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Introduction

Project Overview

This project was conducted to identify factors contributing to sea turtle bycatch in the commercial reef fish bottom longline (BLL) fishery operating in the Gulf of Mexico (GOM), and identify opportunities for conservation measures that could be implemented through future restoration actions. The primary sea turtle species observed as bycatch in this fishery is loggerhead sea turtles (*Caretta caretta*). We conducted a full assessment of the best available data to identify factors, such as fishing gear and fishing practices, involved in the bycatch of sea turtles. We have summarized the findings in this report and have provided information helpful to inform and develop conservation strategies and options for future restoration actions. Funding for this project was provided by the Deepwater Horizon Oil Spill Open Ocean Trustee Implementation Group through selection of the project in the Open Ocean Trustee Implementation Group Restoration Plan #2 and Environmental Assessment as a Sea Turtle Restoration Project.

History of sea turtle bycatch in the Gulf reef fish BLL fishery

The Gulf of Mexico commercial reef fish fishery consists of approximately 800-900 Federally permitted vessels. Primary gears used include bottom longline, vertical line and rod and reel. The predominant target species are groupers, *Epinephelus* spp., and snappers, *Lutjanus* spp. (Scott-Denton et al. 2010)

Bottom longliners off the coast of Florida generally target red grouper, *Epinephelus morio*, in shallow waters, and in deeper waters yellowedge grouper, *E. flavolimbatus*, tilefish (family Malacanthidae), and sharks (family Carcharhinidae). Annually, an average of 64 to 65 vessels use longline gear to land reef fish Gulf-wide. These vessels include longline vessels that operate outside of the eastern Gulf and may use pelagic longline gear, such that they are not required to have an endorsement. These vessels represent approximately 12% of the vessels that annually land reef fish. Annual landings by these longline vessels, however, account for almost a third of annual landings of reef fish by weight and dockside revenue in federal waters (https://repository.library.noaa.gov/view/noaa/27140). In 2006, NOAA's Southeast Fisheries Science Center Observer Program implemented a mandatory observer program to characterize the commercial reef fishery in the Gulf of Mexico (Scott-Denton et al. 2011). The program included protocol sampling modification, randomized vessel selection, and observer deployment through mandatory efforts for the commercial reef fish fishery (Scott-Denton et al., 2011). Through the program, observers were placed on reef fish vessels operating throughout the Gulf of Mexico through randomized selection stratified by season, gear, and region. Proportional sampling effort, based on data from the Coastal Fishery Logbook Program (CFLP), among seasons and gears in the eastern and western Gulf of Mexico was used for vessel selection stratification purposes using annual updated effort data. Observer coverage levels were directed toward regions and gear strata with higher levels of fishing effort, while continuing to sample strata with lower fishing effort (Scott-Denton et al. 2010). As a result of the documented sea turtle interactions during the initial stage of observer coverage between 2006-2009, a seasonal area closure to limit sea turtle bycatch was enacted in 2009 which prohibited BLL gear east of Cape San Blas, Florida. This limited the total number of hooks allowed on board total and those rigged for fishing (1000 and 750, respectively), and reduced vessel participation in the fishery through an endorsement system (Final Rule, 75 FR 21512. Effective May 26, 2010).

Previous research suggests loggerhead sea turtles are present year-round in or near areas open to fishing, despite the seasonal area closure (Hardy et al. 2014). NOAA's sea turtle program identified the need to further analyze existing NOAA Fisheries observer program data, resulting in this Deepwater Horizon Sea Turtle Restoration Project. The goal of the analysis was to model sea turtle interactions in the reef fish BLL fishery in the eastern GOM and conduct monthly spatial predictions of the probability of occurrence of sea turtle bycatch. We used data recorded on observed at-vessel condition of bycaught sea turtles to analyze factors associated with at-vessel condition, and analyses were designed to identify potential factors related to bycatch that could be addressed through future restoration.

Methods

Two analyses were conducted using one data set, the NOAA Fisheries Southeast Fisheries Science Center (SEFSC) Observer Program reef BLL data set (2006 to 2021). The first analysis used statistical models and spatial predictions to determine what environmental factors and fishery components, if any, drive sea turtle interactions in the reef BLL fishery using statistical models and spatial predictions. Because of the limited number of sea turtle interactions compared with the number of fishing sets made, analysis for statistical models of fishery interactions with sea turtles was restricted to fishing sets made in the eastern Gulf of Mexico to limit the number of zeros in the model (Figure 1). The second, separate analysis was focused on at-vessel condition of bycaught sea turtles using a different set of statistical models and included all interactions with sufficient information. Sample sizes included in each analysis are presented in Table 1, as some interactions had to be omitted in one or both analyses due to missing data.

Fishery component covariates

A number of factors were selected for analysis that potentially influence bycatch of sea turtles based on their assumed importance in other studies and our own hypotheses (Table 2). Fishery information included in predictive models of sea turtle interactions included month, time of day (TOD, 6-hour bins), hook offset (straight vs offset), bait type, fishing depth, and effort calculated as hook hours (soak time / number of hooks). Hook size was not included in the analysis because 84% of observed sea turtle interactions occurred on 13/0 and 14/0 circle hooks, which were the dominant hook sizes during the study period and often used together in mixed combinations on a given longline set. Sets using J-hooks, which are no longer used in the fishery and accounted for fewer than 5 sets, or hook sizes outside of the range which captured sea turtles were omitted from analysis to increase statistical power due to the low rate of interaction occurrence. This included 236 of 13,780 longline sets (1.7%) which did not capture any sea turtles.

Multiple bait types are typically used on a single BLL set, which makes analysis of bait type as a covariate of bycatch difficult. Bait was analyzed as a category identifying the mixture of baits: 'squid mix' for any sets using squid bait in combination with bony fish or elasmobranch baits, 'elasmo mix' for any sets that included elasmobranch baits without squid, and 'fish mix' for sets using only a mixture of bony fish bait types. Sets missing bait information were excluded from analysis, which included 1,007 of the 13,544 sets (7.4%).

Environmental covariates

Environmental covariates in the models included sea surface temperature (SST), chlorophyll-a, bathymetry, and lunar phase. Satellite data products were downloaded from the

ERDDAP platform and matched to each set by date and geographic coordinates. SST was extracted from NOAA's National Centers for Environmental Information Optimum Interpolation satellite data product, which are daily values at a 0.25° resolution. Chlorophyll-a (Chla) was extracted from the ESA CCI Ocean Colour Product, which are eight-day composites at a 0.04° resolution to address data bias due to weather conditions. Set fishing depth from the observer data was used in developing the models, and bathymetry information was extracted for spatial predictions from the NOAA ETOPO 2022 data set. Lunar phase was extracted from the *suncalc* package in R v. 4.0.3 (R Core Team 2020).

Modeling

A two-phase modeling approach using generalized additive models (GAMs) was used based off the PRiSM (highly migratory species predictive spatial modeling) framework used by Crear et al. (2021), which employs GAMs because they are able to handle nonlinear relationships with habitat data. A binomial distribution with sea turtle presence/absence as the response variable was used in the models. We used presence/absence due to the extremely low occurrence of multiple sea turtle interactions on the same longline set. Model selection using Akaike information criterion (AIC) included two steps following Crear et al. (2021), in which environmental covariates were analyzed without fishery covariates in the first step, and environmental covariates identified in the best model were then reanalyzed with different combinations of fishery component covariates to develop the final model. All models were fit using the *mgcv* package in R (Wood 2011).

Using the final model, predictions (probability of sea turtle interaction) over the range of each covariate were made using marginal means (Searle et al. 1980, Crear et al. 2021) and estimates of uncertainty were generated from 1000 bootstrapped samples (Efron and Tibshirani 1993, Crear et al. 2021). The final model was validated using a randomized area-under-curve (AUC) metric in which two-thirds of the dataset were used to train the model and the remaining one-third of the data were used as a test data set. This process was repeated 30 times and a mean AUC value was generated. AUC values are scaled from 0 to 1, in which a value of 0.5 indicates the prediction is no different than random and a value of 1 indicates perfect model performance (Fielding and Bell 1997, Crear et al. 2021).

Spatial analysis and monthly predictions

Sea turtle fishery interactions were predicted for each month using three-year means of historical environmental conditions within a spatial area defined by a 99.5% minimum convex polygon (MCP) of the fishery domain in the eastern GOM (Figure 2). SST and chlorophyll-a were averaged for each month from 2019 to 2021 at each spatial grid cell to best represent near-future conditions. The resolution of environmental covariates was rescaled to covariate with the coarsest resolution (SST, 0.25°). Fishery-interaction models were then applied to the respective environmental conditions of each month, which generated a monthly distribution of predictions of probability of fishery interaction ranging from 0 to 1.

Logistic analysis of at-vessel mortality

Factors affecting at-vessel condition of captured sea turtles were analyzed using multiple logistic regression. Fishery and environmental covariates include time of day, SST, hook offset, bait type, soak time, and depth. Bait type in this analysis was not noted as a mix, but was the actual bait type recorded by the observer. All observed sea turtle interactions with sufficient data and information on at-vessel capture condition were included in the analysis (n = 33).

Calculation of observer coverage based on logbook data

To estimate the amount of observer coverage across the fleet in the GOM and better understand how the observer data sets represent the broader fishery, proportional observer coverage was estimated using effort data from the CFLP. Data was requested from the NOAA Fisheries-SEFSC-Fisheries Statistics Division for Coastal Logbook effort data for bottom longline trips from 2005-2021, GOM, targeting snappers and groupers, which was calculated as trips where 2/3 or greater of the total catch was snapper grouper species. These data were pulled from the CFLP, using the standard coastal extraction in the data warehouse (Appendix 1). The total numbers of reef fish BLL trips recorded in logbook records were provided for the eastern GOM, and trips were summarized by statistical zone and year. Estimated percent observer coverage was then calculated using the number of observed trips as a proportion of the total trips from the logbook data in the eastern GOM by year.

Results

Occurrence rate of observed sea turtle bycatch in the GOM reef fish BLL fishery from 2006 to 2021 was less than 0.3%. There were 34 observed interactions in total, all of which occurred with loggerhead sea turtles (*Caretta caretta*). The number of interactions per year declined over the study period (Figure 3). The final model of sea turtle interactions included month, depth, SST, chlorophyll-a, and log effort (hook hours) as an offset variable. Deviance explained by the model was 19.5%, with an r-squared of 0.07. Mean AUC was acceptable at 0.7.

Predicted probability of occurrence values for each covariate calculated using marginal means are presented in Figure 4. Predictive maps of monthly spatial simulations are presented in Figures 5 and 6.

There were 33 interaction events with an observed at-vessel condition (Table 1). The analysis indicated that approximately 24% of turtles were dead or comatose when first assessed by the observer. No covariates had a statistically significant relationship with at-vessel condition of captured sea turtles in the multiple logistic regression analysis, and the model failed to detect a soak time effect on at-vessel condition (Figure 7). There was a relatively high proportion of interactions (24%) with squid bait, but the considerable amount of interactions with unknown bait types (~45%) made determination of the effect of bait type on at-vessel condition difficult (Figure 8).

Observer coverage of the reef fish bottom longline fishery varied by year. Estimated observer coverage on reef fish BLL trips in the eastern GOM from 2006 to 2021 averaged 4.3%, with a range of 0.0% to 13.6% (Table 3).

Discussion

Model results emphasized the relationship of depth with sea turtle interactions in the Gulf reef fish BLL fishery, as well as the increased probability of interaction in the summer season, especially June (Figure 3d). A regulatory seasonal spatial area closure was enacted in 2009 to mitigate the increased bycatch probability in the summer in shallow waters shoreward of the 50-fathom contour in the eastern GOM. While there were statistically significant relationships between sea turtle interactions and both SST and chlorophyll-a, the effects of both variables were extremely weak, and predicted probability of sea turtle occurrence was relatively low in most cases.

The analyses did not find a statistically significant relationship between fishing practices and sea turtle interaction probability or at-vessel condition; however, data were very limited. An occurrence rate of less than 0.3% reduces statistical power, and many interactions were missing data such as specific bait type. In the multiple logistic regression, a sample size of 33 interactions which included five mortalities may have limited statistical power. Additionally, missing data such as bait type, combined with low sample sizes, may have made statistical detection of factors affecting at-vessel condition impossible.

Conclusions

Generally, there were few observed interactions of loggerhead sea turtles in the reef fish BLL fishery operating in the Gulf of Mexico from 2006 to 2021. Monthly predicted probabilities of sea turtle occurrence were low in most months with exception to the summer season (Jun – Aug), and fishing depth was strongly correlated with sea turtle interaction probability. Due to low occurrence rate of sea turtles in the observer data, continued or even increased observer coverage may not yield greater statistical power to detect relationships of fishery components and sea turtle bycatch in the reef fish BLL fishery in the eastern GOM. Estimation of the required sample size to observe a sea turtle interaction indicates that about 850 sets would need to be observed per year with a coefficient of variation of 30% (Carlson, unpublished). The costs to achieve this level of observer coverage is about $200,000-250,000 per year.

Data

Data sets used included the NOAA Fisheries-SEFSC-Observer Program reef BLL data set (2006 to 2021). Data were provided by Elizabeth Scott-Denton at the NMFS Galveston Laboratory on January 03 and March 22, 2022. Fishery information included in the analysis from observer data sets included set latitude and longitude, month, time set, hook offset (straight vs offset), bait type, fishing depth, and effort calculated as hook-hours (soak time / number of hooks). Data sets were manipulated in the R statistical console for analysis.

Acknowledgements

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Table 1. Total numbers of observed sea turtle interactions over the study period (2006-2020), and the numbers included in models of interactions probability and the at-vessel condition analysis.

Total Interactions	**34**
N in models of interactions	**32**
N in at-vessel condition analysis	**33**

Table 2. Candidate factors hypothesized to affect bycatch rates of loggerhead sea turtles, *Caretta caretta*, in the GOM reef BLL fishery.

Variable	Type	Description	Biological Interpretation (hypothesis)
Fishing practices covariates			
Month	Categorical	All months, January - December	Probability of sea turtle encounter may vary throughout the year
Time of day	Categorical	6-hour bins: Morning, Afternoon, Evening, Night	Diel cycle may affect probability of sea turtle interaction
Hook shape	Categorical	0 offset or other offset value	Offset circle hooks may make sea turtle interaction more likely
Bait type	Categorical	Squid mix, elasmobranch mix, fish mix	Bait type may influence probability of sea turtle interaction
Effort (log[hook-hrs])	Continuous	Mathematical log of hook-hours	Fishing effort may affect sea turtle interaction probability
Environmental covariates			
Depth	Continuous	Depth of set recorded by observer	Fishing depth is likely related to probability of sea turtle interaction
Sea surface temperature	Continuous	Daily SST based on geographic location	Sea turtle distribution may be affected by temperature
Chlorophyll-a	Continuous	Chlorophyll-a concentration based on geographic location	Proxy for productivity which may affect sea turtle distribution
Lunar phase	Continuous	Calculated as a continuous variable from 0 -1	Lunar illumination may affect probability of sea turtle interaction

Table 3. Total numbers of reef fish BLL trips in the eastern GOM from logbook data and observer data sets, with estimated percent observer coverage.

Year	Logbook Trips	Observed Trips	Percent Coverage
2006	1165	12	1.0
2007	975	11	1.0
2008	1012	11	1.1
2009	488	28	5.7
2010	384	47	12.2
2011	583	73	12.5
2012	547	16	2.9
2013	567	77	13.6
2014	610	25	4.1
2015	576	22	3.8
2016	684	44	6.4
2017	633	11	1.7
2018	552	4	0.7
2019	533	5	0.9
2020	601	0	0.0
2021	589	8	1.4

Figure 1. All analyzed reef fish BLL sets in the eastern GOM. Green circles represent 0 catch sets, and orange triangles indicate sea turtle interaction.

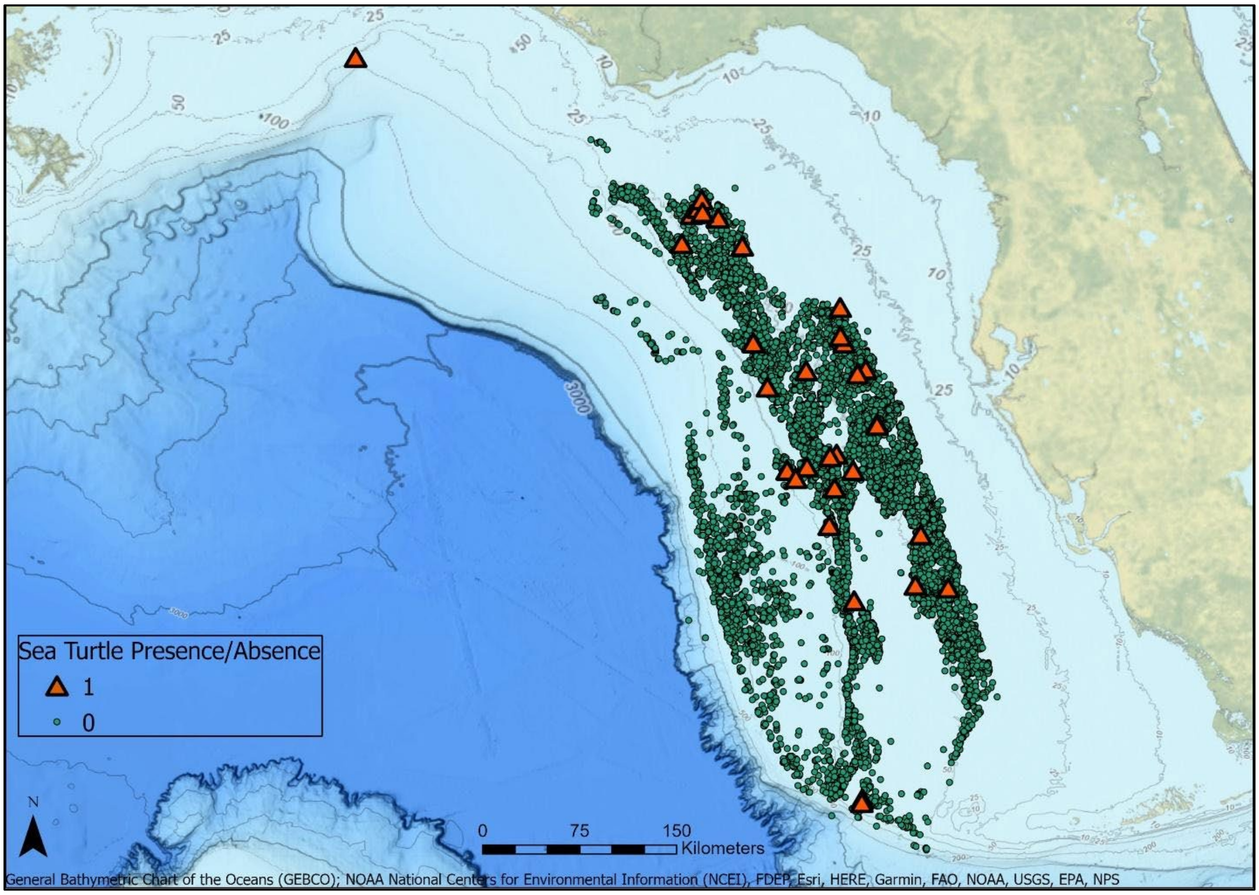

Figure 2. Spatial polygon representing the 99.5% MCP of the fishery domain in the eastern GOM based on observed reef fish BLL sets.

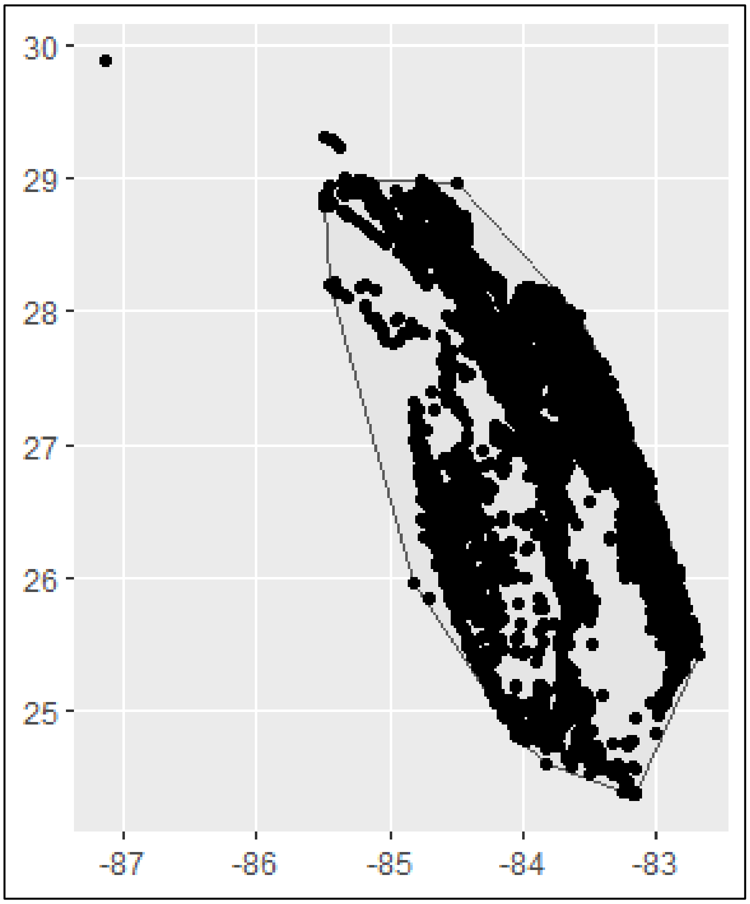

Figure 3. Total number of observed sea turtle interactions in the GOM reef fish BLL fishery by year

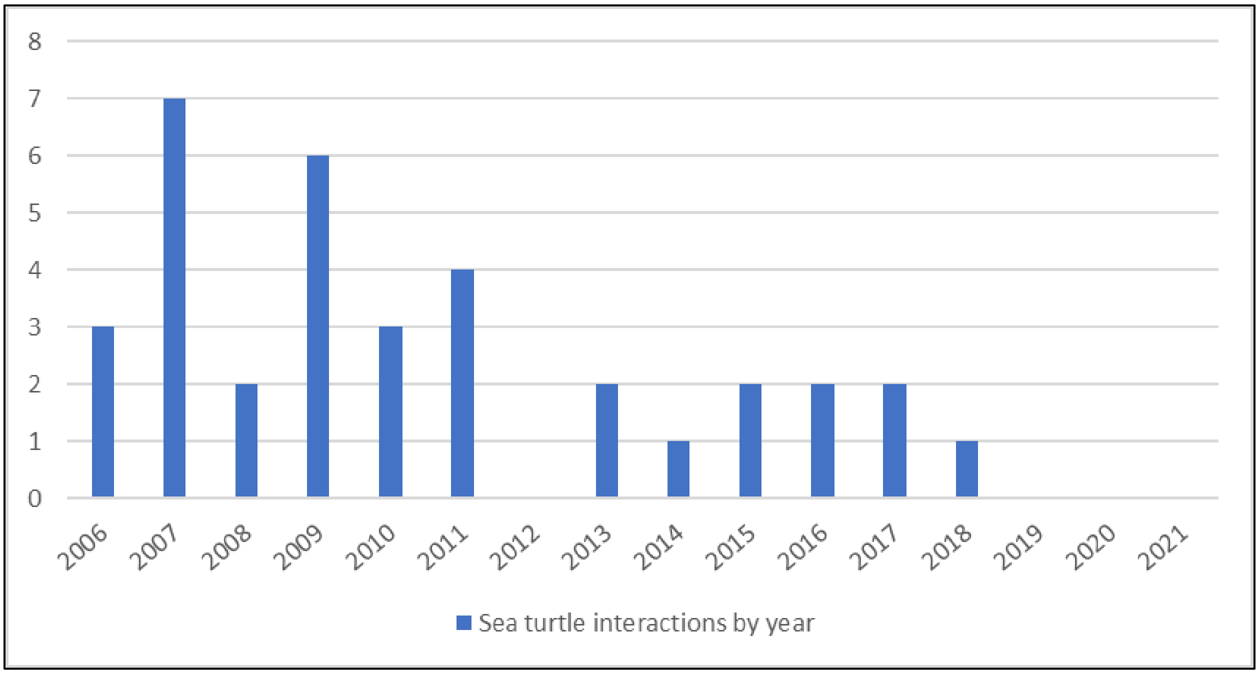

Figure 4. Final model predictions of sea turtle interactions in the GOM reef fish BLL fishery. The black line show the marginal mean predictions and the gray area represents the uncertainty from bootstrapping.

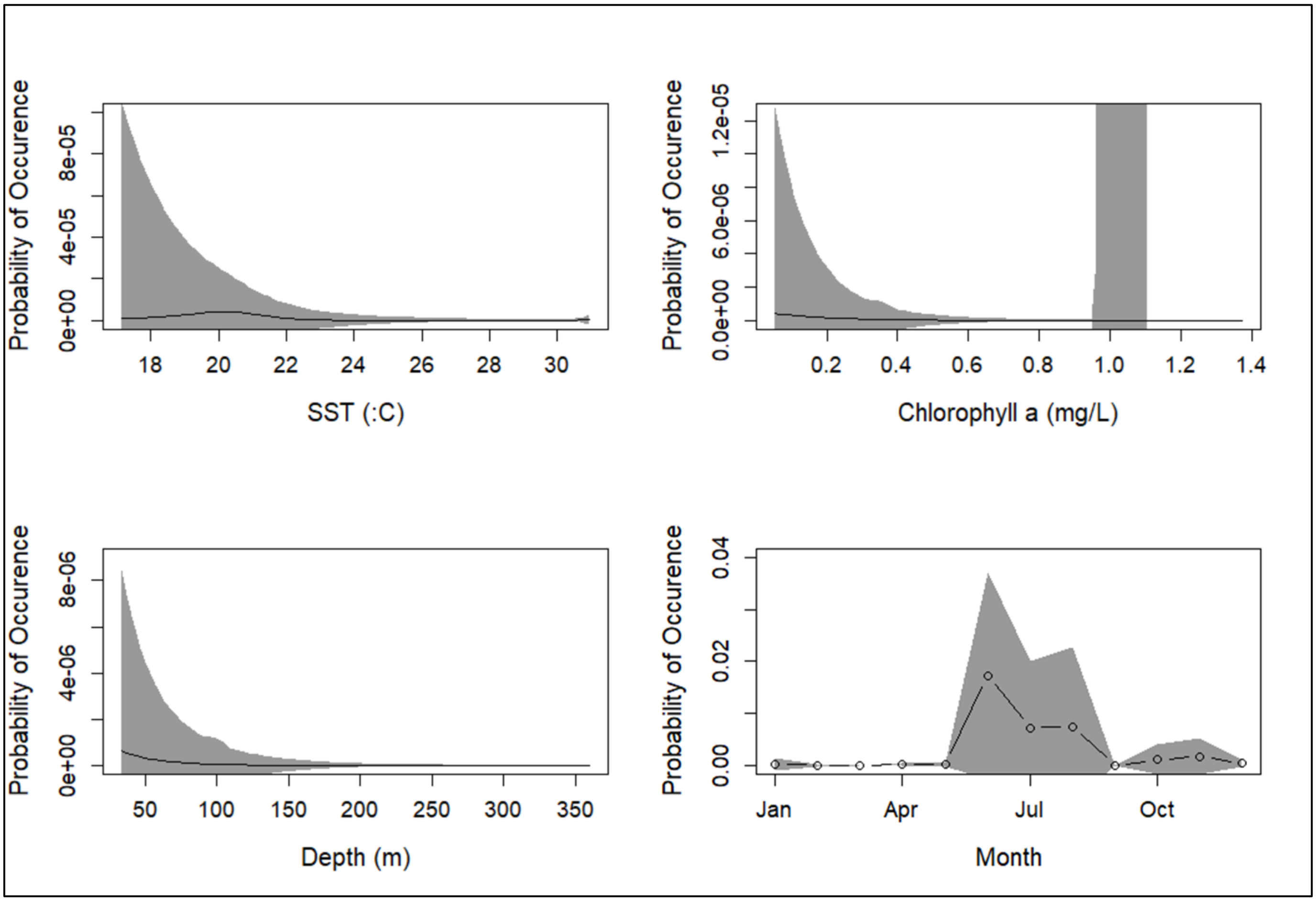

Figure 5. Predictive maps resulting from spatial simulations from January to June (A-F).

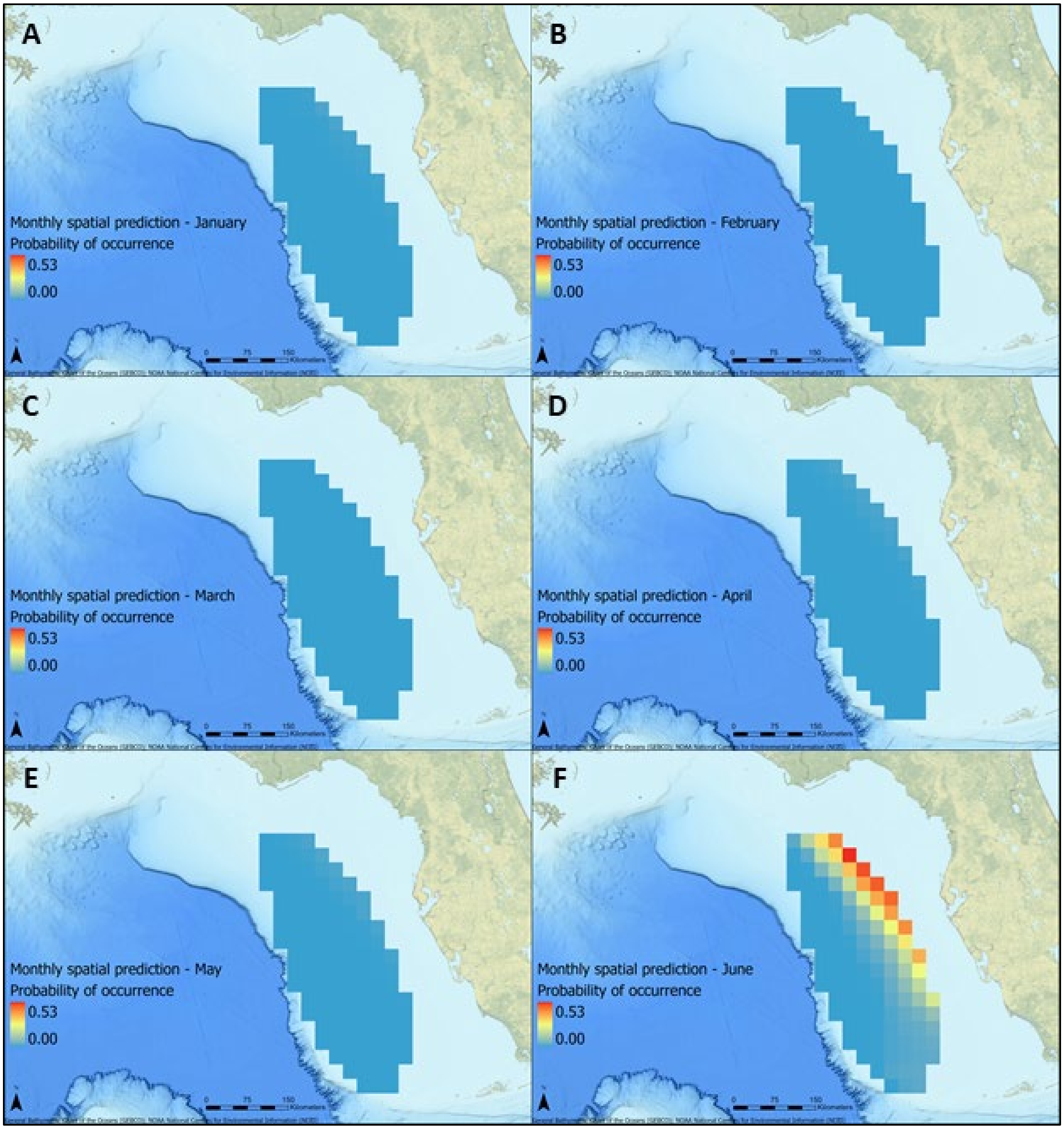

Figure 6. Predictive maps resulting from spatial simulations from July to December (A-F).

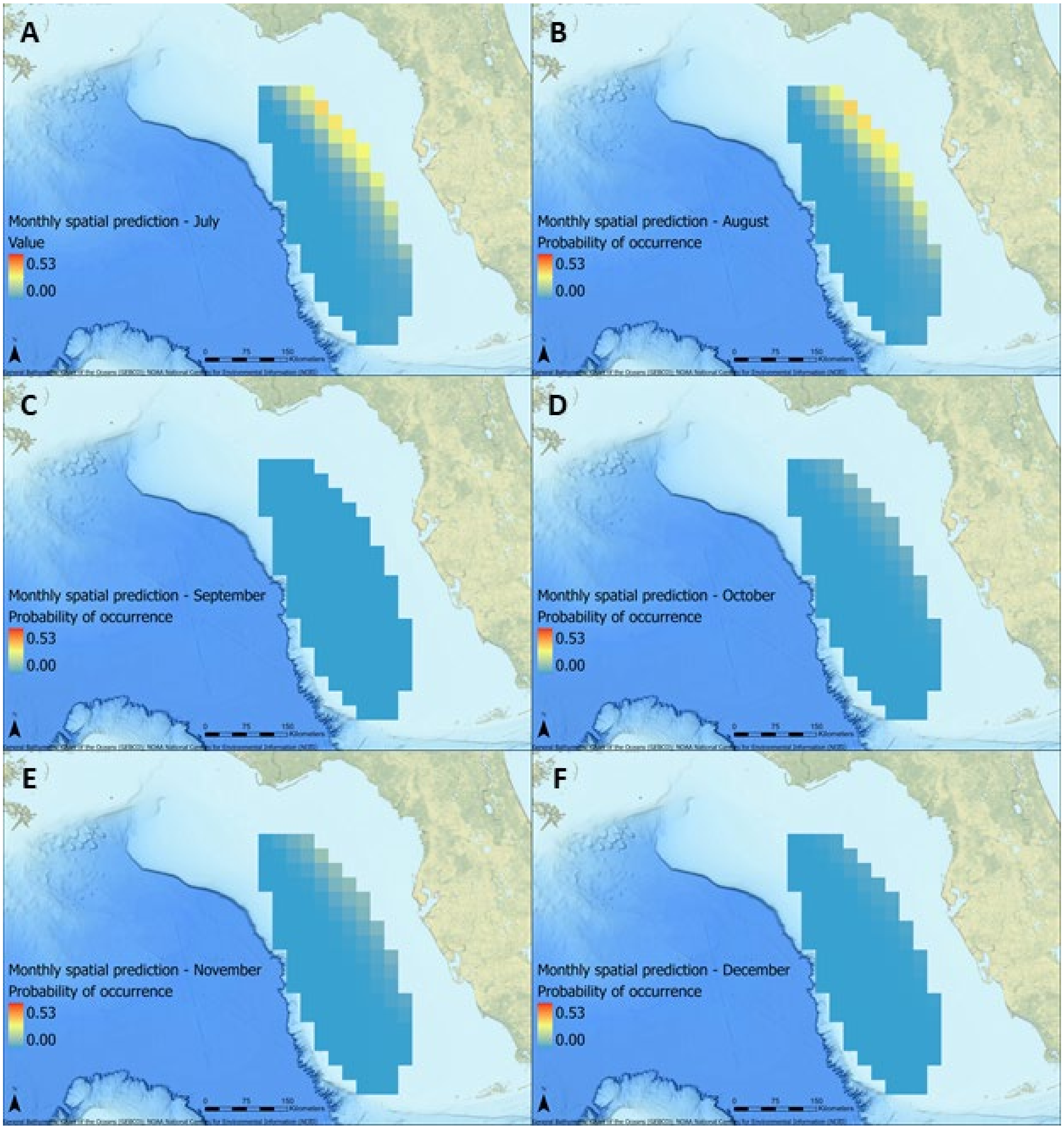

Figure 7. Relationship between at-vessel condition and soak time (i.e. time when 1st hook was deployed to the time when the last hook was retrieved on the longline set), n = 33.

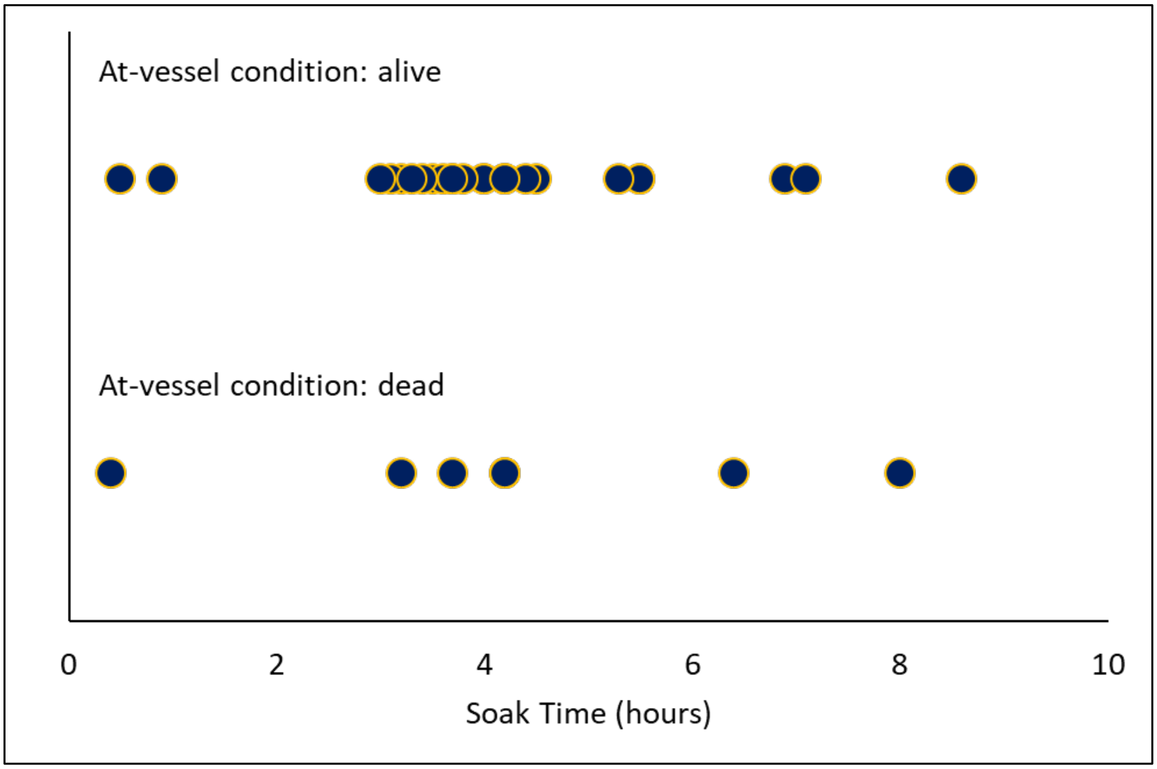

Figure 8. Observed Sea turtle interactions by primary bait type included in analysis of at-vessel condition (n = 33).