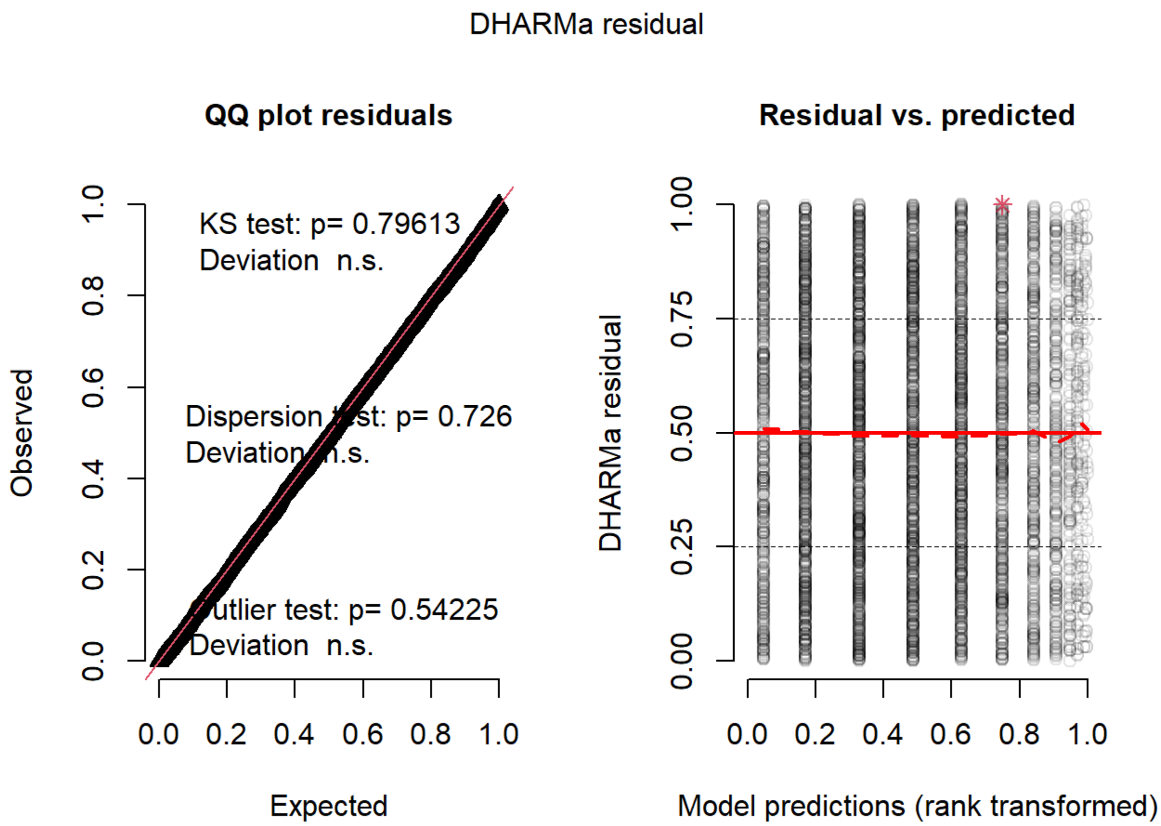
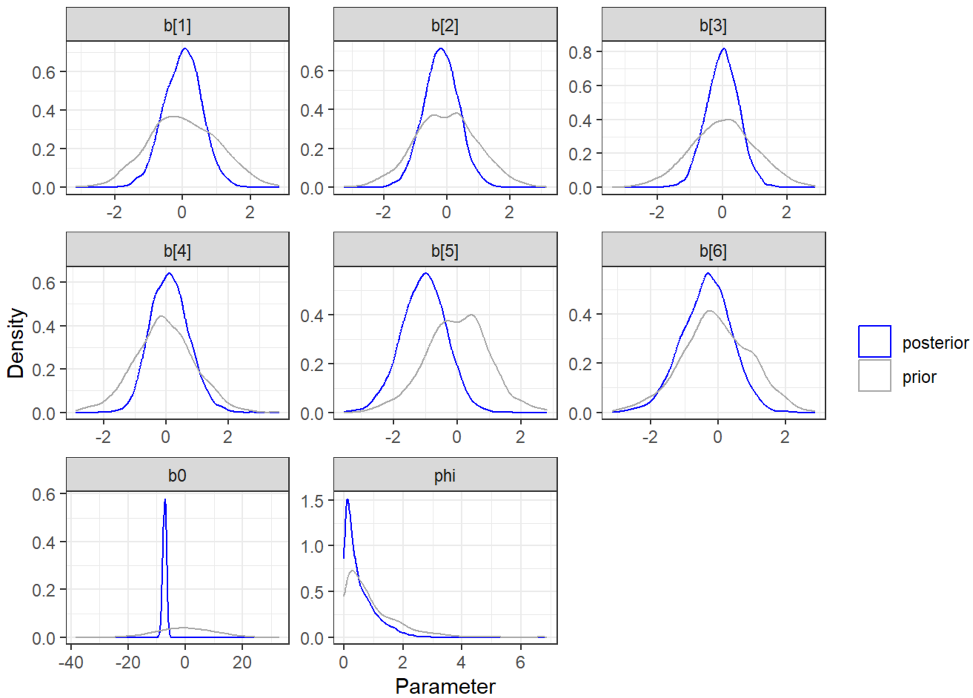


Figure A3-1. Quantile residuals for best Bayesian model (y ~ FourYear + StatZone) for Gulf sawfish.

(a)



(b)

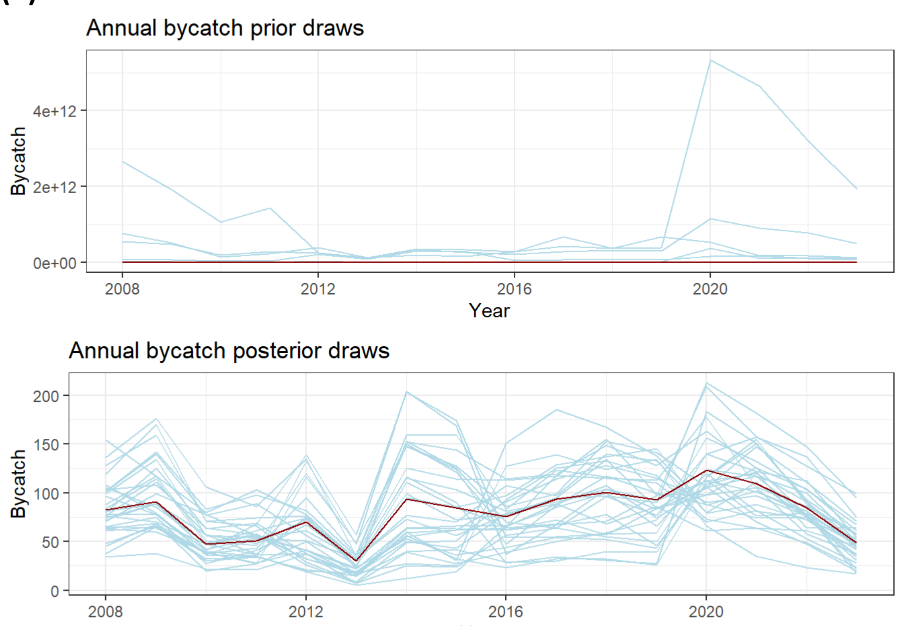


Figure A3-2. Prior and posterior densities of parameters (b0=reference level: FourYear 2008-2011 and StatZone 1, b[1]-b[3]=Difference from reference for FourYear 2012-2015, 2016-2019, and 2020-2023, b[4]-b[6]=difference from reference for StatZones 2-4) (**a**) and prior predictive simulations of bycatch (**b**) and posterior predictive simulations for best Bayesian model (y ~ FourYear+StatZone) for Gulf sawfish.

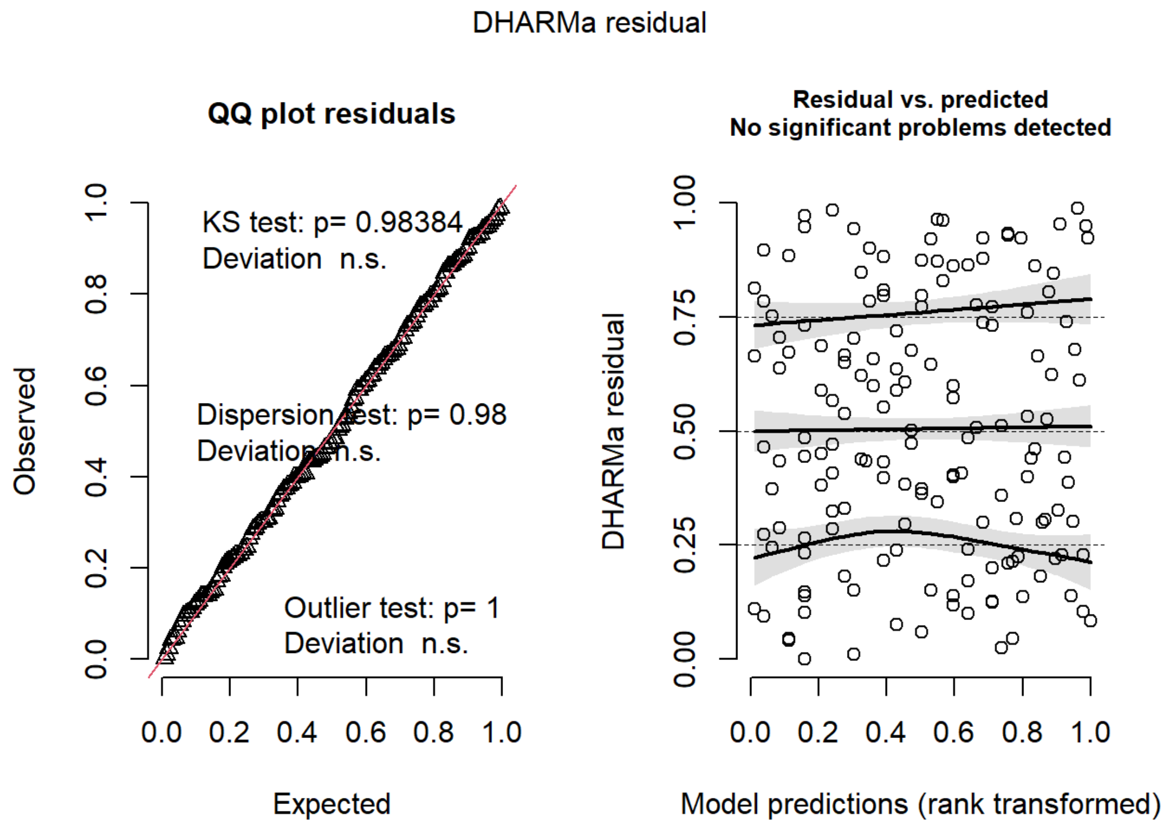


Figure A3-3. Quantile residuals for best Bayesian model (y ~ FourYear + season) for South Atlantic sawfish.

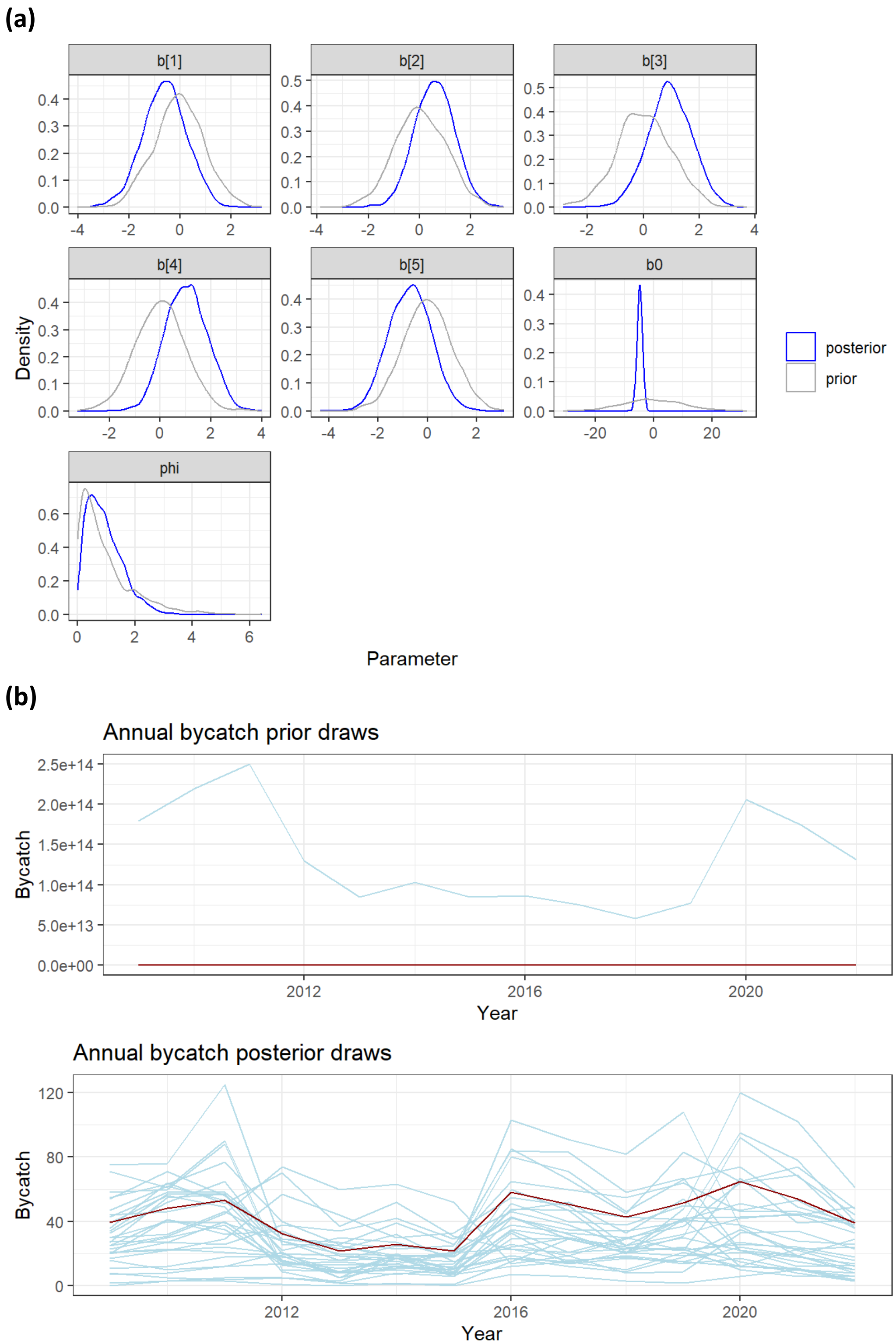


Figure A3-4. Prior and posterior densities of parameters (b0=reference level: FourYear 2008-2011 and Season 1, b[1]-b[3]=Difference from reference for FourYear 2012-2015, 2016-2019, and 2020-2023, b[4]-b[5] = difference from reference for seasons 2-3) (**a**) and prior and predictive simulations of bycatch (**b**) for best Bayesian model (y ~ FourYear+season) for South Atlantic sawfish.

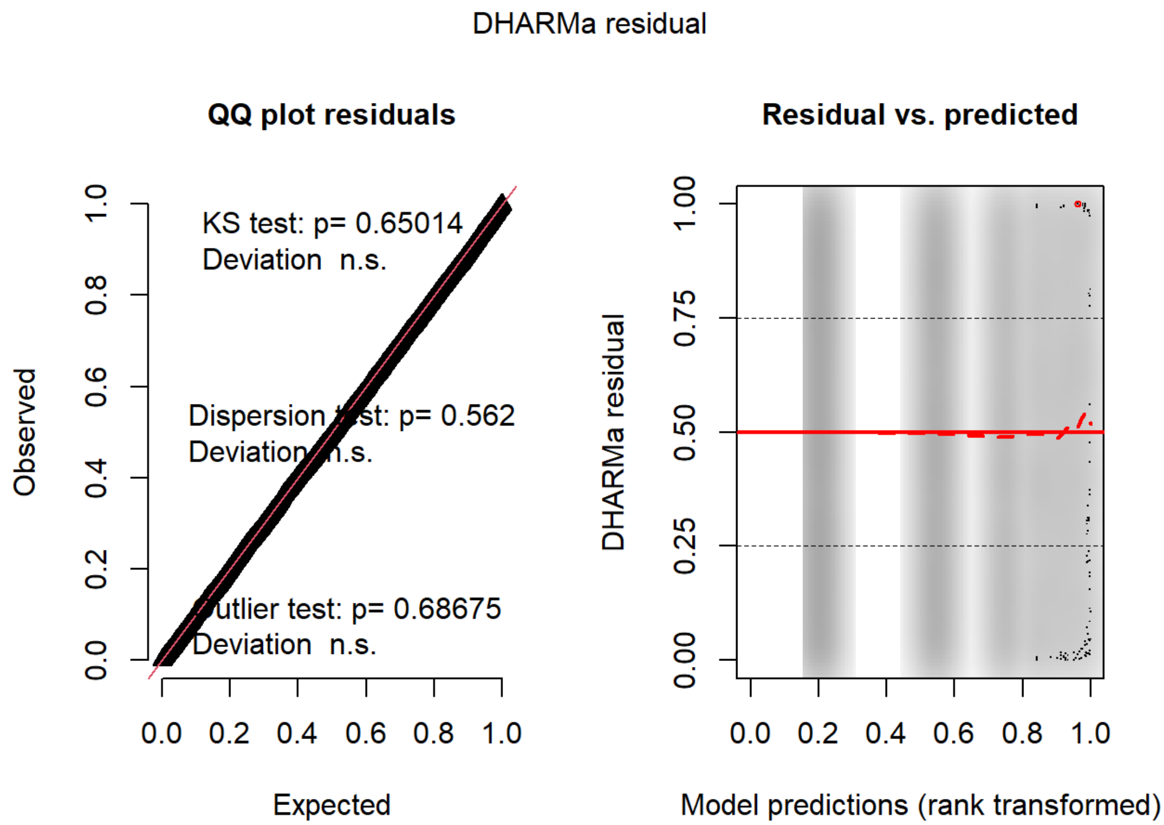
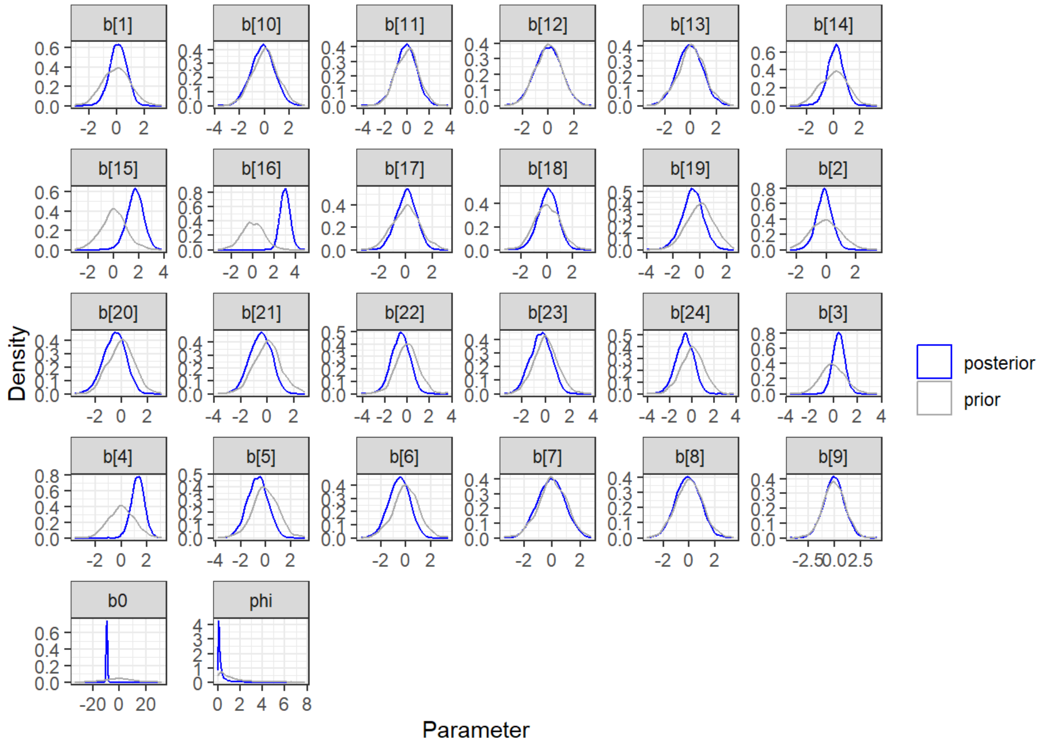


Figure A3-5. Quantile residuals for best Bayesian model (y ~ Year + StatZone) for Gulf manta.

(a)



(b)

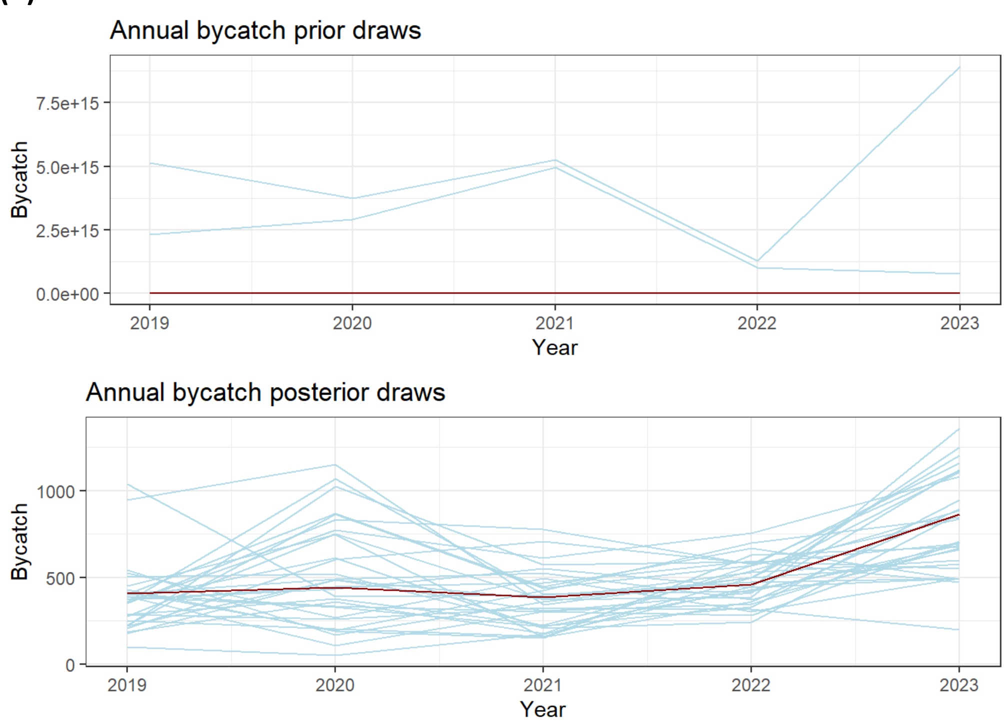


Figure A3-6. Prior and posterior densities of parameters (b0=reference level: Year 2019 and StatZone 1, b[1]-b[4]=Difference from reference for Years 2012 to 2023, b[5]-b[24] =

difference from reference for StatZones 2-21) (**a**) and prior and posterior predictive simulations of bycatch (**b**) for best Bayesian model (y ~ Year+StatZone) for Gulf manta.

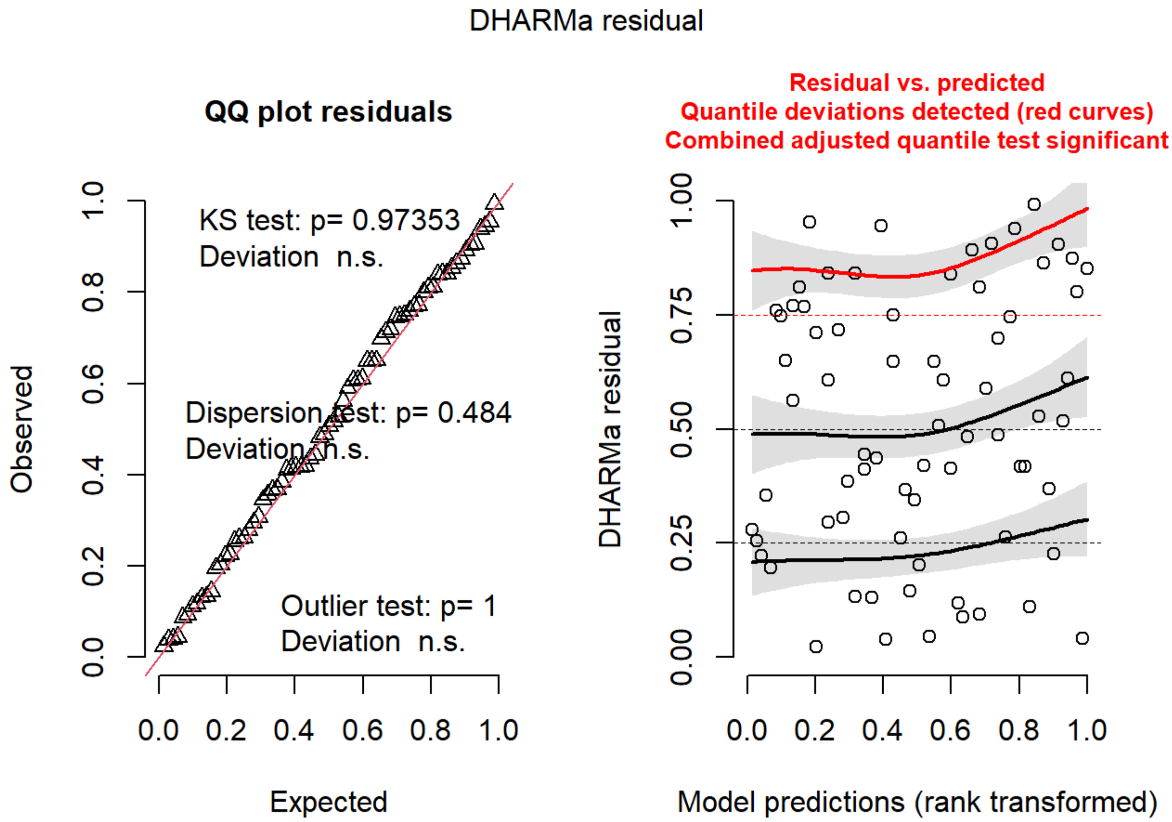


Figure A3-7. Quantile residuals for best Bayesian model (y ~ TwoYear + weightprob) for South Atlantic manta.

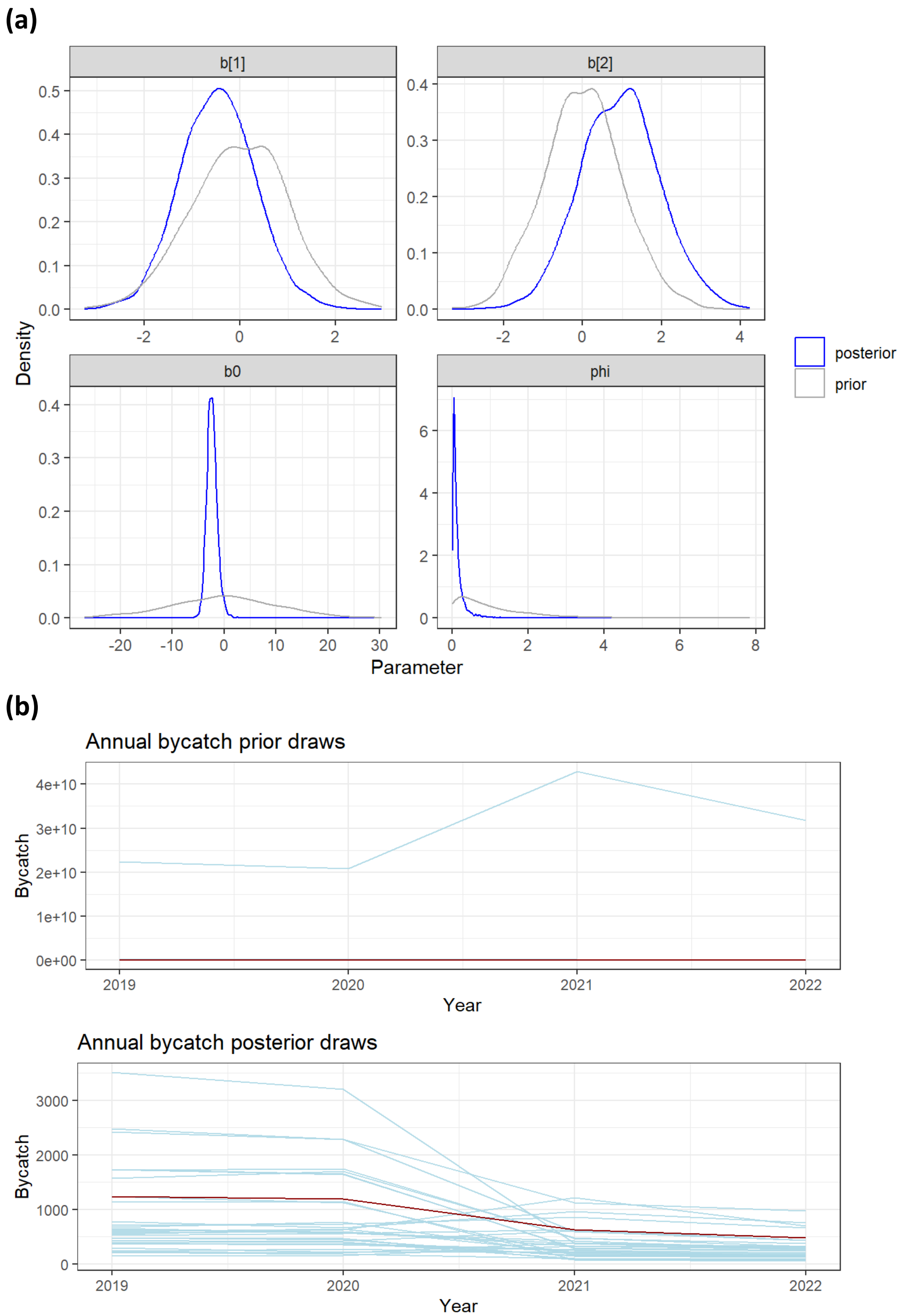


Figure A3-8. Prior and posterior densities of parameters (b0=intercept in year 2019-2020, b[1]=difference in intercept fo years 2021-2022, b[2]=slope with weightprob) (**a**) and prior and posterior predictive simulations of bycatch (**b**) for best Bayesian model (y ~ TwoYear + weightprob) for South Atlantic manta.