Catch rates with variable strength circle hooks and the potential to reduce false killer whale injury in the Hawaii-based tuna longline fleet[1]

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ABSTRACT

The Hawaii-based deep-set tuna longline fleet targets bigeye tuna (*Thunnus obesus*) and infrequently takes false killer whales (FKW, *Pseudorca crassidens*) in incidental catch. In the most recent five years (2004−2008), with 20−26% observer coverage, nine mortalities and serious injuries of pelagic FKW were documented in the deep-set longline fishery in the Hawaii exclusive economic zone, yielding mean take estimates of 7.3 animals per year. Weak hook technology can utilize the size disparity between target and other species to promote the release of larger non-target species. Four vessels tested the catch efficacy and size selectivity of 15/0 "strong" circle hooks (4.5 mm wire diameter) that straighten at 303 lb (138 kg) of pull in comparison with 15/0 "weak" (4.0 mm wire diameter) that straighten at 205 lbs (93 kg) of pull. Vessels alternated hook types throughout the longline gear and maintained a 1:1 ratio of strong and weak hooks. Observers monitored a total of 127 sets of 302,739 hooks, and randomization tests were applied to test for significant differences in catch by hook type for 22 individual species. There were no significant catch differences among hook types for bigeye tuna; however,

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there may be limitations to these statistical inferences because longline trials were not conducted during spring when larger bigeye tuna are available to the fishery. There were no significant differences in mean length of 15 species among hook comparisons. Observers collected 76 straightened hooks, of which 6 were control and 70 were weak hooks. There was one observation of the false killer whale released from a stronger circle hook, thereby reducing the potential for serious injury, but overall there was no statistical reduction in catch rates of bycatch species.

INTRODUCTION

Various regulations on uses of bycatch reduction technologies (BRTs) have been enacted in the Hawaii-based longline fisheries to reduce the frequency and severity of incidental interactions with bycatch species such as seabirds and sea turtles. Longline fisheries based in Hawaii are composed of a deep-set fishery targeting bigeye tuna (*Thunnus obesus*) and a shallow-set fishery targeting swordfish (*Xiphias* gladius). Bycatch mitigation efforts have largely focused on the shallow-set fishery given higher interaction rates with sea birds, such as Laysan (*Phoebastria immutabilis*) and black-footed (*P. nigripes*) albatrosses and sea turtles, including loggerhead (*Caretta caretta*) and leatherbacks (*Dermochelys coriacea*, Gilman et al. 2007, 2008). Seabird mitigation measures were initially adopted in 2001 and subsequently amended in 2005. Measures included several options for fishers, such as: weighted branchlines, blue-dyed baits, strategic offal discards, bird curtains, side versus stern deployment of the longline, and mandatory night-deployment and specific baits for swordfish targeting. Since 2004, the estimated total number of interactions with albatrosses hooked or entangled incidentally in Hawaii pelagic longline fisheries has been reduced by 92 to 99% annually compared to year 2000 or pre-regulation estimates (NMFS 2010).

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Stricter regulatory measures were enacted for the shallow-set fishery in 2004 due to concerns over turtle interactions. Measures mandated a switch from using J-hooks and squid bait to 18/0 circle hooks with no more than a 10° offset, whole fish bait, restricted annual effort, established annual limits for the number of interactions with leatherback and loggerhead sea turtles, 100% observer coverage, vessel possession and use of required mitigation gear (e.g. dehookers, dip nets, Gilman et al. 2007). In addition, renewal of fishing permits is contingent upon annual completion of a NOAA NMFS-sponsored workshop by vessel owners and operators on mitigation techniques (50 CFR 665 Subpart F). Following the introduction of these regulations, there have been significant reductions in catch rates for blue shark (29%, Walsh et al. 2009), loggerheads (90%), and leatherback turtles (83%) while swordfish catch rates significantly increased 16% (Gilman et al. 2007). Despite the recent success of BRTs to reduce bycatch of seabirds and sea turtles in Hawaii's shallow-set fishery, recent concern focuses on interactions with marine mammals within the deep-set tuna sector, especially false killer whale (FKW, *Pseudorca crassidens*) and short-finned pilot whale (*Globicephala macrorhynchus*). Both species are vulnerable to hooking or entanglement while depredating on longline bait or catch.

The United States (U.S.) Marine Mammal Protection Act (MMPA) requires estimation of annual mortalities and serious injuries of marine mammals that occur within US waters. Incidental mortality, serious injury and non-serious injury of marine mammals in the Hawaii and American Samoa longline fisheries are estimated from observer data (McCracken and Forney 2010). U.S. longline fisheries based in Hawaii and American Samoa can potentially interact with four false killer whale management stocks as identified in a recent MMPA stock assessment report

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(Carretta 2010): 1) a Hawaii Insular stock of FKW within 40 km of the main Hawaiian Islands, 2) a Hawaii Pelagic stock of FKW beyond 140 km of the main Hawaiian Islands, 3) a stock of FKW within the Palmyra Atoll Exclusive Economic Zone (EEZ), and 4) a stock of FKW within the American Samoa EEZ. The Hawaii Insular and Pelagic stocks overlap between 40 and 140 km offshore in the main Hawaiian Islands.

From 2004 to 2008, the deep-set longline fishery interacted with 19 false killer whales from the Hawaii Pelagic stock based on 20−26% observer coverage. Nine mortalities and serious injuries of pelagic false killer whale were documented in the deep-set fishery in the Hawaii EEZ, yielding mean take estimates of 7.3 animals per year. During the same period, six serious injuries were documented in the fishery outside of the Hawaii EEZ, resulting in an additional estimated mortality and serious injury of 5.3 animals per year. From 2004 to 2008, the shallow-set fishery with 100% observer coverage documented one hooked or entangled false killer whale which was not seriously injured. False killer whale interactions are rarer in the shallow-set fishery which operates at higher latitudes in cooler waters. The take rate for the Hawaii Pelagic stock exceeds the potential biological removal (PBR) level of 2.5 false killer whales per year, thus the population is considered "strategic" under the MMPA and takes must be reduced. Mean take estimates were 0.6 false killer whales per year for the Hawaii Insular stock, 0.3 for the Palmyra stock and 7.8 for the American Samoa stock. Hawaii. The Insular and Palmyra stocks are not currently considered "strategic" because total fishery mortality and serious injury for these stocks is less than their respective PBR levels. There is no status determination for the American Samoa stock because there are no estimates of abundance or PBR.

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The status of short-finned pilot whales is not considered "strategic" as average annual (2004–2008) mortality and serious injury were 2.0 animals outside of U.S. EEZs, 0.7 within the Hawaii EEZ, and 0.5 within the Johnston Atoll EEZ, the total of which is below the stock's PBR of 52 (Caretta et al. 2010).

Under the MMPA, a take reduction plan (TRP) is required for the Hawaii-based deep and shallow-set fisheries to assist in the recovery and prevent the depletion of the "strategic" Hawaii Pelagic stock of false killer whales. A false killer whale Take Reduction Team (TRT) was established on January 19, 2010 and comprised various stakeholders. The TRT submitted a Draft TRP, consisting of consensus management recommendations, to NOAA Fisheries on July 19, 2010 (http://www.nmfs.noaa.gov/pr/pdfs/interactions/fkwtrp_draft.pdf). Management recommendations consisted of potential changes to the terminal hooks in the longline gear, increased captain training on best practices for reducing marine mammal bycatch, handling and release techniques, and spatial management (closed areas). The paramount longline research recommendation was to evaluate whether fishing with so-called "weak" circle hooks will affect the target catch of bigeye tuna and bycatch of false killer whales.

Operators in the Hawaii-based tuna sector have traditionally used Japanese-style tuna hooks, size 3.6 or 3.8 sun (hereafter referred as "tuna" hooks). Since 2005, several operators have voluntarily changed their terminal gear to circle hooks, typically ranging in size from 14/0 to 16/0, which are generally weaker and straighten with less force than tuna hooks. Hooks are fabricated by two methods – forging or bending a particular gauge of wire. "Weaker" hooks can be achieved by reducing the wire diameter. The use of weak hook technology has been investigated in several

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U.S. pelagic longline fisheries to assess the potential for bycatch reduction while not significantly affecting target species catch rates. Weak hooks were tested in the yellowfin tuna (*T. albacares*) and swordfish longline fisheries in the Mid-Atlantic and South Atlantic Bight, respectively, to evaluate their potential to reduce catch rates of pilot whales (Bayse and Kerstetter 2010). This study found no significant reduction in total retained catch between strong and weak 16/0 circle hooks in 21 sets targeting yellowfin tuna. Nine longline sets targeting swordfish with strong and weak 18/0 circle hooks had similar catches for all species except swordfish, which had statistically higher catch rates (CPUE, number per 1,000 hooks) and landed catches with strong hooks.

In the Gulf of Mexico, a major spawning area for the western Atlantic bluefin tuna (*T. thynnus*) stock exists and weak hooks have been trialed in the Gulf of Mexico yellowfin longline fishery to determine whether they reduce bluefin mortality (Foster and Bergmann 2010). From 2008 to 2010, relatively strong and weak 16/0 circle hooks were trialed on 311 longline sets (198,606 hooks). There were no significant CPUE differences for 20 of the 23 species analyzed, including target yellowfin tuna. Bluefin tuna catches were significantly reduced by 56.5% on weak hooks (n=10) compared to stronger hooks (n=23) and statistically lower CPUE was evident for lancetfish and wahoo on weaker hooks.

Because longline interactions with marine mammals are exceeding rare, an unrealistically large number of longline sets (sample size) would be required to statistically demonstrate the efficacy of a BRT to reduce rare marine mammal interactions. Under these circumstances, field trials testing BRTs are evaluated with regard to maintaining target species catch rates. The specific

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intentions of this study were to quantify the effects of strong and weak circle hooks in the Hawaii-based deep-set fishery targeting bigeye tuna. Specifically, we documented the following with respect to hook strength: 1) catch rates of target, incidental (retained non-target), and bycatch (discarded or released) species; 2) size selectivity; 3) frequency of straightened hooks; 4) historical hook use in the fishery from 2004 to 2010; and 5) an account of a false killer whale interaction.

MATERIALS AND METHODS

PROTOCOLS

VESSEL. — A sample size was estimated based on a request in the Draft TRP that sufficient trials be conducted to statistically detect a 10% or greater reduction in the weight of bigeye tuna caught on weaker hooks compared to the catch on stronger hooks. A power analysis of historical bigeye catch rates in the deep-set fishery indicated that ~120 longline sets would be required to detect a 10% reduction in catch rate, assuming α=0.10 and β=0.2. Four Hawaii-based tuna longline vessels were contracted between October and December 2010 to conduct the experiment comparing control (stronger) and weaker circle hooks. The vessels used Korean-made circle hooks of size 15/0, stainless, and offset 10° (Figure 1). On all longline deployments, vessels sequentially alternated control ("C") circle hooks with a wire diameter of 4.5 mm with weaker ("W") circle hooks of 4.0 mm wire diameter. Strength tests were conducted using a digital hydraulic hook/line tester to ascertain when the stronger control and weaker 15/0 circle hooks would straighten, which was defined as when a hook was deformed to a degree in which fish or marine mammal escapement was likely. The control hook straightened at ~303 lbs (137.7 kgs, n=3, range 300–310 lbs) of pull force and the weaker hook straightened at ~205 lbs (93.2 kgs,

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n=6, range 196–214 lbs) (J. Hall, Hawaii Longline Association, unpubl. data). Two vessels deployed control and weak hooks with rings and the other two vessels deployed non-ringed hooks. Throughout the field trials, all vessels were mandated to alternate hook types throughout the entire longline set and to maintain a 1:1 ratio of hook types throughout the trials. Branchline snaps marked with 10-cm cable ties allowed for easy identification of the terminal hook type and corresponding fish catch. Vessel captains chose where they fished and were allowed to retain and sell their catch.

OBSERVERS. — Data were collected by personnel of the Pacific Islands Regional Observer Program. Observers collected information on all catch by species, hook type, sequential hook number of capture between two floats, caught condition (alive, dead), catch disposition (retained, discarded), length measurements of some landed species, tally of the numbers of each type of hook deployed and retrieved, and a vessel's ability to follow experimental protocols. Hook type was recorded for each species caught. Observers measured eye-fork length (EFL) for billfishes and fork length (FL) for all other fishes that were brought aboard to the nearest whole cm. An approximate length to the nearest whole foot was recorded if the animal was not landed. Straightened hooks were retained by the observer, who recorded the sequential hook number, species, and size of fish if the fish was retained on the hook.

ANALYSES

CATCH. — A total of 127 longline sets were analyzed and two sets were excluded from analysis for not complying with the protocol of deploying a minimum of 2,000 hooks per set. Catch records of 91 fish (1.12%) were deleted due to uncertain hook type or if an animal was caught on

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multiple hooks. The most numerous 22 individual species were chosen for analysis (Table 1), the least numerous of which had an average catch rate of 0.12 fish per set. Additional species were not considered due to their uncommon occurrence, grouping at higher taxa, or uncertain species identifications (Table 1).

A randomization test (Manly 2007) was used to assess catch differences between hook types. The null hypothesis is that there would be no difference in catch between paired hook types. The test statistic (*S*) was the average difference in catch between paired control circle hooks and weak circle hooks by set. A randomization test was written and conducted in the R statistical programming language (R Development Core Team 2008, version 2.7.2 for Linux). Data were randomized, resampled 10,000 times, and scored for whether or not the resampled *S* value was equal to or greater than the observed *S* value. This method provides a measure of the strength of evidence against a null hypothesis rather than estimating significance at a certain probability level. Fish lengths were transformed to natural logarithms and tested for hook type effects using one-way ANOVA.

BIGEYE TUNA LENGTH–WEIGHT RELATIONSHIP AND CATCH RATE IN WEIGHT. — Additional analyses were considered for target bigeye tuna as fishermen preferred analyses structured upon catch weight compared to catch numbers. A randomization test was used to assess differences in the bigeye tuna catches in weight between hook types for each longline set. Bigeye tuna weights were calculated from FL measurements obtained from observers. A length-weight relationship for bigeye tuna was updated from results of Nakamura and Uchiyama (1966) who analyzed 9,144 fish caught in the central Pacific, part of larger dataset collected from 1960 to 1970 that

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included 11,649 length-weight measurements. A length-weight regression equation ($W=aFL^b$) was estimated from logarithmically transformed data as Log W = Log *a* + *b* Log FL where, W is weight (kgs); FL is fork length (cm); *a* is the regression intercept and *b* is the regression slope. Outliers were evident in a visual inspection of these data and the regression was fit as a robust linear model (*rlm*) function in the MASS module in R. The *rlm* computed a robust bisquare estimator for the length-weight regression and observations with relatively small weights were identified as outliers and removed.

Weight estimates were not available for all bigeye tuna due to an observer missing a FL measurement or depredation occurring by sharks or marine mammals so that FL could not be measured. When bigeye FL measurements were not obtained, values were substituted according to two scenarios by using the average FLs by each hook type calculated within a particular trip. In Scenario 1, the vessels catch was calculated by substituting average FLs for any unmeasured individuals. In Scenario 2, the vessels catch without depredation was estimated by substituting average FLs for both unmeasured and depredated individuals.

STRAIGHTENED HOOKS. — Observers obtained and labeled any bent or straightened hooks that were discarded by the crew. Hooks were measured and compared to unfished control and weak 15/0 circle hooks. Hook deformation was characterized by hook measurements of maximum length, straight total length, straight total width, minimum width and gape length (Figure 1). Maximum length was measured from the top of the eye loop or ring to the farthest point of the hook, this being the bend or the point of the tip on the bite. Straight total length was measured from the eye to the lowest part of the hook when the shank was held vertical. Straight total width

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was measured from the shank to the farthest point horizontally when the shank was held vertical. The hook gape was measured from the point of the tip 45° to the hook shank. No gape measurement was possible for some hooks that were straightened.

HOOK TYPES HISTORICALLY USED IN THE DEEP-SET FISHERY. —Historical hook use in the deep-set fishery was documented from observer data from 2004 to 2010 with corresponding annual coverage rates of 20 to 26%. For each longline set, observers recorded the predominant hook style, size, and whether the hook was offset or non-offset. Observers noted the approximate percentages of each hook style and size in the comments field of a particular trip record if a vessel fished with a mixture of styles or sizes. Hook styles and sizes were categorized on a trip basis as: 'Pure circle' for 14/0, 15/0, or 16/0 offset or non-offset circle hooks; 'Pure tuna' for tuna hooks of 3.6 or 3.8 sun; 'Other' for using 18/0 circle or J-hooks; and 'Mixed' for using more than one of the previous categories.

TEMPORAL VARIABILITY IN LANDED BIGEYE SIZE. — Individual bigeye tuna weights of longline landings were obtained from sales records of the United Fishing Agency Ltd. (UFA). Average monthly weight was estimated from 2005 to 2009 for bigeye tuna caught by the deep-set fishery. When bigeye tuna were processed prior to sale (e.g., headed and gutted, gilled and gutted) a conversion factor was applied to convert to whole weight.

RESULTS

CATCH. — Four fishing vessels conducted 10 trips in the vicinity of the Hawaiian Archipelago in an area bounded by 14−16°N and 143−167°W and deployed 127 longline sets with 302,739 hooks. Longline trials occurred from 1 October to 18 December 2010. Longline gear and

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operational characteristics in the trials (Table 2) were similar to previous descriptions of the Hawaii-based tuna sector (Bigelow et al., 2006, Curran and Bigelow 2011). Hook trials caught 8,024 individual animals representing 48 species or species groups (Table 1). Twenty-two species had greater than 14 individuals captured and these species represented 97.9% of the total catch by number. By individual number, bigeye tuna (1,888 individuals) were the most predominant catch, followed by longnose lancetfish (*Alepisaurus ferox*; 1,302), blue shark (1,163), and dolphinfish (*Coryphaena hippurus*; 939). Nominal CPUE (number of fish caught per 1,000 hooks) of all 48 species captured was 26.29 for control and 26.11 for weaker circle hooks and nominal CPUE of retained species was 13.75 for control and 13.81 for weaker hooks. Randomization tests detected no significant differences in CPUE between hook types for 20 species (Table 3, Figure 2). There were significant differences for yellowfin tuna and spearfish (Table 3), but results were inconsistent as yellowfin catches were higher on weaker hooks and spearfish catches were higher on control hooks. Relationships between hook types and fish lengths were tested for 15 species (Table 4, Figures 3–4). The length analysis for 15 species represents a subset of the 22 species considered in the catch rate analysis, because shark species were not landed and therefore not measured. F-tests indicated no significant differences ($P>0.05$, Table 4) between hook types in mean fish length, for all species. Bigeye tuna caught with control hooks had a mean fork length of 106.8 cm (sd=24.43) compared to 107.5 cm (sd=24.01) on weaker circle hooks. The largest bigeye tuna obtained by a control hook (180 cm FL (~128 kg)) was of similar size as the largest on a weak hook (177 cm FL (~122 kg)). The largest blue marlin obtained by a control hook was 228 cm EFL with an estimated weight of 166.5 kg (Uchiyama and Kazama 2003); a similar sized blue marlin (223 cm EFL, 154.3 kg) was landed with a straightened weak hook.

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The trials caught one false killer whale (see below - Straightened hooks) and one olive ridley turtle (65 cm carapace length). The turtle was hooked with a control hook in the front flipper on the 7th hook from the floatline (i.e. hook number 19 while fishing with 25 hooks between floats). The turtle had little response when brought aboard and was pronounced dead after a 22 hr period of resuscitation and monitoring.

BIGEYE TUNA LENGTH – WEIGHT RELATIONSHIP AND CATCH. — The bigeye tuna length-weight regression was based on 11,579 observations, as 70 outliers were identified by the *rlm* (Figure 5). The estimated regression equation $W=3.5146*10^{-5}\ FL^{2.9096}$ (Figure 5, 65.4–193.0 cm FL, $R^2=0.974$) was very similar to the regression computed by Nakamura and Uchiyama (1966) over the subset of data with a somewhat narrower length range ($W=3.6562*10^{-5}\ FL^{2.9018}$,80–190.0 cm FL).

There were no significant differences in bigeye tuna catch per set expressed in number of individuals or weight estimated from fork lengths (Table 3). Summary statistics for bigeye tuna among hook types are presented in Table 5. The estimated total capture weight of bigeye tuna was higher for weaker hooks (29,872 kg) than control hooks (28,733). Depredation by marine mammals and sharks resulted in a 3% loss of bigeye tuna.

STRAIGHTENED HOOKS. — Observers collected 76 straightened hooks, of which 6 were control and 70 were weak hooks (Appendix). Weak hooks had a statistically significant higher rate of straightening ($X^2=53.895$, $P<0.0001$). There was no catch associated with 49 straightened (5

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control and 44 weak) hooks. Straightened weak hooks retained 20 bigeye tuna (average=146.7 cm FL, sd=12.61, range=131–175 cm, n=17), four blue marlin (average=188.0 cm FL, sd=41.61, range=142–223 cm, n=3), one yellowfin tuna (140 cm FL), and one bigeye thresher shark (approximate length of 7 ft). One bigeye tuna (173 cm FL) was retained on a straightened control hook. Of the 76 straightened hooks, 44 hooks had rings and 32 hooks were non-ringed. The magnitude of deformation was estimated from the gape size in relation to a 2.5 cm gape of a non-deformed hook. The gape of a control hook opened an average of 65.6% (gape=4.14 cm, sd=0.71, n=5) while a weak hook opened an average of 50.4% (gape=3.76 cm, sd=0.57, n=53). For the 18 bigeye that were retained on straightened hooks for which FL measurements were obtained, a 131 cm (~50 kg) fish had the largest hook deformation (4.7 cm gape width, Figure 6). The negative relationship between hook deformation and bigeye size (Figure 7) suggests that bigeye escape on weaker hooks at large (>50 kg) sizes.

FALSE KILLER WHALE INTERACTION. — An observer documented the hooking and straightening of a control 15/0 circle hook (Figure 6) by a ~4.3 m (~14 ft) false killer whale on 22 October 2010. During longline retrieval, the observer noticed several false killer whales surfacing 1-2 meters from the port side of the vessel. A whale dove towards a bait on a branchline that had been removed from the mainline and attached to a running line, which hangs from the vessel untended; removed branchlines are held on the running line prior to coiling. The branchline rapidly tightened and moved to the stern where the line slacked and the gear was retrieved by the observer. No injuries to the false killer whale were observed and no gear was entangled or retained on the whale. The interaction lasted a few minutes with the whale displaying typical,

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non-agitated behavior when swimming away upon release. The observer reported that the exact hooking location was unknown, but believed that the whale was hooked in the mouth.

HOOK TYPES HISTORICALLY USED IN THE DEEP-SET FISHERY. — The use of tuna hooks in the deep-set tuna longline fishery declined precipitously from 87% in 2004 to 25% in 2010, while circle hooks ranging in size from 14/0 to 16/0 increased from 5% to 43% (Table 6, Figure 8). The proliferation of the pure circle and mixed hook categories in 2006 suggests that tuna hooks may be entirely replaced by some vessels while other vessels incrementally replace tuna hooks with circle hooks when gear is lost. The use of 18/0 circle or J-hooks appears to be minimal (0–6%) in the deep-set fishery.

TEMPORAL VARIABILITY IN LANDED BIGEYE SIZE. — Bigeye tuna landed in the deep-set tuna longline fishery exhibit moderate temporal variation in size (Figure 9). Monthly average weight of bigeye tuna landed from 2005 to 2009 ranged from a low of 34.1 kg (75.0 lb) in January to a high of 43.9 kg (96.6 lb) in June. Bigeye tuna landed during October–December ranged from 36.8 to 38.4 kg or averaged ~6 kg less than in June. Individual bigeye caught during the longline trials were not weighed; rather, weights of each fish were estimated from the length-weight relationship. The monthly average estimated weight of bigeye tuna from the longline trials was 32.4 kg (range=29.9–33.0 kg, Table 4), ~5 kg less than October–December (2005–2009) averages and ~11kg less than bigeye typically landed in June (c.f. Tables 4 and Figure 9). The monthly proportion of large bigeye (>50 kgs) landed was similar to the average weight trends. Large bigeye comprised the largest proportion of the catch (28.2–33.6%) during April to June and a smaller proportion (22.0–26.3%) during the circle hook trials (Figure 10). If bigeye escape

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on weaker hooks at sizes of >50 kg as suggested by the straightened hook analysis, then the differential effects on catch rates between strong circle hooks and weak circle hooks would be expected to be greater during spring when larger bigeye are more available to the fishery.

DISCUSSION

Management agencies within the U.S. have implemented BRTs, such as hook and/or bait requirements to reduce the incidental capture and mortality of non-target species, especially in shallow-set pelagic fisheries targeting swordfish or yellowfin tuna. For example, U.S. regulations currently require 18/0 circle hooks and whole fish baits in the Atlantic, western Pacific and Gulf of Mexico longline fisheries based on concerns regarding sea turtles. The relatively large (18/0) circle hooks aim to reduce the rate of ingestion and deep-hooking in sea turtles compared to tuna or J-hooks. While the efficacy of using circle hooks and whole fish baits has been demonstrated for sea turtles (Watson et al. 2005, Gilman et al. 2007, Sales et al. 2010), their use has not been shown to reduce bycatch of marine mammals and large fishes. For these species, alternative BRT approaches, such as weak hook technology, may be required.

Longline gear has several components, and expectations in using weak hook technology are to make the hook the weakest component of terminal tackle. Use of the weaker hooks can exploit the size disparity between target and other species to promote the release of larger non-target species. As in other studies, our longline trials sequentially alternated control and weak hooks in order to investigate catch rates of target and bycatch species (Watson et al. 2005, Kerstetter and Graves 2006, Bayse and Kerstetter 2010, Curran and Bigelow 2011). Sequentially alternating hooks worked well operationally on the vessel and ensured that any effects of depth or habitat on

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a species' vulnerability to the longline or effects of spatial patchiness along the length of the longline were the same for both hook types.

Results indicated no significant differences among 15/0 control and weak hooks in target bigeye size and catch rate (number and weight) per longline set. The only significant differences were demonstrated for yellowfin tuna and spearfish, but the results were not consistent. Non-significant statistical differences in catch rate and size selectivity can result from at least two processes: 1) an inadequate sample size to rigorously test the null hypothesis of equality in catch rate and selectivity and 2) large individuals of a particular species are not escaping from weaker hooks at significantly higher rate than control hooks. Bigeye tuna were the most commonly caught animal in this study and a sample size of 127 longline sets provided sufficient statistical power to test the hypothesis that catch rate or size selectivity were equal. The largest weak hook trial has been conducted in the Gulf of Mexico where 311 sets were conducted to study mitigation of Atlantic bluefin bycatch (Foster and Bergmann 2010). Bluefin catch rates are low and the relatively large sample size was required to demonstrate that catches were significantly reduced by 56.5% on 16/0 weak circle hooks (n=10) compared to stronger 16/0 hooks (n=23). Relatively low sample sizes and resulting statistical power may have been an issue in the statistical interpretation of results from weak hooks trials in the western Atlantic yellowfin tuna and swordfish longline fisheries (Bayse and Kerstetter 2010). There was no statistical difference in yellowfin tuna catch rates on 21 sets testing 16/0 strong and weak hooks, but yellowfin tuna caught on strong hooks had a mean length that was significantly greater than for yellowfin caught by the weaker hook. A significantly higher number of swordfish were caught with strong

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18/0 circle hooks compared to weak hooks, but swordfish were significantly heavier on weaker hooks.

Weak hooks in this study were straightened more frequently than control hooks, though the rate of straightening was relatively low. Overall there was a 11.7:1 ratio of straightened weak to control hooks and a 8.8:1 ratio when straightened hooks had no catch. The overall weak hook straightening rate was 0.462 per 1,000 hooks and 0.291 with no catch (Table 7). Seven weak hooks were retrieved straightened in the 16/0 trials in the western Atlantic, and observers retrieved 63 strong and 287 weak hooks that had been straightened to a degree that the animal escaped in the Gulf of Mexico trials (Table 7). The straightening rate of 0.291 per 1,000 weak hooks in this study is much lower than the rate of 2.890 for weak hooks in the Gulf of Mexico (Foster and Bergmann 2010) and lower than in the yellowfin tuna weak hook experiment (0.439) in the western Atlantic (Bayse and Kerstetter 2010).

There were 49 straightened hooks without catch and five species (bigeye and yellowfin tuna, blue marlin, bigeye thresher shark, and false killer whale) demonstrated an ability to straighten at least 27 hooks. Additional species attaining a large size such as mako sharks and other marine mammals may also have straightened hooks. Bigeye tuna may have contributed to the straightening of hooks that did not retain catch, as bigeye had the highest catch rates during the trials, 21 bigeye were caught on straightened control (n=1) and weak (n=20) hooks, and based on hook number of capture (position between floats), the straightened hooks fished at intermediate and deep depths where bigeye are mostly caught (Suzuki et al. 1977, Bigelow and Maunder 2007). Observers documented the species and animal size retained by straightened hooks. While

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these data may indicate the minimum size at which a particular species can straighten a hook, there are no experimental nor theoretical data on what force within the water is required to deform hooks, as pull strength does not equate to animal size. Furthermore, the most important aspect in hook deformation is likely the direction of pull, which is affected by hook attachment to the branchline (e.g., ring versus non-ring) and hooking location on the animal.

The false killer whale caught was hooked with a control circle hook while depredating on longline bait and was released with no injuries when the hook straightened. The whale was estimated to be ~4.3 m (~14 ft) which probably corresponds to a weight of 1100-1200 kg as the maximum size of false killer whales is ~6.1 m and ~1,400 kg (Leatherwood and Reeves 1983). In the western Atlantic yellowfin tuna trials, a pilot whale was hooked on a weak 16/0 circle during longline retrieval (Bayse and Kerstetter 2010). The animal appeared to not be pulling very hard upon the initial approach, but attempted to escape at the sight of the boat, straightened the hook while approximately 10 m from the side of the boat, and subsequently swam away with limited apparent injury. The observer recovered the hook and branchline, thus the whale escaped with no trailing gear.

Statistical results on target bigeye catch rate and selectivity indicated no significant differences between hook types; however, there may be limitations to these statistical inferences because longline trials were not conducted when larger bigeye tuna are available to the deep-set fishery and a large portion of the fishing area was closed during one month of the trials. The trials were conducted during a period of 2.5 months, a time frame predicated by fishery managers who envisaged that regulations for marine mammal bycatch reduction, possibly including

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requirements for circle hooks, would have to be formulated by March 2011. The average weight of bigeye tuna caught during the October–December longline trials was 32.4 kg. Average monthly weights were ~5 kg less than historical October–December (2005–2009) averages and ~11kg less than June (2005–2009). While we cannot postulate if similar results would have been obtained if trials were conducted when bigeye of a larger average size were available to the fishery, the temporal variability in bigeye size in the deep-set fishery depends on several factors such as: 1) spatial distribution of the fleet, 2) migration of age classes, 3) gear depth, as deeper gear catches larger bigeye because there is an ontogenetic change in habitat and depth, and 4) oceanographic effects operating on a variety of scales.

Smaller bigeye tuna captured during trials in December probably result from a shift in fishing to the eastern Pacific Ocean because of tuna-oriented Regional Fisheries Management Organization (RFMO) regulations. The U.S. pelagic longline fisheries in the Pacific are regulated by two tuna-RFMOs: the Western and Central Pacific Fisheries Commission (WCPFC) and the Inter-American Tropical Tuna Commission (IATTC). Jurisdictional separation of the two Commissions occurs to the east of the Hawaiian Archipelago at 150°W. The U.S. is subject to an annual longline catch limit for bigeye tuna in both Commission regulatory areas. The WCPFC area was closed to most of the Hawaii-based deep-set fleet from November 23 to December 31, 2010 because NMFS determined that the longline fleet would likely reach its annual bigeye catch limit on November 22. Vessels moved into the IATTC area, where smaller bigeye occur during December (average=29.9 kg). The bimodal length structure of bigeye catch in this study contained modes at 95 and 135 cm, corresponding to ages of 2.5 and 4.5 years, respectively (Harley et al. 2010). The temporal variability in size may largely be determined by bigeye

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migration of different age classes, though such immigration and emigration to the Hawaii-based fishery is not well understood.

In the absence of fishery regulations, there has been a voluntary progression from using strong to weaker hooks in the Hawaii-based deep-set fishery. Tuna hooks were the dominant hook in the fishery prior to 2007. These hooks require substantially greater force to straighten in comparison to circle hooks and have a higher frequency of deep hooking vs. mouth hooking for sea turtles and marlins which may increase post-release mortality (Watson et al., 2005, Kerstetter and Graves 2006, Gilman et al., 2007, Diaz 2008, Sales et al., 2010). Japanese made tuna hooks of size 3.6 sun (5.0 mm wire diameter) straightened at ~564 lbs (256.5 kgs, n=3 range 512–600 lbs, J. Hall, unpubl. data) of pull force. While this study demonstrated a transition from tuna to circle hooks on observed trips, there were no data on wire size for circle hooks historically used in the deep-set fishery. Assuming that the strongest circle hook currently used would be straightened at ~400 lbs of force, the reduction in strength over time would represent at least 30%. If management agencies consider regulating the wire diameter of circle hooks, the hooks used in this study represent a further strength reduction. The stronger 15/0 control (4.5 mm wire) hook straightened at ~303 lbs, which is 46% weaker than a tuna hook. The weaker 15/0 (4.0 mm wire) hook straightened at ~205 lbs, which is 32% weaker than the 4.5 mm wire circle hook and 64% weaker than a tuna hook. Hook strength was measured in this study, albeit there is subjectivity in defining when a hook was deformed to a degree in which mammal escapement was likely. Fishery managers could regulate hook shape (tuna, circle and J-hooks), cross-section (round, rectangular) and wire diameter, although in reality the actual hook strength of a particular specification is highly variable based on the factory's source metal.

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During the last decade, there have been a plethora of studies comparing hook types in pelagic longline fisheries with the objective of demonstrating that catches of target species can be maintained with a concurrent reduction in bycatch. This study adds to the few published studies on longline trials using the same hook type with variable strength. Results indicated that target bigeye catch rate was not significantly different between hook types. However, this result is for the October–December trial period and may not be representative of other seasons when bigeye tuna have larger average size. There was one observation of a false killer whale caught and released from a stronger circle hook, thereby reducing the potential for serious injury, but overall there was no statistically significant reduction in catch rates of bycatch species by use of the weaker hooks. With regard to the bycatch potential of weak hooks, we concur with Bayse and Kerstetter (2010), who indicated the bycatch reduction potential of weak hooks is limited to species that can obtain relatively large mass, such as pilot whales and false killer whales, and may not be a viable option for reducing the catches of other large bycatch species interacting with the pelagic longline fishery, such as marine turtles, large sharks, manta rays, marlins and sunfish.

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We express our appreciation to the Captains and crews of F/Vs *Kimmy 1*, *Knowledge*, *Lihau* and *Miss Lisa* for adhering to experimental protocols. We also thank J. Hall for conducting hook strength testing and the Pacific Islands Regional Observer Program for coordinating observers and maintaining data quality control. We acknowledge Marti McCracken for providing the randomization test. This research was partially funded by the New England Aquarium Consortium for Wildlife Bycatch Reduction and the Hawaii Longline Association provided an in-kind contribution of hooks, wire and crimps.

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Official PIFSC review and approval pending. Do not cite without explicit permission of primary author.

LITERATURE CITED

Bayse SM, Kerstetter DW. 2010. Assessing bycatch reduction potential of variable strength hooks for pilot whales in a western North Atlantic Pelagic Longline Fishery. J North Carolina Acad. Sci. 126(1):6–14.

Carretta JV, Forney KA, Oleson E, Martien K, Muto MM, Lowry MS, Barlow J, Baker J, Hanson B, Lynch D et al. 2010. Draft U.S. Pacific Marine Mammal Stock Assessments: 2010. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-xxx. 307 p.

Curran D, Bigelow K. 2011. Effects of circle hooks on pelagic catches in the Hawaii-based tuna longline fishery. Fish. Res. 109, 265-275.

Diaz G. 2008. The effect of circle hooks and straight (J) hooks on the catch rates and numbers of white marlin and blue marlin released alive by the U.S. pelagic longline fleet in the Gulf of Mexico. N. Am. J. Fish. Manag. 28, 500–506.

Foster F, Bergmann C. 2010. 2010 Interim Report: update on Gulf of Mexico Pelagic Longline Bluefin Tuna Mitigation Research. NOAA Fisheries, Engineering and Harvesting Branch, SEFSC. 11 p.

Gilman, E, Kobayashi, D, Swenarton, T, Brothers, N, Dalzell, P, Kinan-Kelly, I. 2007. Reducing sea turtle interactions in the Hawaii-based longline swordfish fishery. Biol. Conserv. 139, 19−28.

Harley S, Hoyle S, Williams P, Hampton J, Kleiber P. 2010. Stock assessment of bigeye tuna in the western and central Pacific Ocean. WCPFC-SC6-2010/SA-WP-04, Nuku‘alofa, Tonga, 10-19 August 2010. http://www.wcpfc.int/node/2937.

Kerstetter DW, Graves JE. 2006. Effects of circle versus J-style hooks on target and non-target species in a pelagic longline fishery. Fish. Res. 80(3): 239-250.

Leatherwood S, Reeves, RR. 1983. The Sierra Club handbook of whales and dolphins. San Francisco, Sierra Club Books.

McCracken ML, Forney, KA. 2010. Preliminary assessment of incidental interactions with marine mammals in the Hawaii longline deep and shallow set fisheries. PIFSC Working Paper WP-10-001, Issued 27 April 2010.

Nakamura EL, Uchiyama JH. 1966. Length-weight relations of Pacific tunas. Pages 197–201 *in* T.A. Manar, ed. Proceedings, Governor's Conference on Central Pacific Fishery Resources. Honolulu, Hawaii.

National Marine Fisheries Service. 2010. Annual Report on Seabird Interactions and Mitigation Efforts in the Hawaii Longline Fisheries for 2009. NMFS Pacific Islands Regional Office. Honolulu, HI. 50 p.

Pre-publication draft document distributed for review purposes only. Subject to revision.
Official PIFSC review and approval pending. Do not cite without explicit permission of primary author.

Pacheco, J., Kerstetter, D., Hazin, F., Hazin, H., Segundo, R., Graves, J., Carvalho, F., Travassos, P. 2011. A comparison of circle hook and J hook performance in a western equatorial Atlantic Ocean pelagic longline fishery. Fish. Res. 107:39–45.

Sales, G., Giffoni, B., Fiedler, F., Azevedo, V., Kotas, J., Swimmer, Y., Bugoni, L. 2010. Circle hook effectiveness for the mitigation of sea turtle bycatch and capture of target species in a Brazilian pelagic longline fishery. Aquatic Conserv: Mar. Freshw. Ecosyst. 20, 428−436.

Suzuki Z, Warashina Y, Kishida M. 1977. The comparison of catches by regular and deep tuna longline gears in the western and central equatorial Pacific. Bull. Far Seas Fish. Res. Lab. 15:51–89.

Uchiyama JH, Kazama TK. 2003. Updated Weight-on-Length Relationships for Pelagic Fishes Caught in the Central North Pacific Ocean and Bottomfishes from the Northwestern Hawaiian Islands. Pacific Islands Fish. Sci. Cent., Natl. Mar. Fish. Serv., NOAA, Honolulu, HI 96822-2396. Pacific Islands Fish. Sci. Cent. Admin. Rep. H-03-01, 34 p.

Watson JW, Epperly SP, Shah AK, Foster DG. 2005. Fishing methods to reduce sea turtle mortality associated with pelagic longlines. Can. J. Fish. Aquat. Sci. 62(5): 965–981.

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Table 1. Summary statistics for 48 species or species groups caught on 127 tuna longline sets with strong and weak 15/0 circle hooks.

	Circle hook catch			
Species	Total	Control	Weak	Unknown or multiple hooks
Bigeye tuna *Thunnus obesus* (Lowe)	1888	929	948	11
Yellowfin tuna *Thunnus albacores* (Bonnaterre)	155	63	90	2
Albacore *Thunnus alalunga* (Bonnaterre)	53	31	22	0
Wahoo *Acanthocybium solandri* (Cuvier)	64	28	35	1
Skipjack tuna *Katsuwonus pelamis* (Linnaeus)	278	129	149	0
unidentified tuna Thunnini	6	3	2	1
Swordfish *Xiphias gladius* (Linnaeus)	61	31	30	0
Spearfish *Tetrapturus angustirostris* (Tanaka)	70	44	25	1
Striped marlin *Kajikia audax* (Philippi)	49	25	23	1
Blue marlin *Makaira nigricans* (Lacepède)	17	8	9	0
Sailfish *Istiophorus platypterus* (Shaw)	15	5	10	0
Blue shark *Prionace glauca* (Linnaeus)	1163	581	566	16
Pelagic stingray *Pteroplatytrygon violacea* (Bonaparte)	92	49	43	0
Bigeye thresher *Alopias superciliosus* (Lowe)	45	21	21	3
Shortfin mako shark *Isurus oxyrinchus* (Rafinesque)	21	10	9	2
Longfin mako shark *Isurus paucus* (Guitart Manday)	1	0	1	0
Oceanic whitetip shark *Carcharhinus longimanus* (Poey)	12	4	8	0
Smooth hammerhead shark *Sphyrna zygaena* (Linnaeus)	1	0	1	0
Tiger shark *Galeocerdo cuvier* (Péron and Lesueur)	1	0	1	0
Crocodile shark *Pseudocarcharias kamoharai* (Matsubara)	1	0	1	0
Velvet dogfish *Scymnodon squamulosus* (Günther)	1	1	0	0
unidentified thresher shark Alopiidae	7	4	2	1
unidentified shark Chondrichthyes	3	0	2	1
Dolphinfish *Coryphaena hippurus* (Linnaeus)	939	490	440	9
Pompano dolphinfish *Coryphaena equiselis* (Linnaeus)	4	2	1	1
Opah *Lampris guttatus* (Brünnich)	185	96	86	3
Longnose lancetfish *Alepisaurus ferox* (Lowe)	1302	680	616	6
Snake mackerel *Gempylus serpens* (Cuvier)	750	366	377	7
Escolar *Lepidocybium flavobrunneum* (Smith)	409	178	219	12
Oilfish *Ruvettus pretiosus* (Cocco)	10	4	6	0
Longfin escolar *Scombrolabrax heterolepis* (Roule)	19	8	11	0
Sickle pomfret *Taractichthys steindachneri* (Döderlein)	268	128	139	1
Pomfret *Brama orcini* (Cuvier) and *Brama japonica* (Hilgendorf)	52	22	22	8
Dagger pomfret *Taractes rubescens* (Jordan and Evermann)	14	3	11	0
Lustrous pomfret *Eumegistus illustris* (Jordan and Evermann)	3	3	0	0
Rough pomfret *Taractes asper* (Lowe)	1	1	0	0
Pelagic puffer *Lagocephalus lagocephalus* (Linnaeus)	10	4	6	0
Mola *Mola mola* (Linnaeus)	3	2	1	0
Sharptail mola *Masturus lanceolatus* (Liénard)	1	1	0	0

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Pelagic triggerfish *Canthidermis maculata* (Bloch)	1	1	0	0
Razorback scabbardfish *Assurger anzac* (Alexander)	1	0	1	0
Driftfish Nomeidae (*Cubiceps* spp.)	1	0	1	0
Great barracuda *Sphyraena barracuda* (Edwards)	26	12	13	1
Hammerjaw *Omosudis lowii* (Günther)	2	2	0	0
Crestfish *Lophotus* sp.	3	2	1	0
unidentified bony fish Osteichthyes	14	7	4	3
Olive ridley turtle *Lepidochelys olivacea* (Eschscholtz)	1	1	0	0
False killer whale *Pseudorca crassidens* (Owen)	1	1	0	0
Total	8024	3980	3953	91

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Table 2. Mean and standard deviation among attributes on 127 tuna longline sets monitored with control (strong) and weak 15/0 circle hooks.

Variable	Mean±standard deviation
Begin deployment time (h)	0725±0054
End deployment time (h)	1225±0103
Begin haul time (h)	1649±0105
End haul time (h)	0412±0205
Hooks per set	2384±155
Hooks between floats	25.7±4.16
Floatline (m)	23.7±2.6
Branchline+Leader (m)	12.2±1.2
Leader material	76.4% wire, 23.6% monofilament
Dropper weight size (g)	47.7±4.7
Bait	100% sauries (*Cololabis saira*)

Table 3. Statistical comparison from randomization tests of catch on control (strong) and weak circle hooks for 22 species caught on 127 tuna longline sets. Asterisk indicates statistical difference in catch ($p<0.05$).

Species	p-value
Bigeye tuna number	0.684
Bigeye tuna weight	0.513
Yellowfin tuna	0.038*
Albacore	0.281
Wahoo	0.406
Skipjack tuna	0.252
Swordfish	1.000
Spearfish	0.016*
Striped marlin	0.888
Blue marlin	1.000
Sailfish	0.231
Blue shark	0.671
Pelagic stingray	0.655
Bigeye thresher	1.000
Shortfin mako	1.000
Dolphinfish	0.091
Opah	0.484
Longnose lancetfish	0.117
Snake mackerel	0.711
Escolar	0.053
Longfin escolar	0.601
Sickle pomfret	0.551
Barracuda	1.000

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Table 4. Mean length (cm fork length (FL) or eye fork length (EFL), ±1 standard deviation) by hook type for 15 species and results of one-way ANOVA on length frequencies by hook type.

Species	Mean length ± S.D		*F*-value (*P*>|*F*|)
	Control circle hook	Weak circle hook	
Bigeye tuna	106.8 ± 24.43 (n=888)	107.5 ± 24.01 (n=910)	0.476 (*P*=0.490)
Yellowfin tuna	118.7 ± 22.45 (n=63)	118.7 ± 23.15 (n=89)	0.004 (*P*=0.952)
Albacore	96.4 ± 6.86 (n=29)	99.2 ± 7.21 (n=23)	2.060 (*P*=0.157)
Wahoo	127.0 ± 8.57 (n=16)	123.9 ± 10.70 (n=20)	0.975 (*P*=0.330)
Skipjack tuna	69.7 ± 7.75 (n=123)	70.1 ± 9.43 (n=134)	0.049 (*P*=0.824)
Swordfish	83.7± 31.63 (n=29)	79.4± 27.32 (n=26)	0.252 (*P*=0.618)
Spearfish	136.6± 15.54 (n=40)	140.3± 11.14 (n=24)	1.315 (*P*=0.256)
Striped marlin	144.1± 19.86 (n=25)	152.9± 15.89 (n=23)	2.974 (*P*=0.091)
Blue marlin	168.0± 42.54 (n=7)	183.6± 30.29 (n=8)	0.914 (*P*=0.356)
Dolphinfish	88.9± 13.05 (n=178)	87.6± 12.92 (n=176)	0.896 (*P*=0.344)
Opah	103.5± 9.95 (n=91)	103.3± 6.64 (n=81)	0.005 (*P*=0.946)
Longnose lancetfish	110.4± 26.01 (n=193)	110.4± 28.02 (n=172)	0.037 (*P*=0.847)
Snake mackerel	106.5± 23.34 (n=106)	109.4± 20.35 (n=112)	1.233 (*P*=0.268)
Escolar	73.5± 16.08 (n=62)	71.0± 15.47 (n=75)	0.881 (*P*=0.350)
Sickle pomfret	54.6± 12.01 (n=53)	54.20± 11.87 (n=58)	0.033(*P*=0.857)

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Table 5. Summary statistics by hook type for bigeye tuna for catch rate in number and weight.

	Control	Weak
Catch (number) per 1,000 hooks	6.1 (5.02)	6.2 (5.39)
Catch (kg) per 1,000 hooks	187.1 (152.08)	194.6 (159.37)
Catch (kg) per 1,000 hooks estimated without depredation	194.0 (158.98)	200.6 (162.59)
Total catch in weight (kg)	28733	29872
Total catch in weight (kg) estimated without depredation	29801	30800
Percentage (%) retained	94.7	95.0
	Both hook types	
Average weight (kg) – October to December	32.4 (20.94)	
Average weight (kg) – October	33.0 (18.85)	
Average weight (kg) – November	32.7 (21.20)	
Average weight (kg) – December	29.9 (24.33)	

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Table 6. Annual composition of hooks used in the Hawaii-based tuna longline fishery based on observer data. 'Pure circle' for 14/0, 15/0, or 16/0 offset or non offset circle hooks; 'Pure tuna' for tuna hooks of 3.6 or 3.8 sun; 'Other' for using 18/0 circle or J-hooks; and 'Mixed' for using more than one of the previous categories.

Year	Pure tuna	Pure circle	Mixed	Other
2004	87%	5%	2%	6%
2005	86%	9%	2%	3%
2006	68%	11%	21%	0%
2007	50%	18%	32%	0%
2008	38%	28%	33%	1%
2009	34%	41%	24%	1%
2010	25%	43%	27%	5%

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Table 7. Comparison of the number and rate (number per 1,000 hooks) of straightened hooks obtained in studies testing variable strength circle hooks.

	This study		Bayse and Kerstetter (2010)				Foster and Bergmann (2010)	
Hook size	15/0 - strong	15/0 – weak	16/0 – strong	16/0 – weak	18/0 - strong	18/0 weak	16/0 - strong	16/0 – weak
Fabrication	4.5 mm wire	4.0 mm wire	Forged Lindgren-Pitman, oval cross-section 3.2 mm by 4.0 mm	3.55 mm wire, Mustad model #39960	Forged Lindgren-Pitman, oval cross-section 3.6 mm by 5.0 mm	4.95 mm wire, Mustad model (#39960)	4.0 mm wire with Duratin coating, 0° offset, Mustad model #39960D	3.65 mm wire with Duratin coating, 0° offset, Mustad model #39988D
Pull required to straighten	138 kg	93 kg	113 kg	68 kg	159 kg	102 kg	110-125 kg	72 kg
Effort (hooks)	151,369	151,369	7,784	7,784	2,327	2,327	99,303	99,303
Total number of straightened hooks	6	70	0	7	0	1	63	287
Straightened hook rate (per 1,000 hooks)	0.040	0.462	0	0.899	0	0.439	0.634	2.890
Number of straightened hooks without catch	5	44	0	7	0	0	63	287
Straightened hook rate without catch (per 1,000 hooks)	0.033	0.291	0	0.899	0	0	0.634	2.890

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Figure 1. Lateral view of a control 15/0 circle hook composed of 4.5 mm diameter wire used in the field trials.

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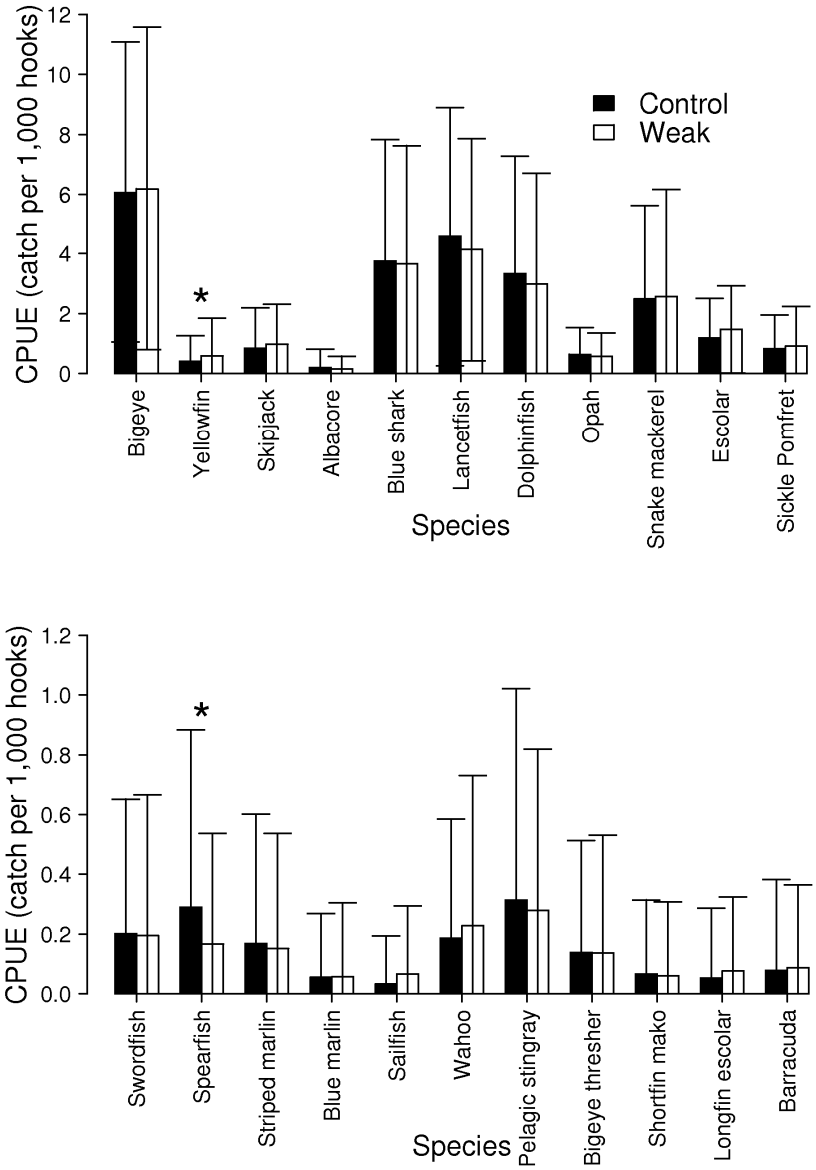

Figure 2. Comparison of mean CPUE (catch per unit effort, number per 1,000 hooks) for 22 species captured from 127 tuna longline sets deploying control (4.5 mm diameter wire) and weak (4.0 mm diameter wire) circle hooks. Vertical bars indicate +/- one standard deviation and an asterisk indicates statistically significant differences in CPUE.

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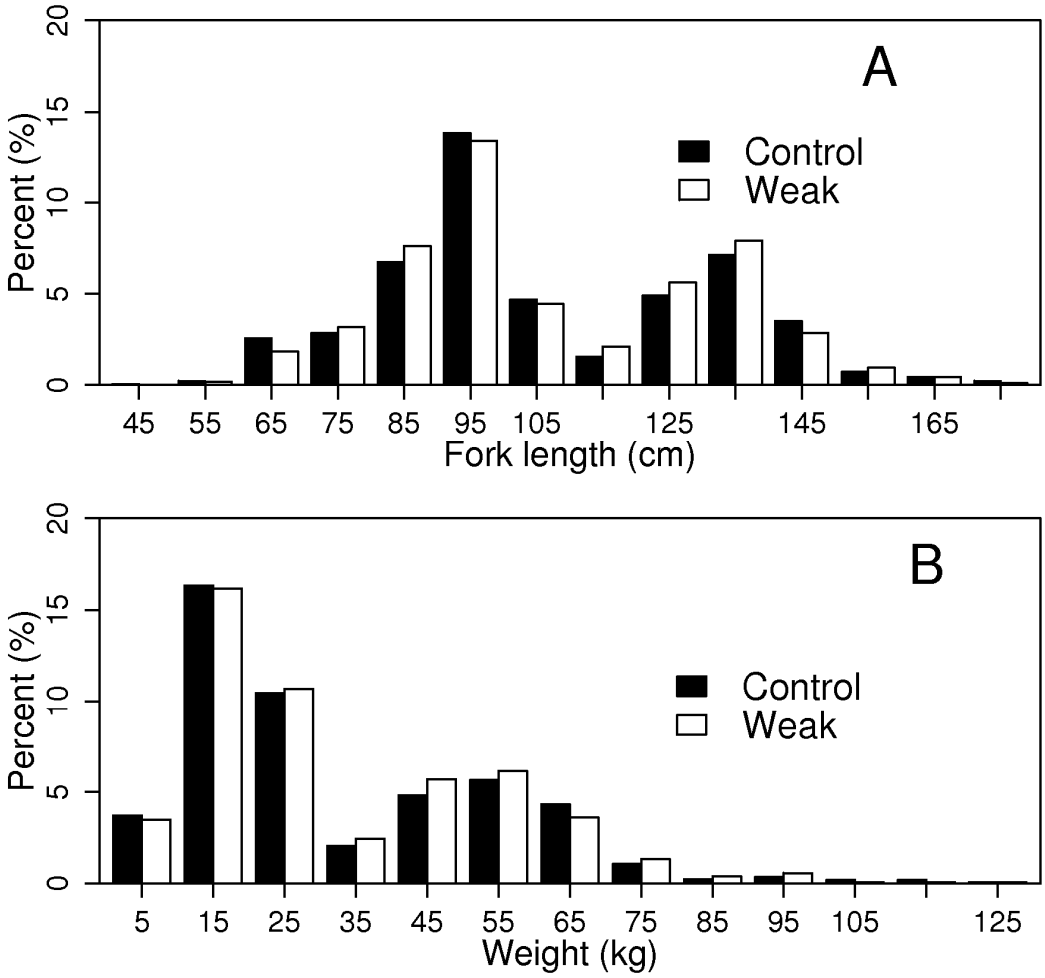

Figure 3. Comparison of bigeye tuna size (A–fork length (cm); B–estimated whole weight (kg)) captured from 127 tuna longline sets deploying control and weak circle hooks.

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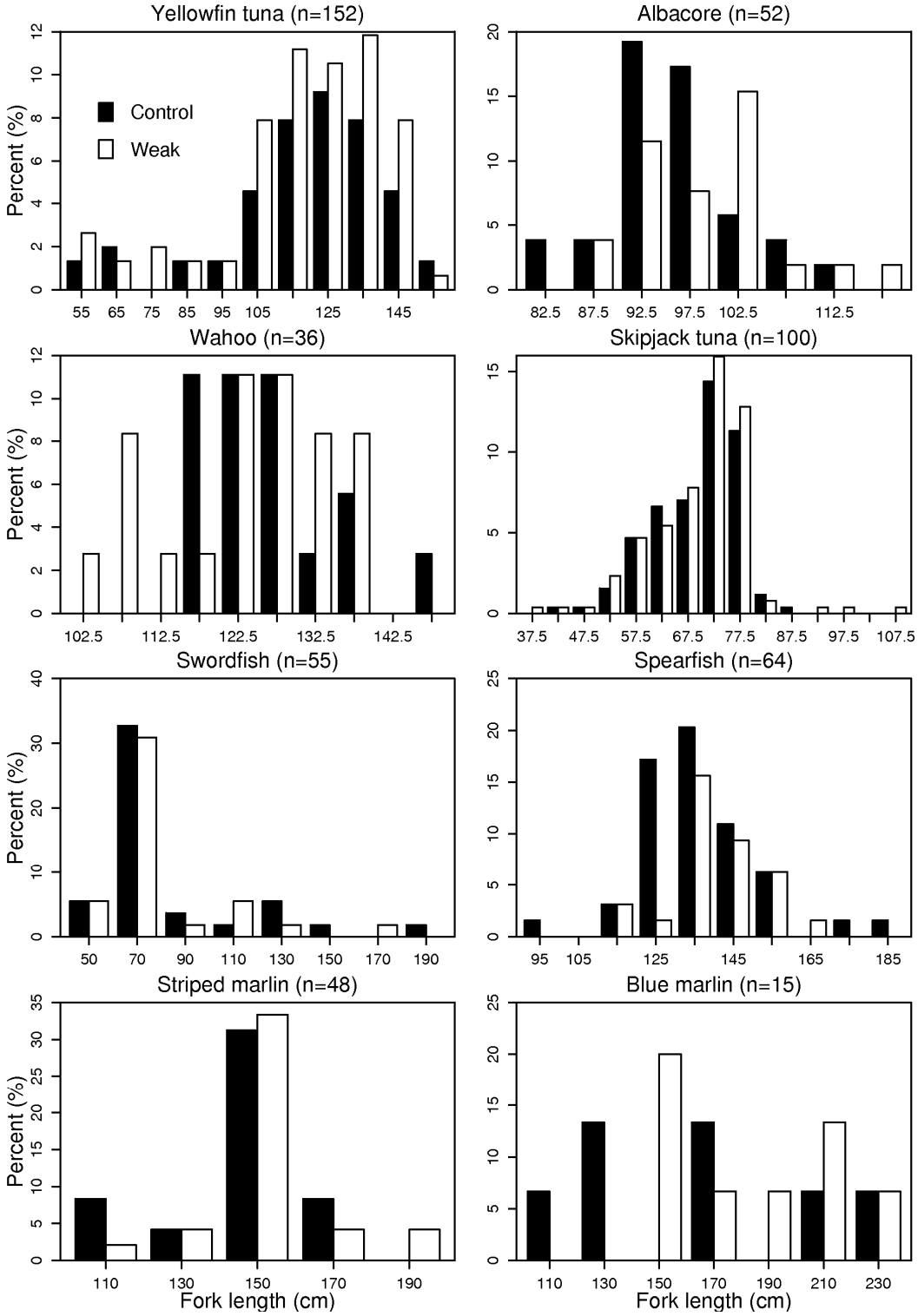

Figure 4. Comparison of length-frequencies for 14 species captured from 127 tuna longline sets deploying control and weak circle hooks.

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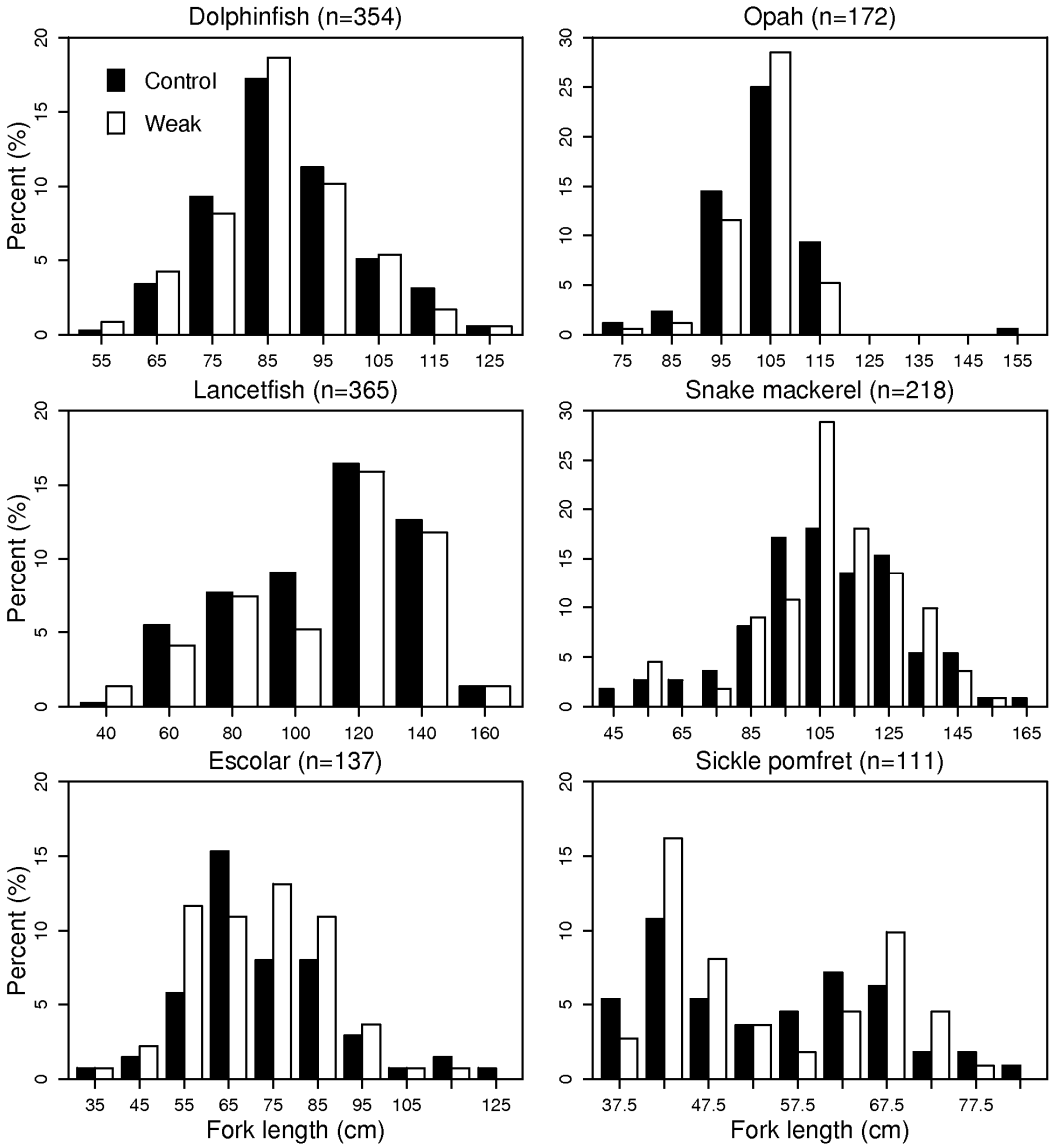

Figure 4 continued.

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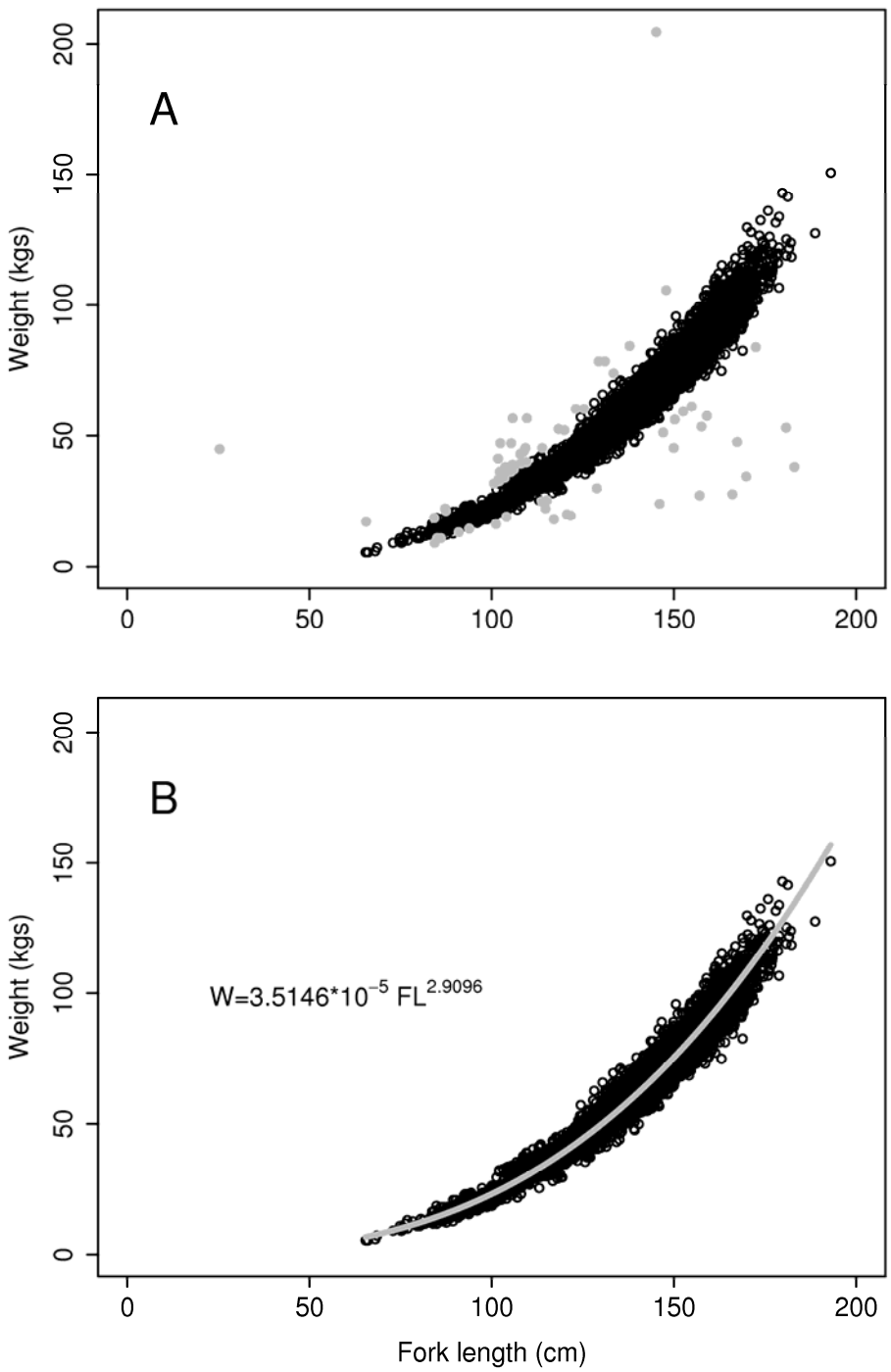

Figure 5. Whole weight (kg) and fork length (cm) relationship from longline caught bigeye tuna in the Hawaii-based longline fishery (1960–1970). All weight-at-length measurements (A) and outliers removed (B). Outliers are denoted in panel A as light gray circles. The length-weight regression equation is presented in panel B.

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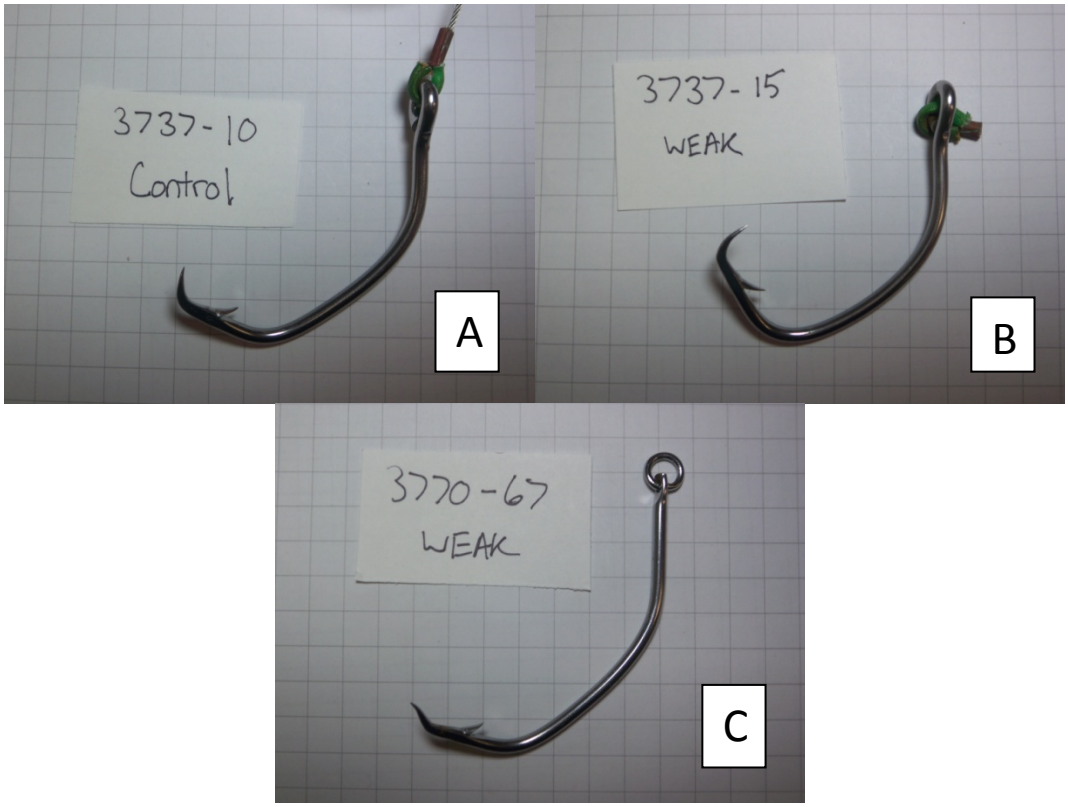

Figure 6. Examples of straightened hooks during trials of 127 tuna longline set deploying control (strong) and weak circle hooks. Control hook straightened by a false killer whale (A), weak hook with a 131 cm FL retained bigeye tuna (B) and a weak hook from an unknown animal (C).

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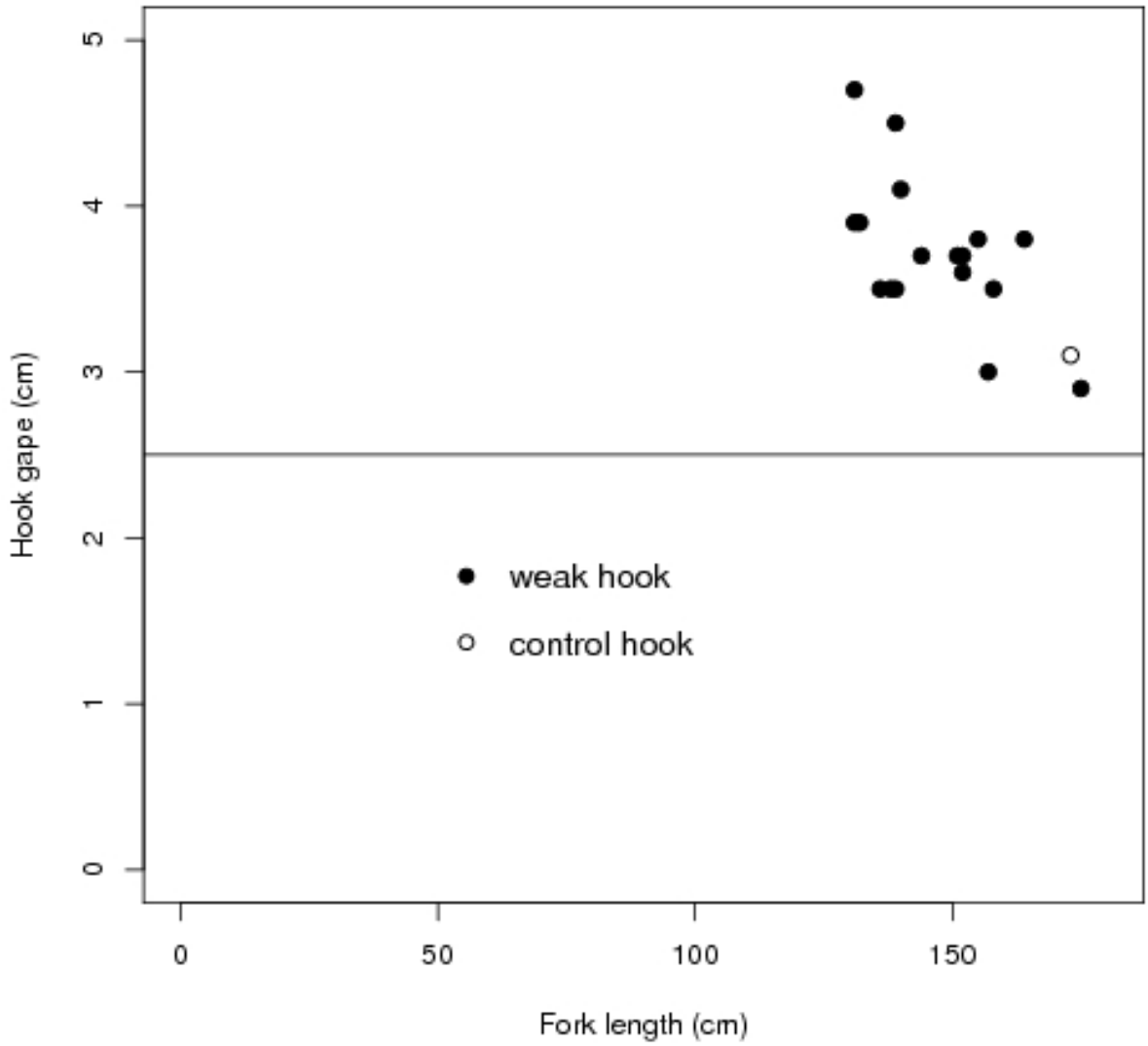

Figure 7. Relationship between the circle hook gape width and bigeye tuna size for straightened circle (open circle) and weak (filled circle) hooks that retained bigeye tuna. Horizontal line at 2.5 cm is the gape width of an unfished hook.

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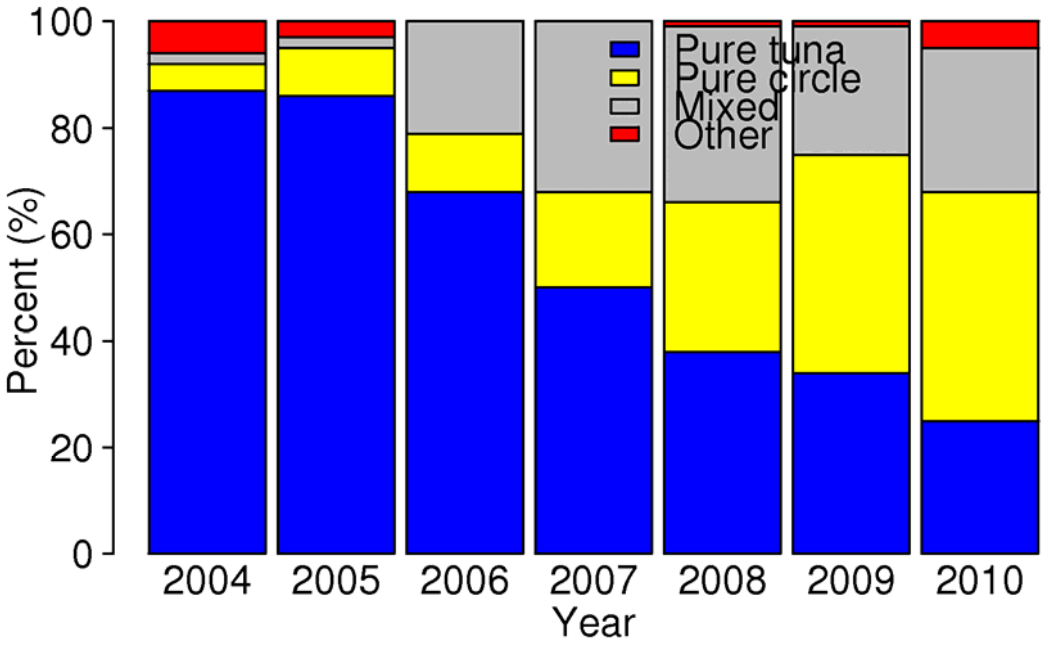

Figure 8. Annual composition of hooks used in the Hawaii-based tuna longline fishery. 'Pure circle' for 14/0, 15/0, or 16/0 offset or non offset circle hooks; 'Pure tuna' for tuna hooks of 3.6 or 3.8 sun; 'Other' for using 18/0 circle or J-hooks; and 'Mixed' for using more than one of the previous categories.

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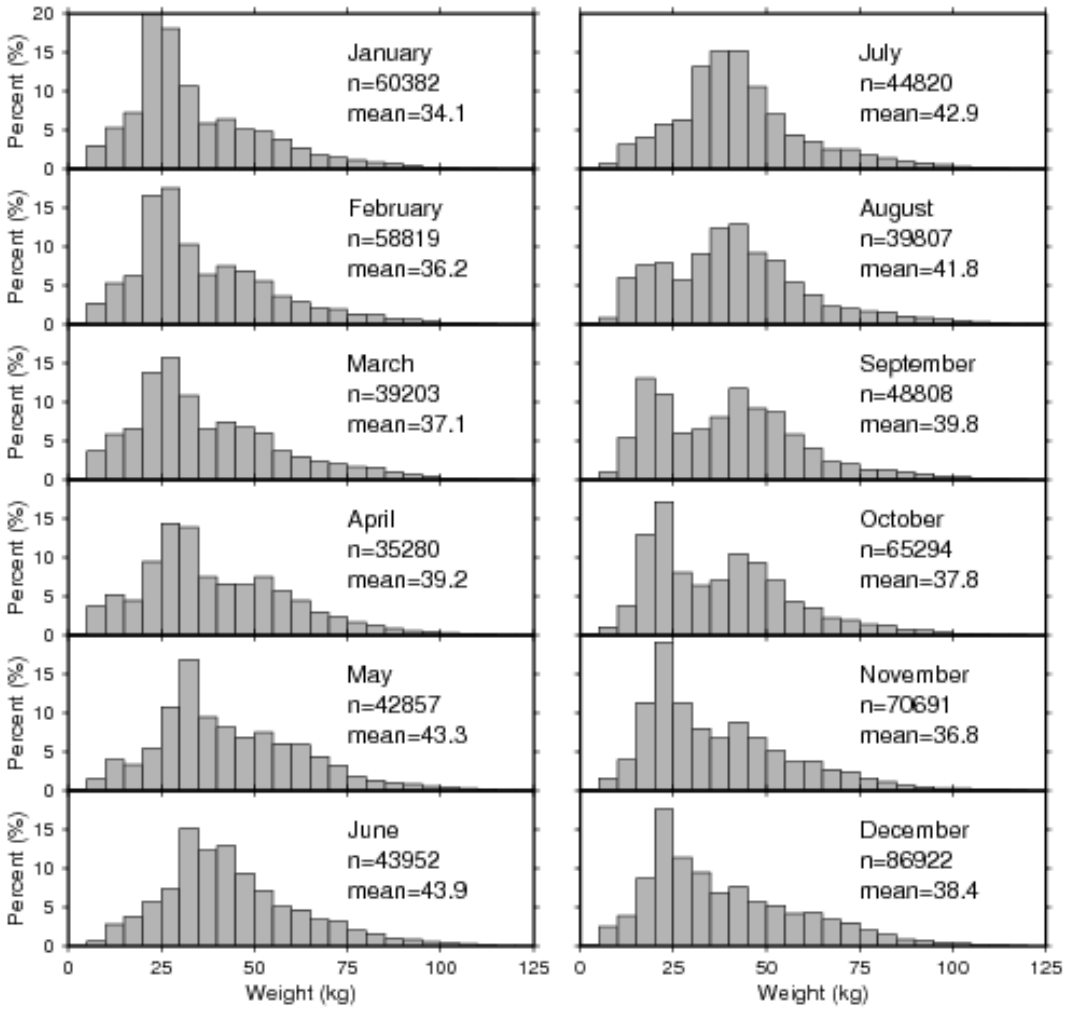

Figure 9. Monthly mean weight of bigeye tuna landed by the Hawaii-based deep-set fishery and marketed at the United Fishing Agency Ltd. from 2005 to 2009.

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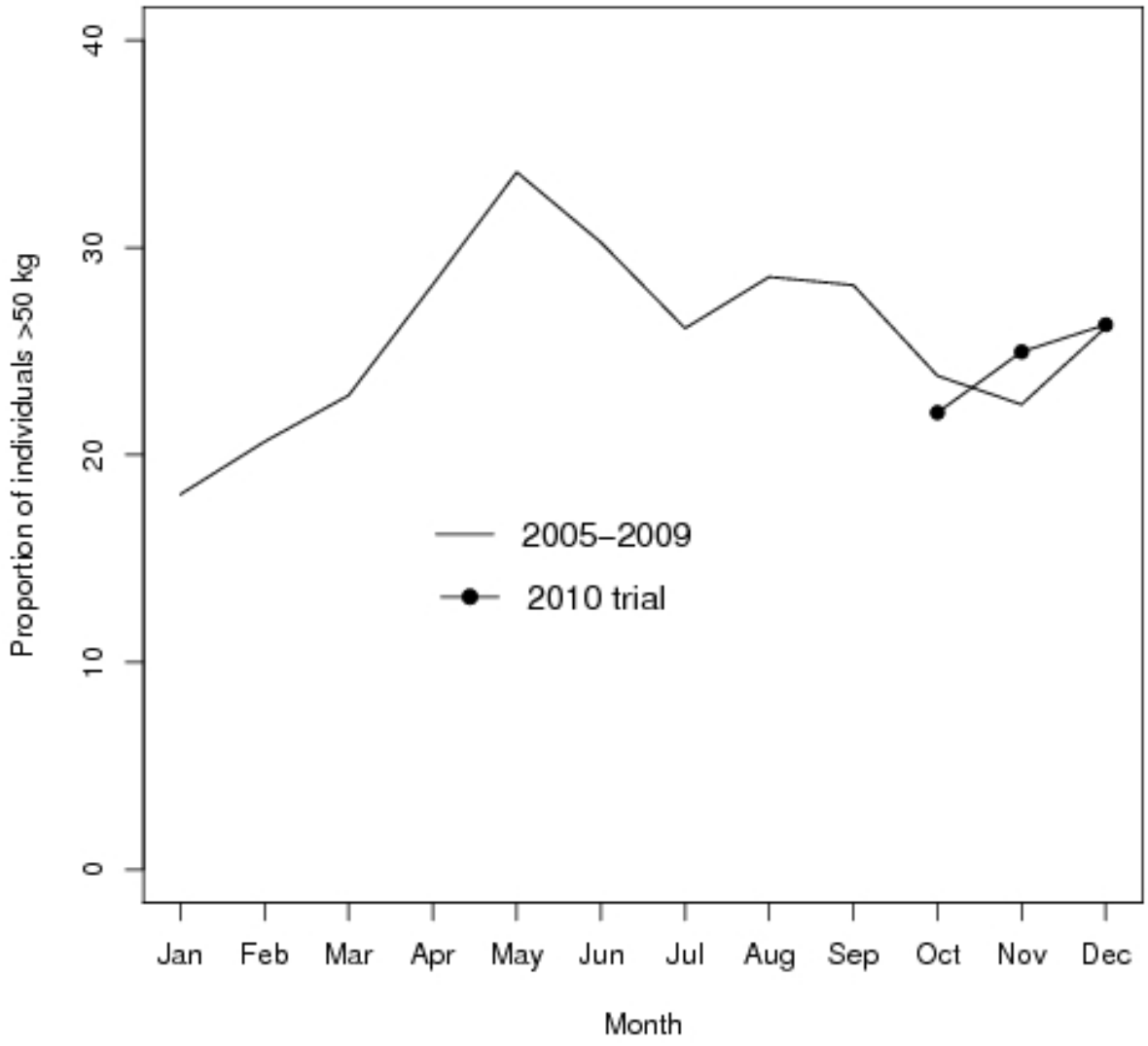

Figure 10. Monthly proportion of large (>50kg) bigeye landed by the Hawaii-based deep-set fishery and marketed at the United Fishing Agency Ltd. from 2005 to 2009 and during the 2010 field trials.

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Appendix. Summary of straightened hooks collected by observers from 127 tuna longline sets deploying control (strong) and weak circle hooks.

								----------Hook morphometrics----------			
Hook ID	Hook Type	Species Landed	Size	Hook number between floats	Hooks per float	Marine mammal depredation evident on set	Marine mammal sightings during set	Max Length (cm)	Straight Total Length (cm)	Straight Total Width (cm)	Gape (cm)
3708 – 1	Weak			11	29	no	No	9.1	7.9	6.6	NA
3708 – 2	Weak			17	29	yes	No	7.7	6.7	5.1	3.8
3726 - 3	Weak			15	29	no	No	7.7	6.7	5.1	3.9
3726 – 4	Weak	blue marlin		1	29	no	No	8.2	7	6.1	4.8
3726 – 5	Weak				29	no	No	7.5	6.5	5	3.8
3726 - 6	Weak			12	29	no	no	7	5.6	4.9	3
3726 – 7	Weak			2	29	no	no	7	6.1	4.8	2.8
3726 - 8	Weak			1	29	no	no	7.4	6.4	5.1	3.5
3726 - 9	Weak			19	29	no	no	7.2	6.2	4.8	3
3737 – 10	Control	FKW	~14 ft	16	25	no	yes	9.1	7.1	7	5
3737 – 11	Control			20	25	no	no	9.6	7.5	7.1	4.2

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Hook ID	Hook Type	Species Landed	Size	Hook number between floats	Hooks per float	Marine mammal depredation evident on set	Marine mammal sightings during set	Max Length (cm)	Straight Total Length (cm)	Straight Total Width (cm)	Gape (cm)
3737 - 12	Weak			5	25	no	no	8	6.6	6.2	5
3737 – 13	Weak				25	no	no	7.7	6.5	5.9	4.5
3737 – 14	Weak				25	no	no	7.3	5.8	5.3	3.3
3737 – 15	Weak	bigeye tuna	131 cm	13	25	no	no	8	6.6	6	4.7
3737 – 16	Weak	blue marlin	142 cm	1	25	no	no	7.1	5.8	5.2	3.5
3737 – 17	Weak			21	25	no	no	7	6	4.8	3.2
3737 – 18	Weak	bigeye tuna	140 cm	19	25	no	no	7.7	6.1	5.4	4.1
3743 - 19	Control			16	20	no	no	7.8	6.6	5.8	4.5
3743 – 20	Weak			10	20	no	no	8.8	7.3	7.2	NA
3743 – 21	Weak	blue marlin	223 cm	5	20	no	no	7.9	7.1	5.4	4

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3743 – 22	Weak			7	20	no	no	9.5	8	6.9	NA
3735 - 23	Control			17	29	no	no	7.6	6.7	5.5	3.9
3735 – 24	Weak	bigeye tuna	144 cm	18	29	yes	yes	7.6	6.6	5	3.7
3735 – 25	Weak				29	no	no	7.5	6.5	5.1	3.9
3735 - 26	Weak				29	no	no	7	6.1	4.9	3.1
3735 – 27	Weak			4	29	no	no	8.2	7	6	NA
3755 – 28	Weak	bigeye tuna		12	29	yes	no	7.1	6.2	5	3.5
3755 - 29	Weak	bigeye thresher	7 ft	6	29	no	no	7.6	6.5	5.5	4.2
3755 – 30	Weak	yellowfin tuna	140 cm	1	29	no	no	8	7	5.5	4.7
3755 – 31	Weak			10	29	no	no	7.5	6.2	5.4	4
3755 – 32	Weak	bigeye tuna	131	6	29	no	no	7.5	6.5	5.1	3.9

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Hook ID	Hook Type	Species Landed	Size	Hook number between floats	Hooks per float	Marine mammal depredation evident on set	Marine mammal sightings during set	Max Length (cm)	Straight Total Length (cm)	Straight Total Width (cm)	Gape (cm)
			cm								
3755 – 33	Weak	bigeye tuna	132 cm	26	29	no	no	7.7	6.5	5.1	3.9
3755 – 34	Weak			20	29	no	no	7.3	6.2	4.9	3.4
3755 – 35	Weak	bigeye tuna	155 cm	14	29	no	no	7.5	6.6	5.2	3.8
3755 – 36	Weak			24	29	no	no	7.4	6.5	5.2	3.9
3755 – 37	Weak			24	29	no	no	7.5	6.6	5	3.6
3764 – 38	Weak	blue marlin	199 cm		25	no	no	7.5	6.8	4.8	3.4
3764 – 39	Weak	bigeye tuna	138 cm		25	no	no	7.5	6.6	5.1	3.5
3764 – 40	Weak	bigeye tuna	164 cm		25	no	no	7.8	7	5.1	3.8
3764 – 41	Weak			13	25	no	no	9.3	7.4	7.3	NA

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3764 – 42	Weak			7	25	no	no	9.4	7.7	7.2	NA
3764 – 43	Weak			8	25	no	no	9	7.5	8.5	NA
3764 – 44	Weak			9	25	no	no	7.8	6.8	5.9	4.3
3764 – 45	Weak			7	25	no	no	7.3	6.4	5	3.6
3764 – 46	Weak	bigeye tuna	157 cm	16	25	no	no	6.6	5.6	4.9	3
3764 – 47	Weak	bigeye tuna	151 cm	24	25	no	no	7.5	6.3	5	3.7
3764 – 48	Weak	bigeye tuna	175 cm		25	no	no	6.7	5.7	4.9	2.9
3764 – 49	Weak	bigeye tuna	152 cm	15	25	no	no	7.8	6.8	5.1	3.7
3764 – 50	Weak	bigeye tuna	139 cm	20	25	no	no	7.3	6.2	5	3.5
3764 – 51	Weak	bigeye tuna		22	25	yes	no	7.5	6.7	5	3.5

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3764 – 52	Weak	bigeye tuna			25	yes	no	7.3	6.4	5	3.4
3764 – 53	Weak			21	25	no	no	7.4	6.4	5	3.5
3770 – 54	Control			20	31	no	yes	NA	NA	NA	NA
3770 – 55	Weak			19	31	no	no	7.3	6.4	4.6	3.2
3770 – 56	Weak				31	no	no	7.2	6.2	5	3.4
3770 – 57	Weak	bigeye tuna	152 cm		31	no	no	7.3	6.4	5	3.6
3770 – 58	Weak	bigeye tuna	136 cm	7	31	no	no	7.2	6.2	5	3.5
3770 – 59	Weak				31	yes	yes	8.5	7.9	6	5.4
3770 – 60	Weak			12	31	no	no	7.1	6.2	4.8	3.2
3770 – 61	Weak				31	no	no	9.8	8.1	6.9	NA
3770 – 62	Weak				31	no	no	8.9	7.2	5.9	NA
3770 – 63	Weak			7	31	no	no	10	8.4	6.8	NA

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3770 – 64	Weak			11	31	no	no	8.4	7.2	6.2	NA
3770 – 65	Control	bigeye tuna	173 cm		31	no	no	7	6.1	4.8	3.1
3770 – 66	Weak				31	no	no	9.3	7.6	6	NA
3770 – 67	Weak				31	no	no	9.5	7.8	7.1	NA
3780 – 68	Weak				21	no	no	8.3	7.5	6	5.1
3780 – 69	Weak				23	no	no	8.5	7.1	7.1	NA
3780 – 70	Weak				23	no	no	9.9	8	7.3	NA
3780 – 71	Weak	bigeye tuna	139 cm	12	21	no	no	7.9	6.7	5.8	4.5
3780 – 72	Weak			9	20	no	no	8.7	7.5	7.1	NA
3780 – 73	Weak	bigeye tuna	158 cm	15	18	no	no	7.1	6	5.2	3.5
3780 – 74	Weak				18	yes	no	8.2	6.9	6.8	NA

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3780 – 75	Weak				18	yes	no	7.5	6.6	5.5	4.2
3780 – 76	Weak				18	yes	no	7.1	6	4.9	3.4

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