Statistical and Monte Carlo Analysis of the Hawaii Deep-Set Longline Fishery with Emphasis on Take and Mortality of Oceanic Whitetip Shark

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Abstract

The study developed a process model from pelagic observer data to describe the take and mortality of oceanic whitetip shark (OCS) in the Hawaii deep-set longline fishery. The process model considered the: 1) probability of interaction (Catch model #1); 2) probability of branchline bite-off (Catch model #2); 3) probability of mortality at retrieval (Fate model #1); 4) probability of mortality due to handling between retrieval and release (Fate model #2); and 5) probability of post-release mortality and mortality of bite-off (Fate model #3). Three scenarios were considered for the OCS process models: 1) the current fishery use of using wire leaders and leaving ~10 m of trailing gear on a released shark (Scenario 1-Status quo); 2) intended use of monofilament, removing all trailing gear (0 m) on a released shark (Scenario 2-Monofilament leaders); and 3) intended use of monofilament, removing all trailing gear (0 m) on a released shark and gear modification by eliminating three hooks adjacent to longline floats (Scenario 3-Monofilament leaders and gear modification). Monte Carlo simulations were conducted for each of the three scenarios. The annual anticipated take level (ATL) for OCS has a mean of 1,708. Mortality at longline retrieval averaged 19.2% (95% CI, 13.1%–27.3%). There was a positive benefit of a reduced catchability for OCS estimated from the voluntary transition from branchlines that have 1 m of wire leader at the terminal end to branchlines being entirely composed of monofilament. Median estimates of annual OCS catch were 1,708 for the status quo, 1,153 for monofilament leaders, and 678 with monofilament leaders and no shallow hooks deployed. Median estimates of annual mortality were 362 for the status quo, 255 with monofilament leaders, and 150 with monofilament leaders and no shallow hooks deployed. The transition from wire to monofilament leaders was estimated to have a 32% and 30% reduction in catch and mortality, respectively. The lowest OCS catch and mortality occurred with monofilament leaders and no shallow hooks deployed; however, a large revenue decrease occurs when no shallow hooks are used due to reduced catch of target and incidental species.

Introduction

Oceanic whitetip sharks (*Carcharhinus longimanus*, OCS) are caught as bycatch in tropical tuna purse seine and longline fisheries. Catches of OCS have declined in both the Western and Central Pacific Fisheries Commission (WCPFC) and the Inter-American Tropical Tuna Commission (I-ATTC), organizations responsible for the conservation and management of tuna and other marine resources in the Pacific Ocean. An OCS stock assessment from 1995 to 2016 in the western and central Pacific Ocean (WCPO) demonstrated that the stock was overfished, and overfishing was occurring relative to commonly used depletion and MSY-based reference points (Tremblay-Boyer et al. 2019). There is no OCS assessment in the I-ATTC convention area. The OCS was once common in the I-ATTC tropical purse seine fishery and comprised 9% of the shark catch in numbers from 1993 to 2009, though catches are rare since 2005 (Hall and Ramon 2013). In addition to depletion in the WCPFC and I-ATTC convention areas, a status

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review concluded that oceanic whitetip sharks across tropical waters across all oceans had considerable historical declines (Young et al. 2017; Young and Carlson 2020).

The WCPFC has adopted two Conservation and Management Measures (CMM2011-04 and CMM2019-04) that include a non-retention policy for OCS across the WCPFC Convention Area. The I-ATTC adopted a management measure to prohibit the retention of oceanic whitetip shark in the eastern Pacific Ocean (I-ATTC 2011). The OCS is listed as 'threatened' under the U.S. Endangered Species Act. There are management measures in place that prohibit OCS retention; however, there is uncertainty in longline catches due to low (~5%) observer coverage. Further population declines may occur due to high mortality rates in purse seine fisheries and unknown post-release mortality (PRM) in purse seine and longline fisheries.

The WCPFC adopted CMM2014-05 (superseded by 2019-04), whereby longline fisheries targeting tuna and billfish comply with either: 1) do not use or carry wire trace as branchlines or leaders; or 2) do not use branchlines running directly off the longline floats or drop lines, known as shark lines. Harley et al. (2015) conducted Monte Carlo simulation modeling for potential measures to reduce impacts to OCS and silky sharks (*C. falciformis*) in the WCPO. The study considered: 1) banning of shark lines and removal of shallow hooks to reduce the initial interactions with longline gear, 2) banning wire leaders to increase the ability of sharks to bite-off the leader, and 3) conversion of tuna hooks to circle hooks. Harley et al. (2015) concluded that either banning shark lines or wire traces (leaders) would not result in sufficient reductions in fishing mortality.

The purpose of this study is to develop an OCS process model and Monte Carlo analysis in a similar framework as Harley et al. (2015) to improve understanding of initial interactions, catch, fate, and potential mitigation methods. Analyses are applied to the Hawaii-permitted deep-set longline fishery, which is defined as deploying 15 or greater hooks between floats. The deep-set fishery is the largest fishery within the jurisdiction of the Western Pacific Regional Fishery Management Council (Council), with 150 active vessels that deployed a record 63,526,030 hooks in 2019 (Pacific Islands Fisheries Science Center 2020). The anticipated take level (ATL) for protected species is estimated from observer data which annually represent 20% coverage of the deep-set fishery. The OCS ATL is estimated to have a mean of 1,708.2 and 95th percentile of 3,185 individuals per year, assuming a similar condition of the fishery from 2013–2017 (McCracken 2019).

One objective of the study was to evaluate changes in species catchability in the deep-set longline fishery due to conversion from branchlines that have 1 m of wire leader at the terminal end to branchlines being entirely composed of monofilament. The Hawaii Longline Association announced in December 2020 that their member vessels would voluntarily eliminate the use of wire leaders by July 1, 2021 and use monofilament nylon leaders or other similar materials. The Council is considering a regulatory change to prohibit the use of wire leaders that would be implemented after the fleet's voluntary transition. Statistical results on anticipated effects in a conversion from wire to monofilament leaders for a variety of species may be of value for the regulatory amendment.

Methods

The analysis developed a process model for OCS that included catch components as the number of fish encountering the gear and fate components on the mortality after a gear interaction. The OCS is designated as a shark pelagic management unit species (PMUS) within the Council's Fishery Ecosystem Plan. Catch models were also conducted for tuna PMUS (albacore (*Thunnus alalunga*), bigeye tuna (*T.*

obesus), skipjack tuna (*Katsuwonus* pelamis), and yellowfin tuna (*T. albacares*)), billfish PMUS (swordfish (*Xiphias gladius*), blue marlin (*Makaira nigricans*), shortbill spearfish (*Tetrapturus angustirostris*), and striped marlin (*Kajikia audax*)), other PMUS (mahimahi (*Coryphaena spp*), opah (*Lampris guttatus*), and ono (*Acanthocybium solandri*)), and other shark PMUS (blue shark (*Prionace glauca*), bigeye thresher shark (*Alopias superciliosus*), shortfin mako shark (*Isurus oxyrinchus*), and OCS).

Data

Analyses were conducted from observed longline trips by the Pacific Islands Region Observer Program (PIROP, Pacific Islands Regional Office 2021), which commenced in 1994. Observer data pertinent to the study included catch by species, location (latitude and longitude), hook type (tuna, J, or circle), sequential hook number of capture between two floats, condition at longline retrieval, catch disposition (retained, discarded) and condition if released, and daily tally of hooks deployed (longline effort).

The Hawaii-permitted longline fisheries correspond to deep daytime sets (≥ 15 hooks between floats) targeting bigeye tuna and shallow nighttime sets (< 15 hooks between floats) targeting swordfish. Both sectors have changed operational characteristics through time due to regulations addressing mitigation of protected species (e.g., sea turtles, seabirds, and marine mammals). Analyses considered deep-set fishery data from 2005 to 2019 based on observer and OCS considerations as: 1) there was relatively low observer coverage prior to 2000, 2) a higher relative abundance of OCS from 1995 to 2000 (Brodziak and Walsh 2013), which may bias operational (branchline leader and hook) effects, 3) prior to 2000, the deep-set sector fished at southern low latitudes in which more OCS occur, and 4) the shallow-set sector almost exclusively uses monofilament branchlines; thus, there is no contrast in branchline material.

The deep-set fishery used tuna hooks and wire leaders between 1994 and 2012 (Figure 1). Circle hooks and wire leader usage started in the deep-set fishery in 2005, and circle hooks were mandated for false killer whale mitigation measures (77 FR 71260) effective December 31, 2012. Catchability and condition at longline retrieval can be related to hook type. Shark bite-off on monofilament leaders is thought to be more frequent on tuna or J-hooks due to their tendency to have a higher deep hooking rate of throat or gut hooking. Circle hooks have been promoted to increase survival in hook and line fisheries (e.g., recreational, longline) by having a higher proportion of mouth or jaw hooking (Afonso et al. 2012; Ward et al. 2008). This study examined longline sets that used only circle hooks, as sets with tuna and J-hooks may have confounded the catchability estimates.

The final data set contained 41,982 longline sets after removing data from 1994 to 2004 and eliminating missing fields or questionable data entries. Data filtering is illustrated in Appendix 1.

Statistical estimation of the catch and fate models

The OCS process model estimated the:

1) probability of interaction (Catch model #1);
2) probability of branchline bite-off (Catch model #2);
3) probability of mortality at retrieval (Fate model #1);
4) probability of mortality due to handling between retrieval and release (Fate model #2); and
5) probability of post-release mortality and mortality of bite-off (Fate model #3).

Three scenarios were considered for the five OCS process models:

1) The current fishery use of using wire leaders and leaving ~10 m of trailing gear on a released shark (Scenario 1-Status quo);
2) Intended use of monofilament, removing all trailing gear (0 m) on a released shark (Scenario 2-Monofilament leaders);
3) Intended use of monofilament, removing all trailing gear (0 m) on a released shark and gear modification by eliminating three hooks adjacent to longline floats (Scenario 3-Monofilament leaders and gear modification).

Catch model #1–Probability of interaction

The probability of initial interaction can be modified by modeling the hypothetical reduction of target, incidental catch, and bycatch by eliminating hooks adjacent to longline floats (Scenario 3). This essentially reduces a species catchability given the joint distribution in vertical profiles of gear depth and species distribution. Observer data were used on hook number of a species capture.

Longline sets had hooks between floats (HBF) that considered a range from 15 to 34 as there were few sets with > 34 HBF. Catch events were deleted if the hook number exceeded the HBF. Hooks were numbered such that hook 1 was the shallowest (closest to the surface) and hook 17 was the deepest. The deepest hook position or catenary hook was in the middle of each section of hooks, so the numbers were symmetrical increasing from hook 1 adjacent to the float to the deepest hook.

Generalized Additive Models (GAMs) were used to model catch rates by hook number for the 15 PMUS. For each species, GAMs predict mean catch (μ_i) as the number of individuals using a smoothing spline on hook position with a log link function as:

$$\log(\mu_i)= N_i+\mathrm{s}(Hook\_number_i)+log(E_i) \qquad \text{(Eq. 1)}$$

where N is the mean local abundance; $Hook\_number$ is the catch of individuals, and offset E is the number of hooks deployed at $Hook\_number$ during longline set i. The GAMs were fitted in R (Version 3.6.2) and considered a Poisson and negative binomial response distributions. Model selection was conducted by AIC and BIC.

Catch model #2 – Probability of branchline bite-off

Generalized Linear Models (GLMs) were used to model catch rates for the 15 PMUS. The model structure was based on explanatory variables in standardizing OCS CPUE in Brodziak and Walsh (2013) with slight modification. For each species, GLMs predict mean catch (μ_i) as the number of individuals using four categorical and two continuous variables with a log link function:

$$\log(\mu_i)= N_i+Y_i+M_i+Region_i+\beta_1Lat_i+\beta_2Lat_i^2+\beta_3Lat_i^3+\beta_4Lon_i+\beta_5Lon_i^2+\beta_6Lon_i^3+SST_i+Leader_i+log(E_i) \qquad \text{(Eq. 2)}$$

where N is the mean local abundance; Y is the year effect; M is the month effect; R is the region effect from the spatial structure in Brodziak and Walsh (2013); *Lat* and *Lon* are third order (cubic) effects of latitude and longitude, SST is sea surface temperature (https://oceanwatch.pifsc.noaa.gov/erddap/griddap/CRW_sst_v1_0_monthly.csv?analysed_sst), *Leader* is the leader type (wire or monofilament) and offset, E is the number of hooks deployed during longline set i. The GLMs considered a Poisson, negative binomial, and both zero inflated Poisson and negative binomial response distributions. Model selection was conducted by AIC and BIC.

Fate model #1 – Probability of mortality at retrieval – OCS

GLMs predict the probability of OCS alive or dead at longline retrieval using the four categorical and three continuous variables in Eq. 2 with a logit-link binomial distribution. Observer data on condition at retrieval (CAUGHT_COND_CODE) include A–alive and active, AG–alive and good, AI–alive and injured, and D–dead. The alive probability was considered as the aggregation of A, AG, and AI.

Fate model #2 – Probability of mortality due to vessel handling between retrieval and release

Observer data on disposition (KEPT_RETURN_CODE) include the same CAUGHT_COND_CODEs with the addition of K – kept. Vessel handling mortality can be estimated from the alive OCS condition at retrieval and alive condition at release. There were 2,605 and 2,567 OCS alive at retrieval and released, respectively. From 2005 to 2013, there were 23 OCS kept; 15 were alive upon retrieval, and alive or dead upon release is unknown. The maximum vessel handling mortality would be 1.45%, assuming that the kept OCS would be dead (100*(1-2,567/2,605)). The minimum vessel handling mortality would be 0.88%, assuming that the kept OCS would have been alive (100*(1-2,582/2,605)). The Monte Carlo analysis for Fate Model #2 assumed the point estimate of 1.45% for the maximum vessel handling mortality.

Fate model #3 – Probability of post-release mortality

Estimates of PRM were available from a large electronic tagging study on five species (blue, bigeye thresher, oceanic whitetip, shortfin mako, and silky sharks) of pelagic sharks in the Hawaii deep-set and American Samoa longline fisheries in the central Pacific Ocean (Hutchinson et al. 2021). The study illustrated post-release survival rates at 1, 30, 60, 180, and 360 days. Results indicated high survival for 1 to 60 days if the sharks are in good condition at release, the branchline is cut to release them from the gear, and trailing gear is minimized. A time-period of 60 days was considered as the most appropriate of the five time points to use in the Monte Carlo analysis. Two distributions were used to characterize OCS probability of PRM with: 1) wire leaders and leaving ~10 m of trailing gear on a released shark (Scenario 1-Status quo) and 2) with monofilament leaders and removing all trailing gear (0 m) on a released shark (Scenarios 2 and 3). The median PRM after 60 days for wire leaders and leaving ~10 m of trailing gear on a released shark is 0.08 and 0.03 for monofilament leaders with removing all trailing gear (0 m) on a released shark (Hutchinson et al. 2021, Table 8).

Estimates of PRM (monofilament leaders and removing all trailing gear (0 m) on a released shark) were also applied to individuals with branchline bite-off in Catch model #2. Harley et al. (2015) assumed a probability of mortality given bite-off as a beta distribution with a mean of 0.0323 for lip-hooked sharks and a mean of 0.0625 for gut-hooked sharks.

Monte Carlo simulations

Monte Carlo simulations were conducted for the five aspects within the OCS process model to assess the number of OCS initial interactions with longline gear and at vessel retrieval along with mortality at various fate components. Simulations assumed that 1,708 OCS initially encountered the gear based on the mean anticipated take level, which is the mean of the posterior (estimated) distribution of annual take levels under similar conditions of the fishery from 2013–2017 (McCracken 2019). A value of 1,708.2 is relatively close to a value of 1,650 OCS based on an annual effort of ~55 million hooks (2015–2019) in the deep-set fishery with a catch rate of 0.03 OCS per 1,000 hooks (2005–2019). Simulations were conducted for the catch components (#1 and #2) for the remaining 14 PMUS to assess reductions in target, incidental catch, and bycatch. Input distributions (below) were generated from the catch (#1 and #2) and fate (#1 and #3) models and sampled 10,000 times with replacement; therefore, each simulation has different draws from each input distribution.

Predictions were estimated from the parameter values (mean and standard deviation) from the GAMs (Catch model #1–Probability of interaction) and GLMs (Catch model #2–Probability of branchline bite-off and Fate model #1–Probability of mortality at retrieval), and input distributions with 10,000 values were generated. The probability of interaction considered GAM predictions of CPUE (catch per 1,000 hooks) for hook positions 1 to 17. An input distribution of 10,000 values was generated for each hook distribution. Hooks were hypothetically eliminated from the three shallowest positions adjacent to longline floats or a total of six hooks between longline floats. The probability of interactions from the three hooks was combined as an input distribution of shallow (1–3) and deep (4–17) hook catchability. Similarly, the probability of branchline bite-off and probability of mortality at retrieval provided an input distribution with 10,000 values. The probability of mortality due to vessel handling between retrieval and release was assumed as a static 1.45% with no distribution. Two input distributions of the posterior distribution of post-release survival were provided from Hutchinson et al. (2021).

Economic impact

The potential economic impact of revenue gain or loss was considered for the: 1) transition from wire to monofilament leader material and 2) transition from wire to monofilament leader and no use of shallow hooks. The average (2015–2019) economic revenue for PMUS in the deep-set fishery was obtained from estimates supporting the SAFE report (Appendix 2).

For transition from wire to monofilament leader material, estimates were obtained by considering the mean and 95% confidence interval estimates of all (significant and non-significant) monofilament coefficients from Catch model #2. For transition from wire to monofilament leader and elimination of no shallow hooks, the reduced catchability for deep (4–17) hooks for various PMUS in Catch model #1 was multiplied by the mean and 95% confidence interval estimates of all (significant and non-significant) monofilament coefficients from Catch model #2. Economic impact was not conducted for any shark species. Sharks may have reduced catchability in Catch models #1 or #2; however, these species are infrequently retained, and any catch rate reductions can be offset by retaining caught individuals. Economic impact was not conducted for pomfrets or oilfishes as revenue is illustrated as assemblages and does not pertain to individual species that could be modeled by GAMs and GLMs.

Results

Analyses considered 41,982 longline sets with 105,915,205 hooks. There was an imbalance in leader material as sets with wire leaders comprised ~95% of the total sets from 2005 to 2019 (Table 1). There were 1,330,592 individuals in the 15 PMUS captured (Table 2) and dominated by bigeye tuna and blue shark. OCS was the least captured species with a total of 3,346 captured in the 15-year time-series with fewer captures on monofilament (146) compared to wire leaders (3,200; Table 3).

Catch model #1 – Probability of interaction

Observers recorded hook position for 95.6% of the PMUS caught (Table 2). Convergence of the GAMs was achieved for all species. A negative binomial distribution with an estimated scale parameter was statistically preferred over a Poisson distribution based on AIC and BIC. Twenty-five HBF was the most common gear configuration; therefore, CPUE predictions at hook numbers 14 to 17 had larger variance (Figures 2, 3).

The probability of interaction of shallow (1–3) and deep (4–17) hooks differed among species (Table 4). Opah had the lowest probability of interaction (0.053) on shallow hooks, while shortbill spearfish had the highest (0.613). Billfishes consistently had a high probability of interactions on shallow hooks (range 0.337–0.613). The probabilities of interaction by hook number are illustrated for the 15 PMUS in Figures 2–3. As an example, OCS had a 0.411 probability of interaction on shallow hooks with CPUE declining to hook number 11 and stability thereafter (Figure 3).

Catch model #2 – Probability of branchline bite-off

The GLM with a negative binomial distribution converged for all species with the exception of albacore which was fit with a Poisson distribution. There were convergence problems when using zero-inflated Poisson and negative binomial distributions. All four categorical and three continuous variables were included in the GLMs with a negative binomial distribution. There was collinearity with the SST and latitude variables, but both were included in the final model as delta AIC differences without SST were moderate (mean=205) for all species. There were no patterns in the Pearson residuals of the negative binominal GLMMs when plotted against fitted values. For OCS in particular, Pearson residuals indicate 19 residuals with values > 15. There was no attempt to remove these from the OCS data as final results are unlikely to have a numerical difference in estimated coefficients.

GLM results are illustrated in Table 5. GLM coefficients for monofilament leaders indicated one species (swordfish) with statistically significant ($p<0.001$) higher catchability, five species (albacore, skipjack tuna, mahimahi, blue shark and shortfin mako shark) with statistically significant ($p\leq0.05$) lower catchability and nine species (bigeye tuna, yellowfin tuna, blue marlin, shortbill spearfish, striped marlin, ono, opah, oceanic whitetip shark, and bigeye thresher shark) with no statistically significant ($p>0.05$) catchability. Monofilament catchability distributions were generated for the 15 PMUS (Figures 4, 5, 6, 7).

Fate model #1 – Probability of mortality at retrieval – OCS

The GLM with a binomial distribution converged for OCS and included variables of Year, Region and Longitude. There was no significant difference ($p=0.737$) in mortality at retrieval due to leader material. Mortality at retrieval averaged 19.2% (95% C.I. 13.1%-27.3%) for OCS and the distribution is illustrated in Figure 8.

Fate model #3 – Probability of post-release mortality

Two distributions were used to characterize OCS probability of PRM with: 1) wire leaders and leaving ~10 m of trailing gear on a released shark (Scenario 1-Status quo) and 2) with monofilament leaders and removing all trailing gear (0 m) on a released shark (Scenarios 2 and 3). The median PRM after 60 days for wire leaders and leaving ~10 m of trailing gear on a released shark is 0.08 and 0.03 for monofilament leaders with removing all trailing gear (0 m) on a released shark. The distributions of survival (1-mortality) are illustrated in Figure 9.

Monte Carlo simulations

There were 29 input distributions to characterize uncertainty—15 probabilities of interaction, 11 probabilities of branchline bite-off, one probability of mortality at retrieval, and two probabilities of

PRM. Monofilament catchability distributions were generated for the 15 PMUS (Figures 4, 5, 6, 7) and 11 were subsequently used due to various difficulties in modeling shark species. The intent was to model the OCS monofilament catchability; however, the study used the distribution for shortfin mako given the following considerations:

1) The catch of OCS on monofilament leaders was small (n=146) during 2005–2019 and provided little contrast with wire leaders.
2) The preference would be to estimate catchability for a congener species such as silky shark (*C. falciformis*); however, this species catch on monofilament leaders was also small (n=200) during 2005–2019.
3) Bigeye thresher shark can be tail hooked instead of mouth hooked; therefore, the coefficients may not represent the ability to bite-off.
4) Shortfin mako had a larger catch on monofilament (n=340) during 2005–2019.
5) Blue shark were the most frequently caught shark species on monofilament (n=8,185) during 2005–2019. There is a non-significant leader coefficient for blue shark, which is probably valid given the catch size.

See the Discussion section for additional rationale based on dentition and activity for assuming shortfin mako catchability for OCS.

The Monte Carlo simulations provided 12 output distributions based on the three scenarios. Estimates of catch and mortality in each stage of the process model are provided in Table 6. The distribution of total mortality for each scenario in the Monte Carlo simulations is illustrated in Figure 10. Median estimates of annual OCS catch were 1,708 for the status quo, 1,153 for monofilament leaders and 678 with monofilament leaders and no shallow hooks deployed. Median estimates of annual mortality were 362 for the status quo, 255 with monofilament leaders, and 150 with monofilament leaders and no shallow hooks deployed. The transition from wire to monofilament leaders was estimated to have a 32% and 30% reduction in catch and mortality, respectively.

Economic impact

The average (2015–2019) economic revenue in the deep-set fishery was $96,149,793 (Appendix 2). The actual revenue estimate for the Hawaii-permitted deep-set fleet is higher as the ~$96 million pertains to only fish landed in Hawaii and does not incorporate Hawaii-permitted vessels landing in California where revenue is unknown. The economic impact for a transition from wire to monofilament leaders is estimated as a mean increase of $2,660,879 (95% CI, 1,750,655–7,333,064; Table 7). The increase of ~2.6 million is largely represented by the increase of $1,840,802 for bigeye tuna with a monofilament coefficient of 1.027 or 2.7% increase. A large revenue decrease occurs with no shallow hooks. The economic impact for transition from wire to monofilament leaders and no shallow hooks is estimated as a mean decrease of $11,515,176 (95% CI, 7,682,133-15,140,908; Table 8). The revenue decrease results from the reduced catchability of tuna, billfish, and incidental species.

Discussion

The OCS process model and subsequent Monte Carlo simulations were based on a relatively large observer data set with greater than 40,000 longline sets monitored and rigorous PRM estimates from 224 sharks tagged in the Hawaii and A. Samoa longline fisheries. The Harley et al. (2015) Monte Carlo study was based on the broader western and central Pacific Ocean and noted that critical gaps existed in gear configurations and a paucity or absence of observer data pertaining to the major distant-water fleets (e.g., Japan, Korea, Taiwan, and China). This study was based on one deep-set fishery and should represent more informed assumptions and parameter distributions with less uncertainty in the Monte Carlo simulations.

The transition from wire to monofilament leaders was estimated to have a statistically significant effect on catchability for some species, no difference in OCS at-vessel mortality, and a negligible effect on fishery economic revenue. The transition from wire to monofilament leaders was estimated to have a 32% and 30% reduction in OCS catch and mortality, respectively. The study applied the shortfin mako leader catchability to the OCS simulations; therefore, this assumption of a 32% catchability reduction may influence the results. The rationale for making this assumption was detailed in the Results section.

Additionally, expert opinion (M. Hutchinson, pers. comm) was sought on a qualitative comparison among OCS, shortfin mako, and blue shark tooth morphology (dentition) and ‘fighting’ behavior at retrieval to address the assumption of using the shortfin mako monofilament catchability. There are significant differences in dentition among the three species; mako teeth are spear shaped and pointed for enhanced puncture and draw performance, while OCS teeth are more triangular and serrated for enhanced cutting (Frazzetta 1988; Whitenack and Motta 2010, Corn et al. 2016). Blue sharks’ teeth were intermediate in cutting performance based on puncture ability and cutting. Differences in both tooth shape and the shape of the protrusible jaws of some shark species may have species-specific effects on their ability to bite through a monofilament branchline; OCS teeth would theoretically have an advantage on cutting ability over shortfin mako sharks and blue sharks. Behavioral 'fighting' characteristics may also have an impact on a shark's ability to bite through fishing gear. Shortfin mako sharks are the most active of the three species, OCS intermediate, and blue shark are relatively calm with little violent post-hooking behavior.

The literature has a variety of leader bite-off estimates, though there are differences due to hook type whereby tuna and J-hooks are ingested and have greater probability of bite-off compared to circle hooks with lip hooking. Santos et al. (2017) tracked bite-offs on 82 shallow longline sets, and wire leaders had a CPUE of 11.5 sharks per set compared to 8.9 for monofilament. The CPUE is reduced by 23% on monofilament though the study used entirely J-hooks. Afonso et al. (2012) conducted a field study with 17 longline sets (17,000 hooks total) and documented that bite-offs and shark catch occurred on 92 monofilament leaders. Bite-offs represented 39.1% (36 of 92) of the monofilament leaders; however, the leaders had both circle hooks and J-hooks. Harley et al. (2015) assumed an OCS bite-off probability of 0.33 based on Afonso et al. (2012); however, the 0.33 appears to represent the proportion of bite-offs to the number of sharks caught on both wire and monofilament leaders and would correspond to 0.25 (48/190). This study did not rely heavily on Afonso et al. (2012) as there were 17 longline sets fished with four different treatments (circle hook and monofilament, J-hook and monofilament, circle hook and wire, and J-hook and wire) that reduce the statistical inference of the results. Observers monitored 177 longline operations consisting of 75,101 Japanese tuna hooks in an Australian tuna fishery (Ward et al. 2008). A total of 147 sharks were captured with CPUE of 1.17 per 1,000 hooks on monofilament and 2.75 for wire, representing a 58% reduction with monofilament. OCS were caught infrequently with 3 sharks on monofilament and 11 on wire.

The transition to no shallow hooks deployed was estimated to have a moderate to large catchability effect for most species and a correspondingly large effect on annual fishery economic revenue (mean decrease $11,515,176, 95% CI, $7,682,133–$15,140,908). The majority of catches followed one of three patterns with respect to their vertical distributions in the water column similar to previous studies for the Hawaii (Bigelow and Mourato 2010) and A. Samoa longline fisheries (Watson and Bigelow 2014), and elsewhere in the Pacific Ocean (Nakano et al. 1997; Campbell and Young 2012). Catch rates were broadly distributed throughout the water column, with highest catch rates at intermediate hook numbers (albacore, bigeye and yellowfin tuna, opah, blue and shortfin mako shark), catch rates decreased with increasing hook number (skipjack tuna, swordfish, blue marlin, spearfish, striped marlin, mahimahi, ono and oceanic whitetip shark) or less often, catch rates increased with hook number (bigeye thresher shark). These three patterns characterized the hypothetical ecological and economic responses of each species to shallow hook elimination. OCS was in the group of eight species with high probability of interaction on shallow hooks (range 0.337–0.613), presumably due to their vertical distribution being largely confined to the mixed layer.

Modeling the reduction of target, incidental catch, and bycatch by eliminating hooks adjacent to longline floats is merely a hypothetical analysis as there are no at-sea experimental trials of gear currently deployed and a gear configuration created by eliminating hooks. There are several considerations in the analysis: 1) the reduction in catch assumes that a species is not captured on deeper hooks, 2) reductions may not occur for shallowly distributed species such as skipjack tuna, blue marlin, spearfish, striped marlin, mahimahi, and ono which may be caught as the longline is retrieved—essentially trolling during retrieval, 3) branchline snaps are not constrained on the mainline and may move up or down depending on adjacent fish catch, and 4) assessing compliance would be difficult if regulated and implemented, especially on unobserved trips.

There are several benefits to eliminating shallow hooks (< 100 m) such as an anticipated reduced catch of sea turtles and marine mammals. The most common gear configuration in the deep-set fishery is 25 hooks between floats. If three shallow hooks (6 total) are eliminated between floats then the effort per longline set would be reduced 24%, resulting in more rapid longline retrieval and less bait deployed. Average annual bait cost in the deep-set longline fishery was $9,856,400 (2015–2019, M. Pan, pers comm.). If 24% of bait were no longer required, this would represent a cost savings of $2,365,500, which would offset the estimated annual revenue loss ranging from $11,564,812–$13,711,313. There are other operational methods to reduce catches of shallow species, such as using longer floatlines and/or branchlines.

Median estimates of annual OCS catch were 1,708 for the status quo, 1,153 for monofilament leaders, and 678 with monofilament leaders and no shallow hooks deployed. Median estimates of annual mortality were 362 for the status quo, 255 with monofilament leaders, and 150 with monofilament leaders and no shallow hooks deployed. The transition from wire to monofilament leaders was estimated to have a 32% and 30% reduction in catch and mortality; respectively. The OCS projections could be revisited to assess the contribution to OCS mortality by the Hawaii-permitted fisheries. The OCS projections also could be revisited given the rigorous PRM estimates (Hutchinson et al. 2021) though PRM assumptions would need to be made on non-USA longline fleets. This study used three scenarios to quantify OCS catch and mortality. The actual impact of USA catch and mortality to the WCPO population would require the development of a population model.

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References

Afonso A, Santiago R, Hazin H, Hazin F. 2012. Shark bycatch and mortality and hook bite-offs in pelagic longlines: Interactions between hook types and leader materials. Fish Res. 131– 133. p. 9– 14.

Bigelow K, Mourato B. 2010. Evaluation of longline mitigation to reduce catches of North Pacific striped marlin in the Hawaii-based tuna fishery. WCPFC-SC6-2010/EB-WP-03. Nuku'alofa, Tonga, 10–19 August 2010.

Brodziak J, Walsh W. 2013. Model selection and multimodel inference for standardizing catch rates of bycatch species: a case study of oceanic whitetip shark in the Hawaii-based longline fishery. Can J Fish Aquat Sci. 70: 1723–1740 (2013) dx.doi.org/10.1139/cjfas-2013-0111

Corn K, Farina S, Brash J, Summers A. 2016. Modelling tooth–prey interactions in sharks: The importance of dynamic testing. R Soc Open Sci. doi:10.1098/rsos.160141

Frazzetta T. 1988. The mechanics of cutting and the form of shark teeth. Zoomorphology 108, 93–107. (doi:10.1007/BF00539785)

Hall M, Román M. 2013. Bycatch and non-tuna catch in the tropical tuna purse seine fisheries of the world. Food and Agricultural Organizaiton of the United Nations, Rome 2013, 568, 262.

Harley S, Caneco B, Donovan C, Tremblay-Boyer L, Brouwer S. 2015. Monte Carlo simulation modelling of possible measures to reduce impacts of longlining on oceanic whitetip and silky sharks. WCPFC-SC11-2015/EB-WP-02 (Rev 2). Pohnpei, Federated States of Micronesia. Session, 5–13 August 2015.

Hutchinson M, Siders Z, Stahl J, Bigelow K. 2021. Quantitative estimates of post-release survival rates of sharks captured in Pacific tuna longline fisheries reveal handling and discard practices that improve survivorship. PIFSC Data Report DR-21-001. Issued 10 March 2021. https://doi.org/10.25923/0m3c-2577

McCracken M. 2019. Hawaii Permitted Deep-set Longline Fishery Estimated Anticipated Take Levels for Endangered Species Act Listed Species and Estimated Anticipated Dead or Serious Injury Levels for the Listed Marine Mammals. Pacific Islands Fisheries Science Center, PIFSC Data Report DR-19-011 Issued 08 April 2019. https://doi.org/10.25923/brkr-c471

Nakano H, Okazaki M, Okamoto H. 1997. Analysis of catch depth by species for tuna longline fishery based on catch by branchlines. Bull Nat Res Inst Far Seas Fish. 24:43–62.

Pacific Islands Fisheries Science Center, 2020: Hawaii and California Longline Logbook Reports 2019, https://repository.library.noaa.gov/view/noaa/27068.

Pacific Islands Regional Office, 2021: Longline Observer Data System, https://www.fisheries.noaa.gov/inport/item/9027.

Tremblay-Boyer L, Carvalho F, Neubauer P, Pilling G. 2019. Stock assessment for oceanic whitetip shark in the Western and Central Pacific Ocean. WCPFC-SC15-2019/SA-WP-06, Pohnpei, Federated States of Micronesia, 12–20 August 2019.

Watson J, Bigelow K. 2014. Trade-offs among catch, bycatch, and landed value in the American Samoa longline Fishery. Conservation Biology, 28(4):1012-1022.

Whitenack L, Motta P. 2010. Performance of shark teeth during puncture and draw: implications for the mechanics of cutting. Biol J Linn Soc. 100, 271–286. (doi:10.1111/j.1095-8312.2010.01421.x)

Young C, Carlson J, Hutchinson M, Hutt C, Kobayashi D, McCandless C, Wraith J. 2017. Status review report: Oceanic whitetip shark Carcharhinus longimanus. Final Report to the National Marine Fisheries Service, Office of Protected Resources. National Marine Fisheries Service, National Oceanic and Atmospheric Administration.

Young C, Carlson J. 2020. The biology and conservation status of the oceanic whitetip shark (Carcharhinus longimanus) and future directions for recovery. June 2020. Reviews in Fish Biology and Fisheries 30(3). (doi:10.1007/s11160-020-09601-3).

Table 1. Number of longline sets using monofilament or wire branchlines in the Hawaii deep–set fishery (2005–2019).

	Branchline type		
Year	Monofilament	Wire	Total
2005	144	76	220
2006	170	517	687
2007	128	1,019	1,147
2008	143	1,691	1,834
2009	153	1,757	1,910
2010	118	2,256	2,374
2011	100	2,677	2,777
2012	141	3,083	3,224
2013	123	3,594	3,717
2014	149	3,617	3,766
2015	133	3,532	3,665
2016	131	3,747	3,878
2017	67	3,762	3,829
2018	121	4,227	4,348
2019	133	4,473	4,606
Total	1,954	40,028	41,982

Table 2. Number of Pelagic Management Unit Species (PMUS) used in the Generalized Linear Models (GLMs) for the Hawaii deep-set longline fishery (2005–2019) analysis and number of captures observed.

Species	Branchline type				
Tuna PMUS	Monofilament	Wire	Total	Hook number	% Hook number observed
Albacore	1,339	26,980	28,319	27,736	97.9%
Bigeye tuna	21,500	462,699	484,199	455,046	94.0%
Skipjack tuna	3,774	88,431	92,205	90,392	98.0%
Yellowfin tuna	3,996	93,111	97,107	93,089	95.9%
Tuna PMUS Subtotal	30,609	671,221	701,830	666,263	
Billfish PMUS					
Swordfish	932	17,837	18,769	17,154	91.4%
Blue marlin	524	11,882	12,406	11,108	89.5%
Spearfish	1,625	37,754	39,379	38,197	97.0%
Striped marlin	1,586	33,229	34,815	33,155	95.2%
Billfish PMUS Subtotal	4,667	100,702	105,369	99,614	
Other PMUS					
Mahimahi	8,266	163,425	171,691	167,216	97.4%
Ono (wahoo)	2,401	54,372	56,773	55,454	97.7%
Opah (moonfish)	2,348	50,605	52,953	50,670	95.7%
Sharks PMUS					
Oceanic whitetip shark	146	3,200	3,346	3,195	95.5%
Blue shark	8,185	195,714	203,899	198,273	97.2%
Bigeye thresher shark	805	21,582	22,387	20,597	92.0%
Shortfin mako shark	340	12,004	12,344	11,333	91.8%
Other and sharks PMUS Subtotal	22,491	500,902	523,393	506,738	
Total pelagics	57,767	1,272,825	1,330,592	1,272,615	95.6%

Table 3. Number and CPUE (# per 1,000 hooks) of oceanic whitetip sharks captured annually using monofilament or wire branchlines in the Hawaii deep-set longline fishery (2005–2019).

	Branchline type				
	Monofilament		Wire		
Year	Number	CPUE	Number	CPUE	Total
2005	10	0.031	7	0.037	17
2006	17	0.050	69	0.060	86
2007	9	0.031	81	0.034	90
2008	21	0.062	53	0.013	74
2009	12	0.040	155	0.037	167
2010	4	0.014	170	0.032	174
2011	8	0.036	178	0.028	186
2012	4	0.012	148	0.020	152
2013	1	0.003	189	0.022	190
2014	10	0.026	351	0.039	361
2015	24	0.067	503	0.056	527
2016	13	0.038	412	0.043	425
2017	2	0.011	239	0.024	241
2018	0	0.000	237	0.021	237
2019	11	0.030	408	0.033	419
Total	146		3,200		3,346

Table 4. The probability of interaction of shallow (1–3) hooks and deep (4–17) hooks for 15 Pelagic Management Unit Species (PMUS). The expected effort reduction in not setting 6 shallow hooks with 34 hooks between floats is 17.6%. The 11 bold estimates for shallow hooks are any probabilities greater than 17.6% for a species.

Species	Probability of interaction	
Tuna PMUS	Shallow (1–3) hooks	Deep (4–17 hooks)
Albacore	0.137	0.863
Bigeye tuna	0.090	0.910
Skipjack tuna	**0.485**	0.515
Yellowfin tuna	**0.245**	0.755
Billfish PMUS		
Swordfish	**0.337**	0.663
Blue marlin	**0.479**	0.521
Spearfish	**0.614**	0.387
Striped marlin	**0.510**	0.490
Other PMUS		
Mahimahi	**0.532**	0.469
Ono (wahoo)	**0.448**	0.552
Opah (moonfish)	0.053	0.947
Sharks PMUS		
Oceanic whitetip shark	**0.411**	0.589
Blue shark	**0.215**	0.785
Bigeye thresher shark	0.075	0.925
Shortfin mako shark	**0.205**	0.795

Table 5. Generalized Linear Model (GLMs) coefficients for the Hawaii deep-set longline fishery (2005–2019) analysis. GLM coefficients are estimates of relative catchability between monofilament and wire branchline types with inclusion of other explanatory variables. Coefficients less than 1.0 indicate lower catchability on monofilament branchlines.

Species	Branchline type (*P*-value)	Monofilament catch rate coefficient (95% C.I.)	Statistically different (*P*<0.05)	Pseudo-R^2	AIC
Tuna PMUS					
Albacore	0.012	0.927 (0.874–0.983)	Yes	0.362	19,089.2
Bigeye tuna	0.163	1.028 (0.989–1.068)	No	0.083	284,530.0
Skipjack tuna	<0.001	0.856 (0.795–0.926)	Yes	0.191	150,189.8
Yellowfin tuna	0.144	1.054 (0.983-1.131)	No	0.272	149,005.1
Billfish PMUS					
Swordfish	<0.001	1.193 (1.101–1.291)	Yes	0.072	72,317.8
Blue marlin	0.287	0.945 (0.851–1.047)	No	0.272	49,593.0
Spearfish	0.081	0.939 (0.876–1.006)	No	0.169	105,244.6
Striped marlin	0.268	0.958 (0.889–1.032)	No	0.187	96,908.2
Other PMUS					
Mahimahi	0.019	0.930 (0.877–0.988)	Yes	0.204	196,456.4
Ono (wahoo)	0.237	1.038 (0.986–1.105)	No	0.351	121,073.2
Opah (moonfish)	0.195	0.964 (0.905–1.021)	No	0.260	111,185.4
Sharks PMUS					
Oceanic whitetip shark	0.590	0.949 (0.783–1.143)	No	0.310	19,089.3
Blue shark	<0.001	0.905 (0.871–0.994)	Yes	0.234	209,056.9
Bigeye thresher shark	0.053	0.894 (0.797–1.002)	No	0.311	60,551.1
Shortfin mako shark	<0.001	0.675 (0.599–0.7589)	Yes	0.091	54,872.9

Table 6. Process model estimates of oceanic whitetip sharks caught annually in the Hawaii-permitted deep-set longline fishery and mortality (median, 95% confidence intervals) at three scenarios.

OCS catch (individuals)		OCS mortality (individuals)		
Catch-hook depth	Catch-leader type with reduction from the status quo	Mortality at retrieval	Mortality at release	Mortality with PRM after bite-off and after vessel release with reduction from the status quo
1) Status quo				
1,708	1,708	328 (303–354)	333 (307–360)	362 (326–417)
2) Monofilament leaders				
1,708	1,153 (1,027–1,298) 32% reduction	222 (192–256)	225 (195–259)	255 (214–337) 30% reduction
3) Monofilament leaders and no shallow hooks				
1,006 (977–1,034)	678 (602–768) 60% reduction	130 (113–151)	132 (114–153)	150 (126–199) 59% reduction

Table 7. Summary of economic revenue for the Hawaii deep-set longline fishery (2005–2019) based on pelagic SAFE reporting. All GLM coefficients for monofilament and wire branchline types were applied to species to estimate revenue gain/loss with 95% confidence intervals.

	Deep-set longline									
	Average 2015-2019 Amount paid	**Mean catchability**	**Mean revenue**	**Mean gain/Loss**	**2.5%**	**2.5% revenue**	**2.5% gain/Loss**	**97.5%**	**97.5% revenue**	**97.5% gain/Loss**
Tuna PMUS										
Albacore	$ 580,781	0.927	$538,589	$ (42,192)	0.874	$507,683	$ (73,098)	0.983	$570,859	$ (9,922)
Bigeye tuna	$ 66,213,530	1.028	$68,054,332	$ 1,840,802	0.989	$65,500,344	$ (713,186)	1.068	$70,728,101	$ 4,514,571
Bluefin tuna	$ 16,964		$16,964	$ -		$16,964	$ -		$16,964	$ -
Skipjack tuna	$ 298,281	0.858	$255,781	$ (42,500)	0.795	$237,120	$ (61,161)	0.926	$276,124	$ (22,157)
Yellowfin tuna	$ 13,005,207	1.054	$13,707,865	$ 702,658	0.983	$12,783,557	$ (221,650)	1.131	$14,706,938	$ 1,701,731
Other tunas	$ 2		$2	$ -		$2	$ -		$2	$ -
Tuna PMUS Subtotal	$ 80,114,765		$82,573,534	$ 2,458,769		$79,045,670	$ (1,069,095)		$86,298,988	$ 6,184,223
Billfish PMUS										
Swordfish	$ 2,321,934	1.193	$2,769,654	$ 447,720	1.101	$2,556,682	$ 234,748	1.291	$2,997,910	$ 675,975
Blue marlin	$ 1,289,787	0.945	$1,218,906	$ (70,881)	0.851	$1,098,217	$ (191,570)	1.047	$1,350,579	$ 60,792
Spearfish	$ 609,071	0.939	$572,103	$ (36,968)	0.876	$533,734	$ (75,337)	1.007	$613,113	$ 4,042
Striped marlin	$ 1,516,730	0.959	$1,454,033	$ (62,697)	0.890	$1,349,853	$ (166,877)	1.033	$1,566,075	$ 49,345
Other marlins	$ 49,973		$49,973	$ -		$49,973	$ -		$49,973	$ -
Billfish PMUS Subtotal	$ 5,787,496		$6,064,670	$ 277,174		$5,588,458	$ (199,038)		$6,577,650	$ 790,154
Other PMUS										
Mahimahi	$ 1,674,951	0.930	$1,558,132	$ (116,818)	0.877	$1,468,313	$ (206,638)	0.988	$1,654,432	$ (20,519)
Ono (wahoo)	$ 2,091,870	0.961	$2,011,123	$ (80,747)	0.906	$1,894,232	$ (197,638)	1.021	$2,134,962	$ 43,093
Opah (moonfish)	$ 3,211,971	1.038	$3,334,472	$ 122,501	0.976	$ 3,133,723.30	$ (78,247)	1.105	$3,548,084	$ 336,113
Oilfish	$ 251,365		$251,365	$ -		$251,365	$ -		$251,365	$ -
Pomfrets (monchong)	$ 2,931,443		$2,931,443	$ -		$2,931,443	$ -		$2,931,443	$ -
PMUS sharks	$ 73,756		$73,756	$ -		$73,756	$ -		$73,756	$ -
Other PMUS Subtotal	$ 10,235,356		$10,160,292	$ (75,064)		$9,752,833	$ (482,523)		$10,594,043	$ 358,687
				$ -						
Non-PMUS pelagics	$ 12,176		$12,176	$ -		$12,176	$ -		$12,176	$ -
				$ -						
Total pelagics	$ 96,149,793		$98,810,672	$ 2,660,879		$94,399,137	$ (1,750,655)		$103,482,857	$ 7,333,064

Table 8. Summary of economic revenue for the Hawaii deep-set longline fishery (2005–2019) based on pelagic SAFE reporting. Deep hook catchability was applied with all GLM coefficients for monofilament and wire branchline types to species to estimate revenue gain/loss with 95% confidence intervals.

	Deep-set longline										
	Average 2015-2019 Amount paid	**Deep hooks catchability**	**Mean catchability**	**Mean revenue**	**Mean gain/Loss**	**2.5%**	**2.5% revenue**	**2.5% gain/Loss**	**97.5%**	**97.5% revenue**	**97.5% gain/Loss**
Tuna PMUS											
Albacore	$ 580,781	0.8627	0.927	$464,641	$ (116,140)	0.874	$437,978	$ (142,803)	0.983	$492,480	$ (88,301)
Bigeye tuna	$ 66,213,530	0.9103	1.028	$61,949,859	$ (4,263,671)	0.989	$59,624,963	$ (6,588,567)	1.068	$64,383,790	$ (1,829,740)
Bluefin tuna	$ 16,964			$16,964	$ -		$16,964	$ -		$16,964	$ -
Skipjack tuna	$ 298,281	0.5154	0.858	$131,829	$ (166,452)	0.795	$122,212	$ (176,069)	0.926	$142,314	$ (155,967)
Yellowfin tuna	$ 13,005,207	0.7551	1.054	$10,350,809	$ (2,654,398)	0.983	$9,652,864	$ (3,352,343)	1.131	$11,105,209	$ (1,899,998)
Other tunas	$ 2			$2	$ -		$2	$ -		$2	$ -
Tuna PMUS Subtotal	$ 80,114,765			$72,914,104	$ (7,200,661)		$69,854,983	$ (10,259,782)		$76,140,760	$ (3,974,005)
Billfish PMUS											
Swordfish	$ 2,321,934	0.6634	1.193	$1,837,389	$ (484,546)	1.101	$1,696,103	$ (625,832)	1.291	$1,988,813	$ (333,121)
Blue marlin	$ 1,289,787	0.5206	0.945	$634,563	$ (655,224)	0.851	$571,732	$ (718,055)	1.047	$703,111	$ (586,676)
Spearfish	$ 609,071	0.3865	0.939	$221,118	$ (387,953)	0.876	$206,288	$ (402,783)	1.007	$236,968	$ (372,103)
Striped marlin	$ 1,516,730	0.4899	0.959	$712,331	$ (804,399)	0.890	$661,293	$ (855,437)	1.033	$767,220	$ (749,510)
Other marlins	$ 49,973			$49,973	$ -		$49,973	$ -		$49,973	$ -
Billfish PMUS Subtotal	$ 5,787,496			$3,455,373	$ (2,332,123)		$3,185,388	$ (2,602,107)		$3,746,086	$ (2,041,410)
Other PMUS											
Mahimahi	$ 1,674,951	0.4685	0.930	$729,985	$ (944,966)	0.877	$687,904	$ (987,046)	0.988	$775,101	$ (899,849)
Ono (wahoo)	$ 2,091,870	0.5516	0.961	$1,109,335	$ (982,534)	0.906	$1,044,858	$ (1,047,011)	1.021	$1,177,645	$ (914,225)
Opah (moonfish)	$ 3,211,971	0.9468	1.038	$3,157,078	$ (54,893)	0.976	$2,967,009	$ (244,962)	1.105	$3,359,326	$ 147,355
Oilfish	$ 251,365			$251,365	$ -		$251,365	$ -		$251,365	$ -
Pomfrets (monchong)	$ 2,931,443			$2,931,443	$ -		$2,931,443	$ -		$2,931,443	$ -
PMUS sharks	$ 73,756			$73,756	$ -		$73,756	$ -		$73,756	$ -
Other PMUS Subtotal	$ 10,235,356			$8,252,963	$ (1,982,392)		$7,956,337	$ (2,279,019)		$8,568,637	$ (1,666,719)
					$ -						
Non-PMUS pelagics	$ 12,176			$12,176	$ -		$12,176	$ -		$12,176	$ -
					$ -						
Total pelagics	$ 96,149,793			$84,634,617	$ (11,515,176)		$81,008,884	$ (15,140,908)		$88,467,659	$ (7,682,133)

Appendix 1. Summary of data preparation and screening prior to fitting the Generalized Linear Models (GLMs) for the Hawaii deep-set longline fishery (2005–2019) analysis.

	Number of sets
Total sets 1994 to 2020	94,563
Removal of research and experimental sets	93,016
Deletion of sets for missing fields of hooks per float	92,940
Deletion of sets for missing fields of set year	92,937
Deletion of sets for missing fields of longitude	92,928
Deletion of sets for missing fields of number of hooks set	92,921
Total sets 1994 to 2019	92,861
Deletion of sets for missing fields of leader material or leader material of 'Other'	91,850
Deletion of sets for number of hooks set < 500	91,292
Retain sets from year 2005 to 2019, deep-set and circle hooks	41,982

Appendix 2. Summary of economic revenue for the Hawaii deep-set longline fishery (2005–2019) based on pelagic SAFE reporting.

	Deep-set longline		Deep-set longline		Deep-set longline		Deep-set longline		Deep-set longline		Deep-set longline
	2015		**2016**		**2017**		**2018**		**2019**		**Average 2015-2019**
	Pounds bought	**Amount paid**	**Pounds bought**	**Amount paid**	**Pounds bought**	**Amount paid**	**Pounds bought**	**Amount paid**	**Pounds bought**	**Amount paid**	**Amount paid**
Tuna PMUS											
Albacore	536,365	$ 873,516	536,749	$ 929,719	196,305	$ 376,765	173,923	$ 303,253	241,837	$ 420,654	$ 580,781
Bigeye tuna	18,102,218	$ 69,371,909	16,911,827	$ 70,695,574	16,506,321	$ 63,434,366	15,606,462	$ 65,504,602	15,901,198	$ 62,061,199	$ 66,213,530
Bluefin tuna	457	$ 3,967	542	$ 2,540	394	$ 3,250	1,555	$ 13,062	10,952	$ 62,003	$ 16,964
Skipjack tuna	322,412	$ 284,888	361,099	$ 326,535	314,303	$ 315,210	225,725	$ 263,520	440,897	$ 301,254	$ 298,281
Yellowfin tuna	1,921,366	$ 5,784,374	3,152,210	$ 9,164,341	5,457,590	$ 15,033,040	5,408,698	$ 19,684,308	4,459,008	$ 15,359,972	$ 13,005,207
Other tunas					3	$ 5	0	$ -	0	$ -	$ 2
Tuna PMUS Subtotal	**20,882,818**	**$ 76,318,654**	**20,962,427**	**$ 81,118,709**	**22,474,915**	**$ 79,162,635**	**21,416,364**	**$ 85,768,745**	**21,053,892**	**$ 78,205,082**	$ 80,114,765
Billfish PMUS											
Swordfish	834,359	$ 2,115,822	803,038	$ 2,593,007	1,025,598	$ 2,308,062	1,102,769	$ 2,437,231	915,160	$ 2,155,551	$ 2,321,934
Blue marlin	1,131,225	$ 1,152,276	952,369	$ 1,459,245	1,242,471	$ 1,647,218	1,043,039	$ 1,184,265	1,655,738	$ 1,005,931	$ 1,289,787
Spearfish	588,175	$ 523,731	756,733	$ 792,914	674,960	$ 763,216	473,903	$ 558,925	454,719	$ 406,569	$ 609,071
Striped marlin	1,128,914	$ 1,312,171	942,010	$ 1,823,763	975,760	$ 1,612,330	1,231,622	$ 1,643,234	1,387,253	$ 1,192,152	$ 1,516,730
Other marlins	43,268	$ 39,200	51,966	$ 65,686	51,464	$ 71,318	39,344	$ 46,687	55,866	$ 26,974	$ 49,973
Billfish PMUS Subtotal	**3,725,941**	**$ 5,143,200**	**3,506,116**	**$ 6,734,615**	**3,970,252**	**$ 6,402,143**	**3,890,677**	**$ 5,870,343**	**4,468,736**	**$ 4,787,178**	$ 5,787,496
Other PMUS											
Mahimahi	700,351	$ 1,833,601	650,150	$ 2,153,165	577,226	$ 1,757,753	515,314	$ 1,377,141	434,896	$ 1,253,094	$ 1,674,951
Ono (wahoo)	768,290	$ 1,595,860	915,994	$ 2,248,915	795,767	$ 2,170,562	882,386	$ 1,944,712	1,252,439	$ 2,499,299	$ 2,091,870
Opah (moonfish)	2,064,369	$ 3,146,677	1,551,010	$ 3,301,147	1,807,856	$ 3,190,504	2,322,756	$ 3,301,780	1,613,401	$ 3,119,745	$ 3,211,971
Oilfish	474,175	$ 271,512	434,579	$ 246,612	310,017	$ 253,798	298,422	$ 233,764	265,879	$ 251,140	$ 251,365
Pomfrets (monchong)	1,323,461	$ 2,820,289	1,115,960	$ 3,294,220	942,575	$ 3,121,659	906,702	$ 2,763,592	764,133	$ 2,657,454	$ 2,931,443
PMUS sharks	90,849	$ 88,015	106,185	$ 75,310	82,304	$ 64,672	87,189	$ 60,263	67,826	$ 80,522	$ 73,756
Other PMUS Subtotal	**5,421,495**	**$ 9,755,954**	**4,773,878**	**$ 11,319,369**	**4,515,745**	**$ 10,558,948**	**5,012,769**	**$ 9,681,253**	**4,398,574**	**$ 9,861,254**	$ 10,235,356
Non-PMUS pelagics	**19,920**	**$ 11,088**	**19,646**	**$ 17,301**	11,678	$ 13,209	15,691	$ 11,961	4,721	$ 7,323	$ 12,176
Total pelagics	**30,050,174**	**$ 91,228,896**	**29,262,067**	**$ 99,189,994**	**30,972,590**	**$ 96,136,935**	**30,335,500**	**$101,332,301**	**29,925,923**	**$ 92,860,837**	$ 96,149,793

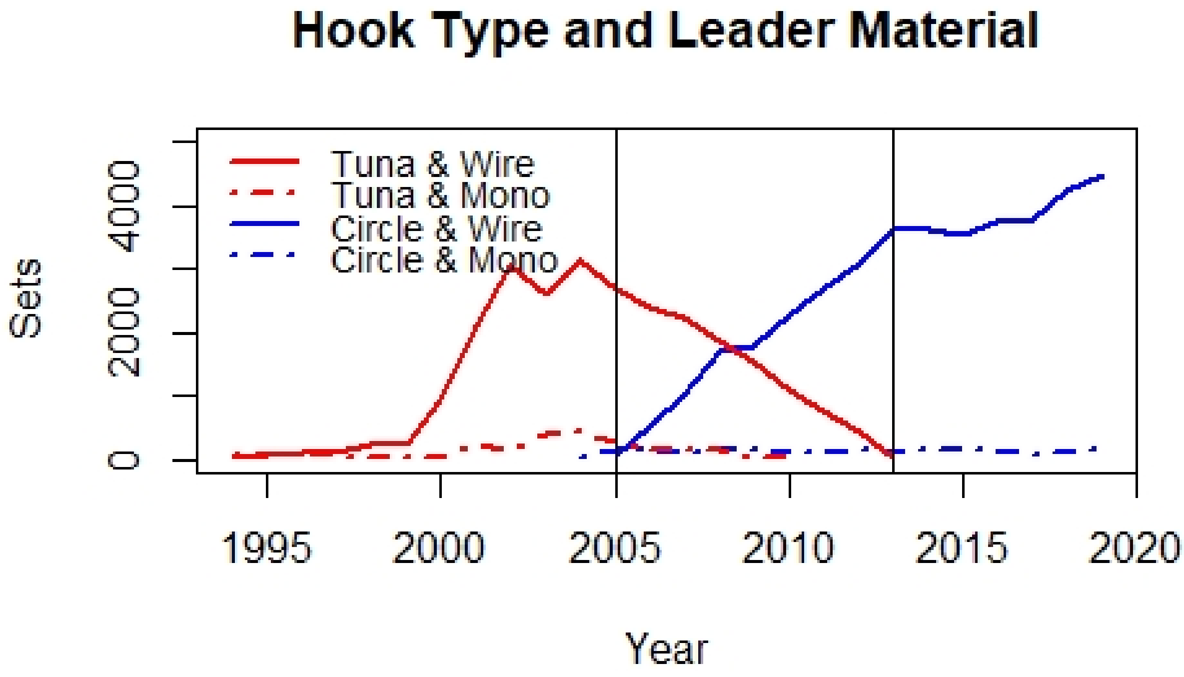

Figure 1. Hook type and leader material (monofilament or wire) observed in the Hawaii deep-set longline fishery annually from 1994 to 2019.

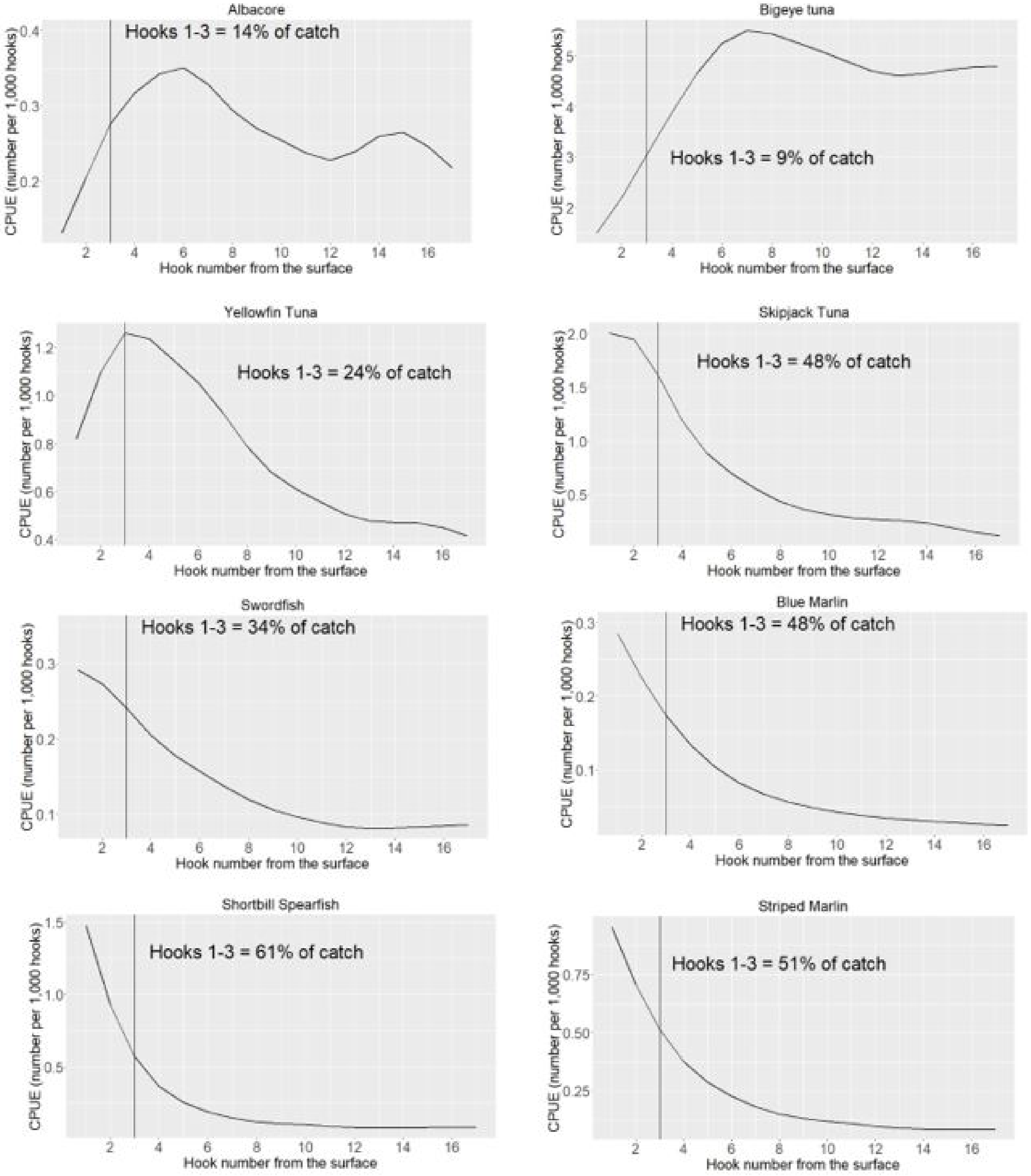

Figure 2. Catch-per-unit-effort (CPUE, per 1,000 hooks) at an observed hook number. Hook #1 is the shallowest and hook #17 is the deepest.

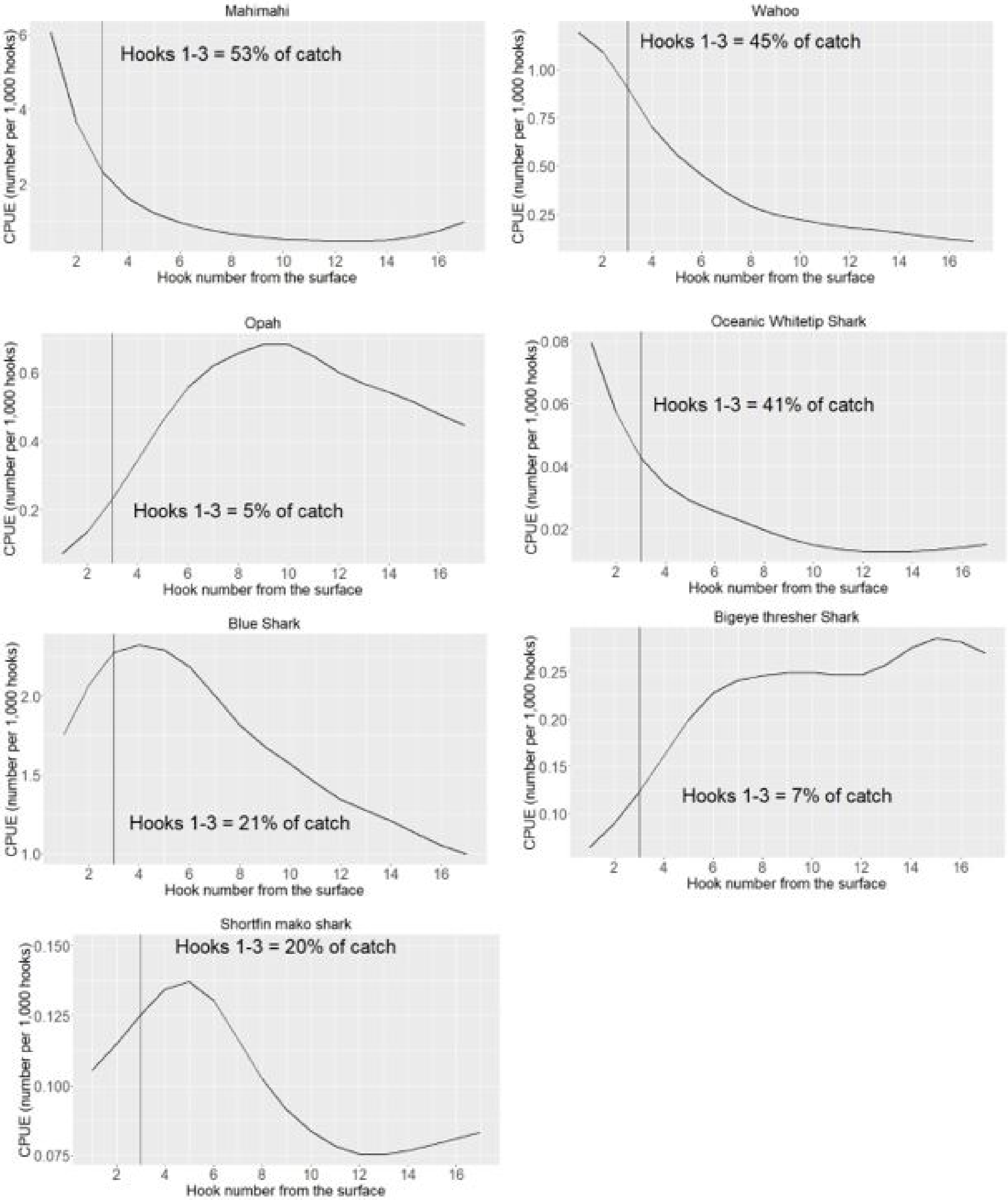

Figure 3. Catch-per-unit-effort (CPUE, per 1,000 hooks) at an observed hook number. Hook #1 is the shallowest and hook #17 is the deepest.

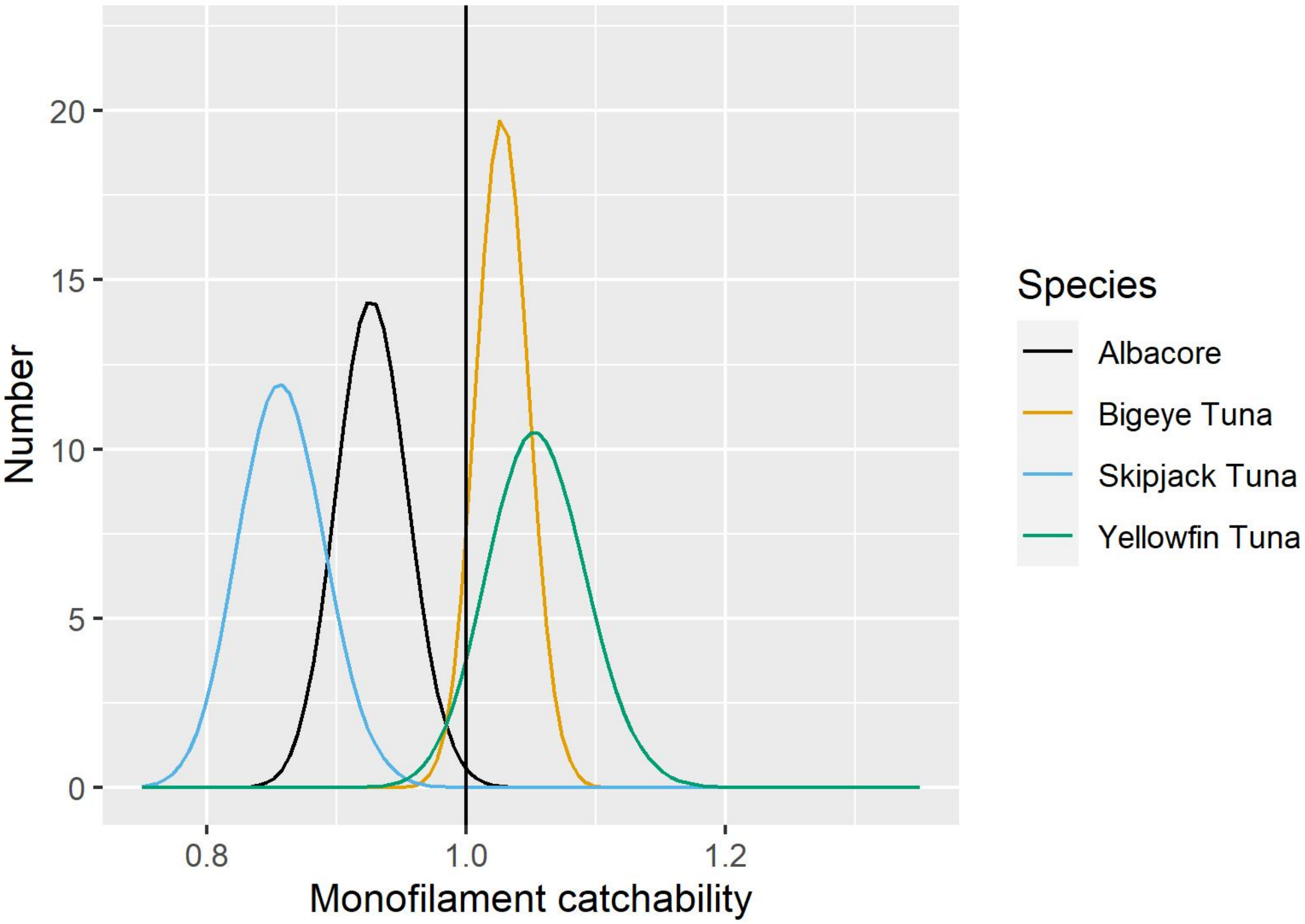

Figure 4. Distributions of tuna catchability using monofilament leaders compared to wire leaders in the Hawaii deep-set longline fishery. Distributions were generated from Generalized Linear Model (GLMs) analysis. Values less than 1.0 indicate lower catchability on monofilament branchlines.

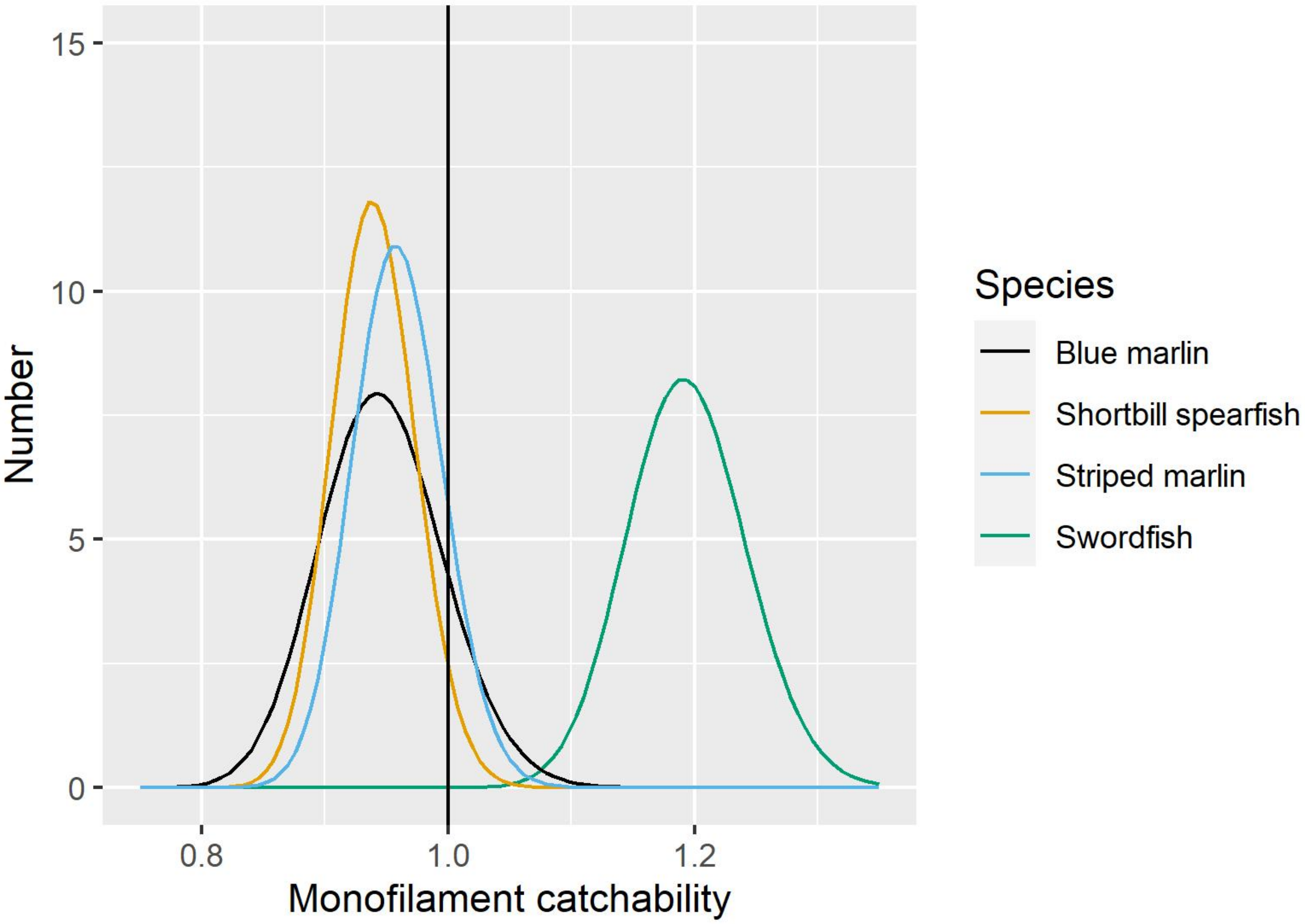

Figure 5. Distributions of billfish catchability using monofilament leaders compared to wire leaders in the Hawaii deep-set longline fishery. Distributions were generated from Generalized Linear Model (GLMs) analysis. Values less than 1.0 indicate lower catchability on monofilament branchlines.

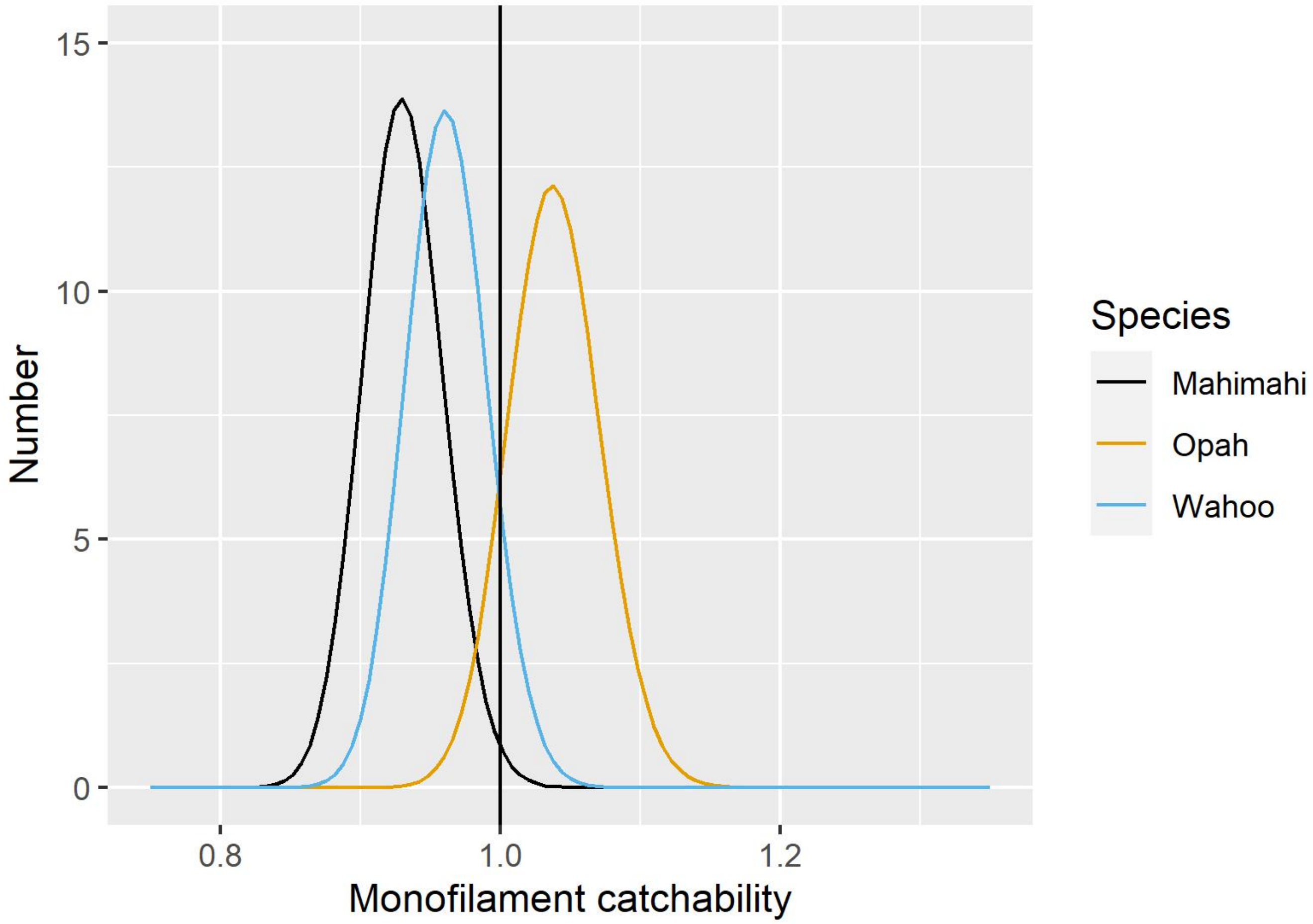

Figure 6. Distributions of mahimahi, opah and wahoo catchability using monofilament leaders compared to wire leaders in the Hawaii deep-set longline fishery. Distributions were generated from Generalized Linear Model (GLMs) analysis. Values less than 1.0 indicate lower catchability on monofilament branchlines.

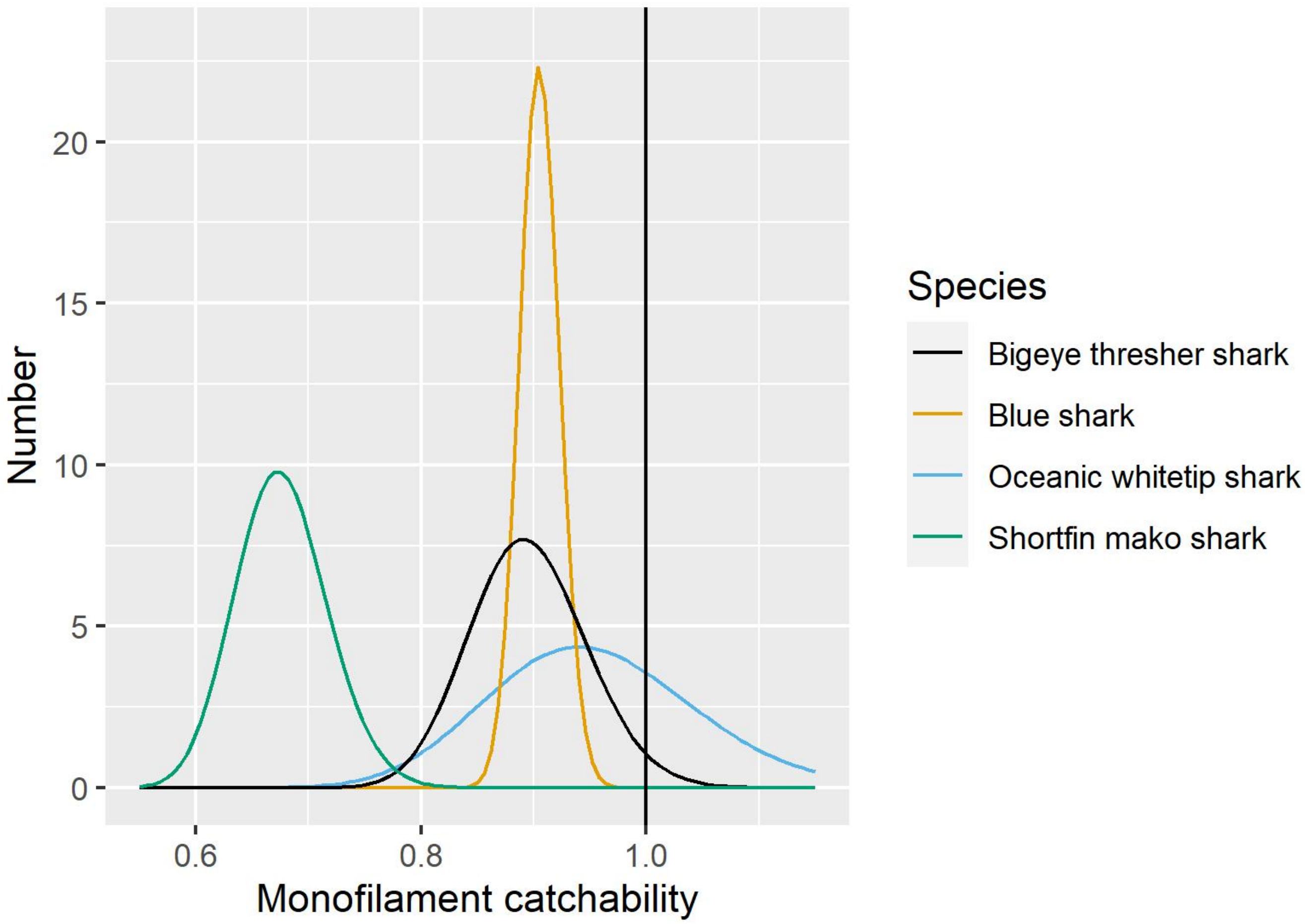

Figure 7. Distributions of shark catchability using monofilament leaders compared to wire leaders in the Hawaii deep-set longline fishery. Distributions were generated from Generalized Linear Model (GLMs) analysis. Values less than 1.0 indicate lower catchability on monofilament branchlines.

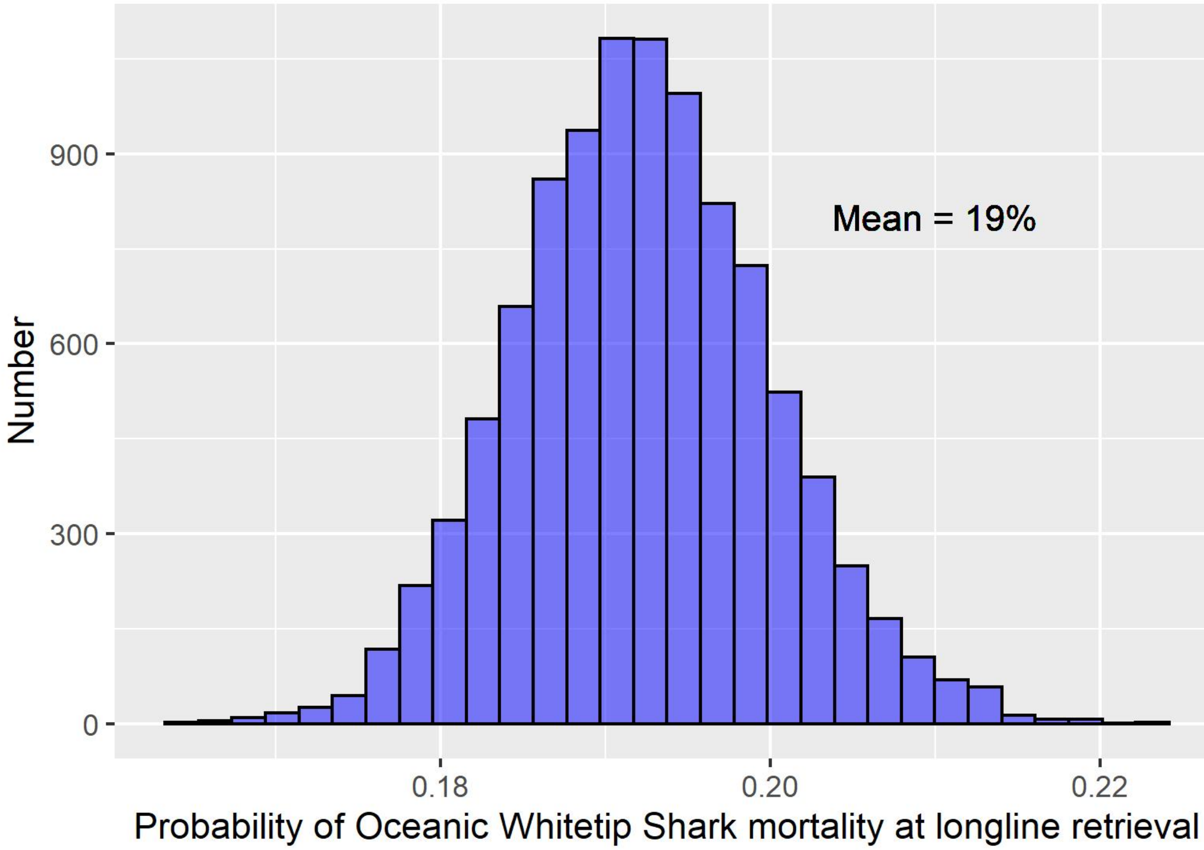

Figure 8. Distribution of at-vessel mortality of oceanic white-tip shark in the Hawaii deep-set longline fishery. Distribution was generated from Generalized Linear Model (GLMs) analysis.

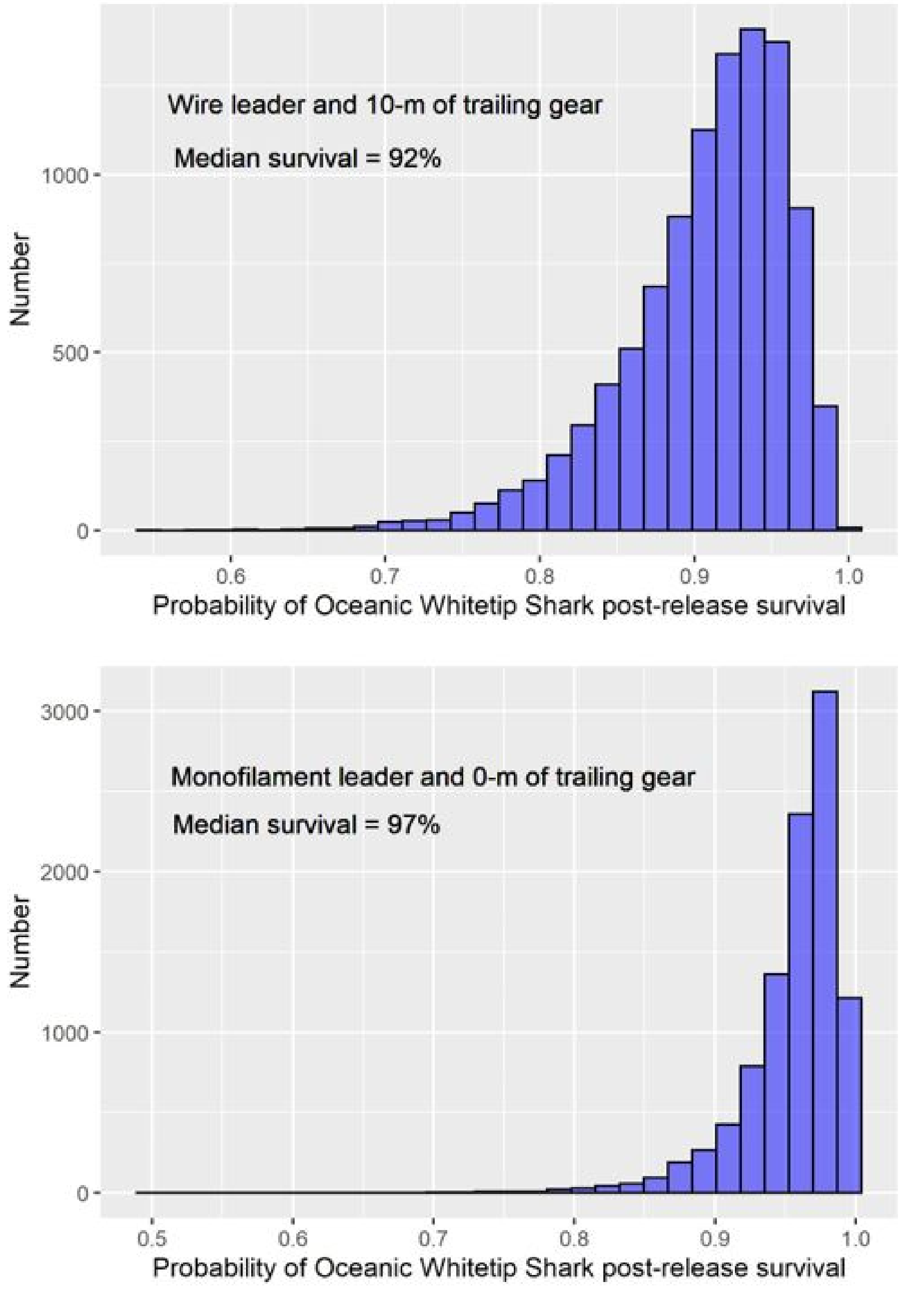

Figure 9. Two distributions of the probability of post-release survival (1-mortality) with wire leaders and leaving ~10 -m of trailing gear on a released shark (top) and with monofilament leaders and removing all trailing gear (0 m) on a released shark (top) and with monofilament leaders and removing all trailing gear (0 m) on a released shark (bottom).

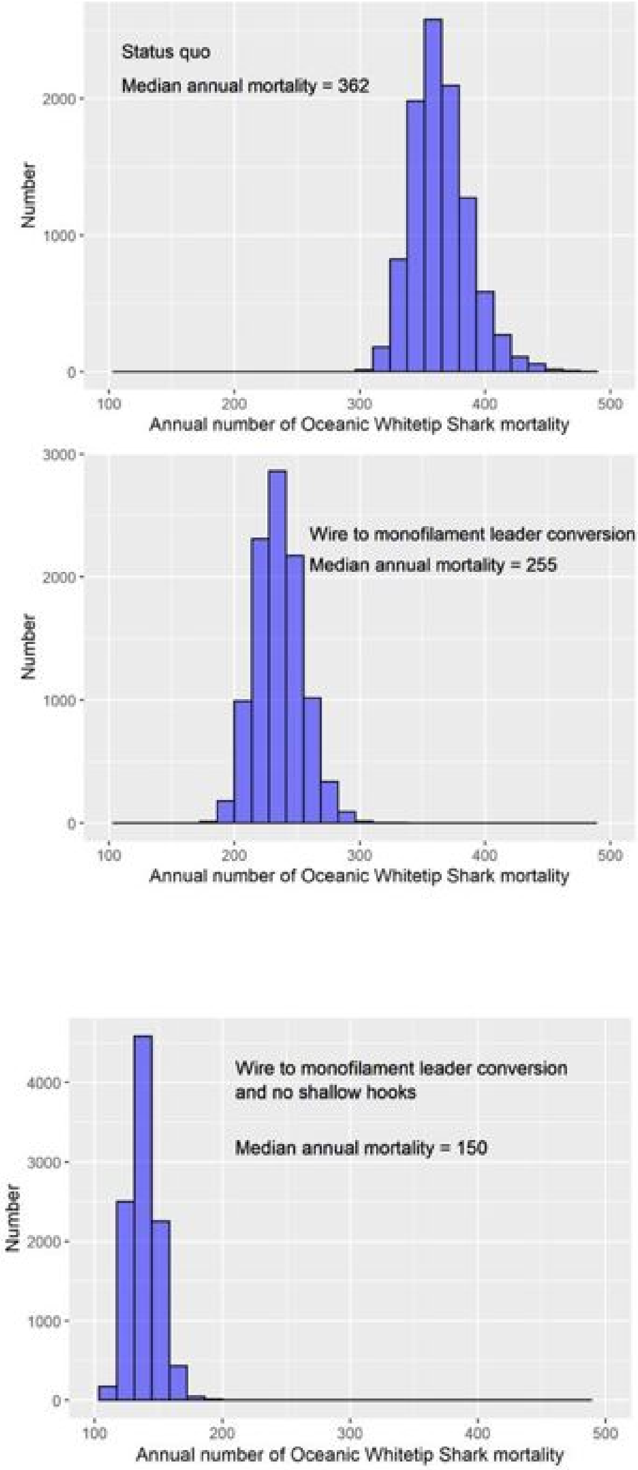

Figure 10. Annual estimated mortality of oceanic whitetip shark in the Hawaii deep-set longline fishery with three scenarios: the current fishery use of using wire leaders and leaving ~10 m of trailing gear on a

released shark (top, Scenario 1-Status quo); intended use of monofilament, removing all trailing gear (0 m) on a released shark (middle, Scenario 2-Monofilament leaders) and intended use of monofilament, removing all trailing gear (0 m) on a released shark and gear modification by eliminating three hooks adjacent to longline floats (bottom, Scenario 3-Monofilament leaders and gear modification).