Title: What’s the catch? Examining optimal longline fishing gear configurations to minimize negative impacts on non-target species.

Authors: Molly Scott[1], Edward Cardona[2], Kaylee Scidmore-Rossing[2], Mark Royer[2], Jennifer Stahl[1], Melanie Hutchinson[1,2]

Affiliations:

[1] Cooperative Institute for Marine & Atmospheric Research, Pacific Islands Fisheries Science Center NOAA-IRC 1845 Wasp Blvd. Bldg 176. Honolulu, Hi 96818

[2] Hawai’i Institute of Marine Biology, University of Hawai’i. 46-007 Lilipuna Rd. Kaneohe Hi 96744

Emails:

molly.scott@noaa.gov * Corresponding author
edwardwc@hawaii.edu
kayleesr@hawaii.edu
royerm@hawaii.edu
jennifer.stahl@noaa.gov
melanie.hutchinson@noaa.gov

Abstract

Changes to fishing gear configurations have great potential to decrease fishing interactions, minimize injury and reduce mortality for non-target species in commercial fisheries. In this two-part study, we investigate potential options to optimize fishing gear configurations for United States Pacific pelagic longline vessels to maintain target catch rates whilst reducing bycatch mortality, injury, and harm. In part one, a paired-gear trial was conducted on a deep-set tuna longline vessel to compare catch rates and catch condition of target and non-target species between wire and monofilament leader materials. Temperature-depth recorders were also deployed on hooks to determine sinking rates and fishing depth between the two leader materials. In part two, hooks of different configurations (size, diameter, shape, metal type, and leader material) were soaked in a seawater flume for 360 days to obtain quantitative estimates of breaking strength, as well as the time taken for gear to break apart. We found that switching from wire to monofilament leaders reduced the catch rate of sharks by approximately 41%, whilst maintaining catch rates of target species (Bigeye tuna, *Thunnus obesus)*. However, trailing gear composed of monofilament did not break apart even after 360 days. In contrast, branchlines with wire leaders began to break at the crimps after approximately 100 days. Additionally, the breaking strength of soaked fishing hooks was greater for larger, forged hooks composed of stainless steel typically used in United States Pacific longline fisheries. These results have direct implications for fisheries management and the operational effectiveness of bycatch mitigation strategies for longline fisheries worldwide.

Keywords: Bycatch Reduction, Longline Fisheries, Fishing Gear Configuration, Fisheries Management, Hook Strength, Conservation

1 Introduction

The unintended capture of non-target species during commercial fishing operations is a fundamental international marine conservation problem [1,2]. Although global estimates of bycatch rates are lacking [3 - 5], overfishing is considered the single largest threat to populations of endangered seabirds, sea turtles, marine mammals, and elasmobranchs (i.e., sharks and rays) globally [6 - 10]. Pelagic longline fishing is directly associated with high rates of bycatch for many species due to extremely high levels of fishing effort and the large spatial extent of operations throughout tropical and temperate regions of the world’s oceans [11, 12].

In the Pacific Ocean, the United States (U.S.) longline fishery is composed of three sectors; the Hawaii permitted longline fishery targets both bigeye tuna (i.e., ‘deep-set’ tuna fishery) and swordfish (i.e., ‘shallow-set’ fishery) while the American Samoa permitted deep-set fishery targets albacore. Effort for these fleets spans from California through the Pacific Island Region (both Hawaii permitted and American Samoa permitted) and the Western Pacific Region (these combined regions and fishing sectors are hereafter referred to as the U.S. Pacific longline fishery). The U.S. Pacific longline fishery operates under extensive regulations to reduce interaction, harm, and mortality of endangered and protected species (Regulations: 50 CFR § 665.800). Mandated bycatch mitigation measures include catch limits of sea turtles, gear configuration (e.g., floatline length, branchline requirements, weights, bait restrictions, use of circle hooks), gear setting requirements (e.g., one hour after sunset to avoid seabirds), and annual exclusion zones to reduce interactions with false killer whales, depending on target species and region (Title 50, Code of Federal Regulations (CFR), Parts 229, 300, 404, 600, and 665). In the Hawaii ‘deep-set’ fishery (bigeye tuna target), gear configuration regulations require float lines to be at least 20 meters in length, a minimum of 15 branchlines between any two floats, a 45-gram weighted swivel within one meter of the hook, mackerel type bait, and no light sticks (Regulation: 50 CFR § 665.800). Until recently, most vessels in the Hawaii permitted sector used wire leaders (gear between hook and swivel). Wire leaders were preferred for crew safety to reduce risk of weighted swivels flying back and causing serious injury in the event of leader breakage during hauling [13].

In 2021, a proposed regulatory requirement to reduce mortality in oceanic whitetip sharks (*Carcharhinus longimanus*) in U.S. Pacific longline fisheries was to have all branchlines be composed of monofilament leader material starting in 2022. Monofilament is a strong, light weight, less visible polyamide [14] and has been shown to significantly reduce shark bycatch by increasing potential for sharks to bite through the line (i.e., ‘bite-offs’), whilst increasing or maintaining catch rates of target species [15, 16]. Therefore, until 2021, a typical branchline was composed of a monofilament branchline (μ = 12.5 m in length), to a 45-gram weighted swivel and 0.5 m of 49 strand (7 x 7) stainless steel wire leader attached to the hook (Figure 1). The 45-

gram weight on a baited line is a bycatch mitigation regulation to sink gear rapidly and reduce the risk of seabirds getting hooked while the vessel is setting gear [2, 17, 18]. In general, hooks used in the U.S. Pacific longline fishery are barbed, stainless steel, circle hooks (14/0 - 18/0) with a 10° offset (Regulation: 50 CFR § 665.800).

Catch rates for sharks in pelagic longline fisheries are higher than in any other fishery world-wide [19]. In the Western Pacific Ocean, oceanic whitetip (*C. longimanus*) and silky (*Carcharhinus falciformis*) shark populations have been assessed as overfished with overfishing still occurring for *C.longimanus* [20 -22]. Both species are listed under Appendix II of the Conservation on International Trade in Endangered Species (CITES) and the Convention on the Conservation of Migratory Species (CMS). In 2018, *C.longimanus* was listed as threatened with endangerment under the United States Endangered Species Act [23]. Due to conservation concerns [24], several regional fisheries management organizations (RFMOs) have instigated efforts to reduce mortality in *C.longimanus* and *C. falciformis* bycatch. This includes a no retention conservation and management measure in the Western and Central Pacific Fisheries Commission [25 - 27] that also requires that sharks be released in a 'manner that minimizes harm' (CMM 2019-04). Although at present, specific guidelines and/or regulations to release sharks with minimal harm do not exist (but see [28]).

In U.S. Pacific longline fisheries, it is estimated that ~ 98% of all sharks caught as bycatch are discarded at sea [25] and of those, ~85% are released by fishers cutting the branchline leaving between 0.5–25 m of trailing gear attached to the animal [27, 28]. This means that discarded sharks are released with a stainless steel circle hook, braided stainless steel wire (or monofilament) leader, a 45-gram weighted swivel, and an average ~ 9 m of monofilament. The length of trailing gear left on a shark at release has been shown to affect post-release survival (PRS) rates, where leaving < 1m attached to an animal can improve PRS of sharks by approximately 40% over 360 days [28]. Large quantities of trailing gear attached to animals are not only energetically costly as a result of drag but may also introduce infection and risk of disease [30, 31], increase susceptibility to predation [32, 33], and cause delayed mortality associated with the retention of fishing hooks [34, 35]. However, small changes to fishing gear configuration can drastically reduce the deleterious impacts of fishing on pelagic shark populations and other discarded bycatch species.

In general, the conventional attitude amongst fishers and managers is that hooks and the accompanying trailing gear will eventually 'rust out' or break apart due to corrosion and, therefore, it is acceptable to leave gear attached to animals. However, the majority of metal types used for hooks in commercial fisheries (i.e., stainless steel, galvanized, nickel plated, and high carbon steel) are selected based on strength, size, and corrosion-resistance [36 – 38]. Hook decay is likely to be affected by several technical factors including hook shape, size, and material [39 – 41] although few published studies have formally investigated corrosion rates and/or the compression (or tensile) strength of hooks (but see [37, 38, 42]). This information is crucial for determining the length of time trailing gear may take to fall off an animal, which has direct implications on post-release survival. Additionally, in fisheries where approved marine mammal handling guidelines suggest hooks be opened or removed from protected species (e.g., for false killer whales in the U.S. Pacific longline fisheries), details on breaking strengths of different hook types is imperative.

The purpose of this study was to examine potential options (i.e., hook characteristics and leader material) for optimal longline fishing gear configuration that may help to minimize injury and/or mortality to non-target species whilst maintaining catch rates of target species. To do this, we:

1) Assessed the effects of leader material (wire or monofilament) on catch rates and catch condition of target and non-target species through a paired gear trial on a longline fishing vessel,
2) Used temperature-depth recorders to quantify sinking rates of branchlines configured with wire and monofilament leaders, and
3) Measured the breaking strength of hooks used in the U.S. Pacific longline fisheries and quantified the time taken for hooks to dissolve or weaken to the point where trailing gear may fall off an animal.

2 Materials and Methods

2.1 Paired gear trials: catch comparison between wire and monofilament gear

Between January and July 2019, paired gear trials were conducted over four trips on a longline commercial fishing vessel targeting tuna. Normal fishing gear configurations on this vessel are shown in Figure 1. Branchlines were composed of monofilament ($\mu = 12.5$ m), a 45-gram weighted swivel, and 0.5 m of 49 strand (7 x 7) stainless steel wire leader to the hook. There were 15–20 sets per trip, 91–142 floats deployed per set, 24 hooks deployed between floats and the distance between floats was ~ 300 – 500 m, (i.e., one 'segment' contained 24 hooks and was ~ 300 – 500 m in length, Figure 1). Hooks used on the vessel were forged and unforged 14/0 and 15/0 offset circle hooks. To compare catch rates between different leader material, the crew duplicated the normal gear configuration for the vessel and exchanged 0.5 m of monofilament for wire as the leader material. Branchline leader materials (i.e., wire or monofilament) were alternated every 10–30 segments to eliminate any influence of spatial variation on catch rates (Figure 1). An observer from the Pacific Island Region Observer Program (PIROP) recorded when the gear changed from monofilament to wire leaders, any bite-offs (i.e., lines that were bitten through before the catch was brought to the vessel), the gear type on which each animal was captured, as well as the condition of the animal when captured. Condition categories were based on existing classifications from the PIROP and included: Alive (A), Alive in good condition (AG), Alive but injured (AI), Injured (I), and Dead (D) [43].

2.1.1 Effect of leader material on hook sinking rate

To quantify whether changing leader material affected sinking rates of hooks and also to determine fishing depth for each hook, 20 temperature-depth recorders (TDRs, Lotek Pty. Ltd. Canada) were placed within one meter of the weighted swivel during each set by the fishers. Half of the TDRs (n=10) were placed on each leader material (wire or monofilament) in the same hook positions, where the starting hook position was determined by the set number. For example, on set number one, TDRs were placed on hook numbers one through ten. One TDR at hook number one nearest the float with monofilament leaders and one TDR on hook number one of the subsequent segment with wire leaders (see Figure 1). In successive sets, the TDRs were placed on the next consecutive hooks, i.e., on set 2, TDRs were placed on hooks 2–11 (for a monofilament segment and a wire segment), set 3, TDRs were placed on hooks 3–12 (for a monofilament segment and a wire segment). TDRs were programmed to record temperature and depth every 45 seconds (Figure 1).

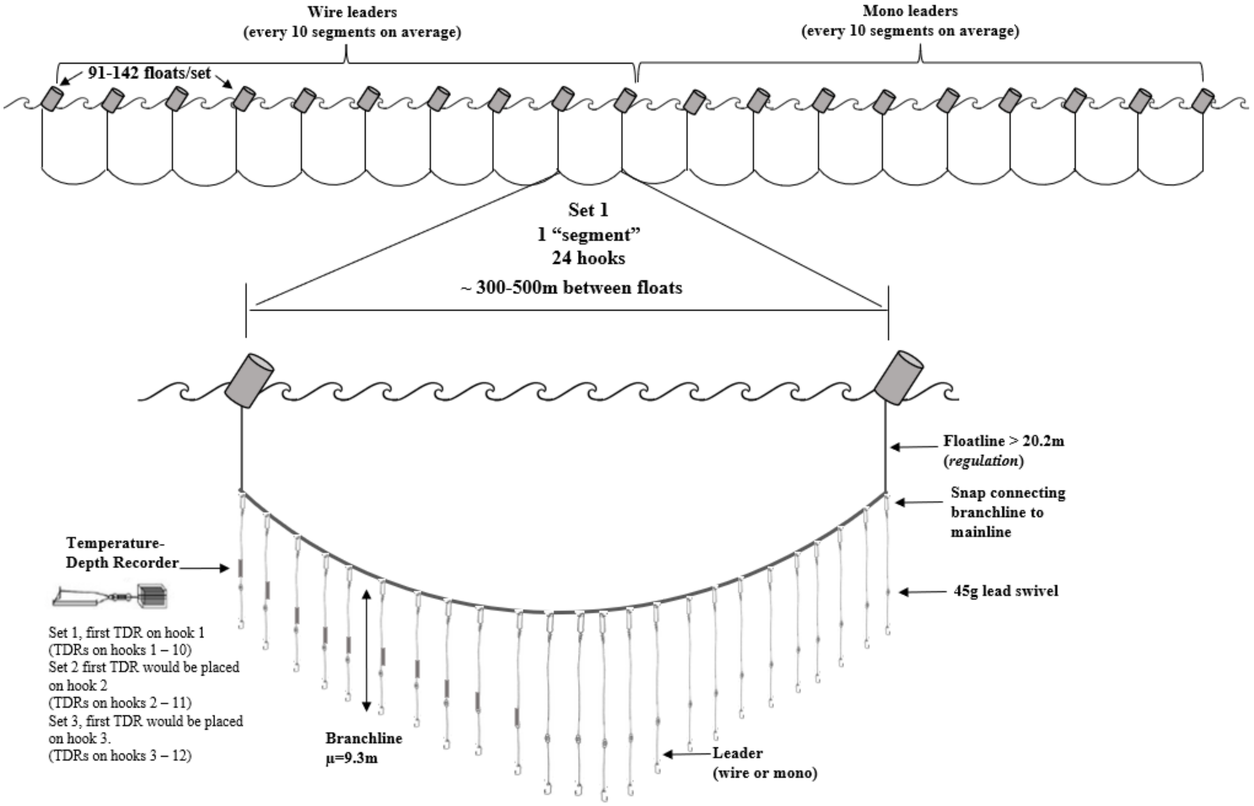


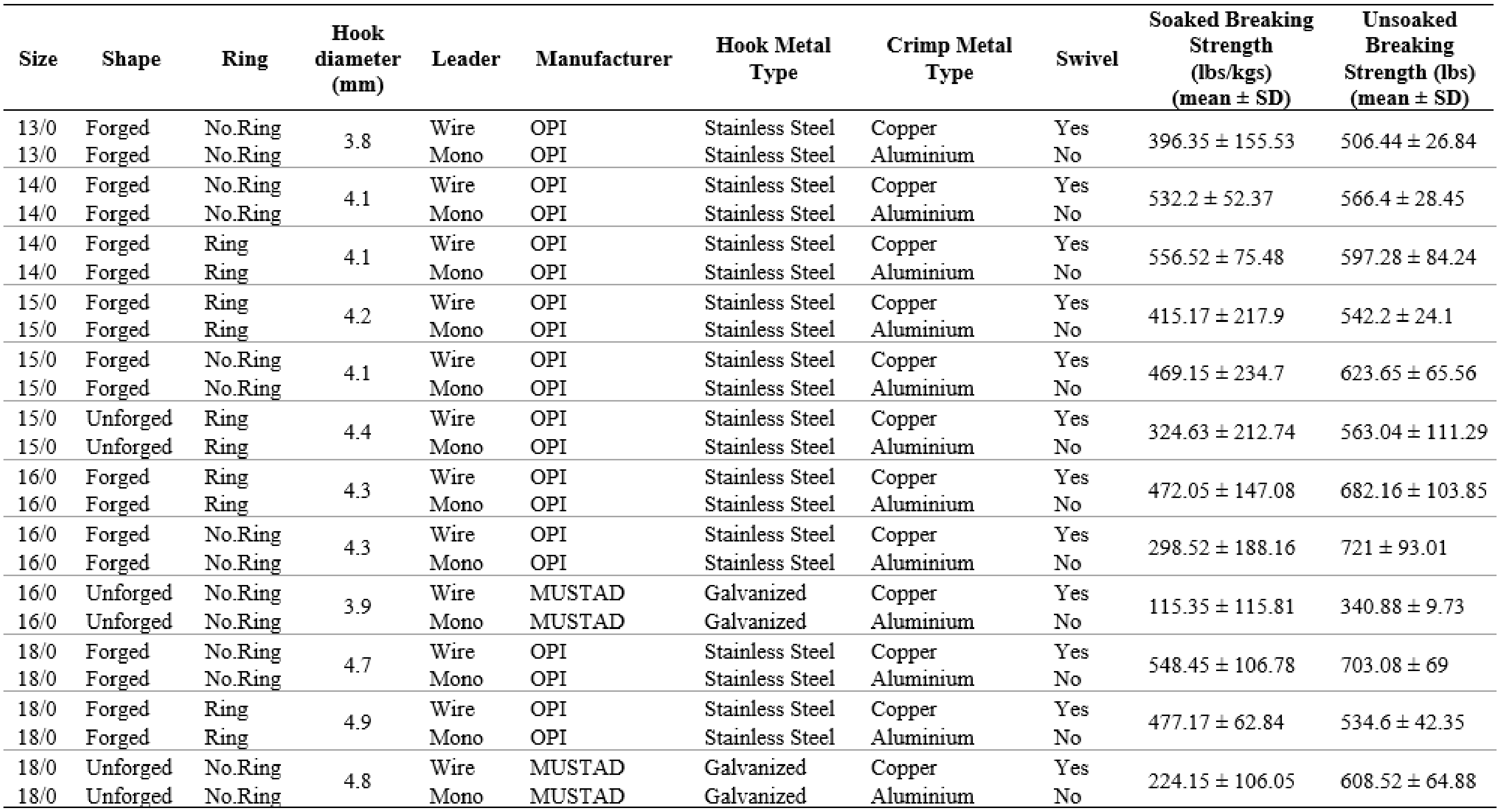
Figure 1: Schematic representation (not to scale) of the paired gear trials from (top) an entire section of pelagic longline gear with segments containing temperature-depth recorders (TDRs), and (bottom) an enlarged diagram of a segment from 'Set 1' equipped with TDRs, hooks, the lengths of the floatline and branchline, distance between branchlines and leader material.

2.2 Quantifying the rates at which the hooks dissolve or weaken to the point where the trailing gear left on sharks will break away.

To quantify hook dissolution, breaking strength, and the time taken for trailing gear to deteriorate and potentially fall off an animal, a controlled experiment was set-up in a flow-through flume at the Hawaiʻi Institute of Marine Biology, O’ahu, Hawaiʻi (Figure S2). Twenty-four gear combinations (i.e., hook and leader material) were trialed, based on common gear configurations used by longline fishing vessels throughout the Western and Central Pacific (PIROP database). Each combination was considered a treatment and differed by these variables; size (13/0 – 18/0), hook diameter (3.8 – 4.9 mm), shape (forged / unforged), ring (ring / no ring), metal type (galvanized / stainless steel), and leader material (wire / monofilament) (Table 1, Figures S1, S2, S3). Treatments with wire leaders had weighted swivels with copper crimps, and treatments with monofilament leaders had no weighted swivels and aluminum crimps (to mimic U.S. Pacific longline fishing gear configurations, Figure S1). Notably, the chafing gear used by some U.S. fishers where the leader is threaded through the hook eye was not used in these experiments. Hook diameter (i.e., the thickness of the metal used to manufacture the hooks) was measured using carbon fiber digital calipers (resolution 0.1 mm, Adoric 0-6”™). Measurements were taken from approximately 1 cm below the ring for all hooks and in front the forged portion (for forged hooks). Five diameters were measured for each hook type and average hook diameter was recorded. There were four replicate hook configurations per treatment and of these, three were embedded in 10 x 5 cm ballistic gel (10% gelatin, Clear Ballistics, Greenville, SC, USA) sections to mimic being embedded in tissue (e.g. the jaw of a marine animal). One hook was left out of the ballistic gel as a control. Two treatments (i.e., 8 hooks from two different gear configurations) were attached to a plexiglass base suspended above the bottom of a flow-through seawater flume by a tagged wooden cross-strut (Figures S2, S3). Hooks were positioned equidistant from one another to eliminate contact within and between treatments. The control hooks (i.e., those that were not embedded in ballistic gel) were laid along-side respective treatments on the bottom of the flume. The flume (24 ft long, 14 in wide, and 14 in deep) had a constant flow (2 km/ hr) of filtered seawater over the submerged hooks (Figures S2, S3). The flume was cleaned twice per week to eliminate any depositing of organic material.

Every 30 days, hooks were removed from the flume, rinsed with freshwater, and cut out of the ballistic gel. Each treatment was then tagged, placed on a baking tray, and dried in an oven at 170°F for 15 minutes to eliminate all moisture. Configurations were brushed using a fine toothbrush to remove any organic material remaining on the hooks (avoiding all rusted parts). Hooks were then weighed and photographed on both sides and the state of dissolution and gear deterioration were categorized into three groups as a proxy for the amount of trailing gear that would remain on an animal: 1) All Gear - all the gear (i.e., hook, leader, and weight) still attached; 2) Wire Leader - the wire leader still attached to the hook (i.e.; the upper crimp nearest the swivel came apart). In this scenario, the weight and branchline monofilament have fallen off; however, an animal would have ~ 1m of wire leader attached; 3) Hook Only - only the hook is still attached (i.e., the lower crimp nearest the hook came apart). In this scenario, only a hook is hypothetically left on the animal. After weighing and classifying, all hooks were placed back in ballistic gel blocks and rotated to a new position in the flume to eliminate any possibility of negative hydrodynamic effects. After 360 days (February 2018–January 2019) the experiment was concluded, and the breaking strength of each soaked hook was measured using a Lindgren-Pitman Line Puller STBRM model 190 (Lindgren-Pitman, Inc. Pompano-Beach, FL). Breaking strength was defined as the amount of pull strength (in pounds) required to either break the hook or open it by straightening it to the point where it came off the machine. This point corresponds to the degree of deformation required for a fish or marine mammal to come off the line or ‘escape’. Breaking strengths for identical unsoaked hooks (i.e., new hooks) were also measured for comparison (Table 1).

Table 1: The 24 different gear configurations (size, shape, ring, diameter, leader material and metal type) used to test gear deterioration and the breaking strengths (lbs) of soaked and unsoaked hooks in the flow-through flume experiment.



Size	Shape	Ring	Hook diameter (mm)	Leader	Manufacturer	Hook Metal Type	Crimp Metal Type	Swivel	Soaked Breaking Strength (lbs/kgs) (mean ± SD)	Unsoaked Breaking Strength (lbs) (mean ± SD)
13/0	Forged	No.Ring	3.8	Wire	OPI	Stainless Steel	Copper	Yes	396.35 ± 155.53	506.44 ± 26.84
13/0	Forged	No.Ring		Mono	OPI	Stainless Steel	Aluminium	No		
14/0	Forged	No.Ring	4.1	Wire	OPI	Stainless Steel	Copper	Yes	532.2 ± 52.37	566.4 ± 28.45
14/0	Forged	No.Ring		Mono	OPI	Stainless Steel	Aluminium	No		
14/0	Forged	Ring	4.1	Wire	OPI	Stainless Steel	Copper	Yes	556.52 ± 75.48	597.28 ± 84.24
14/0	Forged	Ring		Mono	OPI	Stainless Steel	Aluminium	No		
15/0	Forged	Ring	4.2	Wire	OPI	Stainless Steel	Copper	Yes	415.17 ± 217.9	542.2 ± 24.1
15/0	Forged	Ring		Mono	OPI	Stainless Steel	Aluminium	No		
15/0	Forged	No.Ring	4.1	Wire	OPI	Stainless Steel	Copper	Yes	469.15 ± 234.7	623.65 ± 65.56
15/0	Forged	No.Ring		Mono	OPI	Stainless Steel	Aluminium	No		
15/0	Unforged	Ring	4.4	Wire	OPI	Stainless Steel	Copper	Yes	324.63 ± 212.74	563.04 ± 111.29
15/0	Unforged	Ring		Mono	OPI	Stainless Steel	Aluminium	No		
16/0	Forged	Ring	4.3	Wire	OPI	Stainless Steel	Copper	Yes	472.05 ± 147.08	682.16 ± 103.85
16/0	Forged	Ring		Mono	OPI	Stainless Steel	Aluminium	No		
16/0	Forged	No.Ring	4.3	Wire	OPI	Stainless Steel	Copper	Yes	298.52 ± 188.16	721 ± 93.01
16/0	Forged	No.Ring		Mono	OPI	Stainless Steel	Aluminium	No		
16/0	Unforged	No.Ring	3.9	Wire	MUSTAD	Galvanized	Copper	Yes	115.35 ± 115.81	340.88 ± 9.73
16/0	Unforged	No.Ring		Mono	MUSTAD	Galvanized	Aluminium	No		
18/0	Forged	No.Ring	4.7	Wire	OPI	Stainless Steel	Copper	Yes	548.45 ± 106.78	703.08 ± 69
18/0	Forged	No.Ring		Mono	OPI	Stainless Steel	Aluminium	No		
18/0	Forged	Ring	4.9	Wire	OPI	Stainless Steel	Copper	Yes	477.17 ± 62.84	534.6 ± 42.35
18/0	Forged	Ring		Mono	OPI	Stainless Steel	Aluminium	No		
18/0	Unforged	No.Ring	4.8	Wire	MUSTAD	Galvanized	Copper	Yes	224.15 ± 106.05	608.52 ± 64.88
18/0	Unforged	No.Ring		Mono	MUSTAD	Galvanized	Aluminium	No		

3 Statistical Analysis

3.1 Paired gear trials: Catch comparison between wire and monofilament gear

Catch data were separated into single species, species groups, and catch groups (see Table 2). Single species included: bigeye tuna (*Thunnus obesus*, target of this fishery), skipjack tuna (*Katsuwonus pelamis*), yellowfin tuna (*T. albacares*), swordfish (*Xiphias gladius*), blue shark (*Prionace glauca*), bigeye thresher (*Aliopas supercilious*), shortfin mako (*Isurus oxyrhinchus*). Species groups were separated into; tuna (*Katsuwonus pelamis, T. obesus, T. albacares, T.* spp.), billfish (*Istiophoridae, Tetrapturus angustirostris, Xiphias gladius, Tetrapturus audax*), dolphinfish (*Coryphaena equiselis, C. hippurus*), pomfrets (*Taractichthys steindachneri, Taractes rubescens, Bramidae* spp.), oilfish (*Ruvettus pretiosus, Lepidocybium flavobrunneum, Scombrolabrax heterolepis*), and sharks; blue shark, bigeye thresher, shortfin mako, crocodile shark (*Pseudocarcharias kamoharai*), unidentified thresher (*Aliopas* spp.), and unidentified mako sharks *(Isurus* spp). Catch groups included; marketable species, i.e., species and species groups that are sold commercially (tunas, billfish, dolphinfish, oilfish, pomfrets, *lampris guttatus, Escolar, Acanthocybium solandri*), other non-target species, i.e., species and species groups that are marketable but not targeted, some discarded (*Alepisaurus ferox, Gempylus serpens, Scombrolabrax heterolepis, Zu elongatus*), and sharks and rays (rays included; *Dasyatis violacea*). In this study there were three interactions with protected species. Due to low sample size, these species were not included in the analysis.

Generalized Linear Mixed Models (GLMMs) were used to investigate the effect of leader material on catch. GLMMs were employed because longline data are hierarchical [44] in that longline sets occur together in space and time and sets within a trip are expected to be more closely related than sets between trips. Catch data was recorded as the number of individuals of each species caught on either wire or monofilament leader material. Catch data were aggregated (summed) per set for each species, species group and catch group. Due to the discrete nature of the data (i.e. counts) both poisson and negative binomial distributions were tested [45]. Model selection was based on the corrected Akaike Information Criteria (AIC), and model fit and assumptions were examined using residual plots, all of which were satisfactory. Negative binomial error distribution with a log-link was selected to account for the non-normal and overdispersed nature of the count data. For each analysis, the GLMM predicted catch as an interaction between the number of individuals caught and leader type. Due to the differing number of wire and monofilament hooks deployed per set, an offset parameter (i.e., the number of wire or monofilament hooks deployed during a set) was added to the model. To account for spatial and temporal variation within and between sets, a nested variable (trip number/set number) was included in each model providing an estimate of catch over levels of trip. Therefore, for each model the response variable was catch, and predictor variables were the interactions between leader type (either wire or monofilament) and either individual species (each species analyzed separately), species groups (analyzed together), or catch groups (analyzed together). To compare catch of sharks as a group between leader materials, two datasets were generated. One that included 'bite-offs', which used the assumption that all bite-offs were caught sharks following [16], and the second that compared the numbers of bite-offs between monofilament and wire gear only. Each subset of the data (i.e., single species, species groups, catch groups, sharks only) were analyzed separately. All analyses were conducted in R Statistical Program [46] using the packages *lme4* [47], *DHARMa* [48], *glmmTMB* [49], *MASS* [50]. Tukey's adjusted pairwise comparisons (*emmeans;*[51]) were used to examine differences in catch between wire and monofilament gear types for each subset of data. *Emmeans* computes estimated marginal means (or least-squares means) from fitted models and enables comparisons among and between estimates using Tukey's adjustment [51].

3.1.1 Paired gear trials: Catch condition

Catch condition of all sharks brought to the vessel was scored into one of five categories: Alive (A), Alive in good condition (AG), Alive but injured (AI), Dead (D), and Injured (I). Only sharks that were brought to the vessel were included in the analysis, so the response variable (catch) was > 1. Data were again aggregated by catch per set for all sharks and blue sharks. The data were count data that were not overdispersed, so a Poisson distribution with trip number/set number nested within the model and a log link function was used to compare caught condition of sharks as a group and blue sharks (analyzed separately) between monofilament and wire gear types across each trip. The offset parameter (i.e., the number of wire or monofilament hooks deployed during a set) was also included in these models. Again, Tukey's adjusted pairwise comparisons were used to examine differences in catch and catch condition between wire and monofilament gear types [51].

3.1.2 Paired gear trials: Temperature-depth recorders (TDRs)

For each TDR deployment, we classified a) sinking rate—the rate of change in depth across the first 50 m of the hooks deployment and b) fishing depth, i.e., when a hook was not sinking or being hauled, but sitting at a relatively 'stable' depth (as defined by [52]). The sinking period was defined as the first 50 m of the deployment when each consecutive depth reading was ≥ 5 m from the previous. The first 50 m was chosen to ensure that sinking rates were not influenced by setting of gear, currents, or oceanographic features at deeper depths (i.e., ≥ 200 m). Sinking rate was calculated as the average distance (i.e., difference in depth between first reading at deployment and last reading at 50 m) over time (seconds or minutes). To ascertain the initial shape and depth of when the gear reached its fishing depth, average depth was calculated across the same hook number for wire and monofilament gear. Data from two TDRs were excluded due to technical malfunctions. A paired t-test was used to determine whether there were differences in sinking rates and fishing depth between gear types.

3.2 Flume experiment: Gear deterioration & breaking strength

To test the influence of hook characteristics on the breaking strength and deterioration of gear, six variables were examined; hook size (13/0 - 18/0), hook diameter (3.8 - 4.9 mm), shape (forged / unforged), ring (ring / no ring), and metal type (galvanized / stainless steel), as well as leader material (wire / monofilament) (Table 1). There was a direct positive correlation between hook size and hook weight (in grams), so hook weight was used as a proxy for size and added as a continuous variable into our models. Similarly, hook diameter was positively correlated with hook size (Figure S4), so separate models were used to test the influence of hook diameter and hook size explicitly.

3.2.1 Breaking strength

To determine the influence of the six hook characteristics on breaking strength of experimental circle hooks (i.e., those that were soaked in the flume for 360 days) and new hooks (those that were unsoaked), GLMMs with a gamma distribution (log-link function) for continuous non-negative data were employed. Breaking strength (lbs) was the response variable and hook size, diameter, shape, ring, metal type, and leader material were predictors variables. Due to the unbalanced nature of the experimental design (i.e., unequal amount of replicate treatments), the data were re-weighted via an inverse sample size weighting and included in the models as weights. To compare differences in the breaking strength of experimental versus new hooks, a paired t-test was conducted.

3.2.2 Gear deterioration

To quantify the time taken for trailing gear to deteriorate, data were classified into three categories; 1) All gear 2) Wire leader 3) Hook only (see Methodology). Because the same hooks were repeatedly measured through time, and the categories of gear deterioration were ordinal in nature (i.e., All gear, Wire leader, Hook only), an ordinal logistic cumulative link mixed model (CLMM) for repeated measures was used (logit link function, R package: *ordinal,* [53]) to assess the influence of the six hook characteristics on the breakdown of the gear over time. CLMMs are useful for ordinal regression models with random effects and hook was included as a random effect in the model. Estimation via maximum likelihood using the Laplace approximation or adaptive Gauss-Hermite quadrature (for one random effect) was used. Data were again re-weighted via an inverse sample size weighting and were included in the model as weights.

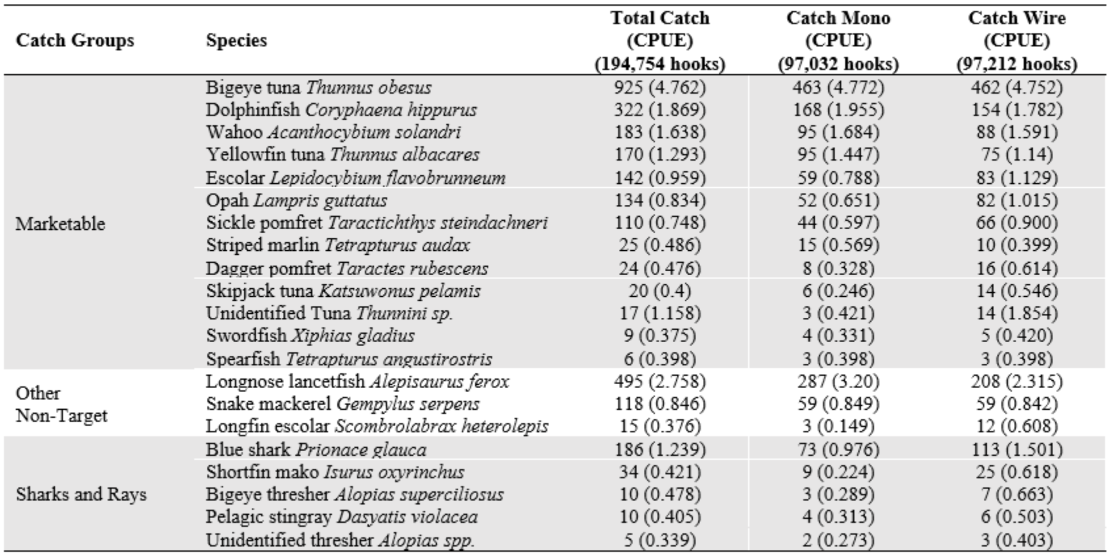
We also wanted to measure corrosion rates, i.e., change in density of hooks across time. Unfortunately, we were unable to measure changes in hook density due to unexpected pitting and exposure blisters in some hooks which overinflated weights and diameters and subsequently impacted hook density. Instead, we sub-sampled data to include only the weight of the hook across the sampling period; this meant there was a gap in data until trailing gear fell off the hook and we were able to measure hook weight only. Due to the nature of these data, the analysis was limited to exploratory plots fitted using locally estimated scatterplot smoothing (LOESS).

4 Results

4.1 Paired gear trials: Catch comparison

The raw catch and nominal CPUE for the 20 most commonly caught species on monofilament (*n* = 97,032 hooks) and wire (*n* = 97,212 hooks) are shown in Table 2. Across the four trips, the vessel deployed between 15 - 20 sets per trip. Within each set, 91 - 142 floats (mean = 129 floats) were deployed, with 24 hooks per float. Therefore, the number of hooks deployed per set varied between 2001 - 3247 (mean = 2948 hooks). Floatline lengths were 20.4 m ± 0.15m (mean ± SD), and branchline lengths were 9.3 ± 0.18 m (mean± SD).

Table 2: Catch summary for the 20 most commonly caught species on wire and mono gear for four commercial longline trips. Numbers are raw catch and nominal CPUE in parentheses.



Catch Groups	Species	Total Catch (CPUE) (194,754 hooks)	Catch Mono (CPUE) (97,032 hooks)	Catch Wire (CPUE) (97,212 hooks)
Marketable	Bigeye tuna *Thunnus obesus*	925 (4.762)	463 (4.772)	462 (4.752)
	Dolphinfish *Coryphaena hippurus*	322 (1.869)	168 (1.955)	154 (1.782)
	Wahoo *Acanthocybium solandri*	183 (1.638)	95 (1.684)	88 (1.591)
	Yellowfin tuna *Thunnus albacares*	170 (1.293)	95 (1.447)	75 (1.14)
	Escolar *Lepidocybium flavobrunneum*	142 (0.959)	59 (0.788)	83 (1.129)
	Opah *Lampris guttatus*	134 (0.834)	52 (0.651)	82 (1.015)
	Sickle pomfret *Taractichthys steindachneri*	110 (0.748)	44 (0.597)	66 (0.900)
	Striped marlin *Tetrapturus audax*	25 (0.486)	15 (0.569)	10 (0.399)
	Dagger pomfret *Taractes rubescens*	24 (0.476)	8 (0.328)	16 (0.614)
	Skipjack tuna *Katsuwonus pelamis*	20 (0.4)	6 (0.246)	14 (0.546)
	Unidentified Tuna *Thunnini sp.*	17 (1.158)	3 (0.421)	14 (1.854)
	Swordfish *Xiphias gladius*	9 (0.375)	4 (0.331)	5 (0.420)
	Spearfish *Tetrapturus angustirostris*	6 (0.398)	3 (0.398)	3 (0.398)
Other Non-Target	Longnose lancetfish *Alepisaurus ferox*	495 (2.758)	287 (3.20)	208 (2.315)
	Snake mackerel *Gempylus serpens*	118 (0.846)	59 (0.849)	59 (0.842)
	Longfin escolar *Scombrolabrax heterolepis*	15 (0.376)	3 (0.149)	12 (0.608)
Sharks and Rays	Blue shark *Prionace glauca*	186 (1.239)	73 (0.976)	113 (1.501)
	Shortfin mako *Isurus oxyrinchus*	34 (0.421)	9 (0.224)	25 (0.618)
	Bigeye thresher *Alopias superciliosus*	10 (0.478)	3 (0.289)	7 (0.663)
	Pelagic stingray *Dasyatis violacea*	10 (0.405)	4 (0.313)	6 (0.503)
	Unidentified thresher *Alopias spp.*	5 (0.339)	2 (0.273)	3 (0.403)

In total, 2984 individuals from 34 species were caught, 1465 on monofilament, 1519 on wire gear. Bigeye tuna, the fishery target, were the most frequently caught species (CPUE = 4.762) across all four sampling trips, followed by the longnose lancetfish (*A. ferox*, CPUE = 2.758) and the common dolphinfish (CPUE = 1.869). A comparison of catch rates for the four most common marketable species; Bigeye tuna, Yellowfin tuna, Skipjack tuna, and Swordfish demonstrated no significant differences in CPUE between wire and monofilament gear types (Table 3, Figure 2b & 2c). For the marketable species group as a whole, there was slightly higher catch on wire compared with monofilament gear (Figure 2c). Although not significant, this difference was primarily driven by higher catch of pomfret and oilfish on wire gear (*p*=0.857, Table 3, Figure 2b).

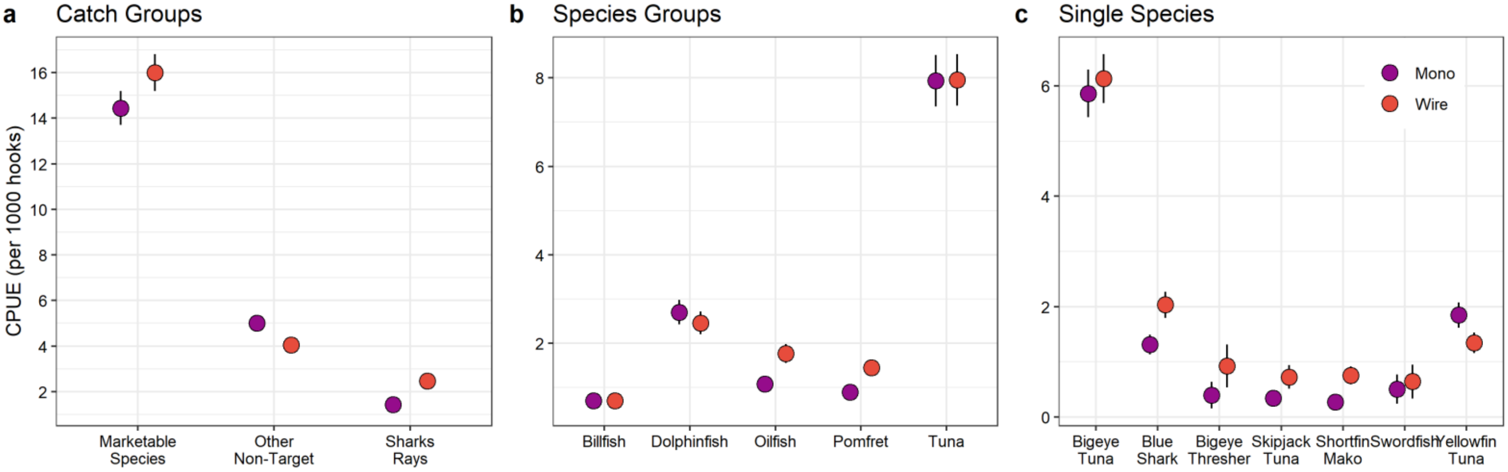


Figure 2. Modelled estimates of mean CPUE of a) catch groups, b) species groups, and c) single species between wire (orange) and monofilament (purple) leader materials for the paired-gear trials (n=4 trips). Error bars indicate standard error.

A total of 235 sharks were captured across the four trips. There were significantly higher (41%) catch rates of sharks (all species grouped together) on wire (CPUE = 1.36) compared with monofilament gear (CPUE = 0.76) (*p*=0.004, Table 3, Figure 3a). However, these data only represented sharks that were brought to the vessel. A total of 55 bite-offs were recorded, four of these bite-offs were on wire leaders and the remaining 51 (94 %) occurred on lines with monofilament leaders (Figure 3b). If we assume that bite-offs were made by undetected sharks, differences in shark catchability between leader types disappear (*p*=0.963, Table 3, Figure 3c). At an individual species level, blue shark was the most commonly caught shark (CPUE = 0.62) comprising 75.9% of the total shark catch (Table 1) and there were 35.3% more blue sharks caught on wire (CPUE = 1.5) compared with monofilament (CPUE = 0.97) gear types (*p*=0.0034, Table 2, Figure 2c). Similarly, there was a 64.5% increase in shortfin mako sharks (*I. oxyrhincus*) caught on wire gear (CPUE = 0.62) compared with monofilament (CPUE = 0.22) leaders (*p*=0.0086, Table 3, Figure 2c).

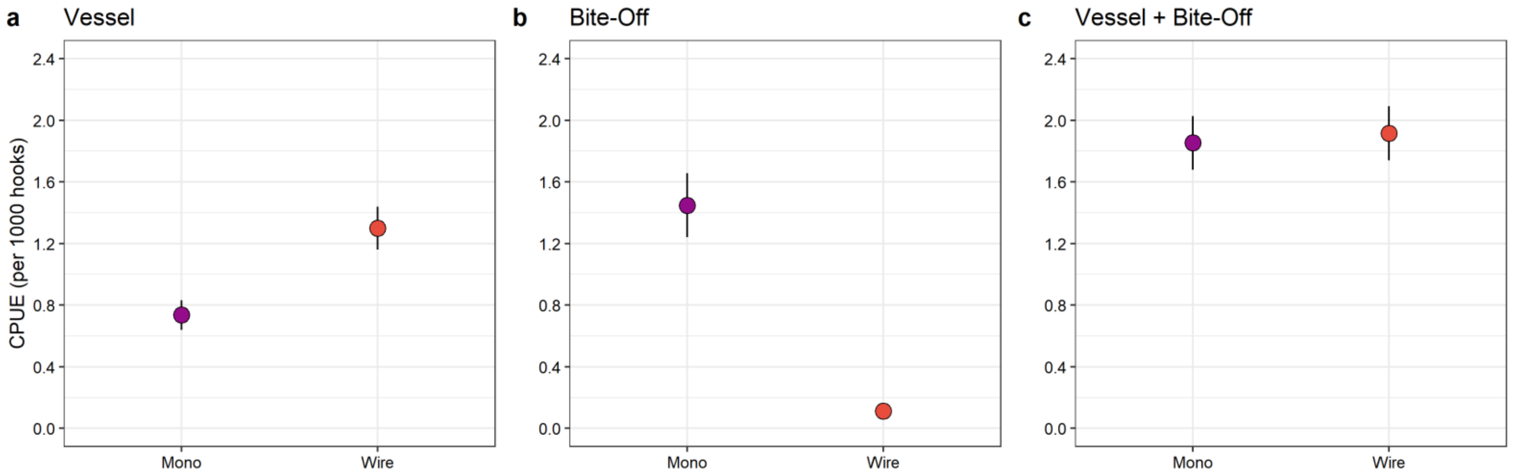
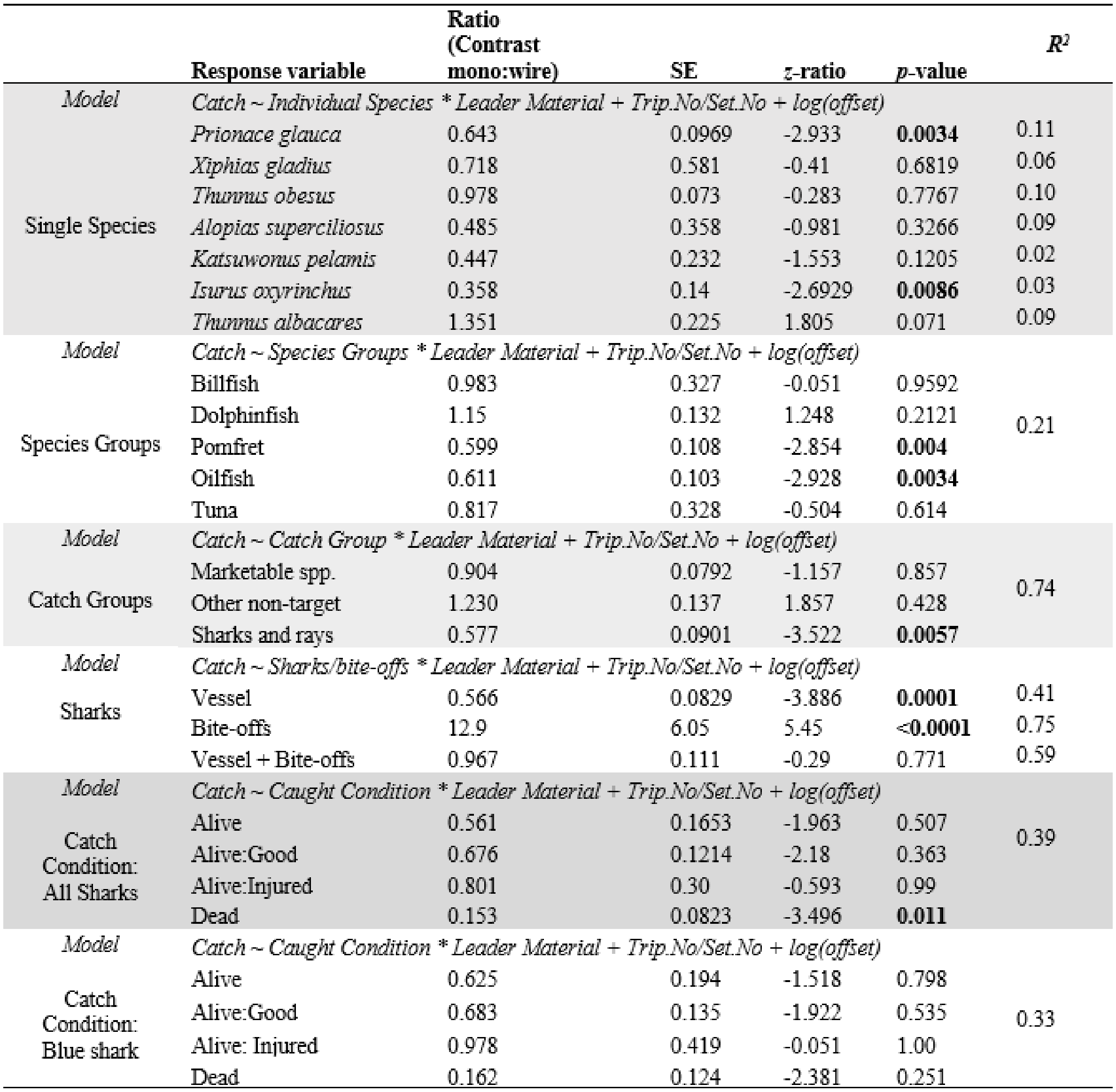


Figure 3: Modelled estimates of mean CPUE between wire and monofilament leader material for a) all sharks brought to vessel, b) bite-off data, and c) sharks plus bite-off data. Error bars indicate standard error.

Table 3: Contrast table (monofilament vs. wire) showing catch comparisons of single species (most commonly captured, each species analyzed separately), species groups, catch groups, and sharks that were i) brought to the vessel, ii) bite offs, ii) combination of vessel and bite offs. The catch condition for all sharks and blue sharks between monofilament and wire is also shown. Model notation is shown in *italics* at the top of each data subset. Individual species were analyzed separately. The p-value in bold indicates a significant difference in catch and / or catch condition between monofilament and wire leader materials.



	Response variable	**Ratio (Contrast mono:wire)**	**SE**	***z*-ratio**	***p*-value**	***R*²**
Model	*Catch ~ Individual Species * Leader Material + Trip.No/Set.No + log(offset)*					
Single Species	*Prionace glauca*	0.643	0.0969	-2.933	**0.0034**	0.11
	Xiphias gladius	0.718	0.581	-0.41	0.6819	0.06
	Thunnus obesus	0.978	0.073	-0.283	0.7767	0.10
	Alopias superciliosus	0.485	0.358	-0.981	0.3266	0.09
	Katsuwonus pelamis	0.447	0.232	-1.553	0.1205	0.02
	Isurus oxyrinchus	0.358	0.14	-2.6929	**0.0086**	0.03
	Thunnus albacares	1.351	0.225	1.805	0.071	0.09
Model	*Catch ~ Species Groups * Leader Material + Trip.No/Set.No + log(offset)*					
Species Groups	Billfish	0.983	0.327	-0.051	0.9592	0.21
	Dolphinfish	1.15	0.132	1.248	0.2121	
	Pomfret	0.599	0.108	-2.854	**0.004**	
	Oilfish	0.611	0.103	-2.928	**0.0034**	
	Tuna	0.817	0.328	-0.504	0.614	
Model	*Catch ~ Catch Group * Leader Material + Trip.No/Set.No + log(offset)*					
Catch Groups	Marketable spp.	0.904	0.0792	-1.157	0.857	0.74
	Other non-target	1.230	0.137	1.857	0.428	
	Sharks and rays	0.577	0.0901	-3.522	**0.0057**	
Model	*Catch ~ Sharks/bite-offs * Leader Material + Trip.No/Set.No + log(offset)*					
Sharks	Vessel	0.566	0.0829	-3.886	**0.0001**	0.41
	Bite-offs	12.9	6.05	5.45	**<0.0001**	0.75
	Vessel + Bite-offs	0.967	0.111	-0.29	0.771	0.59
Model	*Catch ~ Caught Condition * Leader Material + Trip.No/Set.No + log(offset)*					
Catch Condition: All Sharks	Alive	0.561	0.1653	-1.963	0.507	0.39
	Alive:Good	0.676	0.1214	-2.18	0.363	
	Alive:Injured	0.801	0.30	-0.593	0.99	
	Dead	0.153	0.0823	-3.496	**0.011**	
Model	*Catch ~ Caught Condition * Leader Material + Trip.No/Set.No + log(offset)*					
Catch Condition: Blue shark	Alive	0.625	0.194	-1.518	0.798	0.33
	Alive:Good	0.683	0.135	-1.922	0.535	
	Alive: Injured	0.978	0.419	-0.051	1.00	
	Dead	0.162	0.124	-2.381	0.251	

4.1.1 Paired gear trials: Catch condition

Catch condition of all sharks (grouped together) and blue sharks (analyzed separately) that were brought to the vessel were also compared across gear types (Table 3). Of the 172 sharks caught in total, 26 (15%) were brought to the vessel dead (n=4 on monofilament and n=22 on wire). This result suggests wire leaders may cause higher mortality for sharks (as a group).

Surprisingly, for blue sharks, whether they were caught on wire or monofilament leaders had no bearing on their catch condition (Table 3).

4.1.2 Paired gear trials: TDRs - Fishing depth and sinking rates

Temperature-depth recorder data determined the most common depths fished to be 192.9 ± 16.6 m (mean ± SD), the minimum fishing depth was 27.2 m, and the maximum was 330.9 m. Fishing depths were relatively similar between wire and monofilament gear types for shallower hooks (i.e., hooks 1- 8 and 17 - 24) where average fishing depth for hooks with monofilament leaders was 139.3 ± 61.6 m (mean ± SD) and for wire leaders 142.7 ± 63.1 m (mean ± SD) (t=-0.155, p = 0.8775). However, for deeper set hooks (i.e., hooks 9 - 16, > 200 m), the difference in fishing depth between gear types increased significantly so that hooks with wire leaders fished on average 29.3 m deeper (272.3 ± 22.9 m, mean ± SD) than hooks with monofilament leaders (243 ± 12.3 m, mean ± SD) in the same position (t=-3.1812, p = 0.009) (Figure 4). Irrespective of differences in fishing depth, we found no differences in the sinking rates between wire and monofilament leader types (t=1.317, p = 0.188). The mean sinking rate for monofilament gear was 0.21 ± 0.026 m/sec (12.62 ± 1.58 m/min, mean ± SD) and for wire was 0.21 ± 0.037 m/sec (12.37 ± 2.21 m/min, mean ± SD).

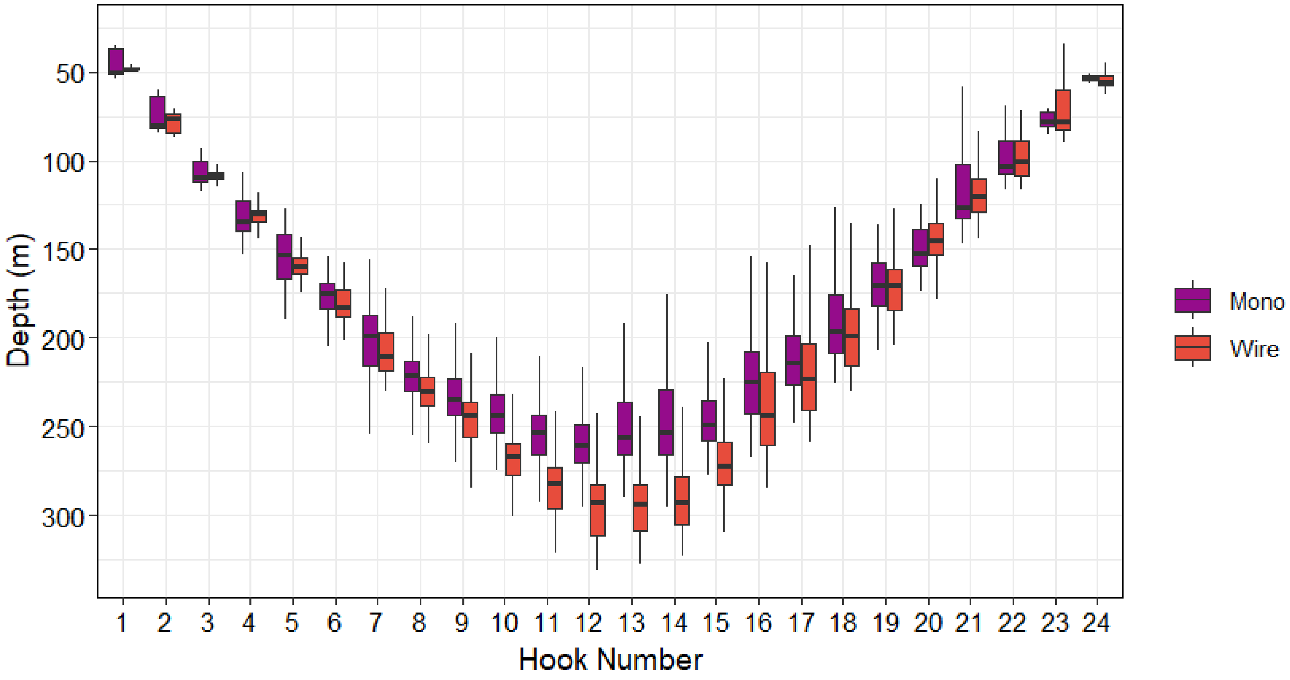


Figure 4: Box-and-whisker plots showing the average fishing depth for each hook (1-24) across wire (orange) and monofilament (purple) gear types. The median depth for each hook is represented by the middle line in each plot, with the upper and lower 25% above and below the median represented by the box. The whiskers are extended to extreme values.

4.2 Flume experiment

4.2.1 Flume experiment: Gear deterioration

For all gear combinations, hooks rigged with monofilament leaders did not break apart, and all gear stayed attached to the hook for 360 days (Figure 5). In contrast, gear rigged with wire leaders began to break apart after an average of 109.61 ± 32.47 days (mean ± SD), primarily due to corrosion of the copperlock crimps composed of dissimilar metals locking the stainless steel wire leader nearest the hook eye/ring or at the weighted swivel in place. Wire leaders remained attached to the hooks for an average of 163.92 ± 47.05 days (mean ± SD); however, the crimps connecting the hooks to wire leaders began to break apart around 174.6 ± 46 days (mean ± SD) (Figure 5). For hooks with wire leaders, metal type and shape had the strongest influence on the time when trailing gear fell apart (Table 4, Figure S5). For example, unforged, galvanized hooks had completely disintegrated after an average of 195 ± 14.4 days (mean ± SD) whereas, forged stainless steel hooks took on average 217.5 ± 24.8 days (mean ± SD) to break apart, although there was a large amount of variability in gear deterioration between hook types (Figure S5).

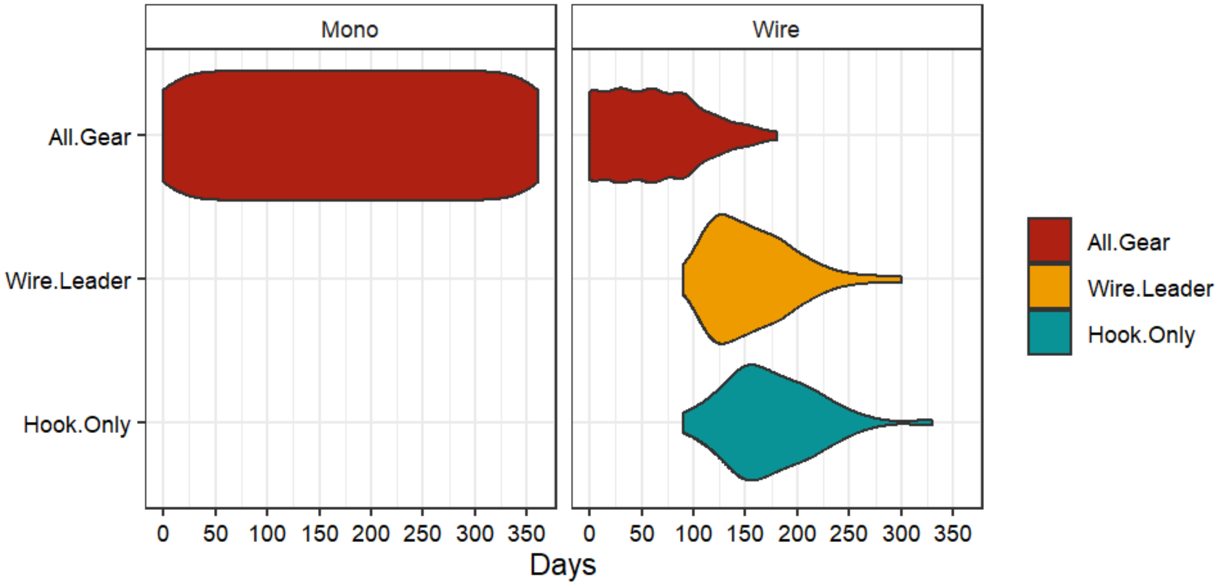


Figure 5: Amount of time (days) taken for various components of trailing gear to fall off hooks rigged with monofilament leaders (left panel) and hooks rigged with wire leaders (right panel). In red: all trailing gear is intact and remains on the hook. In yellow: the crimp near the weighted swivel failed and trailing gear above the wire leader came off. In teal: the crimp nearest the hook failed and the leader plus the swivel came off (i.e., all trailing gear would have come off the animal except the hook).

Table 4: Statistical output for the ordinal repeated measures mixed effects models testing the influence of five hook characteristics on the time taken for trailing gear to deteriorate.

	Coefficients	Estimate	SE	*z*-value	*p*-value	R^2
Gear Deterioration	Soak Time	0.037	0.018	2.009	**0.044**	0.60
	Leader:Wire	32.072	0.043	474.83	**<0.001**	
	Hook.Size	0.171	0.04	4.29	**<0.001**	
	Shape:Unforged	0.176	0.043	4.11	**<0.001**	
	Metal.Type:StainlessSteel	1.597	4.99	0.320	0.749	

4.2.2 Flume experiment: Hook weight change

Though actual rates of corrosion (i.e., change in density of hooks over time) were unable to be determined, Figure 6 shows the change in weight of hooks across time. For all hooks except 14/0 forged, stainless steel there was a gradual decrease in weight between 0 - 360 days. Weight loss was primarily influenced by metal type and hook size, where larger, galvanized hooks lost up to ~11.5% ± 2.9% of their original weight compared with stainless steel hooks that lost ~1.2% ± 0.8% of their original weight between days 0 and 360 (Figure 6).

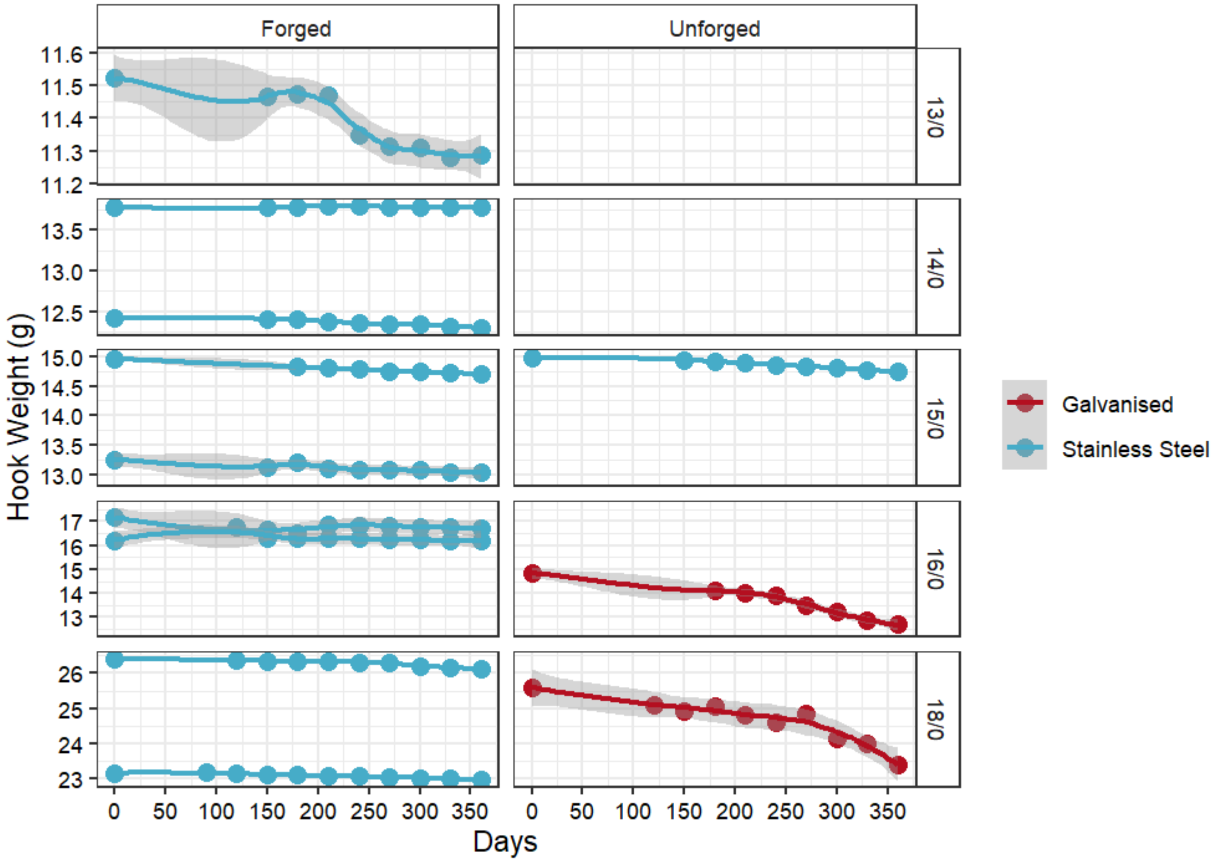


Figure 6: Average weight loss in grams (y-axis, used as proxy for corrosion rate) across 360 days (x-axis) of soaking. Horizontal panels represent hook size, whilst vertical panels compare forged and unforged

hooks This graph shows the data for hooks with wire leaders only.

4.2.3 Flume experiment: Breaking strength

Breaking strength of soaked hooks across the 12 different hook configurations (excluding leader material) varied between 1 - 654.2 lb (398.6 ± 136.15, mean ± SD) and the breaking strength of the unsoaked (i.e., new) hooks varied between 325.6 - 824.8 lb (582.0 ± 117.9 mean ± SD) indicating that hooks that had been soaked for 360 days had a substantially lower breaking strength (up to 178 lb less on average) than their identical unsoaked counterparts (t = -5.10, p <0.001, Table 1, Figure 7). Hook shape (forged / unforged), metal type (galvanized / stainless steel), size (14/0 - 18/0) and diameter (3.8 - 4.9 mm) were the most influential predictors for the breaking strength of soaked hooks (Figure 7, Table 1, Table 5). There was a positive increasing relationship between breaking strength, hook size, and hook diameter where larger hooks, greater in diameter, had higher breaking strengths (Figure 7). However, hook shape was the strongest predictor where forged hooks had consistently higher breaking strengths than unforged hooks. For example, larger, forged, stainless steel hooks required up to 612.35 ± 188.5 lb (mean ± SD) of force to open or break them compared with 175.05 ± 192.35 lb required to open or break smaller, unforged galvanized hooks (Figure 7, Table 1). Interestingly, breaking strength differed markedly for similar sized hooks (i.e., 15/0) of different shapes and diameters. For example, the average breaking strength of a 15/0, forged, 4.2 mm, stainless steel hook was 415.17 ± 217.9 lb (mean ± SD) while the average breaking strength of a 15/0, unforged, 4.4 mm hook was 324.63 ± 212.74 lb (mean ± SD) (Table 1, Figure 7). The difference of 90.54 lb of force required to break or open these similar hook types suggests that both shape and diameter are important predictors of breaking strength (Table 1). The hook with the lowest breaking strength (115.35 ± 115.81 mean ± SD) was the 16/0, 3.9 mm, Mustad, unforged, galvanized hook with no ring (Table 1, Figure 7). Although whether or not a hook had a ring did not influence its breaking strength (Table 1, Table 5). For new (unsoaked) hooks, size, diameter, and metal type were influential predictors of breaking strength (Table 1, Table 5); however, shape (forged / unforged) and whether or not the hook had a ring did not influence breaking strength for unsoaked hooks. Therefore, whether or not a hook is forged may be an important consideration in breaking strength for soaked hooks.

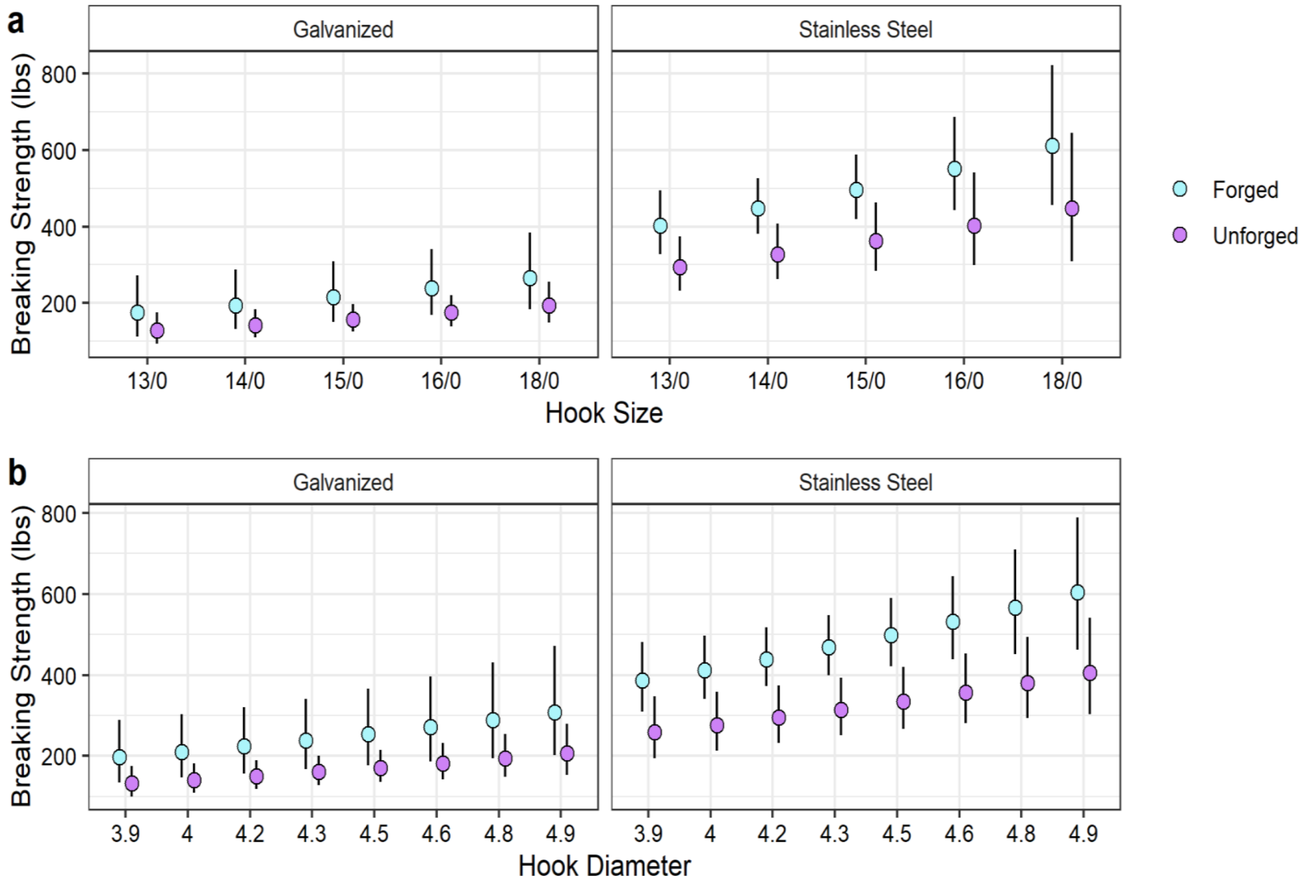
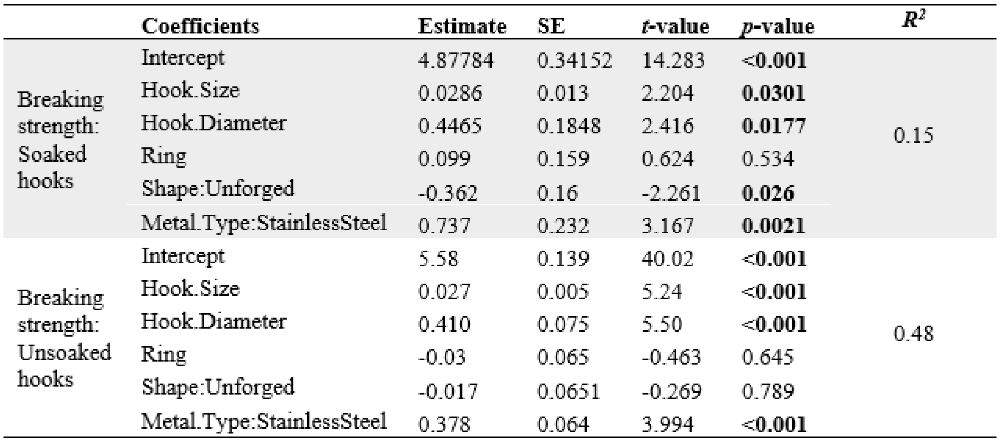


Figure 7: Predicted mean breaking strength (lb) of soaked galvanized (left panel) and stainless steel (right panel) hooks across increasing sizes (x-axis) and shapes; forged (blue circles) and unforged (purple circles). Black vertical lines represent the 95% confidence intervals around the mean.

Table 5: Statistical output for the influence of hook characteristics on the breaking strength of soaked and unsoaked hooks. Bold p-values show which characteristics had the most influence on breaking strength for soaked and unsoaked hooks.



	Coefficients	**Estimate**	**SE**	***t*-value**	***p*-value**	***R*²**
Breaking strength: Soaked hooks	Intercept	4.87784	0.34152	14.283	<**0.001**	0.15
	Hook.Size	0.0286	0.013	2.204	**0.0301**	
	Hook.Diameter	0.4465	0.1848	2.416	**0.0177**	
	Ring	0.099	0.159	0.624	0.534	
	Shape:Unforged	-0.362	0.16	-2.261	**0.026**	
	Metal.Type:StainlessSteel	0.737	0.232	3.167	**0.0021**	
Breaking strength: Unsoaked hooks	Intercept	5.58	0.139	40.02	<**0.001**	0.48
	Hook.Size	0.027	0.005	5.24	<**0.001**	
	Hook.Diameter	0.410	0.075	5.50	<**0.001**	
	Ring	-0.03	0.065	-0.463	0.645	
	Shape:Unforged	-0.017	0.0651	-0.269	0.789	
	Metal.Type:StainlessSteel	0.378	0.064	3.994	<**0.001**	

5 Discussion

As concerns for fishery sustainability have increased over time, some of the largest improvements in bycatch mitigation strategies within U.S. fisheries have been due to changes in fishing gear configurations, where simple adjustments have produced encouraging outcomes [16, 54, 55]. In this study, we show that leader material, as well as hook size, diameter, shape, and metal type are influential factors to consider for optimizing fishing gear configurations, potentially enhancing operational effectiveness and reducing harm and injury to bycatch species in the U.S. Pacific longline fisheries. Our results echo previous studies that demonstrate a reduction in shark bycatch and mortality on monofilament leaders compared with wire, whilst catch rates of target species were maintained or increased [15, 16]. This finding is primarily driven by the assumption that sharks are more likely to bite through monofilament [16, 56] and are therefore less likely to be brought to the vessel on monofilament gear. We found that the number of sharks brought to the vessel was ~ 41% higher on wire leaders compared with monofilament, whereas 94% of bite-offs occurred on monofilament leaders. Although wire leaders reduce the probability of caught individuals escaping the vessel to a large extent [16], we also show that wire leaders increase the potential for at vessel mortality for sharks by up to 20%. Further, the proportion of bite-offs to the number of sharks caught (23.4%) suggests that a significant number of sharks may fail to be accounted for in longline fisheries catch statistics and population assessments when monofilament leaders are used. Therefore, while switching gear types to monofilament may provide an effective mechanism to allow sharks to free themselves from fishing gear and reduce shark mortality rates [28], this could result in an underestimation of shark interaction rates which has significant implications for stock assessment and fisheries management globally [16]. U.S. Pacific observer programs are not required to include the number of bite-offs in a set. However, recording bite-offs may help resolve non-specific shark catch rates that could prove influential in future stock assessments as the U.S. switches from wire leaders to monofilament in the Hawaii permitted deep-set tuna fishery.

However, switching gear types from wire to monofilament may only be beneficial to non-target species that are discarded alive if trailing gear is minimized. We found that monofilament gear did not 'rust out' or break apart under laboratory settings during our sampling period of 360 days. This finding indicates that sharks and other protected species released with monofilament trailing gear may be burdened with it for at least a year. In contrast, the copper crimps used by most U.S. Pacific longliners on branchlines with wire leaders began to break apart after ~100 days in the lab setting which could substantially decrease the amount of time an animal is carrying trailing gear. This switch in gear types may evidently lead to a trade-off between allowing sharks to bite through monofilament and the negative effects of carrying trailing gear for up to a year if it is not removed. Post-release survival (PRS) studies of sharks have documented a 40% increase in PRS rates over 360 days for animals released with less than 1m of trailing gear; however, survival rates dropped from 90% at 60 days post release to 73% after 180 days if > 10 m of trailing gear was left on an animal [28]. Trailing gear attached to animals is likely to reduce survival by restricting swimming efficiency (as a result of drag) which may increase susceptibility to predation [32, 33] and potentially introduce infection and disease through hook retention and gear abrasion [34, 35]. Thus, fishery managers should consider handling and release recommendations that require fishers to remove as much trailing gear as possible [27, 28, 57]. More specifically, in the U.S. Pacific fisheries where weights are required for seabird bycatch mitigation, fishers should be instructed to ensure the weights are removed. Recently, there have been promising technological advancements in the development of biodegradable monofilament that can degrade within 2 years [58]. And, although the majority of current research is focused on gill nets [59], there is a push for the expansion of this material to longline fisheries [60]. Therefore, a combination of certain hook types with biodegradable monofilament may provide an optimal gear configuration to reduce harm, interaction, and injury to bycatch species that cannot be brought to the vessel for gear removal. Further research on the efficacy of biodegradable monofilament is warranted.

In general, longline fisheries around the world use a variety of hooks of different, sizes, diameters, shapes, and metal types [61]. Here, we show that these four characteristics (shape, size, diameter and metal type) as well as leader material strongly influence the breaking strength of hooks and the time taken for the gear to deteriorate or theoretically 'rust out' of an animal. These data have direct implications for the management of several protected species, but primarily false killer whales. The current regulatory measures under the False Killer Whale Take Reduction Plan (FWKTRP) require the use of 'strong' monofilament branchlines greater than 2 mm in diameter and 'weaker' hooks less than 4.5 mm in diameter [62]. Protected species handling guidelines require the vessel to create enough tension on the branchline to open or straighten the hook by tying the line off and backing the vessel away from the animal [63]. It is assumed that stronger branchlines and weaker hooks will reduce the force required to unbend or 'open' the hook so an animal can be released without embedded hooks and trailing gear [62, 64]. Our results confirm previous studies demonstrating weaker hooks < 4.5 mm in diameter have lower breaking strength than hooks with larger diameters [64, 65]. However, we highlight the importance of also considering the shape of the hook. Weak hooks are often formed from bent wire that is circular in cross section (i.e., round, unforged hooks) compared to traditional forged 'strong' hooks that are oval in cross section [65]. Our results demonstrate that the breaking strength of hooks of the same diameter is ~163 lb less on an unforged hook compared with a forged hook. Studies have shown unforged, polished steel, Mustad circle hooks (sizes; 9/0, 16/0 and 18/0) to be 'weaker' and more readily removed from the jaw of pelagic odontocetes compared with forged Korean 16/0 and 18/0 hooks that had higher breaking strengths and caused more destructive tissue injuries [42]. However, the same study found that both Mustad 16/0 and Korean 18/0 hooks were strong enough to potentially fracture the mandible of odontocetes [66]. This information supports a determination of serious injury should a hook become entangled in the jaw of a small cetacean [67] and warrants additional investigation. Further, our results determined metal type to be a strong predictor of breaking strength, where galvanized hooks had a lower breaking strength than stainless steel. Currently, under the FKWTRP, there are no requirements for hook shape or metal type used in the U.S. Pacific longline fisheries. Therefore, we suggest that the FKWTRP consider the use of unforged and / or galvanized hooks < 4.5 mm in diameter, as these characteristics may reduce the amount of force required to break (straighten or open) a hook by up to ~70%, substantially minimizing harm and injury to protected species.

Finally, it is widely recognised that increasing the sinking rate of a baited hook is the single most effective means of reducing seabird bycatch in longline fisheries [2, 17, 18]. However, it is unclear whether a switch from wire to monofilament leaders may influence the sinking rate of hooks. There was no difference in the sinking rate of hooks between wire and monofilament gear types in this study (~0.21 m/sec or 12.5 m/min) with values very similar to the 6 – 12 m/min values reported for longline vessel hooks by [68]. This information is encouraging for vessel operators and fisheries managers as the U.S. Pacific longline fishery switches to monofilament branchlines to ensure that monofilament leaders will not affect the sinking rate of gear. Furthermore, TDR data collected in this study indicate that hooks deployed on a U.S. tuna longline vessel fished a range of depths between 27 - 331 m. The average depth fished was 193 m, and the median fishing depth was 205 m, with 80% of hooks fishing deeper than 100 m. These results are similar to previous studies of Japanese longline hooks (15 hooks per float), where hooks fished depths between 100 - 200 m 60% of the time [69]. Notably however, our results show that a switch from wire to monofilament leaders may lead to deeper hooks (i.e. those fishing > 200 m) fishing up to 30 m shallower than wire gear. For example, we found that hooks with monofilament leaders, set for > 200 m, fished on average 30 m shallower than a hook on wire gear set for the same depth. This difference is most likely driven by differences in weight between monofilament and wire, and lighter monofilament gear being more affected by abiotic drivers such as wind and current that shoal the longline [70]. This information is important for vessel operators to consider when targeting depths > 200 m as the fishery switches to monofilament gear.

Conclusion

In conclusion, this study examines possible options for optimal U.S. longline fishing gear configurations that may assist in minimizing injury, harm, and mortality to non-target species. Simple changes to gear configurations are often more readily accepted and implemented by vessel owners, skippers, and crew [15]. Importantly, gear trials conducted on a U.S. tuna longline vessel showed no difference in the capture rates of target species (i.e., tunas) while reducing catch rates of sharks. These results should be broadly applicable to other longline fisheries because the U.S. Pacific longline fishery exhibits similar operational characteristics (e.g., deep daytime sets) and target species (e.g., *Thunnus obesus*) to other fishing nations globally [71]. We show that a gear switch from wire to monofilament leaders has the potential to allow sharks and other protected species to bite through monofilament and free themselves from the gear, thereby reducing mortality. However, monofilament gear may not deteriorate even after 360 days. This suggests a potential trade-off in the gear switch such that animals that are not able to bite through the line close to the hook could be burdened with trailing gear for over one year. Recent developments in biodegradable monofilament for longline fishing vessels may provide a solution to this problem, and more research into the efficacy of biodegradable fishing gear is strongly encouraged. It is strongly recommended that crew remove as much trailing gear as possible from animals that are brought to the vessel to increase post-release survival rates of discarded individuals. Furthermore, smaller (in diameter and size), unforged, and/ or galvanized hooks with lower breaking strength are recommended to reduce harm and injury to false killer whales. Finally, the results of this study reaffirm the critical need to collect a range of information from fisheries on fishing practices which influence the performance of fishing gears. These data provide a strong baseline against which future changes in fishing practices and fishing effectiveness can be compared.

Acknowledgements

We would like to thank the owner, operator, and crew of the fishing vessel used for facilitating the gear trial experiments. We would also like to acknowledge the hard work of Jose Vazquez the PIROP fishery observer that assisted in conducting the experiments. We thank Kim Holland and Dan Schar at HIMB for use of their facilities for a year of hook corrosion experiments. We thank Sean Martin and the crew at Pacific Ocean Producers in Honolulu for use of their line puller to test hook breaking strengths. We also thank Marie Ferguson who assisted with early exploratory analyses and Adrianna McMahon who helped with the monthly hook measurements. This research was funded by the 2018 NOAA Bycatch Reduction Engineering Program NA18NMF4720282.

Supplementary Information

Figure S1: An example of one treatment. Two different configurations of hook size, shape, leader material, ring, and weighted swivel. Monofilament gear configurations are shown in the top four hooks, and wire gear with the weighted swivel in the bottom four hooks.

Figure S2: Image of the gear configuration set up in the flume at HIMB. Each strut contains two treatments (i.e., eight hooks). The flume dimensions were: 24 ft long, 14 in wide and 14 in deep, and the wooden cross struts holding the treatments were 17.5 in wide. The ballistic gel cut-offs holding the control hooks were 12 in wide.

Figure S3: Depiction of two treatments (i.e. 8 hooks from two different gear configurations) attached to wooden struts and a plexiglass base suspended above the bottom of the flow-through flume with hooks embedded in balistic gel to mimic being embedded in tissue (of a marine mammal). One hook from each configuration was left out of the gel as a control.

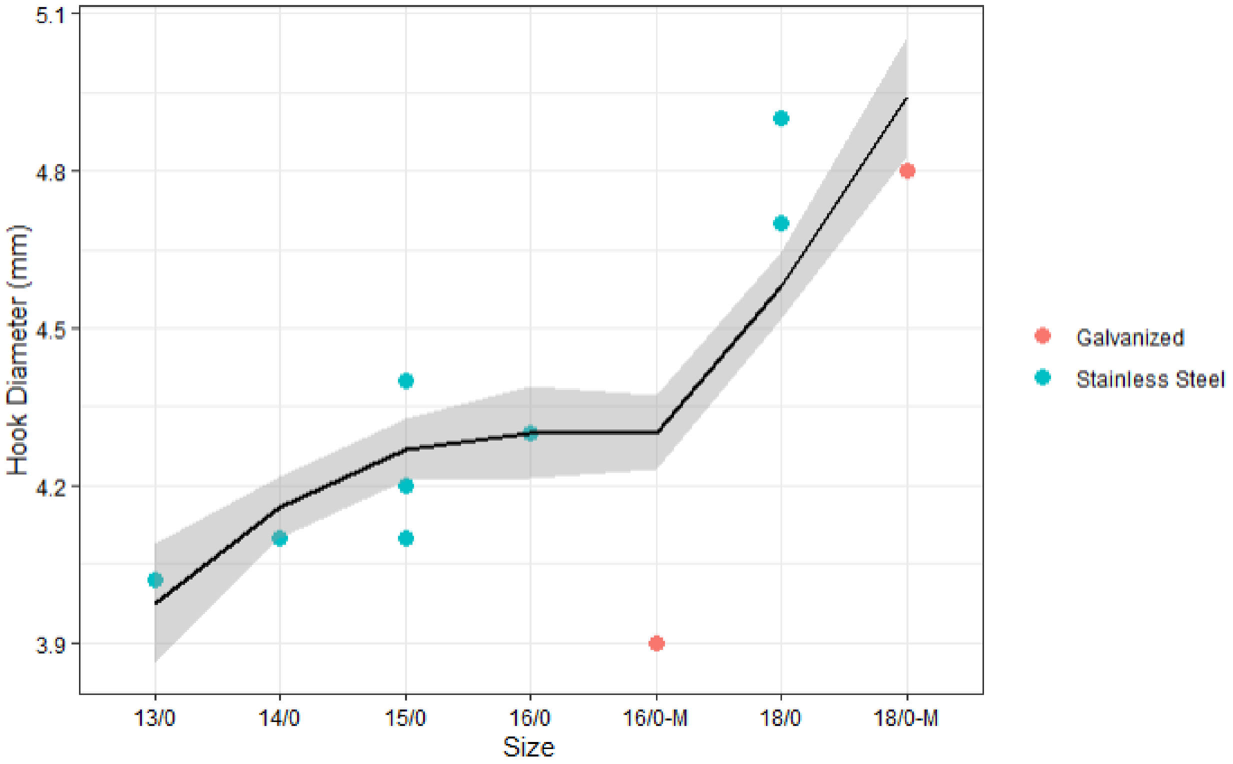


Figure S4: Positive correlation between hook diameter and size. Hook sizes with ‘-M’ are Mustad, galvanized hooks.

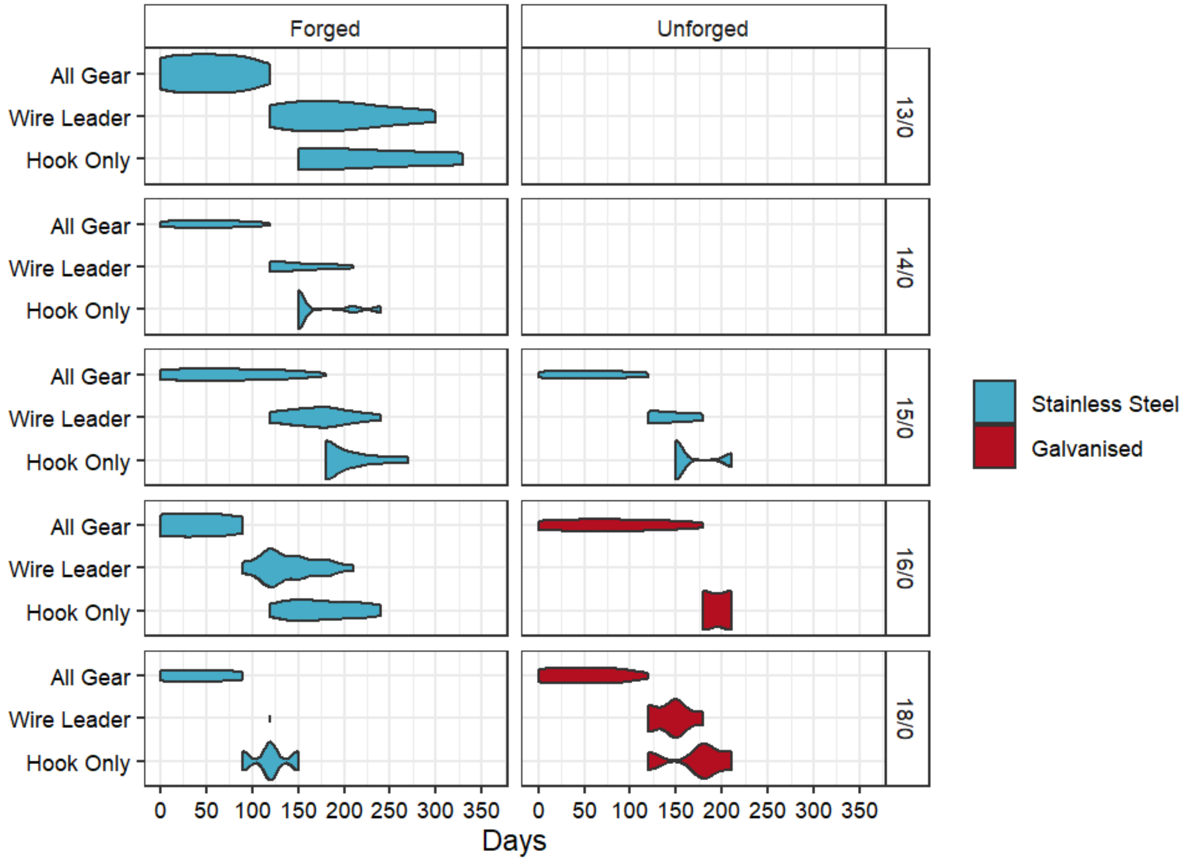


Figure S5: Amount of time (days) taken for All Gear, Wire Leaders, and Hook Only (y-axis) to remain components of trailing gear to break apart from hooks rigged with **wire leaders only**.

References

1. Kelleher, K. (2005). Discards in the World’s Marine Fisheries An Update. FAO Fisheries Technical Paper 470

2. Dietrich, K.S., E.F. Melvin, & L. Conquest. (2008). Integrated weight longlines with paired streamer lines – Best practice to prevent seabird bycatch in demersal longline fisheries. *Biological Conservation*. 141:1793-1805.

3. Nel, D.C., & Taylor, F.E. (2003) Globally threatened seabirds at risk from longline fishing: international conservation responsibilities. BirdLife International Seabird Conservation Programme, BirdLife South Africa, Cape Town. Available at www.birdlife. org/action/campaigns/save_the_albatross/ fao_doc3.pdf (Accessed 20 Nov 2009)

4. James, K., Lewison, R., Dillingham, P., Curtis, K., & Moore, J. (2016). Drivers of retention and discards of elasmobranch non-target atcch. *Environmental Conservation*, *43*(1), 3-12. doi:10.1017/S0376892915000168

5. Pauly, D., Zeller, D. Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nat Commun* **7,** 10244 (2016). https://doi.org/10.1038/ncomms10244

6. Brothers, N.P., Cooper, J., & Lokkeborg, S. (1999). The incidental catch of seabirds by longline fisheries: worldwide review and technical guidelines for mitigation. FAO Fisheries Circular No. 937. Food and Agriculture Organization of the United Nations, Rome, Italy.

7. Lewison, R. L., Crowder, L. B., Read, A. J., & Freeman, S. A. (2004). Understanding impacts of fisheries bycatch on marine megafauna. *Trends in ecology & evolution*, *19*(11), 598-604.

8. Camhi, M. D. (2008). Conservation status of pelagic elasmobranchs. In M. D. Camhi, E. K. Pikitch, & E. A. Babcock (Eds.), Sharks of the open ocean: Biology, fisheries and conservation (pp. 397–417). Oxford, UK: Blackwell Scientific Publications. https://doi. org/10.1002/9781444302516

9. Dulvy, N. K., Baum, J. K., Clarke, S., Compagno, L. V. J., Cortés, E., Domingo, A., & Valenti, S. (2008). You can swim but you can't hide: The global status and conservation of oceanic pelagic sharks. Aquatic Conservation and Marine and Freshwater Ecosystems, 18, 459–482. https://doi.org/10.1002/aqc.975

10. Dulvy, N. K., Fowler, S. L., Musick, J. A., Cavanagh, R. D., Kyne, P. M., Harrison, L. R., White, W. T. (2014). Extinction risk and conservation of the world's sharks and rays. eLife, 3, 1001.

11. Camiñas, J., Báez, J., Valeiras, X., & Real, R. (2006). Differential loggerhead bycatch and direct mortality due to surface longlines according to boat strata and gear type. Sci. Mar.70, 661–665. doi: 10.3989/scimar.2006.70n4661

12. Swimmer, Y., and Gilman, E. (2012). Report of the Sea Turtle Longline Fishery Post-release MortalityWorkshop, November 15-16, 2011. U.S. Dep. Commerce, NOAA Tech. Memo, NOAA-TM-NMFS-PIFSC-34, 31.

13. Sullivan, B. J., Kibel, P., Robertson, G., Kibel, B., Goren, M., Candy, S. G., & Wienecke, B. (2012). Safe Leads for safe heads: safer line weights for pelagic longline fisheries. *Fisheries Research*, *134*, 125-132.

14. Watson, J. W., & Kerstetter, D. W. (2006). Pelagic longline fishing gear: a brief history and review of research efforts to improve selectivity. *Marine Technology Society Journal*, *40*(3), 6-11.

15. Ward, P., Lawrence, E., Darbyshire, R., & Hindmarsh, S. (2008). Large-scale experiment shows that nylon leaders reduce shark bycatch and benefit pelagic longline fishers. Fisheries Research, 90, 100–108.https://doi.org/10.1016/j.fishres.2007.09.034

16. Afonso, A. S., Santiago, R., Hazin, H., & Hazin, F. H. (2012). Shark bycatch and mortality and hook bite-offs in pelagic longlines: interactions between hook types and leader materials. *Fisheries Research*, *131*, 9-14.

17. Agnew, D.J., Black, A.D., Croxall, J.P., & Parkes, G.B. (2000) Experimental evaluation of the effectiveness of weighting regimes in reducing seabird by-catch in the longline toothfish fishery around South Georgia. CCAMLR Sci 7:119–131

18. Robertson, G., McNeill, M., Smith, N., Wienecke, B., Candy, S., & Olivier, F. (2006). Fast sinking (integrated weight) longlines reduce the mortality of white-chinned petrels (*Procellaria aequinoctialis*) and sooty shearwaters (*Puffinus griseus*) in demersal longline fisheries. Biol Conserv 132:458–471

19. Oliver, S., Braccini, M., Newman, S. J., & Harvey, E. S. (2015). Global patterns in the bycatch of sharks and rays. *Marine Policy*, *54*, 86-97.

20. Rice, J., & Harley, S. (2013). Updated stock assessment of silky sharks in the western and central Pacific Ocean. *Scientific Committee Ninth Regular Session*, 6-14.

21. Tremblay-Boyer, L., Carvalho, F., Neubauer, & P., Pilling, G. (2019). Stock assessment for oceanic whitetip shark in the Western and Central Pacific Ocean. Pohnpei, FSM. 8–19 August 2019. WCPFC-SC15-2019 SA-WP-06.

22. Rigby, C.L., Sherman, C.S., Chin, A. & Simpfendorfer, C. (2021). *Carcharhinus falciformis* (amended version of 2017 assessment). *The IUCN Red List of Threatened Species* 2021: e.T39370A205782570. https://dx.doi.org/10.2305/IUCN.UK.2021-3.RLTS.T39370A205782570.en.

23. Endangered Species Act of 1973 (ESA or "The Act"; 16 U.S.C. § 1531 et seq.)

24. Walsh, W.A., & Clarke, S.C. (2011). Analyses of Catch Data for Oceanic Whitetip and Silky Sharks reported by Fishery Observers in the Hawaii-based Longline Fishery in 1995–2010. Western and Central Pacific Fisheries Commission, Doc. Nr. WCPFC–SC7–2011/EB–WP–03.

25. Western Pacific Regional Fisheries Management Council. (2021). Annual Stock Assessment and Fishery Evaluation Report Pacific Island Pelagic Fishery Ecosystem Plan 2020. Remington, T., Fitchett, M., Ishizaki, A., DeMello, J. (Eds.) Western Pacific Regional Fishery Management Council. Honolulu, Hawaii 96813 USA. 410 pp. + Appendices. https://www.wpcouncil.org/wp-content/uploads/2021/08/Pelagic-FEP-SAFE-Report-2020_v2.pdf

26. Hutchinson, M., Poisson, F., & Swimmer, Y. (2017). Developing best handling practice guidelines to safely release mantas, mobulids and stingrays captured in commercial fisheries.

27. Hutchinson, M., & Bigelow, K. (2019). Assessing shark bycatch condition and the effects of discard practices in the Hawaii-permitted tuna longline fishery. Pohnpei. FSM. 8–19 August 2019 WCPFC-SC15-2019 EB-WP-04.

28. 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. NOAA PIFSC Data Report DR-21-001 https://doi.org/10.25923/0m3c-2577

29. Western Pacific Regional Fisheries Management Council. (2021). Annual Stock Assessment and Fishery Evaluation Report Pacific Island Pelagic Fishery Ecosystem Plan 2020. Remington, T., Fitchett, M., Ishizaki, A., DeMello, J. (Eds.) Western Pacific Regional Fishery Management Council. Honolulu, Hawaii 96813 USA. 410 pp. + Appendices. https://www.wpcouncil.org/wp-content/uploads/2021/08/Pelagic-FEP-SAFE-Report-2020_v2.pdf

30. Borucinska, J., Martin, J., & Skomal, G. (2001). Peritonitis and pericarditis associated with gastric perforation by a retained fishing hook in a blue shark. *Journal of Aquatic Animal Health*, *13*(4), 347-354.

31. Borucinska, J. D., Harshbarger, J. C., & Bogicevic, T. (2003). Hepatic cholangiocarcinoma and testicular mesothelioma in a wild-caught blue shark, *Prionace glauca*. *Journal of Fish Diseases*, *26*(1), 43-49.

32. Parga, M. L. (2012). Hooks and sea turtles: a veterinarian's perspective. *Bulletin of Marine Science*, *88*(3), 731-741.

33. Fowler, S.L. (2016) Draft best practice mitigation guidelines for sharks and rays taken in purse seine and long-line fisheries. Memorandum of understanding on the conservation of

migratory sharks. First Workshop of the Conservation Working Group, 31 October−1 November 2016, Bristol. https:// www. cms. int/ sites/ default/ files/ document/ CMS _ Sharks _ CWG1 _ Doc _ 3 _ 2. Pdf

34. Adams, D. H., Borucinska, J. D., Maillett, K., Whitburn, K., & Sander, T. E. (2015). Mortality due to a retained circle hook in a longfin mako shark *Isurus paucus* (Guitart-Manday). *Journal of fish diseases*, *38*(7), 621-628.

35. Begue, M., Clua, E., Siu, G., & Meyer, C. (2020). Prevalence, persistence and impacts of residual fishing hooks on tiger sharks. *Fisheries Research*, *224*, 105462.

36. Kitano, Y., Satoh, K., Yamane, K., & Sakai, H. (1990). The corrosion resistance of tuna long-line fishing hook using fish monofilament, *Nippon Suisan Gakkaishi* (Japan) (Formerly *Bulletin of the Japanese Society of Scientific Fisheries*, 56(11), pp 1765-1772.

37. Varghese, M. D., George, V. C., & Gopalakrishna Pillai, A. G. (1997). Properties and performance of fishing hooks.

38. Edappazham, G., Thomas, S. N., Meenakumari, B., & Ashraf, P. M. (2008). Physical and mechanical properties of fishing hooks. *Materials letters*, *62*(10-11), 1543-1546.

39. Hulbert, P. J. and R. Engstrom-Heg. (1980). Hooking mortality of worm-caught hatchery brown trout. N.Y. Fish and Game 1. 27: 1-10.

40. Schill, D. J. (1996). Hooking mortality of bait-caught rainbow trout in an Idaho trout stream and a hatchery: implications for special-regulation management. *North American Journal of Fisheries Management*, *16*(2), 348-356.

41. McGrath, S. P., Butcher, P. A., Broadhurst, M. K., & Cairns, S. C. (2011). Reviewing hook degradation to promote ejection after ingestion by marine fish. *Marine and Freshwater Research*, *62*(10), 1237-1247.

42. McLellan, W. A., Arthur, L. H., Mallette, S. D., Thornton, S. W., McAlarney, R. J., Read, A. J., & Pabst, D. A. (2015). Longline hook testing in the mouths of pelagic odontocetes. *ICES Journal of Marine Science*, *72*(5), 1706-1713.

43. Pacific Islands Regional Office Observer Program. (2017). Hawaii Longline Observer Program Field Manual. Version: LM.17.02. https://media.fisheries.noaa.gov/dam-migration/obs_hi_manual_feb_2017.pdf

44. McCracken, M., 2004. Modeling a very rare event to estimate sea turtle bycatch:lessons learned. NOAA-TM-NMFS-PIFSC-3, 25

45. Maunder, M. N., & Punt, A. E. (2004). Standardizing catch and effort data: a review of recent approaches. *Fisheries research*, *70*(2-3), 141-159.

46. R Development Core Team. (2021). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL: http://www.R-project.org.

47. Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software, 67(1), 1-48. doi:10.18637/jss.v067.i01.

48. Hartig, F (2021). DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models. R package version 0.4.4. https://CRAN.R-project.org/package=DHARMa

49. Brooks, M.E., Kristensen, K., van Benthem, K.J., Magnusson, A., Berg, C.W., Nielsen, A., Skaug, H.J., Maechler, M., & Bolker, B.M. (2017). "glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling." *The R Journal*, **9**(2), 378–400. https://journal.r-project.org/archive/2017/RJ-2017-066/index.html.

50. Venables, W.N., & Ripley, B.D. (2002). *Modern Applied Statistics with S*, Fourth edition. Springer, New York. ISBN 0-387-95457-0, https://www.stats.ox.ac.uk/pub/MASS4/.

51. Lenth, V.R. (2021). emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.7.0. https://CRAN.R-project.org/package=emmeans

52. Campbell, R. A., & Young, J. W. (2012). Monitoring the behaviour of longline gears and the depth and time of fish capture in the Australian Eastern Tuna and Billfish Fishery. *Fisheries Research*, *119*, 48-65.

53. Christensen, R.B. (2019). ordinal - Regression Models for Ordinal Data. R package version 2019.12-10. https://CRAN.R-project.org/package=ordinal.

54. Stone, H.H., Dixon, L.K., (2001). A comparison of catches of swordfish, *Xiphias gladius*, and other pelagic species from Canadian longline gear configured with alternating monofilament and multifilament nylon gangions. Fish. Bull. 99, 210–216.

55. Swimmer, Y., Suter, J., Arauz, R., Bigelow, K., Lopez, A., Zanela, I., Bolanos, A., Ballestero, J., Suarez, R., Wang, J., Boggs, C. (2011). Sustainable fishing gear: the case of modified circle hooks in a Costa Rican longline fishery. Mar. Biol. 158, 757–767.

56. Berkeley, S.A., & Campos, W.L. (1988). Relative abundance and fishery potential of pelagic sharks along Florida's East coast. Mar. Fish. Rev. 50, 9–16.

57. Francis M. (2019). Common Oceans (ABNJ) Tuna Project. Report of the workshop on joint analysis of shark post-release mortality tagging results. Pohnpei, FSM. 8–19 August 2019. WCPFC-SC15-2019 EB-WP-01.

58. Kim, S., Kim, P., Lim, J., An, H., & Suuronen, P. (2016). Use of biodegradable driftnets to prevent ghost fishing: physical properties and fishing performance for yellow croaker. *Animal conservation*, *19*(4), 309-319.

59. Gilman, E. (2015). Status of international monitoring and management of abandoned, lost and discarded fishing gear and ghost fishing. Marine Policy 60, 225–239.

60. Deroine, M., Pillin, I., Le Maguer, G., Chauvel, M., & Grohens, Y. (2019). Development of new generation fishing gear: A resistant and biodegradable monofilament. *Polymer Testing*, *74*, 163-169.

61. Gilman, E., Zollett, E., Beverly, S., Nakano, H., Davis, K., Shiode, D., Dalzell, P., & Kinan, I. (2006). Reducing sea turtle by-catch in pelagic longline fisheries. *Fish and Fisheries*, *7*(1), 2-23.

62. False Killer Whale Take Reduction Plan. (2010). *Submitted on behalf of the False Killer Whale Take Reduction Team to the NMFS Pacific Islands Regional Office, Protected Resources Division*.

63. National Marine Fisheries Service, Pacific Islands Regional Office. 2020. Protected Species Workshop: Handling, Release, and Identification Guidelines. https://s3.amazonaws.com/media.fisheries.noaa.gov/2020-10/handling-release-all-fnl-508.pdf?null=)

64. Bigelow, K. A., Kerstetter, D. W., Dancho, M. G., & Marchetti, J. A. (2012). Catch rates with variable strength circle hooks in the Hawaii-based tuna longline fishery. *Bulletin of Marine Science*, *88*(3), 425-447.

65. Bayse, S. M., & Kerstetter, D. W. (2010). Assessing bycatch reduction potential of variable strength hooks for pilot whales in a western north Atlantic pelagic longline fishery. *Journal of the North Carolina Academy of Science*, 6-14.

66. Oremland, M. S., Allen, B. M., Clapham, P. J., Moore, M. J., Potter, C. W., and Mead, J. G. (2010). Mandibular fractures in short-finned pilot whales, Globicephala macrorhynchus. Marine Mammal Science, 26: 1–16.

67. Andersen, M. S., K. A. Forney, T. V. N. Cole, T. Eagle, R. Angliss, K. Long, L. Barre, L. Van Atta, D. Borggaard, T. Rowles, B. Norberg, J. Whaley, & L. Engleby. (2007). Differentiating Serious and Non-Serious Injury of Marine Mammals: Report of the Serious Injury Technical Workshop, 10-13 September 2007, Seattle, Washington. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-OPR-39. 94 p.

68. Mizuno, K., Okazaki, M., Watanabe, T., & Yanagi, S. I. (1996). A micro bathythermograph system for tuna longline boats in view of large scale ocean observing system. *Bull. Nat. Res. Inst. Far Seas Fish*, *33*, 1-15.

69. Hampton, J., Bigelow, K., & Labelle, M. (1998). A summary of current information on the biology, fisheries and stock assessment of bigeye tuna (Thunnus obesus) in the Pacific Ocean, with recommendations for data requirements and future research. Sec. Pacific Comm., Oceanic Fish. Prog. Technical Report. No. 36, p. 46.

70. Bigelow, K., Musyl, M. K., Poisson, F., & Kleiber, P. (2006). Pelagic longline gear depth and shoaling. *Fisheries research*, *77*(2), 173-183.

71. Curran, D., & Bigelow, K. (2011). Effects of circle hooks on pelagic catches in the Hawaii-based tuna longline fishery. *Fisheries Research*, *109*(2-3), 265-275.