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Blue shark and swordfish catch rates in Hawaii's shallow-set longline fishery: before and after regulations aimed to reduce sea turtle bycatch

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Abstract

To reduce capture and mortality of endangered and threatened sea turtles, United States longline vessels targeting swordfish in the Pacific Ocean have operated under extensive fisheries regulations since 2004. We analyzed longline observer data from the Pacific Ocean to assess the impact of these regulations on targeted swordfish (*Xiphias gladius*) and bycatch of blue sharks (*Prionace glauca*). Using generalized additive mixed models (GAMMs), we investigated relationships between the nominal catch-per unit effort (CPUE) of blue sharks and swordfish and using operational components such as fishing location, hook type, bait type, hooks between floats, use of light sticks, and sea surface temperature. For blue sharks, GAMMs identified a significantly higher catch on J hooks with squid or fish bait relative to circle hooks with fish bait. For swordfish, J hooks with squid bait caught significantly more relative to circle hooks with fish bait, however there was no significant difference of catch when comparing J hooks with fish bait to circle hooks with fish bait. Confounding variables such as year and terminal gear components (hook type, bait) are discussed. Single factor analysis identified that catch rates of blue sharks and swordfish were significantly lower after the regulations, which were lower by over 2.4 times for blue sharks, yet by only ~8% for swordfish. These results indicate that the use of mitigation measures to reduce sea turtle bycatch, specifically large circle hooks and fish bait, can provide a significant conservation value by reducing blue shark bycatch, yet may also result in a slight reduction in targeted swordfish catch rates.

Introduction

Mitigating the effects of fisheries bycatch is a conservation priority worldwide, and the United States (U.S.) has actively addressed these concerns in domestic fisheries. In 2004, the U.S. imposed strict regulations in Atlantic and Pacific commercial shallow set longline fisheries in order to reduce sea turtle bycatch (NMFS, 2004b). The mandated changes include reducing or eliminating the use of squid bait in favor of fish bait and requiring the use of relatively large circle hooks. Overall, these actions have been effective at reducing sea turtle bycatch in both ocean basins (Swimmer et al. 2017).

In Hawaii, regulations were imposed in the shallow-set sector of the fishery that targets swordfish (*Xiphias glaidius*) and with baited hooks set ~100m from the surface and with fewer than 15 hooks between floats. The mandated changes were initiated with the re-opening of the fishery after it had been temporary closed for approximately three years, from 2001-2004. The post-regulation gear requirements included use of relatively large (18/0 [~4.9 cm minimum width]) circle hooks in combination with fish bait, which was previously determined to reduce loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) sea turtles in the Atlantic Ocean (Watson et al. 2005). Prior to these regulations, U.S. commercial fishermen used 9/0 J hooks and primarily squid bait.

Evaluation of these measures confirm strong conservation value for sea turtles in both ocean basins, but in particular in Hawaii where mean bycatch rates declined by 84 % and 95%, for leatherback and loggerhead turtles, respectively, for the post-regulation period (Swimmer et al. 2017). There is concern, however, that use of mitigation measures aimed to protect one taxonomic group can result in population declines of other taxa or species (Gilman et al 2016). This analysis responds to a need to better understand cross-taxa impacts of bycatch mitigation efforts in pelagic longline fisheries. In this study we investigate how mitigation methods serving one taxa, specifically sea turtles, affect other taxa within a fishery.

In this investigation, we used long-term fisheries observer data to assess the impacts of regulatory measures on the magnitude of blue shark (*Prionace glauca*) and swordfish catch rates in Hawaii's shallow-set fishery. We tested the null hypothesis that catch per unit effort (CPUE) was the same before and after regulations for both species. Additionally, we used statistical models to identify explanatory variables associated with the CPUE in order to provide further insight into the impacts of the regulations on species' catch risks. We also note that in addition to the regulations aimed to reduce sea turtle bycatch, there was also a reduction in shark captures due the restrictions on shark finning, whereby fins are removed and sharks' bodies are discarded to sea. This practice became unlawful after the regulations due to the 2000 Shark Finning Prohibition Act, and which may also contribute to the results in this analysis.

As managers strive to use an ecosystem-based fisheries management approach, cross-taxa bycatch reduction studies will become increasingly important. Studies like this will serve as the building blocks for cross-taxa bycatch reduction strategies.

Methods

Data

Observer data for the analysis was requested from NMFS' Pacific Islands Regional Office. Data analyzed were limited to the shallow-set (swordfish-target) sector of the fishery from 1994 to 2014. Pre-regulation data include data prior to February 2002, and the post-regulation period after May 2004. Between 1994 and 2000, observer coverage ranged from 3 to 10% (mean ~5%) and increased to 20.5% in 2001. Observer coverage became mandatory (100% coverage) for all Hawaii-permitted pelagic longline vessels targeting swordfish when the fishery re-opened in 2004. Prior to 2004, the terminal gear consisted primarily of J hooks size 9 and primarily squid bait. Post-regulations, all hooks were circle size 18/0 with 100% use of fish bait.

Summarized data are in Table 1. Nominal catch per unit effort (CPUE) was calculated as number of individual animals on each unique set per 1,000 hooks.

Our statistical analyses included Sea Surface Temperature (SST) data derived from 5-day composites from AVHRR Pathfinder v. 4.1 (1985 - 2003). These SST data were continued by the AVHRR Global Area Coverage dataset (January 2003 – April 2016) with a spatial resolution of 0.1° x 0.1°. Analyses included the weekly values when available, otherwise monthly data were used.

Comparisons of CPUE Before and After Regulations

We used non-parametric statistics (Wilcoxon signed ranks) to compare CPUE for time-periods before and after the regulations for blue sharks and swordfish.

Generalized Additive Mixed Models of Shark and Swordfish CPUE

Observer data were analyzed to relate blue shark and swordfish CPUE to operational characteristics using Generalized Additive Mixed Models (GAMMs). GAMMs are an extension of a GAM, which is a non-linear regression technique in which the relationships between the dependent and the independent variables are modeled with nonparametric smooth functions and make allowances for complex relationships (Hastie and Tibshirani 1990; Wood 2006). To account for the repeated trips by single fishing vessels, mixed models were constructed with vessel ID as random effect. Full models for swordfish and blue shark were constructed with a dependent variable y and a set of *x* independent covariates. The dependent term in each model was either blue shark or swordfish log-transformed CPUE, and either one- or two- dimensional cubic spline smoothing functions for each independent continuous covariates were used. We included hook type and bait type as an interaction term in the full model as well as evaluating models with each as single additive terms. Predictor variables included in all full models included month, Latitude and Longitude, SST, bait type (categories: squid, fish, other), hook type (circle, J, other), light stick to hook ratio, soak duration of gear, and number of hooks between floats.

‘Year’ as a co-variate was confounded with gear changes and was thus omitted as a covariate in the models, similar to previous analyses (Swimmer et al. 2017). Hook size, bait size, or hook offset were not analyzed due to limited sample sizes before and after regulations. A backward selection approach was used to identify the best model. Full species-specific models included independent covariates described in Table 2 and Appendix Table 1. As assessed with model diagnostics, all models met the assumptions of constant variance and normal residuals. We determined the best-fit models by minimizing the Akaike Information Criterion (AIC) (Akaike, 1973). Model co-variates specific to blue shark or swordfish are outlined in Tables 2 and 3. All GAMM analyses were carried out using the ‘mgcv’ package in R (R Development Core Team, v. 3.4.3).

Results

Descriptive Summary of Catch Data

In total, our data were from 15,472 sets from 460 unique trips during 1994–2014. Mean CPUE of blue shark was 21.05 before and 8.63 after the regulations, which was significantly different ($p<0.001$, W=5834900), and suggests a ~2.4x reduction of blue shark catch after the regulations.

Swordfish CPUE was 15.92 before regulations and 13.05 after the regulations, which was also significantly different ($p<0.001$, W=9197500), yet only by a relatively small margin (~8%).

Model Outputs & catch relationships with model covariates

The best-fit models with the final terms for each species and region are summarized in Table 2 and 3. The partial effect of different gear characteristics in the model for both blue shark and swordfish are shown in Figure 1 and 2. Model estimates of the individual variable effects on CPUE for each species for all years of data collections are in Table 2 and 3.

GAMM results for Blue Shark CPUE

The GAMM predicted highest CPUE of blue shark at SST < ~18^{o}C and an increase in CPUE after approximately 26^{o}C. Lowest CPUE was between ~22-24^{o}C. Catch is predicted highest during July through October, and lowest in late winter to spring months (February to May). Light sticks and soak time were not significant. After accounting for other variables in the model, J hooks with fish and squid bait caught higher CPUE of blue sharks compared to circle hooks with fish bait (Figure 1).

GAMM results for Swordfish CPUE

The GAMM predicted highest CPUE of swordfish with SST between ~18^{o}C and 20^{o}C and with the use of J hooks with squid bait. Catch is predicted highest during December through March and lowest between June and November. There was also a significantly higher CPUE of swordfish with a higher ratio of light sticks to hooks. There were no observed effects due to soak time. Higher CPUE was observed with fewer hooks between floats. Circle hooks with fish bait caught significantly less swordfish than when using J hooks with squid bait, but no significant difference between J hooks used with fish bait when compared to circle hooks with fish bait (Figure 2).

Discussion

This paper evaluates the impacts of the regulatory changes incurred in Hawaii on two species of concern, one for potential bycatch—blue shark, and the other regarding potential for economic loss, the targeted swordfish. Previous studies have demonstrated the conservation value of use of large circle hooks and fish bait to reduce catch and severity of injury in both loggerhead and leatherback sea turtles (Watson *et al.* 2005, Yokota *et al.* 2009, Curran and Bigelow 2011, Santos *et al.* 2012, Serafy *et al.* 2012). This study further investigates how those regulations impacted the predominant shark species caught in most longline fisheries, blue sharks, as well as targeted swordfish.

Blue Sharks

Blue sharks are the most commonly caught shark species in global longline fisheries, including Hawaii (Walsh et al 2009). In this study, we found that SST, hook depth, month, as well as the interactions of hook and bait influenced the catch rates of blue sharks.

The significantly lower capture rate of blue sharks on circle hooks and fish bait during the post- regulation period is similar and reflects even more extreme reductions to a previous analysis with a more limited time series data set in the Hawaii shallow-set fishery (Walsh et al. 2009). Similar to our study, analysis of data before and after the regulations identified that blue shark catch rates declined by 28.8% after the fisheries regulations in 2004 (Walsh et al. 2009). It is possible that fishermen have identified means to avoid capture of blue sharks given finning ban and elimination of any economic incentive for their capture.

Our reduced rates of capture of blue sharks on circle hooks are within the range of highly variable results previously published and reviewed in meta-analyses (see Reinhardt et al. 2017, Gilman et al. 2016). In general, there are numerous operational factors that play a role in species' vulnerability to capture, including hook type and size, bait type (fish, squid), leader material, as well as a variety of environmental factors (Bigelow et al. 2002). Further, it is also possible that given the reduction of profits gained from shark finning, fishermen may have found ways to reduce blue shark catches.

Sea surface temperature has been previously identified as playing a strong role in influencing blue shark capture rates (Bigelow et al. 2002, Foster et al. 2012). Our findings of a bi-modal pattern of CPUE in relation to SST is similar to other studies in the North Pacific Ocean (Walsh and Kleiber 2001, Bigelow et al. 2002) and could indicate a segregation of this species by sex and size during their life cycle. This study did not include sizes of individuals and thus such a theory is only hypothetical, but can provide a plausible explanation for the distinct differences in CPUE across a range of SST.

Given the confounded effects of the interaction of hook and bait, it is unclear if the reduction in blue sharks after the regulations is a result of the hook shape or bait, as both have been shown to influence catch risk (Foster *et al.* 2012; Santos *et al.* 2013; Gilman *et al.* 2016b). The catch rates of blue sharks on circle hooks versus conventional J hooks have had mixed results in other fisheries around the world, and some have found no effect of hook or bait changes on blue shark catch rates (Pacheco et al. 2011, Fernandez-Carvalho et al). The combination of this terminal gear may have contributed to the reduced capture rates of blue sharks in this fishery and provides further information about the regulation aimed to reduce sea turtle bycatch may also significantly reduce bycatch of blue sharks. We also acknowledge that shark finning regulations went into effect before the fishery was reopened, and as such, may have also influenced catch rates reported here and in a previous analysis (Walsh et al. 2009).

Swordfish

This study found a slightly lower (~16 vs ~13 CPUE), yet significant nominal catch rate of swordfish after the mandated use of large circle hooks with fish bait, which was not a surprise, per se, but confirms industry fears regarding adoption of such gear.

Our findings of reduced swordfish capture rates on circle hooks are similar to most field trials that controlled for hook type in the Atlantic (Watson, et al., 2005; Domingo, et al., 2012; Piovano, et al., 2009; Sales, et al., 2010), and yet differs from other results (Pacheco, et al., 2011, Foster et al. 2012). Explanations for these results are difficult but could be related to differences in bait type. Watson and colleagues (2005) reported that that use of fish bait (vs. squid) alone could offset the loss (19% by weight) of swordfish caught on circle hooks compared to J hooks. In response, regulations in U.S. commercial fisheries allow for modifications regarding hook type and bait to balance fisheries and conservation needs (Serafy, et al., 2012).

In our study, use of GAMMs identified a weak effect of SST regarding swordfish CPUE, which has been previously reported (Foster et al 2012, Bigelow et al. 2002). However, our GAMM models identified that a higher ratio of light sticks used was linked to increased swordfish CPUE. This information is well known to the fishing industry as lightstick use has been an industry standard since early longline fishing targeting swordfish, and has also been previously identified in modeling efforts (Bigelow et al. 2002). In general, lights are placed near each hook on swordfish-style sets and every-other hook in a mixed target set in order optimize swordfish fishing effort.

Data concerns

These data have unique challenges given the simultaneous nature of regulatory requirements and gear changes in the Hawaii shallow-set fishery that confound data and limit some analysis. The 2004 regulations created an immediate change in use of both bait and hook type, making no allowances for an overlap of different combinations (such as circle hooks with squid bait), rendering it difficult to separate the explanatory effects of bait and hook type. In this type of scenario, the degree of interrelatedness among hook type, bait type, and year is sufficiently high as to essentially be represented by a single variable.

Additional data concerns regard changes in the geographic distribution of observer coverage as during the study period as well as temporal considerations. As such, we included an interaction of latitude and longitude in our models to account for spatial effects of observer coverage. Walsh et al. (2009) used a similar data set and identified that the majority of sets were deployed east of 130°W in 1996, 1998 and 2000, but there was no shallow-set activity in these waters in 2004–2006. Further, understanding temporal changes in population size can be important to assessing changes in catch rates as a function of mitigation measures. Inclusion of 'year' as a variable in these models is possible, as it could begin to account for population level changes that vary through time. However, as the 'year' term may also capture mitigation measure effects (switching hook and bait types), such as those this fishery, the use of this covariate results in a less than clear interpretation of model results. Future follow-up analysis of this data will also incorporate lunar cycle as fishers set gear at variable depths depending on moon phase that has in turn been shown to have an effect on CPUE (Poisson et al. 2010, Bigelow et al. 2004).

Conclusion

Fisheries managers strive towards ecosystem-based management despite the many challenges. One urgent need is to resolve the uncertainty regarding potential effects that mitigation methods used to protect one taxonomic group will have on other species. This study advances this challenge by investigating how use of modified fishing gear specifically designed to reduce sea turtle bycatch impacted capture rates of blue sharks and swordfish. Such analyses have been recommended by numerous scientific bodies of international regional fisheries management organizations (WCPFC14 paragraph 362).

Further research is necessary to evaluate biological and economic factors associated with mandated operational changes, such as catch sizes (see Bigelow & Swimmer, WCPFC 2018 working paper), value per unit effort (VPUE), as well as the haul-back mortality rates of other non-turtle bycatch species. For example, specific to regulated use of circle hooks, Reinhardt and colleagues (2017) have confirmed that for a number of species across multiple taxa, an increased potential catch rate can be offset by increases in rates of survival given the location and severity of injuries associated with circle hooks. These additional components, such as mortality and population-level impacts must also be considered in light of potential mitigation methods.

In this analysis, we identified that use of circle hooks and fish bait resulted in lower catch rates of blue sharks, perhaps the single most frequently captured species in global longline fishing (Walsh et al. 2009). Additionally, while the capture rates of targeted swordfish were lower for the period after the regulation, we contend that this loss should simply be factored in as a tradeoff for the effective reduction in capture and mortality of protected bycatch species, including blue sharks as well as sea turtles. Other bycatch species, such as different elasmobranch species, should also be investigated in relation to operational and environmental characteristics. As with other bycatch reduction techniques, conservation successes in one group must be considered in light of other effects.

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Table 1. General characteristics from the Hawaii-based shallow-set longline fishery~ 1992-2014.

General Data Characteristics	
Approximate time of initial set	Sunset
Number of hooks between floats	Majority 4-5 (range: 3-21)
Mean number of light sticks per hook	0.57
Hook used primarily pre-regulations	J 9
Hook used after regulations	Circle 18/0
Bait primarily used pre-regulations	Squid
Bait used post-regulations	Fish only(Mackerel most common)
Sets with fish-only bait	13,713
Sets with squid-only bait	1,532

Table 2. CPUE of Blue shark (*Prionace glauca*) modeled using a Generalized Additive Mixed Model as a function of temperature and operational characteristics of longline fishing operation in the Hawaii shallow-set longline fishery. Coefficients and approximate significance are reported for the best model as determined by minimization of AIC.

Parametric coefficients

Fish-bait combinations	***Estimate***	***Std. Error***	***t value***	***Pr(>|t|)***	
C-FISH	2.03468	0.03894	52.249	< 2e-16	***
C-OTHER	0.22402	0.073	3.069	0.00215	**
J-FISH	0.4094	0.20323	2.014	0.04398	*
J-SQUID	0.52992	0.02887	18.358	< 2e-16	***
J-OTHER	0.32948	0.12449	2.647	0.00814	**
OTHER-FISH	0.4459	0.03679	12.119	< 2e-16	***
OTHER-SQUID	0.2284	0.0875	2.61	0.00905	**
OTHER-OTHER	0.28188	0.12176	2.315	0.02063	*

Smooth term (approximate significance)

Smooth terms	***edf***	***Ref.df***	***F***	***p-value***	
te(AVE_LON,AVE_LAT)	11.477	11.477	72.88	<2e-16	***
s(MONTH)	2.99	2.99	124.3	<2e-16	***
s(ave_temp_C)	2.964	2.964	153.5	<2e-16	***

Table 3. CPUE of Swordfish (*Xiphias gladius*) modeled using a Generalized Additive Mixed Model as a function of temperature and operational characteristics of longline fishing operation in the Hawaii shallow-set longline fishery. Coefficients and approximate significance are reported for the best model as determined by minimization of AIC.

Parametric coefficients

Fish-bait combinations	***Estimate***	***Std. Error***	***t value***	***Pr(>|t|)***	
C-FISH	2.45286	0.0247	99.316	< 2e-16	***
C-OTHER	0.06951	0.05556	1.251	0.211	
J-FISH	-0.15408	0.15583	-0.989	0.323	
J-SQUID	0.18117	0.02202	8.227	< 2e-16	***
J-OTHER	0.01826	0.09331	0.196	0.845	
OTHER-FISH	0.20775	0.02807	7.402	1.41E-13	***
OTHER-SQUID	0.05454	0.06568	0.83	0.406	
OTHER-OTHER	0.04637	0.09204	0.504	0.614	

Smooth term (approximate significance)

Smooth terms	***edf***	***Ref.df***	***F***	***p-value***	
te(AVE_LON,AVE_LAT)	11.183	11.183	25.874	< 2e-16	***
s(MONTH)	2.979	2.979	39.325	< 2e-16	***
s(ave_temp_C)	2.829	2.829	3.721	0.00715	**
s(log(LIGHT_RATIO + 1))	1	1	36.107	1.91E-09	***
s(HKS_PER_FLT)	2.631	2.631	80.758	< 2e-16	***

Figure 1. Partial effects of gear characteristics and weekly averaged satellite derived sea surface temperature (ave_temp_C) on CPUE of blue sharks. The y-axis represents deviation from the mean log transformed CPUE of blue sharks. The shaded area represents the upper and lower twice-standard-error curves. For factors (categorical variables), solid lines are the mean and the first factor is the reference group centered at zero, dashed lines represent upper and lower twice-standard errors. Vertical ticks on the x-axis indicate data distribution. A) Month, B) SST, C) number of hooks between floats, D) interaction of hook and bait, E) map of the partial effect of geographic set location on catches of blue shark (warmer (orange) to colder (blue) colors represent high to low nominal catch rates, respectively).

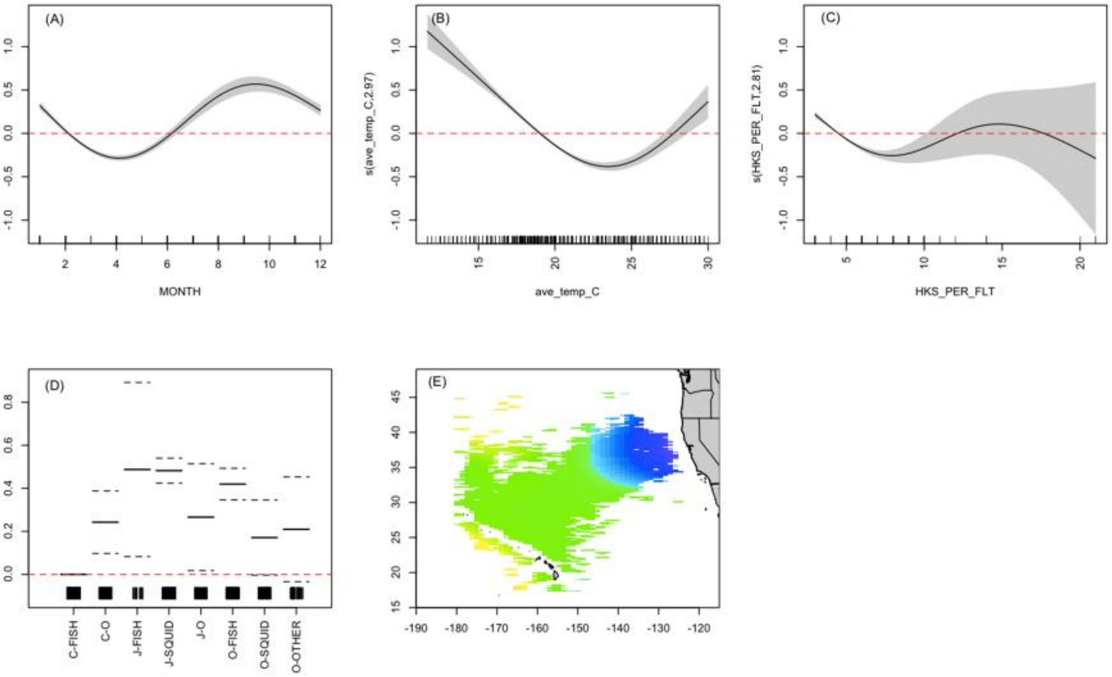
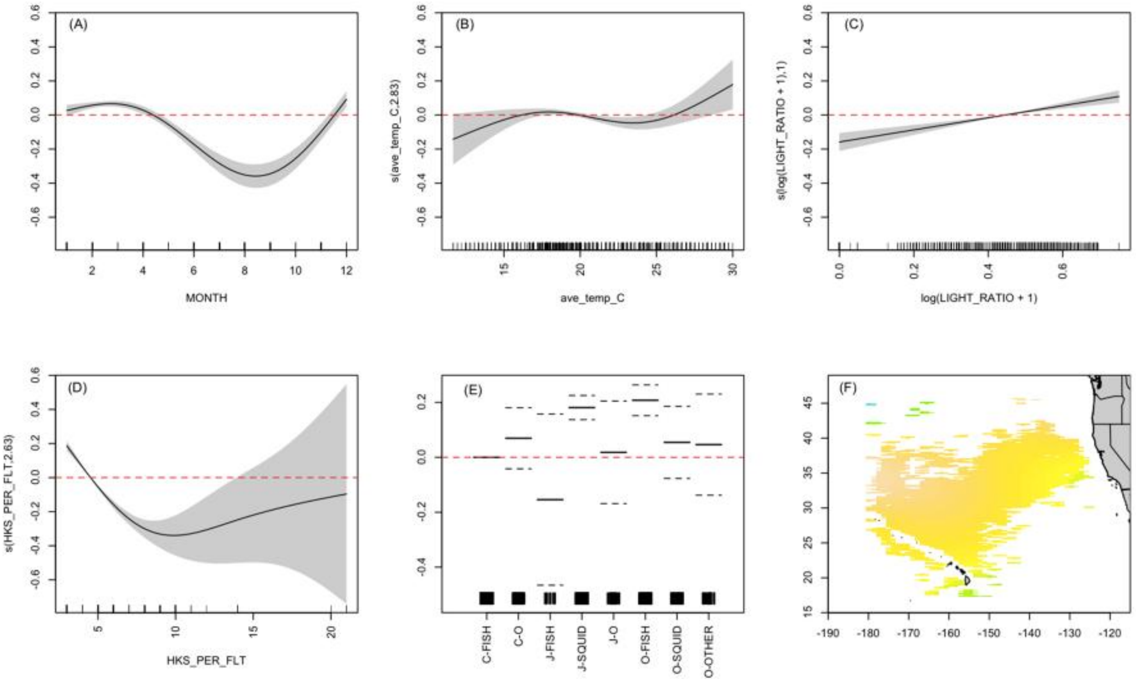


Figure 2. Partial effects of gear characteristics and weekly averaged satellite derived sea surface temperature (ave_temp_C) on CPUE of swordfish. The y-axis represents deviation from the mean log transformed CPUE of swordfish. The shaded area represents the upper and lower twice-standard-error curves. For factors (categorical variables), solid lines are the mean and the first factor is the reference group centered at zero, dashed lines represent upper and lower twice-standard errors. Vertical ticks on the x-axis indicate data distribution. A) Month, B) SST, C) ratio of light sticks to hooks (log scale due to improve model fit), D) number of hooks between floats, E) interaction of hook and bait, F) map of the partial effect of geographic set location on catches of swordfish (warmer (orange) to colder (blue) colors represent high to low nominal catch rates, respectively).



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