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ANALYSIS OF WCPO LONGLINE OBSERVER DATA TO DETERMINE FACTORS IMPACTING CATCHABILITY AND CONDITION ON RETRIEVAL OF OCEANIC WHITE-TIP, SILKY, BLUE, AND THRESHER SHARKS

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1. Executive summary

Here we present an updated and expanded analysis of factors impacting the catch rates and condition of several key shark species. It builds on the analyses of Bromhead et al. (2013) by including additional data and shark species / species groups, plus analyses of condition of sharks on retrieval and impact of hook position on catch rates.

We used the same three fisheries defined in Bromhead et al. (2013) and added another fishery for US-flagged vessels fishing in American Samoa. The original intention was to also include the mako and hammerhead shark species groups, but these were excluded due to time constraints – these also had the least records across the four fisheries.

Species/Species groups	Fisheries
Oceanic whitetip (OCS)	Marshall Islands and Federated States of Micronesia (M1)
Silky shark (FAL)	Fiji (M2_Fiji)
Blue shark (BSH)	American Samoa (M2_AS)
Thresher sharks (THR)	Hawaii (deepset fishery only) (M7)

1.1 Modelling Approach

- Three response types were considered for the key questions:
  i. A CPUE response (catch-per-1000 hooks) at the set level to consider gross influences on species catch rates.
  ii. A CPUE response (catch-per-100 hooks) at the hook level to investigate catch rates at the hook position level.
  iii. A binary condition response at the individual catch level to investigate influences on shark mortality at time of retrieval.

- The models applied to these response respectively were:
  i. Log-link, Tweedie errors, Generalized Linear Models (GLMs) & Generalised Additive Models (GAMs) fitted with to investigate structural relationships between set level catch-rates and the available covariates.
  ii. Log-link, Tweedie errors, Generalized Linear Models (GLMs) & Generalised Additive Models (GAMs) fitted with to estimate hook-position catch rates conditioning on fishery or flag.
  iii. Logit-link, binomial errors, Generalized Linear Models (GLMs) & Generalised Additive Models (GAMs) were fitted with to investigate structural relationships between condition and the available covariates.

1.2 Results and Discussion

As found by Bromhead et al. (2013) there is substantial confounding between some potential covariates and the key predictors of interest, even considered at the fishery level. Further, differences in fishery characteristics and data collection protocols meant that not all key factors of interest were relevant for all fisheries. Across fisheries, species/species groups and analysis types, 48 models were developed.

1.2.1 Set-level catchability

Shark lines were only found in the M1 and M2_Fiji data sets and had significant and positive impacts on catch rates of oceanic whitetips and silky sharks (Fiji only). This confirms previous findings that shark lines are essentially used to target these two species.

The use of wire trace was found to have a significant effect on catch rates in three cases and in each case the effect was positive, oceanic white tips and blue sharks in the Fiji fishery and blue sharks in the Hawaii deepset fishery. This is positive effect is consistent with a reduced ability for 'bite-offs' with wire leaders.

Shark-bait use was only recorded in the M1 and M2_Fiji data sets and there were two instances where it was significant, but the direction of the effect differed. In the M1 fishery shark-bait had a positive effect on silky shark catches, but a negative one on blue shark catches. This must be treated with some caution as only reflects 'some' use of shark bait on the set, the relative proportion is not known.

There was insufficient contract to examine hook type in M1 fishery, but it was possible in the other three. Hook type was found to be significant on eight occasions and in six of these catch rates were significantly higher on circle hooks than the alternatives (tuna or J-hooks depending on the fishery). The two exceptions were for J-hooks and thresher sharks in the M2_Fiji fishery and blue shark and J-hooks in the Hawaii deepset fishery. Circle hooks were associated with higher catch rates of oceanic whitetips in all three fisheries were hook-type was examined.

1.2.2 Hook-level catchability

The analysis of hook position on catch rates was also another opportunity to examine the effect of shark lines (denoted hook position 0 in this analysis) in the M1 and M2_Fiji fisheries. In these fisheries and particularly for oceanic white-tips sharks (but also to a lesser extent for silky sharks), catchability was significantly higher for the shark line than the shallowest hooks in the basket 'proper' (i.e., the true hooks between floats as compared to the shark-line which is attached to the float line between baskets. We have again clearly demonstrated the high catchability for these two species on shark lines.

For the 'true' hooks between floats, patterns were generally consistent across fisheries, but the trends for the American Samoa fishery (M2_AS) were generally less distinct and more uncertain that for the other fisheries. There was typically a declining trend in catchability with hook position for oceanic white-tip and silky sharks and an increasing trend in catchability for the thresher shark species complex. Trends for blue sharks were less clear, generally catchability was higher on intermediate or deeper hooks. It is possible that oceanographic variation (e.g., water temperature at depth across regions) maybe another important covariate.

1.2.3 Condition on retrieval

There were far fewer significant factors in these analyses. Wire trace was significant on four occasions and in three of these, it was predicted to lead to an increase in the probability of being dead at retrieval, but in one (blue shark in the Hawaii deepset fishery) it had lower probability.

Shark lines were significant for three of four species for the M1 fishery (all except oceanic white-tips) and in each case associated with a significant decrease in the probability of being dead at retrieval.

Hook type was significant for both oceanic white-tip and blue sharks in the Fiji fishery with circle hooks having a significantly lower probability of mortality at retrieval.

1.3 Overall summary and suggested way forward

The primary purpose of this analysis was to identify potential mitigation options to reduce overall fishing impacts on sharks. Here we have examined factors that were related to catch rates and the condition of sharks at the point of retrieval, but in fact the overall process is much more complex than this and overall fishing-related impacts on these species will also involve mortality for those that escape the line (e.g., bite-off's), and handling practices for sharks that might be released. Patterson et al. (2014; Figure 1) provide schematic that outlines a more complete process for fishing related mortality.

The next stage of this analysis will be to take these results and undertake Monte Carlo simulations to examine the potential impact of alternative packages of mitigation measures. It is very clear that banning shark-lines and wire trace, hook position (e.g., removal of shallow hooks), and restrictions around hook types all offer potential ways to reduce catches of sharks, but it will be critical to integrate these effects in a overall model that accounts for 'bite-off's' and any associated mortality, especially for consideration of wire leaders and hook types. Incorporation of information on post-release mortality and handling will be critical (Curran 2014).

Finally, across the various species and fisheries, factors such as set time, soak time, and hooks between floats were often significant, but as these were modeled using splines and sometimes significant in complex interactions we don't describe the results in this report, but results can be found in the supplementary information. These were generally second-order or lesser effects and while they could be considered in the Monte Carlo simulations, we suggest that they be a lesser priority.

2. Introduction

In response to the stock assessments of oceanic white-tip and silky sharks, the WCPFC-SC tasked SPC with examining potential mitigation options for these two shark species which are taken in tropical, and sub-tropical longline fisheries. These analyses are documented in Bromhead et al. (2013) and OFP (2012). These analyses were hindered by the paucity and unbalanced nature of the observer data. The analyses did identify that there was some deliberate shark targeting using shallow lines attached to the floats, appropriately called 'shark lines', but conceded that the data made it difficult to make many other conclusions regarding wire leaders or hook types.

The purpose of this paper is to further develop the analyses undertaken by Bromhead et al. (2013) in five main ways:

1. Inclusion of observer data from longline fishery in American Samoa;
2. Expansion of the species considered to include blues, makos, thresher, and hammerhead sharks;
3. Consideration of other potential influencing factors on catch rates (catchability), e.g., hook depth and soak time;
4. Analysis of these factors and other factors on the reported condition of sharks at the time of retrieval;
5. Monte Carlo simulation of some 'what-if' scenarios on predicted impacts of potential mitigation measures that integrate estimates of catchability and condition with post-release survival estimates from the literature.

2.1 Scope of present study

The study reported up here is a subset of the project described above. Specifically this study addresses the following goals:

i. Estimate the effect of various fishing gear specifications on catch rates for the shark species groups based on the observer data sets described in Table 9. Gear characteristics of particular interest include leader material, hook type, hooks between floats, soak time, and use of shark lines and bait. The analysis should also consider other variable that can impact catch rates such as location, season, oceanographic variables, and flag/vessel effects.

ii. Estimate the effect of various fishing gear specifications on condition at time of retrieval for the same species and same observer data sets described above. Data will grouped into alive and dead only (i.e., the full suite of life-status categories used in the observer data base will not be considered). Variables similar to those considered under (i) above should be considered.

iii. Estimate the potential effect of eliminating shallow hooks from branchlines on for the same species and same observer data sets described above. This analysis could be integrated into that undertaken under (i) above or undertaken separately.

iv. **A future phase of the project will address the following goal -** Monte Carlo simulations of some 'what-if' scenarios of potential mitigation measures by integrating estimates of catchability and condition from (i – iii) above, and post-release survival estimates from the literature.

3. Methods

3.1 Summary of data and pre-treatment

The data for the analyses were a combination of longline observer data held by SPC and WCPFC, plus additional observer data for US-flagged longline vessels that fish out of Hawaii and American Samoa, but is not held by SPC/WCPFC and was provided specifically for these analyses.

Data for all available years were included in the analyses and the same fishery definitions used were similar to those used in Bromhead et al. (2013), with the addition of the data for American Samoa. The four fisheries were:

- M1: Chinese and FSM-flagged vessels fishing in FSM and RMI;
- M2_Fiji: Fiji-flagged vessels fishing in the waters of Fiji, Vanuatu, Solomon Islands;
- M2_AS: US-flagged vessels fishing in American Samoa[3]; and
- M7: US-flagged vessels operating out of Hawaii and undertaking deep sets.

Initial grooming of the data involved excluding records that:

- Were missing hooks between floats and number of hooks set; and
- Had less than 1000 hooks set or less than 5 hooks per basket or more than 40 hooks per basket.

There were some differences in the data collection procedures between the SPC-regional and US observer data so it was decided to standardize on a single 'alive' category for condition on retrieval. Further sharklines or shark-bait (use of cut-up catch species, e.g., tuna) were not recorded in the US-data. To estimate hook position in the basket we standardized this based on the distance from the nearest float, e.g., in a basket of 24 hooks, hooks 1 and 24 were assigned position '1' and hooks 5 and 19 were position '5' etc. Sharklines set of floats were position 0.

The final data for analysis comprised of three datasets:

- Effort and fishing gear data at a set level, comprising key factors such as start time, soak time, hooks between floats, hook type, shark bait use, wire trace use and shark line use.
- Shark catch data at a hook level (i.e. hook position between floats in a set), describing the condition (dead or alive) of caught sharks.
- Oceanographic estimates data, comprising relevant environmental variables such as sea surface temperature and height, wind stress, current speed and isotherm depths (mainly sourced from GODAS[4] and ASCAT[5]).

Further data treatment prior to modelling involved primarily checking the provided data for inconsistencies and errors before combining the datasets together for the exploratory data analysis. Data was subsequently processed and reshaped accordingly for each type of response under analysis. For example, data for the analysis of catch rates of a given shark species by a fishery/fleet was obtained by summing over the number caught in each of the sets observed in that fishery/fleet, allocating zeros to sets with no catches of the species under consideration.

3.2 Modelling overview

Model selection in terms of the systematic components, was conducted in a number of ways:

[3] The original intention was to model these fisheries together, but differences in data collection and fishery operations meant that this was not possible.

[4] NCEP Global Ocean Data Assimilation System

[5] Advanced Scatterometer on board the METOP-A European Earth observation satellite

1. In the first instance, cases of highly related covariates were identified using naïve Generalized Linear Models (naïve meaning without interaction terms and assuming independence of errors). These were used as the basis for calculating Generalized Variance Inflation Factors (GVIFs). Particularly large GVIFs indicated variables that might be collinear, leading to inflated variances around parameter estimates. Model selection methods may resolve this in an automated manner, but from an interpretative point of view, a qualitative selection between such variables is preferred.
2. Subject to this a priori reduction in potential covariates, a speculative "saturated" model was specified, including interaction terms (up to level four in some instances). The interactions were restricted to variables thought to logically have potential interactions, rather than consider all possible interaction terms. These saturated models are presented in their respective sections, but typically consisted of greater than 20 terms, consisting of quantitative covariates, factor covariates and various interactions therein.
3. Examination of preliminary models indicated non-linearities ought to be considered in all models. Hence, Generalized Additive Models (Hastie & Tibshirani, 1986, 1990) were the favoured modelling framework - specifically the implementations offered in mgcv (Wood, 2000; 2003; 2004; 2006 & 2011) which offer tools for optimising complexity and model selection. Model selection for GAMs was via the Null space penalization, whereby all terms are retained in their model, but their relevance in the model is reduced by penalties accordingly (Marra & Wood, 2011).

The models fitted were of two main types:

1. For catch rate responses (set and hook-level), Generalized Additive Models (GAMs) were used. To account for the prevalence of zeros in the data, Tweedie distributions were used, which are a generalisation of several exponential family distributions. In particular they permit a compound Poisson-Gamma distribution. The continuous, skewed, catch rate data observed here would be suited by a Gamma distribution, but for a mass at zero, which is not permitted under a Gamma. Tweedie parameters were estimated in each case to parameterise this compound Poisson-Gamma error distribution. The default log-link function was adopted. Smooth terms were specified where appropriate (both univariate and bivariate) and were penalised regression splines – the smoothing parameters being optimised via multiple Generalized Cross-Validation.
2. For condition models, the response was alive/dead leading to logit-link binomial errors GAMs as befits binary response data. Smooth terms were specified where appropriate (both univariate and bivariate) and were penalised regression splines – the smoothing parameters being optimised via multiple Generalized Cross-Validation.

The following primary assumptions were considered in the modelling process:

1. Non-linearities: where considered a priori likely, these were accommodated via smoother terms specified in the GAMs. The combination of optimised smoothing parameters and term selection via Null space penalisation is to account for complexities in the systematic component.
2. Zero-rich data and general adequacy of assumed error distributions: a compound Poisson-Gamma distribution was utilised in the GAMs via Tweedie distributions, which can accommodate levels of mass at zero. The Tweedie parameter was estimated as part of the process and the resulting error distributions checked for adequacy via diagnostics on quantile residuals. Quantile residuals were also used to test the adequacy of the assumed error distribution in the binary response GAMs.

Independence of errors: *a priori* the likelihood of correlated errors seems high given the nature of sets. This was checked via quantile residuals with runs tests and autocorrelation functions, where the sets were ordered in a logical fashion. In the vast majority of cases the correlation in the errors was ignorable once proper account had been taken of the preponderance of zero catch observations.

4. Results

A total of 48 final models were produced (4 fisheries x 4 species/species groups x 3 analyses [set-level catch rate, hook-level catch rate, and hook-level condition]) so it is not feasible to provide all full model details (e.g., diagnostics, output tables) for every model run. In addition to detailed exploratory data analysis that supported each of the 48 models, the supplementary information provides diagnostics of model fit and model selection and plots of significant model factors.

We summarize the results of these 48 models in three ways; 1) a graphical display of which variables were chosen (i.e., significant) in each analysis and the nature of the effect (e.g., positive, negative etc.) (Tables 1-8); 2) provide plots of the partial coefficients relating to some key variables, i.e., sharklines, wire trace, hook type, and shark-bait, when these were significant (Figures 1-12); and 3) for the same significant variables in (2) we transform the coefficients into more meaningful parameter space (e.g., probabilities for the condition at retrieval analysis) and provide confidence intervals and p-values in tabular form (Tables 11-13[6]).

We go through the analyses by fishery and analysis type.

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[6] Please note that for the condition analysis it is the relative change from the baseline which is important, not the absolute values.

4.1 Federated States of Micronesia / Marshall Islands longline fishery (M1)

4.1.1 Set-level catchability

Table 1: Significant variables from the <u>set-level catchability analysis for the FSM/RMI fishery (M1).</u>

	Set-level catch-rate models				
	Fishery	Species			
	Species	OCS	FAL	THR	BSH
Temporal	Year	Complex	Complex	Complex	Complex
	Month	Complex	Complex	Complex	Complex
"Key" variables	Wire Trace	NS	NS	NS	NS
	Shark Lines	Positive	Positive	NS	NS
	Hook Types	NS	NS	NS	NS
	Shark Bait	NS	Positive	NS	Positive
Further set characteristics	Trip ID				
	Set ID				
	Flag	NS	NS	NS	NS
	Set Start Time	Complex	Positive	Negative	NS
	Soak time	Complex	Positive	Negative	Complex
	Hooks between floats	Negative	Complex	NS	Complex
	Hook position				
Oceanographic	SST	Complex	Complex	Complex	Negative
	Height	NS	NS	Negative	Positive
	Current (u)	NS	Complex	Negative	Negative
	Current (v)	NS	Negative	Positive	NS
	Isodepth	Positive	Complex	Complex	Negative
	Wind Stress	Complex	NS	NS	Complex
	Latitude	Complex	Complex	Complex	Complex
	Longitude	Complex	Complex	Complex	Complex

Colour key

Not significant	NS
Significant and positive	Positive
Significant and negative	Negative
Significant and complex	Complex

The overall conclusions from this analysis were:

- Hook-type could not be considered due to a lack of contrast.
- Catch rates of OCS were significantly higher in the presence of shark-lines.
- Catch rates of FAL were significantly higher in the presence of shark-bait & shark-lines.
- There were no significant associations between THR catch-rates and the key gear variables.
- Catch rates of BSH were significantly higher in the presence of shark-bait.

4.1.2 Hook-level catchability

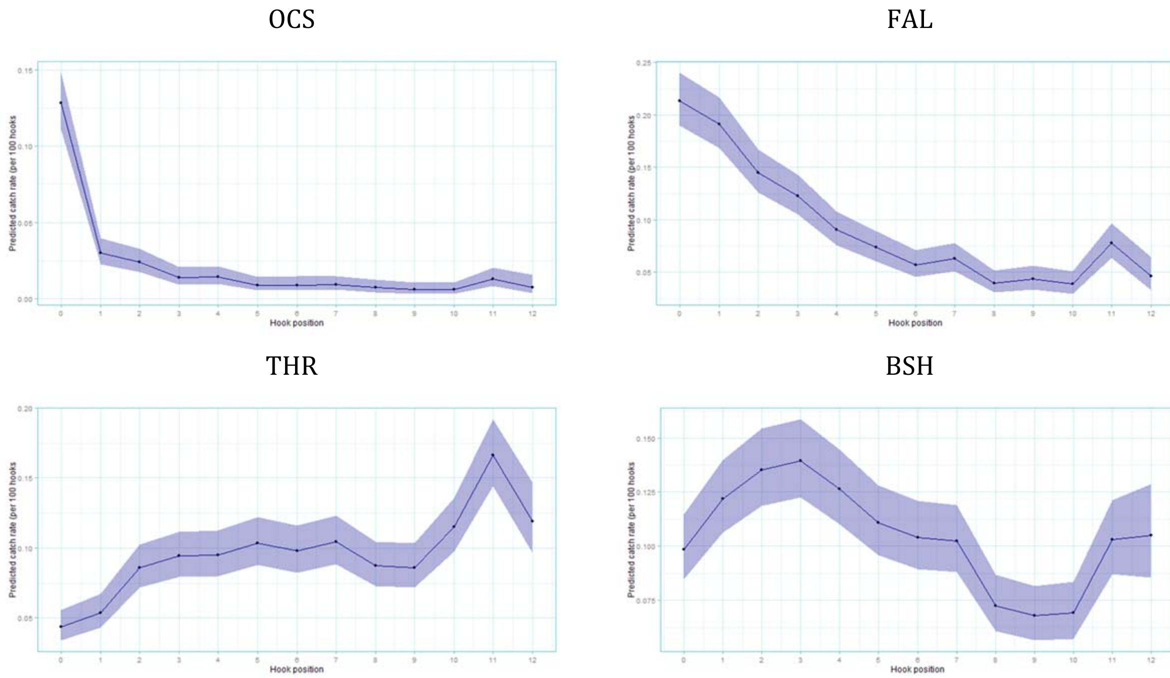

Figure 1: Estimated coefficients for the analysis of hook position on catchability for the FSM/RMI fishery (M1).

The overall conclusions from this analysis were:

- The catch-rates of OCS are significantly and markedly higher on the position 0 hooks. The catch rates are estimated to be 0.128 (95% CI: [0.11, 0.15]) per 100 hooks at position 0, dropping to 0.03 (95% CI [0.23, 0.39]) at position 1. This is approximately 47% (95% CI: [40%-54%]) of the total catch over the first 12 hook positions.
- The catch-rates of FAL differed significantly with hook-position, with a clear decreasing trend with increasing hook-position. The catch rates are estimated to be 0.214 (95% CI: [0.19, 0.24]) per 100 hooks at position 0, dropping to 0.19 (95% CI [0.17, 0.22]) at position 1. This is respectively 18% (95% CI: [15.7%-20%]) and 15.7% (95% CI: [14%-18%]) of the total catch over the first 12 hook positions.
- There was a generally increasing catch rate of THR with increasing hook-position, with position 0 being the lowest. The catch rates are estimated to be 0.044 (95% CI: [0.03, 0.06]) per 100 hooks at position 0. This is approximately 3.5% (95% CI: [2.7%-4.5%]) of the total catch over the first 12 hook positions.
- There was no monotonic trend of BSH catch rates with respect to hook position, with positions 2-4 being highest.
- The catch rates of BSH are estimated to be 0.099 (95% CI: [0.08, 0.11]) per 100 hooks at position 0, rising to 0.12 (95% CI [0.11, 0.14]) at position 1. This is respectively 7.3% (95% CI: [6.3%-8.5%]) and 9% (95% CI: [7.8%-10.3%]) of the total catch over the first 12 hook positions.

4.1.3 Condition on retrieval

Table 2: Significant variables from the analysis of <u>condition on retrieval for the FSM/RMI fishery (M1)</u>.

	Condition at retrieval models				
	Fishery	Species			
	Species	OCS	FAL	THR	BSH
Temporal	Year		Significant and complex	Significant and positive	
	Month				
"Key" variables	Wire Trace		Significant and positive		Significant and positive
	Shark Lines		Significant and positive	Significant and positive	Significant and positive
	Hook Types				
	Shark Bait				
Further set characteristics	Trip ID				
	Set ID				
	Flag				
	Set Start Time			Significant and negative	Significant and complex
	Soak time			Significant and positive	Significant and complex
	Hooks between floats		Significant and positive		
	Hook position				
Oceanographic	SST			Significant and complex	Significant and complex
	Height				Significant and complex
	Current (u)		Significant and complex		Significant and negative
	Current (v)			Significant and complex	
	Isodepth	Significant and complex			
	Wind Stress		Significant and complex		
	Latitude	Significant and complex	Significant and complex	Significant and complex	Significant and complex
	Longitude	Significant and complex	Significant and negative	Significant and complex	Significant and negative

Colour key
- Not significant
- Significant and positive
- Significant and negative
- Significant and complex

The overall conclusions from this analysis were:

- Hook-type could not be considered due to a lack of contrast.
- There were no significant effects on OCS mortality rates related to the key gear variables.
- The probability of being dead on retrieval was significantly higher for FAL under shark-lines and wire-traces.
- The probability of being dead on retrieval was significantly higher for THR under shark-lines.
- The probability of being dead on retrieval was significantly higher for BSH under shark-lines and wire-traces.

4.2 Fiji longline fishery (M2_Fiji)

4.2.1 Set-level catchability

Table 3: Significant variables from the <u>set-level catchability analysis for the Fiji fishery (M2_Fiji).</u>

	Set-level catch-rate models				
	Fishery	Species			
	Species	OCS	FAL	THR	BSH
Temporal	Year				
	Month				
"Key" variables	Wire Trace				
	Shark Lines				
	Hook Types				
	Shark Bait				
Further set characteristics	Trip ID				
	Set ID				
	Flag				
	Set Start Time				
	Soak time				
	Hooks between floats				
	Hook position				
Oceanographic	SST				
	Height				
	Current (u)				
	Current (v)				
	Isodepth				
	Wind Stress				
	Latitude				
	Longitude				

Colour key

Not significant

Significant and positive

Significant and negative

Significant and complex

The overall conclusions from this analysis were:

- Catch rates of OCS were significantly higher in the presence of wire-trace and shark-lines.
- Catch rates of OCS were significantly higher on type-C hooks compared to type-J hooks.
- Catch rates of THR were significantly higher on type-J hooks compared to type-C hooks.
- Catch rates of BSH were significantly higher in the presence of shark-lines.

4.2.2 Hook-level catchability

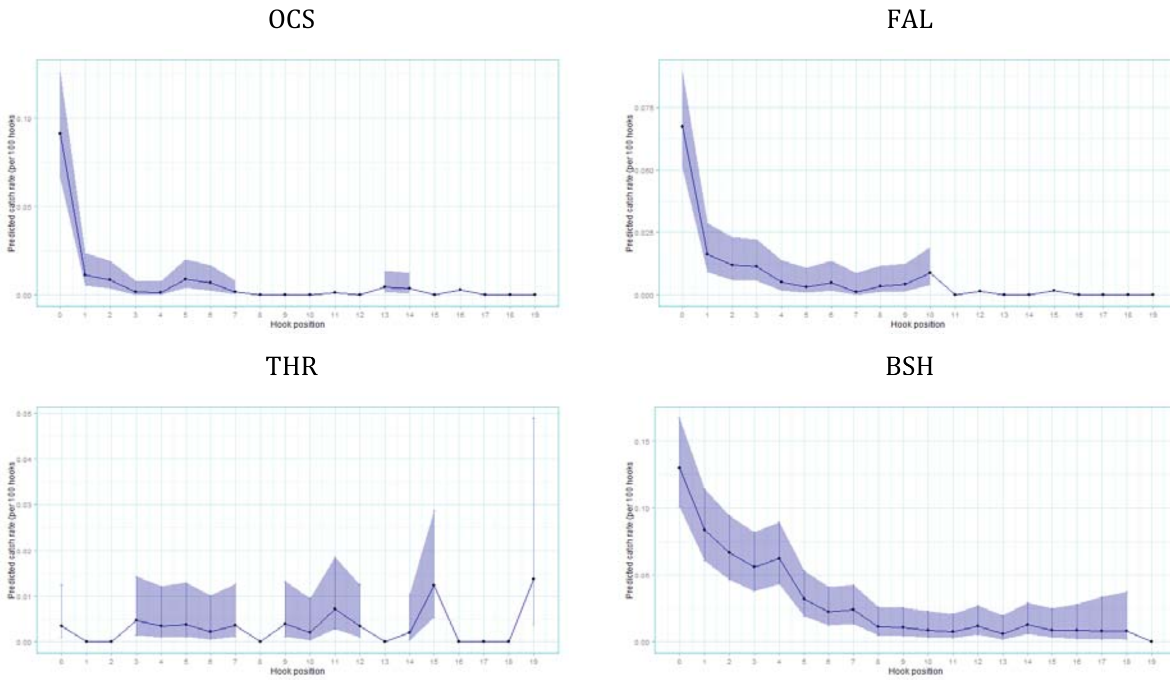

Figure 2: Estimated coefficients for the analysis of <u>hook position on catchability for the Fiji fishery (M2_Fiji)</u>.

The overall conclusions from this analysis were:

- There is a markedly higher catch rate for OCS at hook-position 0 compared to other positions. The catch rate at position 0 is 0.091 per 100 hooks [0.066 to 0.127, 95% CI]. This translates to approximately 63.2% [45.6% to 87.8%, 95% CI] of the catch of this species observed in this fisheries data. Beyond position 0, there is little clear pattern other than catches being generally near zero for positions 7+.
- The catch-rates of FAL differed significantly with hook-position, with a clear decreasing trend with increasing hook-position. The catch rates are estimated to be 0.067 (95% CI: [0.05, 0.09]) per 100 hooks at position 0, dropping to 0.016 (95% CI [0.009, 0.03]) at position 1. This is respectively 47.6% (95% CI: [35.6%-63.2%]) and 11.5% (95% CI: [6.5%-20.3%]) of the total catch over the first 19 hook positions.
- There was no particular trend catch rate of THR with increasing hook-position, with position 0 being relatively low. The catch rates are estimated to be 0.004 (95% CI: [0.001, 0.012]) per 100 hooks at position 0. This is approximately 5.3% (95% CI: [1.5%-18.8%]) of the total catch over the first 19 hook positions.
- There was a decreasing trend of BSH catch rates with respect to hook position. The catch rates of BSH are estimated to be 0.13 (95% CI: [0.1, 0.17]) per 100 hooks at position 0, falling to 0.08 (95% CI [0.06, 0.11]) at position 1. This is respectively 22.4% (95% CI: [17.3%-28.8%]) and 14.4% (95% CI: [10.5%-19.8%]) of the total catch over the first 19 hook positions.

4.2.3 Condition on retrieval

Table 4: Significant variables from the analysis of <u>condition on retrieval for the Fiji fishery (M2_Fiji)</u>.

	Condition at retrieval models				
	Fishery	Species			
	Species	OCS	FAL	THR	BSH
Temporal	Year				
	Month				
"Key" variables	Wire Trace				
	Shark Lines				
	Hook Types				
	Shark Bait				
Further set characteristics	Trip ID				
	Set ID				
	Flag				
	Set Start Time				
	Soak time				
	Hooks between floats				
	Hook position				
Oceanographic	SST				
	Height				
	Current (u)				
	Current (v)				
	Isodepth				
	Wind Stress				
	Latitude				
	Longitude				

Colour key

Not significant

Significant and positive

Significant and negative

Significant and complex

The overall conclusions from this analysis were:

- The probability of being dead on retrieval was significantly higher for OCS and BSH with type-J hooks, compared to type-C hooks.
- The probability of being dead on retrieval was significantly higher for BSH under shark-lines.

4.3 American Samoa longline fishery (M2_AS)

4.3.1 Set-level catchability

Table 5: Significant variables from the <u>set-level catchability analysis for the American Samoa fishery (M2_AS).</u>

		Set-level catch-rate models			
	Fishery	Species			
	Species	OCS	FAL	THR	BSH
Temporal	Year				
	Month				
"Key" variables	Wire Trace				
	Shark Lines				
	Hook Types				
	Shark Bait				
Further set characteristics	Trip ID				
	Set ID				
	Flag				
	Set Start Time				
	Soak time				
	Hooks between floats				
	Hook position				
Oceanographic	SST				
	Height				
	Current (u)				
	Current (v)				
	Isodepth				
	Wind Stress				
	Latitude				
	Longitude				

Colour key
Not significant
Significant and positive
Significant and negative
Significant and complex

The overall conclusions from this analysis were:

- Only hook-types could be contrasted.
- Catch rates of OCS and THR were significantly higher on circle hooks than tuna hooks.

4.3.2 Hook-level catchability

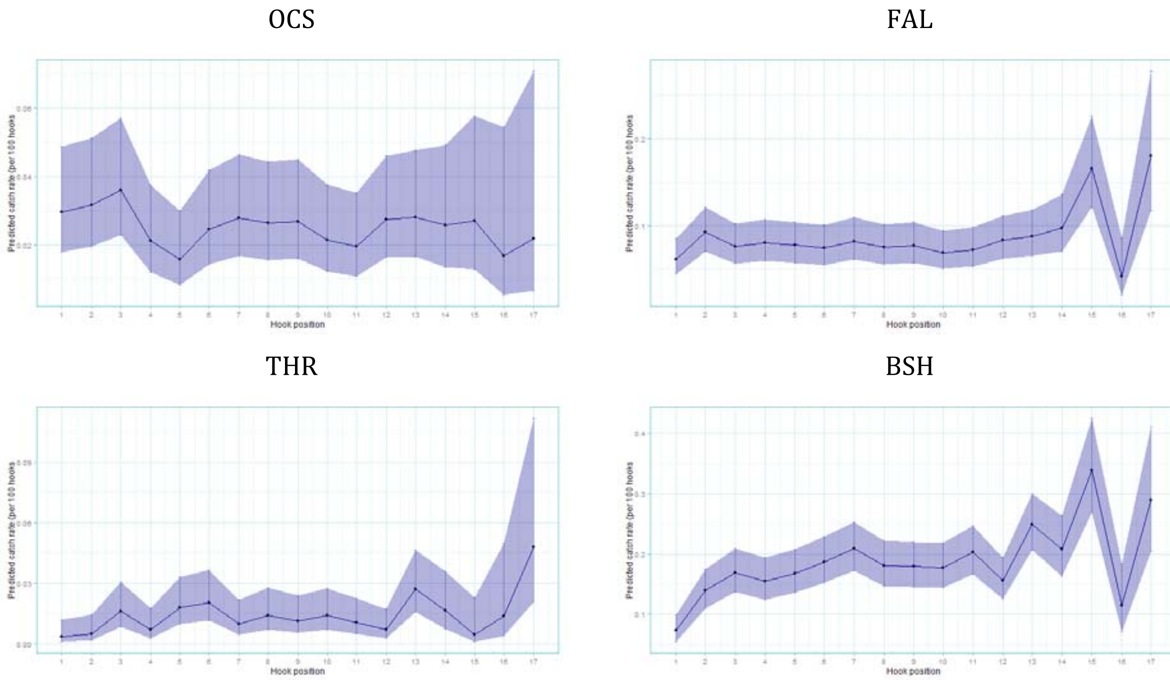

Figure 3: Estimated coefficients for the analysis of hook position on catchability for the American Samoa fishery (M2_AS).

The overall conclusions from this analysis were:

- There is no particular relationship between the hook-positions and the catch rates for OCS. The shallowest position (1) is estimated at 0.03 per 100 hooks [0.018 to 0.049, 95% CI]. This translates to approximately 6.9% [4.21% to 11.4%, 95% CI] of the catch of this species observed in this fisheries data.
- The catch-rates of FAL tended to be flat with respect to increasing hook position, with some marked fluctuations at the deeper positions (15 to 17). The shallowest position (1) is estimated at 0.06 per 100 hooks [0.044 to 0.085, 95% CI]. This translates to approximately 4.1% [2.95% to 5.7%, 95% CI] of the catch of this species observed in this fisheries data.
- The catch-rates of THR tended towards mild increases respect to increasing hook position, with some marked fluctuations at the deeper positions (13 to 17). The shallowest position (1) is estimated at 0.003 per 100 hooks [0.001 to 0.012, 95% CI]. This translates to approximately 1.4% [0.4% to 4.9%, 95% CI] of the catch of this species observed in this fisheries data.
- The catch-rates of BSH tended towards mild increases respect to increasing hook position, with some marked fluctuations at the deeper positions (13 to 17). The shallowest position (1) is estimated at 0.07 per 100 hooks [0.054 to 0.1, 95% CI]. This translates to approximately 2.3% [1.7% to 3.1%, 95% CI] of the catch of this species observed in this fisheries data.

4.3.3 Condition on retrieval

Table 6: Significant variables from the analysis of condition on retrieval for the American Samoa fishery (M2_AS).

		Condition at retrieval models			
	Fishery	Species			
	Species	OCS	FAL	THR	BSH
Temporal	Year	Not significant	Significant and negative	Not significant	Significant and negative
	Month	Not significant	Not significant	Not significant	Not significant
"Key" variables	Wire Trace				
	Shark Lines				
	Hook Types	Not significant	Not significant	Not significant	Not significant
	Shark Bait				
Further set characteristics	Trip ID				
	Set ID				
	Flag				
	Set Start Time	Not significant	Significant and complex	Not significant	Significant and complex
	Soak time	Significant and complex	Significant and positive	Not significant	Significant and complex
	Hooks between floats	Significant and complex	Not significant	Not significant	Significant and complex
	Hook position	Significant and complex	Significant and complex		Significant and complex
Oceanographic	SST	Not significant	Significant and complex	Not significant	Significant and complex
	Height	Not significant	Significant and complex	Not significant	Significant and complex
	Current (u)	Significant and positive	Significant and complex	Not significant	Significant and complex
	Current (v)	Significant and negative	Significant and complex	Not significant	Significant and complex
	Isodepth	Significant and complex	Significant and complex	Not significant	Significant and complex
	Wind Stress	Significant and negative	Significant and complex	Not significant	Significant and complex
	Latitude	Not significant	Significant and complex	Not significant	Significant and complex
	Longitude	Not significant	Significant and complex	Not significant	Significant and complex

Colour key
Not significant
Significant and positive
Significant and negative
Significant and complex

The overall conclusions from this analysis were:

- Only hook-type could be contrasted and there were no significant differences in terms of condition at retrieval for any species considered.

4.4 Hawaii deepset longline fishery (M7)

4.4.1 Set-level catchability

Table 7: Significant variables from the set-level catchability analysis for the Hawaii deepset fishery (M7).

		Set-level catch-rate models			
	Fishery	Species			
	Species	OCS	FAL	THR	BSH
Temporal	Year				
	Month				
"Key" variables	Wire Trace				
	Shark Lines				
	Hook Types				
	Shark Bait				
Further set characteristics	Trip ID				
	Set ID				
	Flag				
	Set Start Time				
	Soak time				
	Hooks between floats				
	Hook position				
Oceanographic	SST				
	Height				
	Current (u)				
	Current (v)				
	Isodepth				
	Wind Stress				
	Latitude				
	Longitude				

Colour key

Not significant

Significant and positive

Significant and negative

Significant and complex

The overall conclusions from this analysis were:

- Catch rates of OCS were significantly higher on type-C hooks compared to type-T hooks (with type-J being intermediate and not distinct from T in particular).
- Catch rates of BSH were significantly higher on type-J hooks compared to type-T and type-C hooks.
- Catch rates of OCS and BSH were significantly higher in the presence of wire-trace.

4.4.2 Hook-level catchability

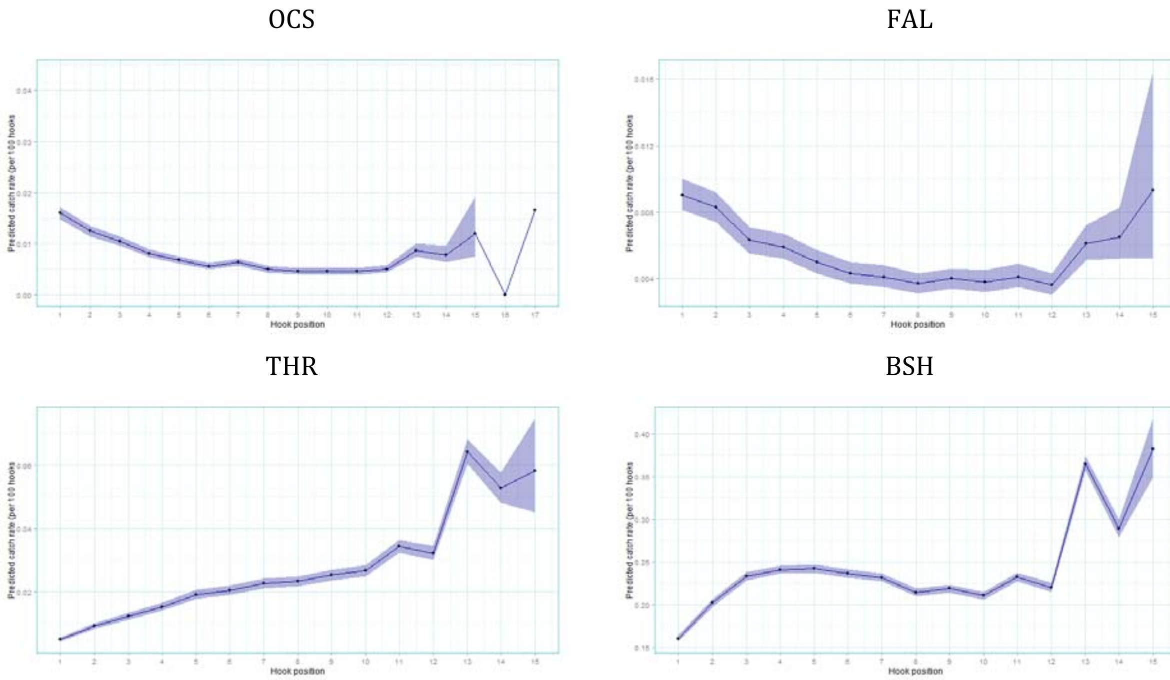

Figure 4: Estimated coefficients for the analysis of <u>hook position on catchability for the Hawaiian deepset longline fishery (M7)</u>.

The overall conclusions from this analysis were:

- There is no particular relationship between the hook-positions and the catch rates of OCS. The shallowest position (1) is estimated at 0.03 per 100 hooks [0.018 to 0.049, 95% CI]. This translates to approximately 6.9% [4.21% to 11.4%, 95% CI] of the catch of this species observed in this fisheries data.
- The catch-rates of FAL differed significantly with hook-position, tending to be high at both low and high hook-positions. The catch rates are estimated to be 0.009 (95% CI: [0.008, 0.01]) per 100 hooks at position 1, dropping to 0.008 (95% CI [0.007, 0.009]) at position 2. This is respectively 10.7% (95% CI: [9.7%-12%]) and 9.9% (95% CI: [8.8%-11%]) of the total catch over the first 15 hook positions. There was evidence of correlations in the errors unaccounted for in these models, likely giving confidence intervals that are spuriously narrow.
- There was a clear increasing catch rate of THR with increasing hook-position, with position 1 being the lowest. The catch rates are estimated to be 0.005 (95% CI: [0.004, 0.006]) per 100 hooks at position 1. This is approximately 1.2% (95% CI: [1%-1.3%]) of the total catch over the first 15 hook positions. There was evidence of correlations in the errors unaccounted for in these models, likely giving confidence intervals that are spuriously narrow.
- There was a clear increasing catch rate of BSH with increasing hook-position, with position 1 being the lowest. The catch rates are estimated to be 0.16 (95% CI: [0.156, 0.164]) per 100 hooks at position 1. This is approximately 4.3% (95% CI: [4.2%-4.5%]) of the total catch over the first 15 hook positions. There was evidence of correlations in the errors unaccounted for in these models, likely giving confidence intervals that are spuriously narrow.

4.4.3 Condition on retrieval

Table 8: Significant variables from the analysis of <u>condition on retrieval for the Hawaii deepset fishery (M7)</u>.

	Condition at retrieval models				
	Fishery	Species			
	Species	OCS	FAL	THR	BSH
Temporal	Year				
	Month				
"Key" variables	Wire Trace				
	Shark Lines				
	Hook Types				
	Shark Bait				
Further set characteristics	Trip ID				
	Set ID				
	Flag				
	Set Start Time				
	Soak time				
	Hooks between floats				
	Hook position				
Oceanographic	SST				
	Height				
	Current (u)				
	Current (v)				
	Isodepth				
	Wind Stress				
	Latitude				
	Longitude				

Colour key

Not significant

Significant and positive

Significant and negative

Significant and complex

The overall conclusions from this analysis were:

- ➢ The probability of being dead on retrieval was significantly lower for BSH with wire-traces.

5. Acknowledgements

We acknowledge NMFS for making Hawaiian and American Samoa observer data available for this analysis.

6. References

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Table 9: Species and fisheries under consideration for this study.

Species/Species groups	Fisheries
Oceanic whitetip (OCS)	Marshall Islands and Federated States of Micronesia (M1)
Silky shark (FAL)	Fiji (M2_Fiji)
Blue shark (BSH)	American Samoa (M2_AS)
Thresher sharks (THR)	Hawaii (deepset fishery only) (M7)

Table 10: Explanatory variables and corresponding abbreviations used in model structures throughout this preliminary report.

Variable	Abbreviation in modelling
Year (2008-2103)	yy
Month within year (1-12)	mm
Hook type (types C, J, T)	hook_type
Wire trace (yes/no)	wire_trace
Shark lines (yes/no)	nbshark_lines
Shark bait (yes/no)	sharkbait
Latitude (decimal)	lat
Longitude (decimal)	lon
Start time for set	set_start_time
Sea Surface Temperature (SST °C)	sst
Sea Surface Height (m)	height
Current speed (v and u, m/s)	vcur, ucur
Depth of 20^0C degree isotherm	isodepth
Wind stress (Newton/m^2)	windStress
Number of hooks between floats	hk_bt_flt
Number of hooks used on the set	hook_set
Position of the hook to nearest float	hook_pos
Soak time (hours)	soak

Table 11: Exponentiated link-scale parameter estimates, 95% confidence intervals and significance tests for key variables across the four species / species groups and four fisheries groupings for the set-level catch rate models. The model applied uses a log-link, so while the raw coefficients are additive for log-catch, those presented are multiplicative on the catch-rate scale. ***For example: for the M1 FM fishery, the OCS catch-rate multiplier for shark-lines (Y) is estimated at 3.39 (95% CI: 2.61, 4.39) indicating that a move from no shark-lines to presences of shark-lines, more than triples the catch rate. The 95% confidence bounds put this at a 2.6 to 4.4 times increase in catch-rates. The increase is highly statistically significant (p-value = 1.19×10-19).***

			Set level catch models															
			OCS				FAL				THR				BSH		
	Key variable		Estimate	Lower CI	Upper CI	*p*-value	Estimate	Lower CI	Upper CI	*p*-value	Estimate	Lower CI	Upper CI	*p*-value	Estimate	Lower CI	Upper CI
M1 FM	Wire trace																
	Shark lines		3.3867	2.6100	4.3900	0.0000	1.3851	1.1600	1.6600	0.0004							
	Hook types	Baseline															
	Shark bait						1.4029	1.0200	1.9200	0.0348					0.5595	0.4000	0.7800
M2 Fiji	Wire trace		20.9891	1.5600	282.1800	0.0221									3.0929	1.6100	5.9200
	Shark lines		3.5114	1.3000	9.5100	0.0138											
	Hook types	Baseline															
		Type J	0.2705	0.0900	0.8100	0.0202					2.9453	1.1000	7.9000	0.0324			
	Shark bait																
M2 AS	Wire trace																
	Shark lines																
	Hook types	Baseline															
		Type T	0.0946	0.0100	0.7200	0.0231					0.0592	0.0000	0.9700	0.0478			
	Shark bait																
M7 HW DP	Wire trace														1.2735	1.2400	1.3100
	Shark lines																
	Hook types																
		J	0.8159	0.6700	1.0000	0.0471									1.1300	1.0700	1.1900
		T	0.7864	0.6900	0.9000	0.0003									0.9694	0.9400	1.0000
	Shark bait																

Table 12: Link-scale parameter estimates, 95% confidence intervals and significance tests for key variables across the four species / species groups and four fisheries groupings. The model applied uses a logit-link so the coefficients are additive for log-odds (i.e., log(probability of mortality/1-probability of mortality)). To aid interpretation, these have been expressed as probabilities relative to a reference set of covariate values (within the red box).

			Condition models																	
			OCS					**FAL**					**THR**					**BSH**	
	Key variable		**Estimate**	**Lower CI**	**Upper CI**	***p*-value**		**Estimate**	**Lower CI**	**Upper CI**	***p*-value**		**Estimate**	**Lower CI**	**Upper CI**	***p*-value**		**Estimate**	**Lower CI**
M1 FM	**Wire trace**							1.7602	0.5821	2.9384	0.0034							2.4337	0.6802
	Shark lines							-0.6560	-0.9333	-0.3786	0.0000		-0.3490	-1.6754	-0.1912	0.0052		0.3899	0.0293
	Hook types	**Baseline**																	
	Shark bait																		
M2 Fiji	**Wire trace**																	10.6019	2.2456
	Shark lines																		
	Hook types	**Baseline [C]**																	
		Type J	3.3530	0.3550	6.3510	0.0284												6.4772	1.7909
	Shark bait																		
F2AS	**Wire trace**																		
	Shark lines																		
	Hook types	**Baseline**																	
		Type T																	
	Shark bait																		
M7 HW DP	**Wire trace**																	-0.2260	-0.3448
	Shark lines																		
	Hook types																		
		J																	
		T																	
	Shark bait																		
			baseline					baseline					baseline					baseline	
	M1_FM	**Intercept**	0.0833	-2.3982				**0.5765**	0.3084				**0.3054**	-0.8218				**0.7629**	1.1684
	M2_Fiji	**Intercept**	**0.4237**	-0.3076				0.0034	-5.6765				0.0000	-96.5187				**0.1013**	-2.1827
	M2_AS	**Intercept**	0.0000	-14.4235				0.3872	-0.4589				0.0000	-41.4928				0.4864	-0.0544
	M7_HD	**Intercept**	0.1834	-1.4933				0.0100	-4.5968				0.1397	-1.8177				**0.6342**	0.5503

Table 13: Shift in these probabilities of mortality when moving from one level of the key variables to another. Based on the coefficients and baseline probablities in Table 12. ***For example: for the M2 Fiji fishery, the baseline probability of OCS mortality is estimated at 0.4237 (see table above) and would increase to 0.95 (95% CI: 0.51, 0.998) when moving from circle to J hooks. The increase is statistically significant (p-value = 0.028). <u>The baseline is NOT the average mortality, but a prediction with other significant covariate included so only the relative change is relevant</u>.***

			Condition models (example probability)																	
			OCS					**FAL**					**THR**					**BSH**	
	Key variable		**Estimate**	**Lower CI**	**Upper CI**	***p*-value**		**Estimate**	**Lower CI**	**Upper CI**	***p*-value**		**Estimate**	**Lower CI**	**Upper CI**	***p*-value**		**Estimate**	**Lower CI**
M1 FM	**Wire trace**							0.8878	0.7090	0.9626	0.0034							0.9735	0.8640
	Shark lines							0.4140	0.3487	0.4825	0.0000		0.2367	0.0761	0.2664	0.0052		0.8261	0.7681
	Hook types	**Baseline**																	
	Shark bait																		
M2 Fiji	**Wire trace**																	0.9998	0.5157
	Shark lines																		
	Hook types	**Baseline [C]**																	
		Type J	0.9546	0.5119	0.9976	0.0284												0.9865	0.4033
	Shark bait																		
M2 AS	**Wire trace**																		
	Shark lines																		
	Hook types	**Baseline**																	
		Type T																	
	Shark bait																		
M& HW DP	**Wire trace**																	0.5804	0.5512
	Shark lines																		
	Hook types																		
		J																	
		T																	
	Shark bait																		

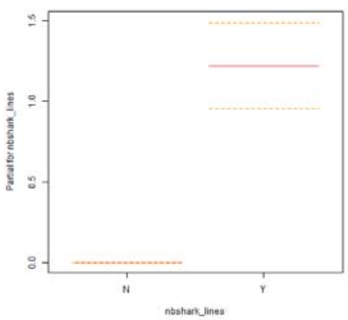
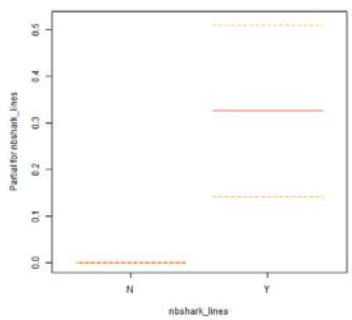
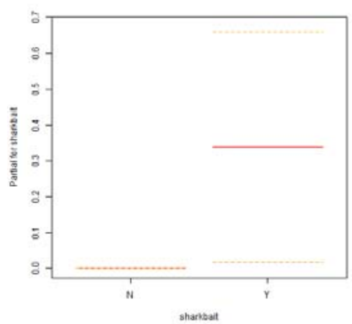
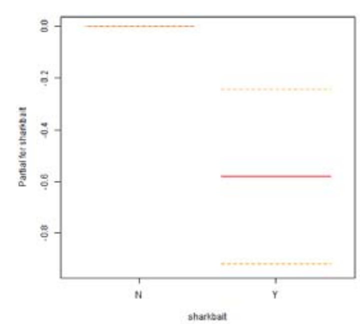
	OCS	FAL	THR	BSH
Wire trace				
Shark lines				
Hook_type				
Shark bait				

Figure 5: Parameter estimates and 95% confidence intervals for significant factors (p-value < 0.05) across the key variables for set-level catchability the FSM/RMI fishery (M1).

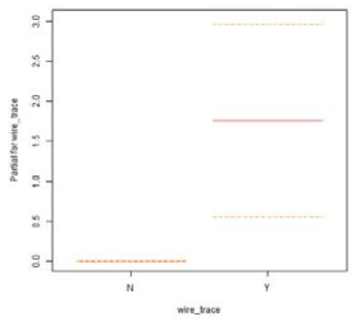
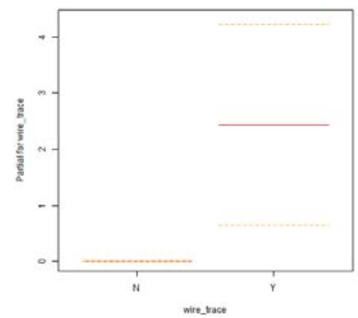
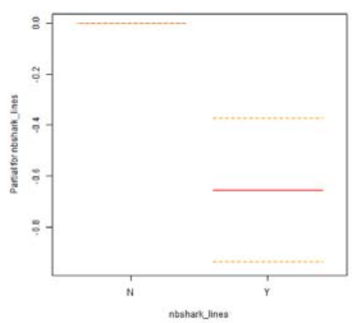
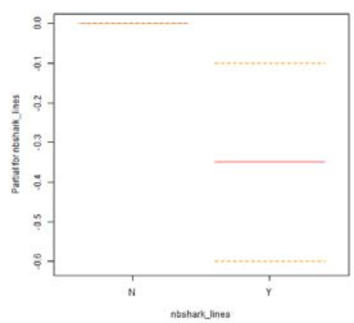
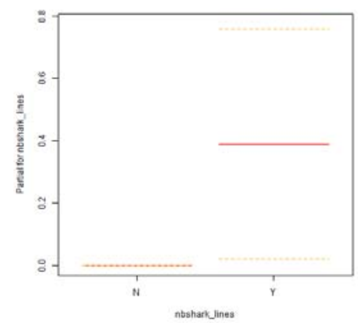
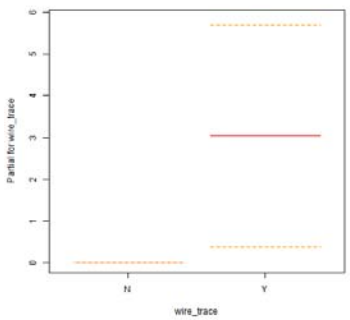
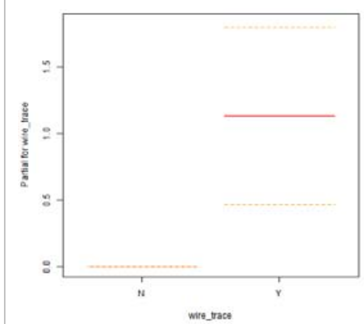
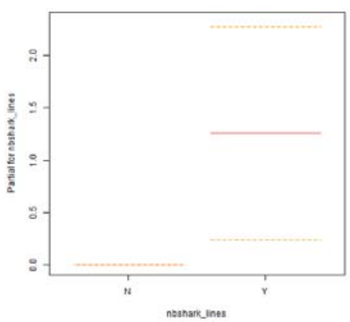
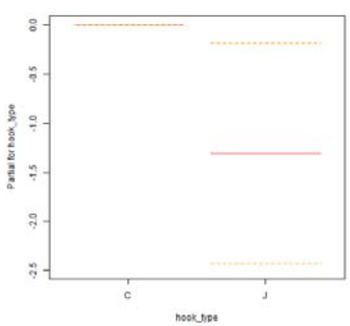
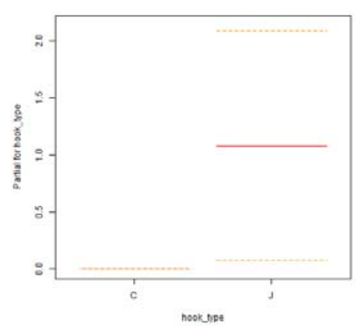
	OCS	FAL	THR	BSH
Wire trace				
Shark lines				
Hook_type				
Shark bait				

Figure 6: Parameter estimates and 95% confidence intervals for significant factors (p-value < 0.05) across the key variables for <u>hook-level condition on retrieval in the FSM/RMI fishery (M1)</u>.

	OCS	FAL	THR	BSH
Wire trace				
Shark lines				
Hook_type				

Shark bait				

Figure 7: Parameter estimates and 95% confidence intervals for significant factors (p-value < 0.05) across the key variables for set-level catchability the Fiji fishery (M2_Fiji).

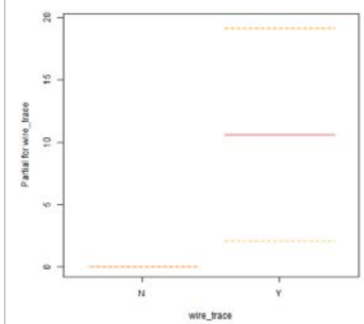
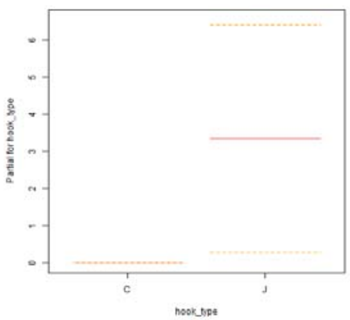
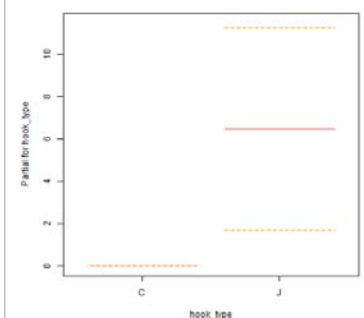
	OCS	FAL	THR	BSH
Wire trace				
Shark lines				
Hook_type				
Shark bait				

Figure 8: Parameter estimates and 95% confidence intervals for significant factors (p-value < 0.05) across the key variables for hook-level condition on retrieval in the Fiji fishery (M2_Fiji).

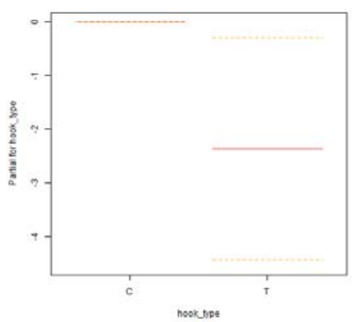
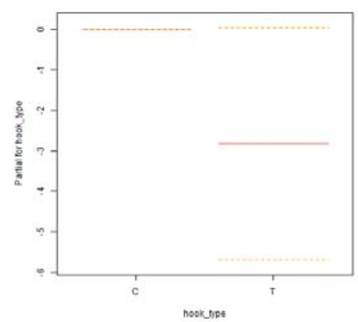
	OCS	FAL	THR	BSH
Wire trace				
Shark lines				
Hook_type				
Shark bait				

Figure 9: Parameter estimates and 95% confidence intervals for significant factors (p-value < 0.05) across the key variables for <u>set-level catchability the American Samoa fishery (M2_AS)</u>.

	OCS	FAL	THR	BSH
Wire trace				
Shark lines				
Hook types				
Shark bait				

Figure 10: Parameter estimates and 95% confidence intervals for significant factors (p-value < 0.05) across the key variables for hook-level condition on retrieval in the American Samoa fishery (M2_AS).

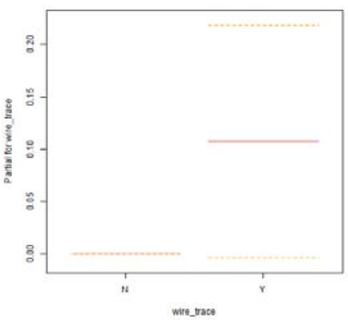
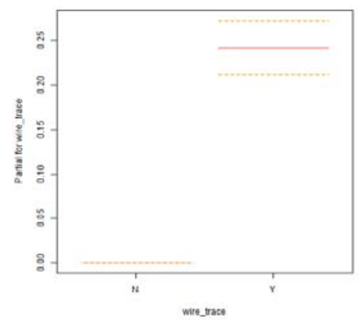
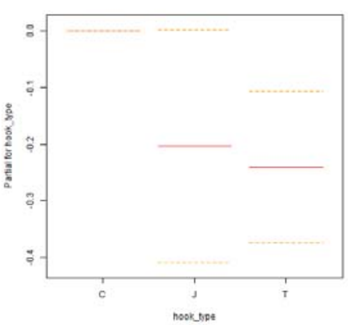
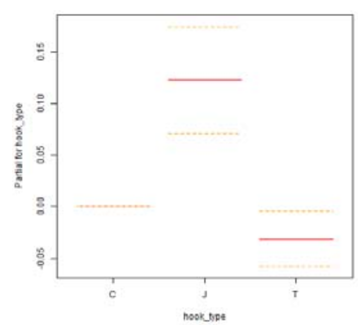
	OCS	FAL	THR	BSH
Wire trace				
Shark lines				
Hook_type				
Shark bait				

Figure 11: Parameter estimates and 95% confidence intervals for significant factors (p-value < 0.05) across the key variables for <u>set-level catchability the Hawaii deepset fishery (M7)</u>.

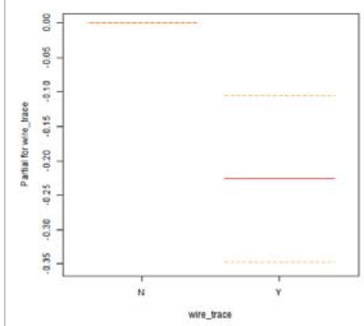
	OCS	FAL	THR	BSH
Wire trace				
Shark lines				
Hook_type				
Shark bait				

Figure 12: Parameter estimates and 95% confidence intervals for significant factors (p-value < 0.05) across the key variables for <u>hook-level condition on retrieval in the Hawaii deepset fishery (M7)</u>.