6.E.1(2)
185th CM

Effects of circle hooks on pelagic catches in the Hawaii-based tuna longline fishery

Article *in* Fisheries Research · May 2011

DOI: 10.1016/j.fishres.2011.02.013

2 authors:

Daniel S Curran
National Oceanic and Atmospheric Administration
10 PUBLICATIONS **643** CITATIONS
SEE PROFILE

Keith A. Bigelow
National Oceanic and Atmospheric Administration
52 PUBLICATIONS **2,300** CITATIONS
SEE PROFILE

Fisheries Research 109 (2011) 265–275

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Effects of circle hooks on pelagic catches in the Hawaii-based tuna longline fishery

Daniel Curran, Keith Bigelow*

Pacific Islands Fisheries Science Center, 2570 Dole St., Honolulu, HI 96822, USA

ARTICLE INFO

Article history:
Received 29 November 2010
Received in revised form 16 February 2011
Accepted 17 February 2011

Keywords:
Tuna hook
J-hook
Deep setting
Survival
Bycatch

ABSTRACT

Sixteen vessels within the deep-set Hawaii-based tuna longline fleet tested the catch efficacy, fish size selectivity and survival on longline retrieval of large-size 18/0 circle hooks vs. Japanese style tuna hooks, size 3.6 sun and vs. size 9/0 "J" hooks. Vessels alternated hook types throughout the longline gear and maintained a 1:1 ratio of circle hooks to their existing tuna or J-hooks. Observers monitored a total of 1393 sets; 1182 sets were circle hooks vs. tuna hooks and 211 sets were circle hooks vs. J-hooks. The 18 most-caught species were analyzed representing 97.6% of the total catch by number. Two statistical methods were used to assess differences in catch (randomization test) or catch rate (generalized linear mixed models (GLMMs)). There were no significant catch or catch rate (catchability) differences among hook types for bigeye tuna (*Thunnus obesus*), the primary target species, with either statistical method. However, GLMMs indicated that catch rates on circle hooks were significantly lower for 16 and 8 species compared to tuna and J-hooks, respectively. There were no significant differences in mean length of bigeye tuna among hook comparisons. Caught condition at retrieval varied considerably among the 18 species. Large circle hooks had greater effects on catch rates than on fish size selectivity and fish survival. We contend that reduced catch rates are a function of 18/0 circle hook shape, where the minimum width (4.9 cm) was 57% and 25% wider than the Japanese tuna (3.1 cm) and J-hook (3.9 cm), respectively. In contrast to tuna hooks, large circle hooks have conservation potential for use in the world's pelagic tuna longline fleets for some highly migratory species, with catch rate reductions of 29.2–48.3% for billfish species and 17.1–27.5% for sharks.

Published by Elsevier B.V.

1. Introduction

There is international agreement stressing the importance of reducing the longline capture of non-target species, such as istiophorid billfishes, sharks, sea turtles, seabirds and marine mammals, while maintaining sustainable populations of target species such as tunas (*Thunnus* spp.) and swordfish (*Xiphias gladius*). Pelagic longlines have often been described as a threat to endangered sea turtle and seabird populations worldwide (Brothers et al., 1999; Lewison et al., 2004). Billfishes (i.e., marlins and relatives) are also caught in large numbers by longline fisheries, and there is concern for overfished Atlantic populations of blue (*Makaira nigricans*), and white marlin (*Kajikia albidus*, ICCAT, 2006), possibly overfished Atlantic sailfish (*Istiophorus platypterus*, ICCAT, 2009) and North Pacific striped marlin (*Kajikia audax*, Brodziak and Piner, 2010).

Mortality can occur both during capture and after release from longline gear, which constrains the ability to estimate mortality accurately. Minimum capture induced mortality can be quantified by ascertaining caught condition (dead/alive) of an individual fish at time of gear retrieval (Camiñas et al., 2006). Post-release mortality of individuals released alive can be estimated by electronic tagging (Campana et al., 2009; Chaloupka et al., 2004; Sasso and Epperly, 2007). Mortality estimation is difficult for individuals escaping from hooks during the longline soak.

One method to reduce non-target catch is to avoid gear encounters by altering the temporal and spatial aspects of fishing. Mitigation can also occur by modifying longline gear to reduce the catch rate (catchability), by altering the size of individuals (size selectivity) captured, and by decreasing the soak time to increase the survival rate of species released from the fishing gear. Modifications of pelagic longline to alter catchability of sea turtles have focused on deploying gear deeper in the water column and changing bait type, leader material, and hook design and sizes. Research on alternative hook and bait types has largely focused on shallow set (<100 m target fishing depth) longline fisheries targeting swordfish because interaction rates with sea turtles are much higher than in deep-set

---

* Corresponding author at: NOAA Fisheries, Pacific Islands Fisheries Science Center, 2570 Dole Street, Honolulu, HI 96822, USA. Tel.: +1 808 983 5388; fax: +1 808 983 2901.
E-mail address: Keith.Bigelow@noaa.gov (K. Bigelow).

0165-7836/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.fishres.2011.02.013

(~100–300+ m) tuna fisheries (Gilman et al., 2007). Lastly, the use of safe handling techniques or best practices (FAO, 2009) can be used to minimize the impacts of fishing by reducing post-release mortality.

Circle hooks are generally circular or oval in shape and have a point perpendicular to the shank that curves inward and is less exposed in comparison to J- (straight shank) and Japan tuna style hooks where the point is parallel to the shank (Fig. 1; Cooke and Suski, 2004; Serafy et al., 2009). Circle hooks have been promoted in swordfish longline fisheries (Watson et al., 2005; Gilman et al., 2007; see review by Read, 2007) because of these hooks' potential to reduce sea turtle interaction rates, and they have a higher frequency of mouth hooking vs. deep hooking for sea turtles and fishes, which may reduce post-release mortality. The Hawaii-based swordfish longline fishery was closed in 2001, as a result of concerns with seabird and sea turtle interactions, and re-opened in 2004 with a mandate directing fishermen to switch from using J-hooks and squid bait to using 18/0 circle hooks and whole fish bait (Gilman et al., 2007). After the fishery re-opened in 2004, swordfish catch rates increased significantly by 16%, with significant reductions in catch rates for blue shark (*Prionace glauca*) (29%, Walsh et al., 2009), loggerhead (*Caretta caretta*) (90%) and leatherback sea turtles (*Dermochelys coriacea*) (83%, Gilman et al., 2007).

Comparisons of circle hook catchability and mortality rates that were made from conducting longline studies of hook types and recreational hook and line fisheries have yielded variable results and substantial inter-study variation. Two meta-analyses (Cooke and Suski, 2004; Serafy et al., 2009) summarized the performance of circle hooks and J-hooks regarding capture efficiency, mortality rate and injury caused by hooking and bleeding. Circle hooks in 28 studies of marine recreational fisheries indicated an overall tendency for lower mortality, as circle-hooked fish were more frequently jaw-hooked than deep-hooked (Cooke and Suski, 2004). A quantitative review (Serafy et al., 2009) of 11 istiophorid studies of circle and J-hook performance in recreational rod-and-reel and commercial longline fisheries provided 30 species-specific comparisons, with 13 statistically significant differences between hook types. No significant differences in catch rates were evident for 4 billfishes (striped, white, blue marlin and sailfish) among 9 comparisons. Four of 11 mortality rate comparisons indicated significantly higher mortality (average = 8%) associated with J-hooks for 3 longline caught species (sailfish, blue and white marlin) and one species (sailfish) caught with rod-and-reel. J-hooks showed a statistically higher deep hooking rate within five of seven comparisons, with corresponding higher bleeding rates with deep hook ingestion.

The disparate results on hook effects in pelagic longline fisheries may be a result of several factors: (1) species-specific differences in mouth morphology, (2) confounding results by simultaneously changing bait and hook types and sizes, (3) a lack of standardization in hook shape and measurement terminology, (4) conducting experiments with many covariates resulting in little power for statistical inference, and (5) geographic variability in longline size selectivity. The lack of consistent results between circle and conventional (tuna, J) hooks have led several researchers (e.g., Cooke and Suski, 2004; Read, 2007; Serafy et al., 2009) to recommend that fishery managers promote circle hooks only when appropriate scientific data from rigorous field experiments support their use.

The specific intentions of this study were to quantify the effects of three hook types in the Hawaii-based tuna longline fishery on (1) catchability of target, incidental (retained non-target), and bycatch (discarded) species; (2) size selectivity; (3) caught condition (survival) on longline retrieval; and (4) the economic viability in changing hook types.

2. Materials and methods

2.1. Vessel protocols

Sixteen Hawaii-based tuna longline vessels were contracted between June 2005 and February 2006 to alternate large, non-ringed, stainless steel circle hooks ("C" hooks size 18/0 made in Korea) with the vessel's conventional hooks composed entirely of Japanese style, ringed, stainless steel tuna hooks size 3.6 sun (hereafter referred as "tuna" hooks) or non-ringed, stainless steel "J" hooks (size 9/0) (Fig. 1) on all longline deployments. Vessels sequentially alternated two types (e.g., C, tuna, C, tuna or C, J, C, J) throughout the longline set. To ensure that the first hook after a float would alternate by hook type, vessels were requested to deploy an odd number of hooks between floats. To minimize sources of variation, no change was made to any other operational characteristic. Vessel captains chose where they fished and were allowed to retain and sell their catch. Six vessels deployed 10° offset circle hooks and the remaining vessels deployed non-offset hooks. At the beginning of the field trials, all vessels were required to alternate hook type 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.

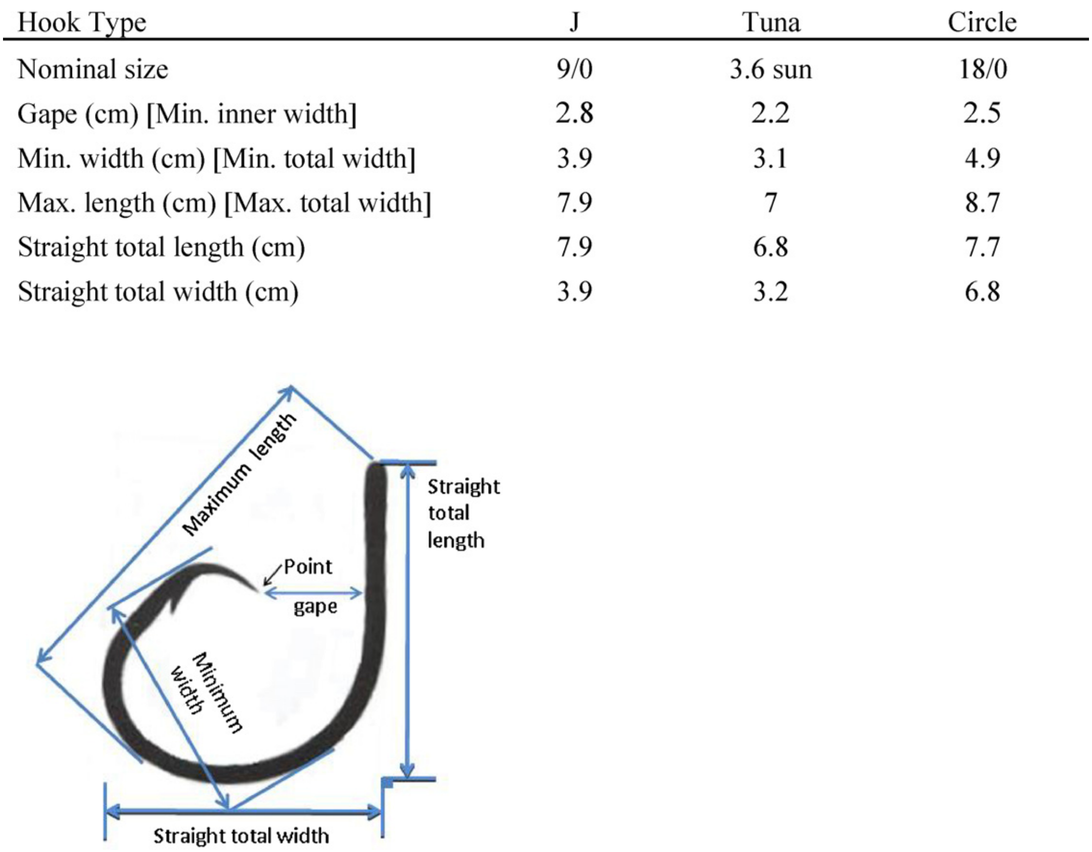
2.2. Observer protocols

Data were collected by personnel of the Pacific Islands Regional Observer Program. The observers collected information on all catch by species, hook type, sequential hook number of capture between two floats, caught condition, catch disposition (retained, discarded), length measurements of some landed species, daily tally of the numbers of each type of hook deployed, 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. Length measurement prioritization was given to tunas, billfishes and other species such as sharks, opah (*Lampris guttatus*), and pomfrets (Bramidae). Observers categorized caught condition as alive or dead at the time of retrieval with any responsiveness being categorized as alive. The animal was recorded as dead if an observer was unable to see or determine if an individual was alive or dead at retrieval.

2.3. Statistical methods

All observed sets were reviewed for compliance with vessel and observer protocols and any questionable sets ($n = 69$) were excluded from analysis. A total of 1393 longline sets were analyzed with 1182 sets comparing catch by species of circle and tuna hooks, and 211 sets comparing circle and J-hooks (Table 1). Catch records of 783 fish (1.2%) from included sets were deleted based on uncertain hook type. The most numerous 18 individual species were chosen for analysis (Table 1, Fig. 2) with the least numerous having an average catch rate of 0.14 fish per set. Additional species (Table 1) were not considered due to their uncommon occurrence, grouping at higher taxa or uncertain species identifications.

Two statistical methods were used to assess catch or catch rate differences between hook types as described in a review on experimental design and statistical methods for longline fisheries (IATTC, 2008). A randomization test (Manly, 2007) is straightforward with minimal assumptions. 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 circle and tuna or circle and J-hooks by set. Data were randomized and resampled 10,000 times using the software package Resampling Stats for Excel



Hook Type	J	Tuna	Circle
Nominal size	9/0	3.6 sun	18/0
Gape (cm) [Min. inner width]	2.8	2.2	2.5
Min. width (cm) [Min. total width]	3.9	3.1	4.9
Max. length (cm) [Max. total width]	7.9	7	8.7
Straight total length (cm)	7.9	6.8	7.7
Straight total width (cm)	3.9	3.2	6.8

Fig. 1. Terminology (adapted from Yokota et al., 2006) and dimensions of 9/0 J-hook, 3.6 sun Japanese tuna and 18/0 circle hooks used in the hook field trials [terms used by Yokota et al. 2006 in brackets where they differ from the terms used here].

(version 4.0) and scored for whether or not the resampled *S* value was equal to or greater than the observed *S* value. This method results in a probability of randomness (*P*) estimate that is a measure of the strength of evidence against a null hypothesis rather than showing significance at a certain level.

In addition to randomization tests, GLMMs were fitted to explicitly model the underlying processes in the catch rate (CPUE, number per 1000 hooks) data and to estimate relative catchability between hook types. GLMMs were employed because longline data are hierarchical (McCracken, 2004) in that longline sets occur together in

Table 1
Summary statistics for 18 most commonly caught species on experiments with tuna, J-, and circle hooks in the Hawaii-based tuna longline fishery.

Species	Catch	Catch (CPUE) from 1182 sets		Catch (CPUE) from 211 sets	
		Circle	Tuna	Circle	J-hook
Bigeye tuna *Thunnus obesus*	11,125	4722 (4.029)	4630 (3.951)	930 (4.330)	843 (3.925)
Yellowfin tuna *Thunnus albacares*	2552	960 (0.819)	1097 (0.936)	232 (1.080)	263 (1.225)
Wahoo *Acanthocybium solandri*	1015	337 (0.288)	440 (0.375)	98 (0.456)	140 (0.652)
Albacore *Thunnus alalunga*	405	144 (0.123)	207 (0.177)	25 (0.116)	29 (0.135)
Skipjack tuna *Katsuwonus pelamis*	1068	403 (0.344)	466 (0.398)	93 (0.433)	106 (0.494)
Striped marlin *Kajikia audax*	1131	370 (0.316)	642 (0.548)	48 (0.224)	71 (0.331)
Spearfish *Tetrapturus angustirostris*	952	265 (0.226)	510 (0.435)	66 (0.307)	111 (0.517)
Swordfish *Xiphias gladius*	397	120 (0.102)	231 (0.197)	19 (0.088)	27 (0.126)
Blue marlin *Makaira nigricans*	288	94 (0.080)	133 (0.113)	20 (0.093)	41 (0.191)
Blue shark *Prionace glauca*	8895	3435 (2.931)	4044 (3.451)	630 (2.934)	796 (3.706)
Bigeye thresher *Alopias superciliosus*	375	117 (0.100)	156 (0.133)	47 (0.219)	55 (0.256)
Pelagic stingray *Pteroplatytrygon violacea*	350	76 (0.065)	241 (0.206)	8 (0.037)	25 (0.016)
Dolphinfish *Coryphaena hippurus*	6147	2060 (1.758)	3560 (3.038)	204 (0.905)	323 (1.504)
Opah *Lampris guttatus*	1200	448 (0.382)	591 (0.504)	76 (0.354)	85 (0.396)
Sickle pomfret *Taractichthys steindachneri*	2655	902 (0.770)	1165 (0.994)	281 (1.308)	307 (1.430)
Longnose lancetfish *Alepisaurus ferox*	17,063	6129 (5.230)	8337 (7.114)	1145 (5.332)	1452 (6.761)
Escolar *Lepidocybium flavobrunneum*	1816	733 (0.625)	882 (0.753)	83 (0.386)	118 (0.549)
Snake mackerel *Gempylus serpens*	2492	571 (0.487)	1690 (1.442)	60 (0.279)	171 (0.796)

Other species with catches of 10 or more individuals: shortfin mako shark *Isurus oxyrinchus* (194), pomfret *Brama orcini* and *Brama japonica* (142), oceanic whitetip shark *Carcharhinus longimanus* (129), great barracuda *Sphyraena barracuda* (127), unidentified tuna Thunnini (121), slender mola *Ranzania laevis* (97), dagger pomfret *Taractes rubescens* (97), oilfish *Ruvettus pretiosus* (73), crocodile shark *Pseudocarcharias kamoharai* (66), longfin escolar *Scombrolabrax heterolepis* (52), silky shark *Carcharhinus falciformis* (45), velvet dogfish *Scymnodon squamulosus* (36), rough pomfret *Taractes asper* (26), lustrous pomfret *Eumegistus illustris* (25), crestfish *Lophotus* species (21), unidentified shark Chondrichthyes (20), pelagic puffer *Lagocephalus lagocephalus* (19), pelagic thresher shark *Alopias pelagicus* (18), sailfish *Istiophorus platypterus* (16), unidentified billfish Xiphiidae and Istiophoridae (15), unidentified thresher shark Alopiidae (12), pompano dolphinfish *Coryphaena equiselis* (11), sandbar shark *Carcharhinus plumbeus* (11), rainbow runner *Elagatis bipinnulata* (10), and longfin mako shark *Isurus paucus* (10).

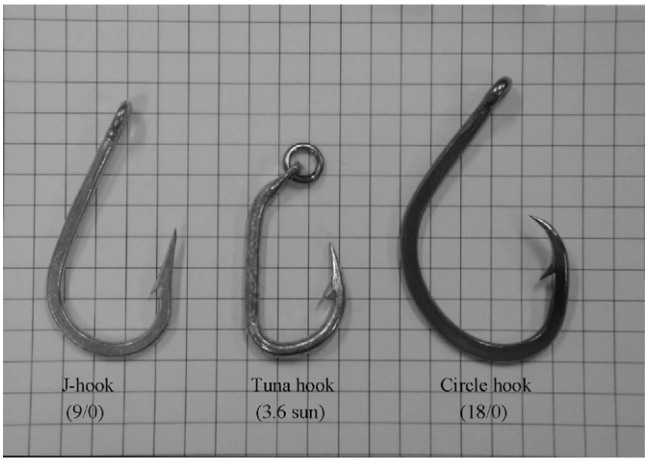


Fig. 2. Lateral view of 9/0 J-hook, 3.6 sun Japanese tuna and 18/0 circle hooks used in the field trials.

space and time, and sets within a trip are expected to be more closely related than sets among trips. For each species, the GLMM predicts mean catch (μ_i) as the number of individuals using three categorical and two continuous variables with a log link:

$$\log(\mu_i) = N_i + H_i + T_i + V_i + \beta_1 Lat_i + \beta_2 Lat_i^2 + \beta_3 Lat_i^3 + \beta_4 Lon_i + \beta_5 Lon_i^2 + \beta_6 Lon_i^3 + \log(E_i)$$

where N is the mean local abundance; H, hook-type effect; T, time (year:quarter) effect; V, vessel effect; Lat and Lon are third order (cubic) effects of latitude and longitude and offset E is the number of hooks deployed during longline operation i. Catch rates are correlated within a trip, thus trip was assigned as the grouping variable in the GLMMs. GLMMs were fitted using the glmm.ADMB module in R (R Development Core Team, 2008, version 2.7.2 for Linux) and considered the Poisson and negative binomial response distributions as data sets were characterized by a high percentage of zero observations, such that 13 of the 18 species had >60% zero observations. Model selection was conducted by AIC and log likelihood tests. GLMMs initially considered an analysis with tuna, J-hooks and circle hooks disaggregated by offset and non-offset types and final models considered offset and non-offset circle hooks aggregated into a single group.

Fish lengths were transformed to natural logarithms and tested for hook type effects using one-way ANOVA. A posteriori differences among means were detected with Tukey's test, which controlled experiment wise error rate at $P < 0.05$ (Steel and Torrie, 1980). The chi-square test (χ^2) was used to compare differences in caught condition (survival) on longline retrieval. Odds ratios calculated the relative increase in survival for the three-way hook comparisons. As an example, if an odds ratio $(p(alive_{circle})/p(dead_{circle}))/(p(alive_{tuna})/p(dead_{tuna}))$ has a value greater than 1.0, then higher survival occurs on circle hooks than on tuna hooks.

2.4. Economic impacts

The economic impact of replacing conventional tuna hooks with circle hooks was estimated from mean annual (2006–2008) fishery-wide ex-vessel revenue for the deep-set tuna sector. Sales records on numbers of fish by species, pounds sold and dollar value per individual were provided by the Hawaii Division of Aquatic Resources. If the GLMM coefficients indicated that relative catchability differed significantly between conventional tuna and circle hooks for a given species, the mean annual gross ex-vessel revenue was multiplied by the catchability coefficient to estimate fishery-wide ex-vessel revenue. Assumptions include that the retention to discard ratio would be the same under both scenarios. The estimation is slightly positively biased for pomfret catch which is not disaggregated by species. The fishery-wide revenue estimation did not incorporate fish sizes between hook types, as fish lengths are not recorded on sales records.

Table 2
Mean and standard deviation (SD) of longline attributes among the 1393 tuna sets monitored.

Variable	Mean (SD)
Begin set time (h)	0841 (0102)
End set time (h)	1304 (0111)
Begin haul time (h)	1734 (0128)
End haul time (h)	0239 (0242)
Hooks per set	1990 (348)
Hooks between floats	24.7 (1.75)
Floatline (m)	23.4 (3.3)
Branchline + Leader (m)	12.5 (1.8)
Leader material	95.3% wire, 4.7% monofilament
Dropper weight size (g)	51.5 (9.8)
Bait	89.7% sauries (*Cololabis saira*), 9.0% sardines (Clupeidae), 1.3% mixed

3. Results

3.1. Fishing gear and catches

Sixteen fishing vessels conducted 97 trips in the vicinity of the Hawaii Archipelago in an area bounded by 14–22°N and 147–168°W and deployed 1393 longline sets with 2,773,427 hooks. Longline gear and operational characteristics in the trials (Table 2) were similar to previous descriptions of the Hawaii-based tuna sector (Bigelow et al., 2006).

Hook trials caught 61,388 individuals representing 70 species, of these, 27 species had fewer than 10 individuals captured, 43 species had 10 or more individuals captured, and 18 species had greater than 200 individuals captured (Table 1). These 18 species (Table 1, Fig. 3) represented 97.6% of the total catch by number. By individual number, longnose lancetfish (*Alepisaurus ferox* – 17,063) were the most predominant catch, followed by bigeye tuna (11,125), blue shark (8,895), and dolphinfish (*Coryphaena hippurus* – 6147). Nominal CPUE (number of fish per 1000 hooks) was greater on circle hooks versus tuna and J-hooks for bigeye tuna, but lower for all other 17 species analyzed. Nominal CPUE for all 70 species captured on 1182 sets was 19.1 for circle and 25.4 for tuna hooks and nominal CPUE of retained species was 9.6 for circle and 12.0 for tuna hooks. Nominal CPUE for all species caught on 212 sets was 19.3 for circle and 23.8 for J-hooks and nominal CPUE of retained species was 9.8 for circle and 11.1 for J-hooks.

3.2. Generalized Linear Mixed Modeling

Convergence of the GLMMs was achieved for all species. A negative binomial distribution with an estimated scale parameter was statistically preferred over a Poisson distribution based on AIC and log likelihood tests. Model diagnostics indicated that a Poisson distribution provided an inadequate fit because there was evidence of overdispersion in the residuals. There were no patterns in the Pearson residuals of the negative binominal GLMMs when plotted against fitted values and each explanatory variable in the model. Initial GLMMs indicated 6 of 18 species had significant catchability differences between offset and non-offset circle hooks (Appendix A). However, delta AIC differences between models were small for all species (average = 1.3) and the small catchability differences (cf. Appendix A and Table 3) pertained to trip effects rather than hook offset and non-offset effects. Of the 5 explanatory variables in the

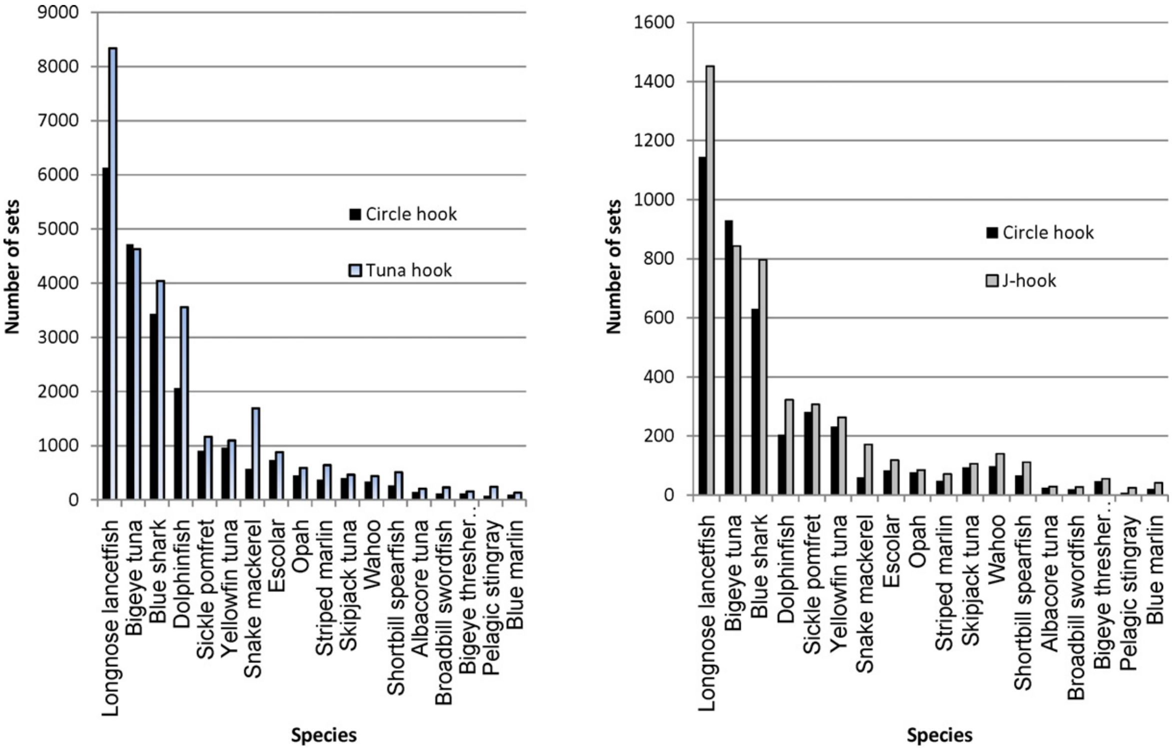


Fig. 3. Total catch (number caught) by hook type (18/0 circle hook vs. 3.6 sun Japanese tuna hook) in the Hawaii-based tuna longline fishery.

final GLMMs (Appendix B), the spatial effect was most often the initial entrant ($n = 11$ models), followed by hook type ($n = 6$) and time ($n = 1$). The least important explanatory variable was vessel effect which was included in 7 GLMMs.

3.3. Catch and catchability

3.3.1. Circle and tuna hooks

Randomization tests detected no significant differences in catch between hook types for 3 tuna species (bigeye (*T. obesus*), yellowfin (*T. albacares*) and skipjack tuna (*Katsuwonus pelamis*)); however, there were, significant differences for the remaining 15 species (Table 3). Catchability results from GLMMs were consistent with the randomization tests except for yellowfin tuna. The GLMM hook-type coefficients reflect relative catchability and were interpreted as the magnitude of the catch rate differences between hook types with all other predictors held constant. For example, the circle hook catchability coefficient for blue marlin was 0.708 which indicated that the circle hook catchability was ~29.2% less than tuna hooks. Two species (bigeye and skipjack tuna) had non-significant differences between hook types, with 95% confidence intervals (CI) for the circle hook coefficients that included 1.0, the base coefficient

Table 3

Statistical comparison among circle, tuna and J-hook types on catch (randomization test) and catch rates (Generalized Linear Mixed Modeling (GLMM)) of 18 species caught in the Hawaii-based tuna longine fishery. GLMM coefficients are estimates of relative catchability between hook types with values greater than 1.0, indicating higher catchability with circle hooks.

Species	Circle and tuna hooks				Circle and J-hooks			
	Catch (Randomization)		Catch rate (GLMM)		Catch		Catch rate (GLMM)	
	P-value	Statistically different ($P < 0.05$)	Coefficient (95% CI)	Statistically different	*P*-value	Statistically different ($P < 0.05$)	Coefficient (95% CI)	Statistically different
Bigeye tuna	0.6116	No	1.011 (0.949–1.073)	No	0.2551	No	1.089 (0.948–1.230)	No
Yellowfin tuna	0.1780	No	0.847 (0.707–0.987)	Yes	0.4860	No	0.884 (0.591–1.177)	No
Wahoo	0.0018	Yes	0.762 (0.610–0.914)	Yes	0.0182	Yes	0.705 (0.422–0.988)	Yes
Albacore	0.0088	Yes	0.664 (0.423–0.906)	Yes	0.7164	No	1.070 (0.499–1.642)	No
Skipjack tuna	0.1619	No	0.865 (0.699–1.032)	No	0.7119	No	0.904 (0.510–1.298)	No
Striped marlin	0.0001	Yes	0.574 (0.431–0.718)	Yes	0.0544	No	0.666 (0.273–1.059)	No
Spearfish	0.0001	Yes	0.517 (0.357–0.676)	Yes	0.0049	Yes	0.592 (0.259–0.924)	Yes
Swordfish	0.0001	Yes	0.519 (0.298–0.740)	Yes	0.3106	No	0.715 (0.224–1.205)	No
Blue marlin	0.0198	Yes	0.708 (0.434–0.982)	Yes	0.0362	Yes	0.485 (0–0.982)	Yes
Blue shark	0.0007	Yes	0.829 (0.768–0.889)	Yes	0.0391	Yes	0.809 (0.671–0.947)	Yes
Bigeye thresher	0.0498	Yes	0.725 (0.462–0.989)	Yes	0.6509	No	0.931 (0.461–1.401)	No
Pelagic stingray	0.0001	Yes	0.309 (0.050–0.569)	Yes	0.0114	Yes	0.368 (0–0.899)	Yes
Dolphinfish	0.0001	Yes	0.543 (0.462–0.625)	Yes	0.0020	Yes	0.683 (0.457–0.909)	Yes
Opah	0.0006	Yes	0.740 (0.603–0.877)	Yes	0.5524	No	0.896 (0.585–1.206)	No
Sickle pomfret	0.0001	Yes	0.766 (0.659–0.873)	Yes	0.5974	No	0.959 (0.732–1.187)	No
Longnose lancetfish	0.0001	Yes	0.730 (0.679–0.780)	Yes	0.1423	No	0.779 (0.656–0.902)	Yes
Escolar	0.0066	Yes	0.803 (0.685–0.920)	Yes	0.0537	No	0.770 (0.479–1.060)	No
Snake mackerel	0.0001	Yes	0.335 (0.216–0.453)	Yes	0.0001	Yes	0.364 (0.060–0.668)	Yes

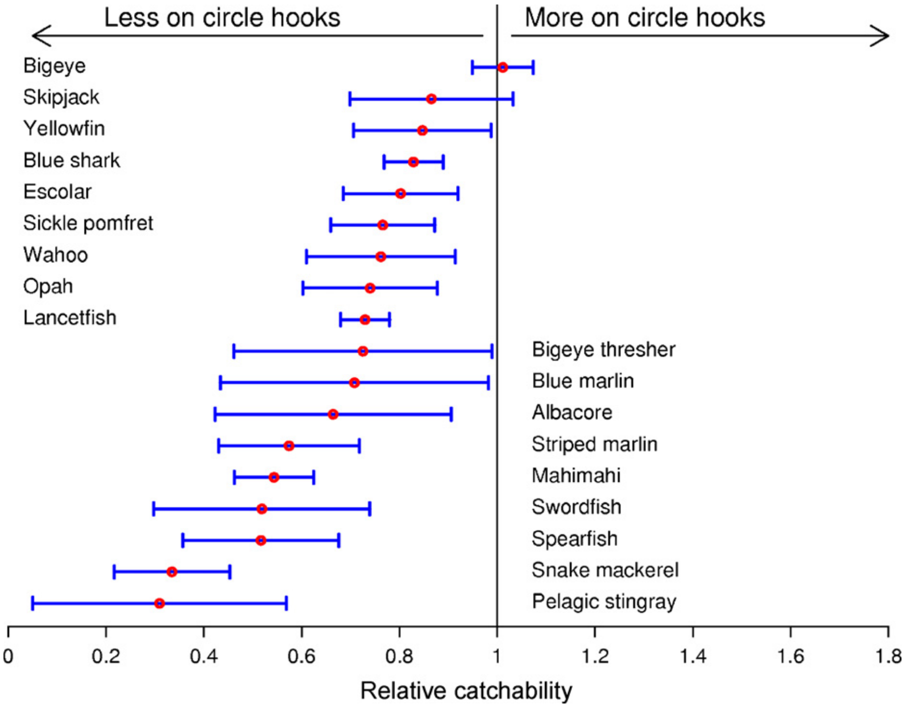


Fig. 4. Comparison of circle and tuna hook catchability for 18 species caught in the Hawaii-based tuna longline fishery. Mean catchability (circles) is the exponent of the GLMM estimated hook type parameters and horizontal lines are the 95% confidence intervals around the estimate.

for comparison with the tuna hook type (Table 3, Fig. 4). Sixteen species had significant catchability differences between hook types (95% CI that did not bracket 1.0). Yellowfin tuna was the only species that differed in significance between the randomization test and GLMM. The randomization test indicated non-significance between hook types, while the GLMM upper 95% CI was 0.987, very close to a value of 1.0 which would be non-significant (Table 3). In comparison to tuna hooks, circle-hook catchability coefficients for individual species within broad taxonomic groups were relatively high for tunas (mean = 0.803, range 0.664–1.011), moderately high for sharks (mean = 0.777, range 0.725–0.828 for blue and bigeye thresher (*Alopias superciliosus*)), moderate for billfishes (mean = 0.579, range = 0.517–0.708), low for pelagic stingray (*Pteroplatytrygon violacea*, 0.309), and highly variable for the other fishes analyzed (mean = 0.653, range = 0.335–0.803).

3.3.2. Circle and J-hooks

Randomization tests indicated significant differences in catch between hook types for 7 species (wahoo (*Acanthocybium solandri*), spearfish (*Tetrapturus angustirostris*), blue marlin, blue shark,

Table 4
Mean length (cm) ± standard deviation by hook type for 11 species and results of one-way ANOVA on length frequencies by hook type.

Species	Mean length (SD)				Significance of mean difference (Tukey HSD)		
	Tuna hook	Circle hook	J-hook	*F*-value ($P>\|F\|$)	Circle–Tuna	J–Tuna	Circle–J
Bigeye tuna	116.2 ± 23.07 (n = 4499)	117.1 ± 22.33 (n = 5523)	116.7 ± 21.64 (n = 826)	2.300 (P = 0.100)			
Yellowfin tuna	107.5 ± 23.29 (n = 1052)	107.4 ± 22.61 (n = 1152)	106.6 ± 25.42 (n = 255)	0.515 (P = 0.597)			
Albacore	100.9 ± 9.98 (n = 200)	101.1 ± 7.23 (n = 158)	100.8 ± 9.15 (n = 27)	0.111 (P = 0.894)			
Skipjack tuna	65.9 ± 7.52 (n = 428)	67.7 ± 7.32 (n = 469)	68.6 ± 5.43 (n = 101)	10.290 (P < 0.001[a])	P < 0.001[a]	P = 0.0011[b]	P = 0.383
Striped marlin	125.3 ± 24.71 (n = 612)	128.5 ± 23.69 (n = 398)	138.5 ± 22.50 (n = 71)	10.112 (P < 0.001[a])	P = 0.088	P < 0.001[a]	P = 0.004[b]
Spearfish	133.4 ± 11.17 (n = 474)	132.3 ± 12.97 (n = 306)	133.1 ± 10.52 (n = 109)	1.034 (P = 0.355)			
Swordfish	86.0 ± 30.98 (n = 206)	102.7 ± 39.01 (n = 125)	93.4 ± 30.60 (n = 24)	9.529 (P < 0.001[a])	P < 0.001[a]	P = 0.488	P = 0.508
Blue marlin	161.5 ± 33.52 (n = 128)	168.9 ± 34.16 (n = 112)	149.6 ± 33.64 (n = 41)	5.783 (P = 0.003[b])	P = 0.181	P = 0.084	P = 0.003[b]
Opah	94.8 ± 13.12 (n = 578)	96.7 ± 11.33 (n = 516)	98.0 ± 11.33 (n = 85)	5.420 (P = 0.004[b])	P = 0.013[c]	P = 0.052	P = 0.670
Sickle pomfret	58.1 ± 10.39 (n = 1146)	60.2 ± 9.26 (n = 1145)	60.1 ± 8.31 (n = 303)	15.719 (P < 0.001[a])	P < 0.001[a]	P < 0.001[a]	P = 0.977
Longnose lancetfish	124.1 ± 17.92 (n = 36)	121.3 ± 25.71 (n = 28)	No result	1.392 (P = 0.256)			

[a] $0 \leq P < 0.001$.
[b] $0.001 \leq P < 0.01$.
[c] $0.01 \leq P < 0.05$.

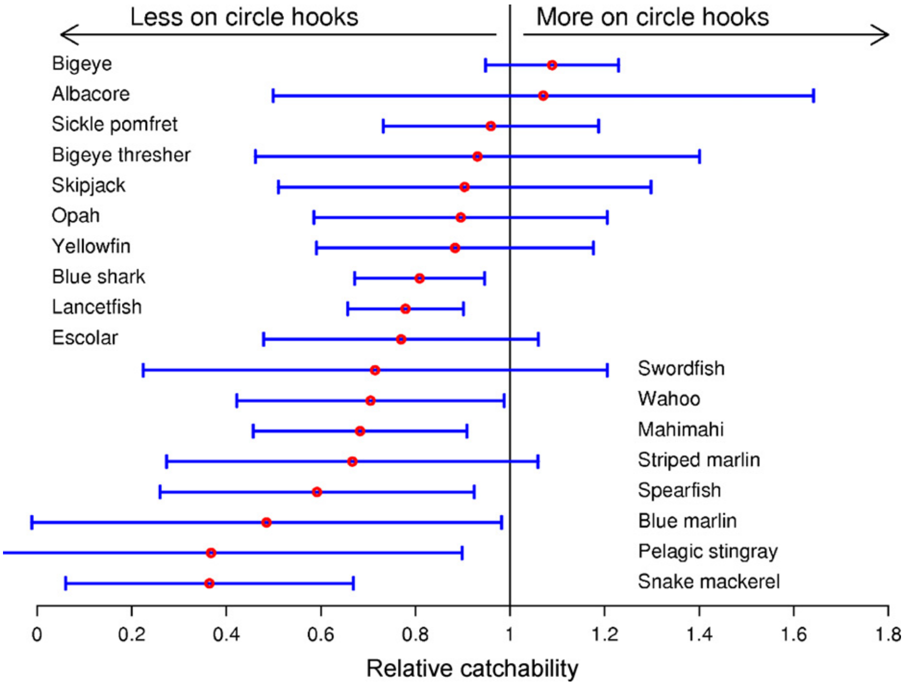


Fig. 5. Comparison of circle and J-hook catchability for 18 species caught in the Hawaii-based tuna longline fishery. Mean catchability (circles) is the exponent of the GLMM estimated hook type parameters and horizontal lines are the 95% confidence intervals around the estimate.

pelagic stingray, dolphinfish and snake mackerel (*Gempylus serpens*)). Catchability results from GLMMs were consistent with the randomization tests, as GLMMs indicated significant catchability differences for the same 7 species with the addition of longnose lancetfish (Table 3, Fig. 5). Estimated standard errors of the circle-hook coefficients averaged 2.2 times larger in circle-J-hook analyses than the tuna-circle hook analyses. The larger standard errors and resulting wider confidence intervals (Table 3, Figs. 4 and 5) result from the smaller sample size ($n = 211$ sets) of the J-circle hook trials.

3.4. Fish size

Relationships between hook types and lengths were tested for 11 species (Table 4). *F*-tests indicated significant differences ($P < 0.01$, Table 4) for six species (skipjack tuna, striped and blue marlin, swordfish, opah (*Lampris guttatus*) and sickle pomfret (*Taractichthys steindachneri*)). Lengths were significantly shorter ($P < 0.05$, Tukey, Table 4) on tuna hooks compared to both circle hooks (four species: skipjack tuna, swordfish, opah and sickle pomfret) and J-hooks (3 species: skipjack tuna, striped marlin and sickle pomfret). Blue marlin were significantly larger on circle hooks compared to J-hooks while striped marlin were shorter ($P < 0.01$, Tukey).

3.5. Caught condition at retrieval

Caught condition at retrieval varied considerably among the 18 species (Table 5). Survival was significantly higher for 6 species (odds ratio range 1.09–1.78) captured on circle hooks compared to

Table 5
Effect of hook type on caught condition (survival) of 18 most abundant species.

Species	Percent survival			Odds ratio (*P*-value)		
	Tuna hook	Circle hook	J-hook	Circle–Tuna	J–Tuna	Circle–J
Bigeye tuna	77.9 ($n = 4630$)	81.8 ($n = 5652$)	79.1 ($n = 843$)	1.27 (<0.001[a])	1.07 (0.432)	1.18 (0.066)
Yellowfin tuna	53.6 ($n = 1097$)	58.7 ($n = 1192$)	57.4 ($n = 263$)	1.23 (0.014[c])	1.16 (0.265)	1.05 (0.696)
Wahoo	16.1 ($n = 440$)	15.6 ($n = 435$)	17.9 ($n = 140$)	0.96 (0.838)	1.12 (0.633)	0.85 (0.534)
Albacore	43.0 ($n = 207$)	39.1 ($n = 169$)	27.6 ($n = 29$)	0.84 (0.439)	0.51 (0.114)	1.68 (0.238)
Skipjack tuna	4.1 ($n = 466$)	6.9 ($n = 495$)	5.7 ($n = 106$)	1.73 (0.058)	1.41 (0.472)	1.23 (0.651)
Striped marlin	38.8 ($n = 642$)	41.4 ($n = 418$)	54.9 ($n = 71$)	1.11 (0.398)	1.92 (0.008[b])	0.58 (0.033[c])
Spearfish	28.4 ($n = 510$)	30.7 ($n = 329$)	42.3 ($n = 111$)	1.11 (0.481)	1.84 (0.004[b])	0.60 (0.024[c])
Swordfish	44.6 ($n = 231$)	59.0 ($n = 139$)	66.7 ($n = 27$)	1.78 (0.007[b])	2.48 (0.030[c])	0.72 (0.456)
Blue marlin	39.8 ($n = 133$)	47.4 ($n = 114$)	34.1 ($n = 41$)	1.35 (0.234)	0.78 (0.511)	1.73 (0.143)
Blue shark	97.7 ($n = 4044$)	97.4 ($n = 4055$)	97.4 ($n = 796$)	0.88 (0.398)	0.87 (0.565)	1.01 (0.937)
Bigeye thresher	83.3 ($n = 156$)	87.2 ($n = 164$)	94.5 ($n = 55$)	1.36 (0.329)	3.46 (0.038[c])	0.39 (0.131)
Pelagic stingray	98.8 ($n = 241$)	98.8 ($n = 84$)	100.0 ($n = 25$)	No results	No results	No results
Dolphinfish	63.8 ($n = 3560$)	68.2 ($n = 2264$)	62.5 ($n = 323$)	1.21 (<0.001[a])	0.94 (0.639)	1.28 (0.042 [c])
Opah	65.8 ($n = 591$)	72.9 ($n = 524$)	62.3 ($n = 85$)	1.40 (0.011[c])	0.86 (0.530)	1.62 (0.046 [c])
Sickle pomfret	94.1 ($n = 1165$)	94.4 ($n = 1183$)	94.1 ($n = 307$)	1.06 (0.721)	1.01 (0.969)	1.05 (0.846)
Longnose lancetfish	18.7 ($n = 8337$)	20.0 ($n = 7274$)	32.0 ($n = 1452$)	1.09 (0.031[c])	2.05 (<0.001[a])	0.53 (<0.001[a])
Escolar	89.2 ($n = 882$)	91.2 ($n = 816$)	88.9 ($n = 118$)	1.25 (0.178)	0.97 (0.936)	1.27 (0.439)
Snake mackerel	63.7 ($n = 1690$)	65.3 ($n = 631$)	67.8 ($n = 171$)	1.07 (0.468)	1.20 (0.279)	0.89 (0.534)

[a] $0 \leq P < 0.001$.
[b] $0.001 \leq P < 0.01$.
[c] $0.01 \leq P < 0.05$.

Table 6
Percentage of retained catch by species (assumed to be unaffected by hook types) and gross ex-vessel economic value with tuna and circle hooks of the Hawaii-based tuna longline fishery.

Species	Percentage retained (%) from 2006 to 2008	Mean annual value (2006–2008, US$)	Estimated annual value (2006–2008, US$) had circle hooks been used	Loss (US$) in value (%)
Bigeye tuna	96.9	40,372,752	40,372,752	0 (0)
Yellowfin tuna	94.0	5,047,477	4,275,213	772,264 (15.3)
Wahoo	96.2	1,068,139	813,922	254,217 (23.8)
Albacore	98.3	1,022,123	678,690	343,433 (33.6)
Skipjack tuna	92.2	53,270	53,270	0 (0)
Striped marlin	95.1	1,143,834	656,561	487,273 (42.6)
Spearfish	93.6	343,805	177,747	166,058 (48.3)
Swordfish	53.9	1,272,189	669,266	611,923 (48.1)
Blue marlin	97.2	665,478	471,158	194,320 (29.2)
Blue shark	0.0			
Bigeye thresher	8.3	29,912	21,687	8,226 (27.5)
Pelagic stingray	1.7			
Dolphinfish	95.0	1,560,647	847,431	713,216 (45.7)
Opah	98.7	2,072,812	1,533,881	538,931 (26.0)
Sickle pomfret	97.0	1,374,535	1,052,893	321,641 (23.4)
Longnose lancetfish	0.0			
Escolar	92.0	872,510	700,626	171,885 (19.7)
Snake mackerel	1.6			
	Total	56,899,484	52,316,098	4,583,387 (8.1)

tuna hooks and for 5 species (odds ratio range 1.84–3.46) captured on J-hooks compared to tuna hooks. Five species had significant differences in survival between circle and J-hooks, although survival was not consistent among hook types, as dolphinfish and opah had higher survival on circle hooks, while striped marlin, spearfish and longnose lancetfish had higher survival on J-hooks (Table 5).

3.6. *Economic impact*

The mean annual gross ex-vessel value (2006–2008) of the Hawaii-based tuna longline sector catch totaled US$ 56.9 million (range = 49.2–65.5 million) for 14 marketable species landed (Table 6). The estimated value would have been US$ 52.3 million or 8.1% less if 18/0 circle hooks had been used throughout the fleet. Four of the 18 species (yellowfin tuna, swordfish, dolphinfish and opah) had estimated annual losses in excess of US$ 0.5 million.

4. Discussion

This study examined catchability, fish size and fish caught condition (survival) with 18/0 circle hooks, Japanese style tuna hooks and J-hooks. Hook testing was conducted on a greater scale than in all previous pelagic longline circle-hook studies. Experimental protocols combined with a large amount of monitored effort (∼2.7 million hooks) enabled robust species-specific statistical inferences that were not confounded by testing many covariates, such as combining hook types and sizes within a single study. These results should be broadly applicable elsewhere, because the Hawaii-based tuna longline fishery exhibits similar operational characteristics (deep daytime sets) and target species (bigeye tuna) as conducted worldwide by many distant-water fishing nations.

4.1. *Catchability comparisons*

There were no significant catchability differences among hook types for bigeye tuna, the target species; however, GLMMs indicated that large circle hooks reduced catchability for 16 and 8 species compared to tuna and J-hooks, respectively. Results on capture efficiency were highly consistent for both statistical methods. The only inconsistencies in statistical interpretation occurred for yellowfin tuna (circle vs. tuna hooks) and longnose lancetfish (circle vs. J-hooks).

Comparisons among hook efficiency studies are problematic, based on trials with different hook types and sizes. Additionally, failure to demonstrate significant differences between hooks in a study may relate to small sample sizes or a poor experimental design where too many explanatory variables lead to non-robust statistics. There are few comparison studies on tuna and circle hook catchability. There was no significant difference in bigeye tuna catch rates ($n = 507$ captured) between tuna and 3 circle hook types (15/0–18/0) in a Korean longline experiment that monitored 62,464 hooks (Kim et al., 2008). A Japanese longline experiment monitored 48,600 hooks composed of 3.8-sun tuna hooks, 4.3 (∼16/0) and 5.2-sun (∼18/0) circle hooks and indicated no statistical differences for blue shark ($n = 3353$ caught, Yokota et al., 2006) that is inconsistent with our results, which indicated a ∼17.1% reduction in blue shark catchability with circle hooks. From the same survey, nominal CPUE was similar for bigeye and reduced for swordfish and striped marlin (Minami et al., 2006); however, the small sample sizes were insufficient for statistical analysis. Ward et al. (2009) observed 95,150 hooks in Australia on 10 trips targeting several species (bigeye, yellowfin and swordfish). Four sizes of circle hooks (13/0–18/0) were deployed with 12 swordfish targeted sets (18,076 hooks) with 18/0 circle hooks. Circle hooks had statistically higher catchability for 4 (albacore (*T. alalunga*), yellowfin, black oilfish (reported as *Lepidocybium flavobrunneum*) and striped marlin) of the 28 species considered. Bigeye tuna catchability was not significantly different between tuna and circle hooks. Large (18/0) circle hook coefficients for all species are probably confounded in the Ward et al. (2009) study as the estimated lower catchability (e.g., 96% reduction between 13/0 and 18/0 circle hooks for bigeye tuna) results from night swordfish sets where bigeye are not the target and where their behavior and catchability may be different from that in day tuna fishing.

Catchability comparisons among 18/0 circle and J-hooks are available for several studies. Longline field trials in the western equatorial Atlantic Ocean demonstrated a significantly higher catchability for bigeye tuna on 18/0 circle hooks compared to J-hooks, which is contrary to our results (Pacheco et al., 2011). Catchability on 18/0 circle hooks in our study was reduced for incidental and bycatch species compared to J-hooks which is in contrast to most studies, especially for billfish. No significant catchability differences were demonstrated between circle and J-hooks in 6 longline comparisons (see review Serafy et al., 2009) based on 3 species (sailfish, white marlin and blue marlin) in 3 studies (Kerstetter et al., 2006; Kim et al., 2006; Diaz, 2008). Mean catch rate was higher (0.26 billfish per 1000 hooks) on J-hooks and the lack of statistical differences may be related to the hook types – 9/0 J-hook and 16/0 circle hook (Kerstetter and Graves, 2006), 4/0 J-hook, 15/0 and 18/0 circle hook (Kim et al., 2006) or insufficient sample sizes. No significant catchability differences were demonstrated between 18/0 circle and J-hooks for 4 of 5 billfish species in the western Atlantic (Pacheco et al., 2011). Kerstetter and Graves (2006) monitored a total of 71,200 9/0 J-hooks and 16/0 circle hooks in the US coastal Atlantic longline fishery targeting swordfish in the spring and yellowfin tuna in the fall. No species or species group in the spring had statistically significant catch rate differences between hook types. Two species had significant differences in the fall fishery: yellowfin tuna catch rates were higher (10.7 per 1000 hooks) on circle hooks than J-hooks (6.4 per 1000 hooks), while pelagic stingray catch rates were higher (12.5 per 1000 hooks) on J-hooks than circle hooks (4.4 per 1000 hooks).

A portion of the trials used 10° offset hooks and GLMMs indicated significant differences for 6 species; however the differences were related to individual trip rather than offset effects. Randomization tests could not be applied to estimate offset and non-offset effects based on a lack of paired comparisons. Results of ∼10° hook offset on catch rates is consistent with Swimmer et al. (2010) who demonstrated a lack of significant difference in catch rates between non-offset and 10° offset 14/0 circle hooks for dolphinfish, sea turtles, sharks and pelagic stingrays.

4.2. *Fish size*

There were no significant differences in mean length of bigeye tuna among hook comparisons. Several species showed significant differences in mean length, especially billfish that were longer on circle hooks compared to tuna hooks. Size differences for pelagic species have not been routinely demonstrated among hook types. Striped marlin was the only species with mean size differences in Ward et al. (2009), and Kerstetter and Graves (2006) found season-specific differences for yellowfin tuna and dolphinfish.

4.3. *Caught condition at retrieval*

Circle hooks have been promoted to increase survival in hook and line fisheries (e.g., recreational, longline) by having a higher proportion of jaw hooking compared to deep or gut hooking for depressed sea turtles (Watson et al., 2005; Sales et al., 2010) and marlin species (Kerstetter and Graves, 2006; Diaz, 2008). Circle hooks facilitate jaw hooking by sliding over soft tissue and rotating as the eye of the hook exits the mouth (Cooke and Suski, 2004). While hooking location was not addressed in this study, catch on tuna hooks had the lowest survival percentage among hook types (13 of the 18 species) and 6 species showed significantly greater survival percentage on circle hooks compared to tuna hooks. Circle hooks have been advocated in billfish catch-and-release programs to reduce fishing mortality. Our results are equivocal with regard to increased survival with circle hooks, as striped marlin and spearfish had statistically greater survival on J-hooks, while swordfish had statistically lower survival on tuna hooks. Blue marlin survival was highest on circle hooks, but not significantly different.

4.4. *Circle hook shape influencing catchability*

Large (18/0) circle hooks had greater effects on catchability than on fish size selectivity and fish survival compared to tuna and J-hooks. Circle hooks have been shown to reduce sea turtle interactions based on overall shape and size effects (Gilman et al., 2005). Reduced catchability occurred for most species in this study, and we contend that these reductions are a function of 18/0 circle hook shape. Although a myriad of types, sizes, and shapes of hooks are used within longline fisheries around the world (Gilman et al., 2006), the minimum width appears to be the primary metric influencing catchability rather than gape or straight total length. The 18/0 circle hook had a minimum width (4.9 cm) that was 57% and 25% wider than the Japanese tuna (3.1 cm) and J-hook (3.9 cm), respectively. The larger minimum width relates to a smaller probability of ingestion and probably accounts for the reduced catchability of non-tuna species. Fourteen of the 18 species had larger catchability reductions between circle and tuna hooks than with circle and J-hooks. This would be expected from the minimum size metrics, as the 9/0 J-hooks are of an intermediate size. Catchability was substantially reduced for smaller-mouthed species such as dolphinfish (45.7% circle to tuna hooks; 31.7% circle to J-hooks), snake mackerel (66.5% circle to tuna hooks; 63.6% circle to J-hooks) and pelagic stingray (69.1% circle to tuna hooks; 63.2% circle to J-hooks). A significant reduction has been shown in pelagic stingray catches with 16/0 circle hooks compared to J-hooks (∼80%, Piovano et al., 2010) and 18/0 circle hooks compared to J-hooks (∼89%, Pacheco et al., 2011).

4.5. *Billfish, shark conservation and economic considerations*

In contrast to tuna hooks, use of large 18/0 circle hooks in a central Pacific Ocean longline fishery have the potential to reduce mortality rates for various species, with catch reductions of 29.2–48.3% for billfish species and 17.1–27.5% for sharks. Bycatch should also be reduced as a result of lower catchability, especially for blue shark, pelagic stingray, longnose lancetfish and snake mackerel. The economic loss was estimated at 8.1% based primarily on reduced catch of yellowfin tuna, billfishes, dolphinfish and opah. The economic loss may be reduced as a result of unanalyzed effects, such as higher quality and prices of bigeye tuna from increased survival on circle hooks and an increased price of incidental species based on lower volumes. The estimated catch reduction for swordfish was 48.1%; however, the impact on total landings and revenue is minor in the tuna longline sector where catch is composed of relatively small and young swordfish (<age 1 = 102 cm EFL – DeMartini et al., 2007).

4.6. *Considerations in implementing circle hooks*

Gilman et al. (2003) identified considerations in implementing measures to reduce bycatch (discards). Such measures would have to meet the following conditions: (1) must significantly reduce bycatch, (2) not cause increase of bycatch of protected or endangered species, (3) require a minimal amount of alteration of traditional fishing practices and provide operational benefits, (4) be practical for crew to employ and not increase safety hazards, (5) increase fishing efficiency and (6) be feasibly enforced when limited resources for enforcement are available. Large circle hooks complied with 4 of these criteria (1, 3, 4 and 6). Bycatch was reduced and the replacement costs (∼US$ 1 per hook or ∼US$ 3000 for each vessel) and fabrication are relatively minimal. There are no anticipated safety hazards and the crew may save time, as fewer animals would require discarding. While the incidence of hooking depth (jaw vs. deep) was not quantified, the use of large circle hooks may have a labor benefit, as hooks are more easily removed from the mouth, whereas crew typically cut the terminal end of a branchline on deeply hooked animals which require replacement. Fishing with large circle hooks is easily enforced either at dockside or at sea. There was no evidence on the mitigative properties of large circle hooks for reducing sea turtle or marine mammal interactions (criterion 2) as a result of the rare occurrence, as 2 sea turtles and 3 mammal takes occurred with a monitored fishing effort of ∼2.7

million hooks. There was no increase in fishing efficiency for bigeye tuna (criterion 5), although large circle hooks may reduce bait competition by the demonstrated catchability reduction of other species.

Domestic management agencies and tuna-Regional Fisheries Management Organizations have implemented bait and/or hook requirements to reduce the incidental capture and mortality of non-target species in longline fisheries, but primarily in shallow-set swordfish fisheries. Based on concerns regarding sea turtles, the United States has promulgated regulations requiring circle hooks and whole fish baits in pelagic longline fisheries in the Atlantic, western Pacific and Gulf of Mexico. The Western and Central Pacific Fisheries Commission adopted a conservation and management measure (CMM2008-03) that required shallow-set swordfish fisheries to use at least 1 of 3 methods (large circle hooks with an offset not to exceed 10°, whole finfish for bait, develop a mitigation plan) to reduce the capture, injury and mortality of sea turtles. The International Commission for the Conservation of Atlantic Tunas (ICCAT) has no binding circle hook regulations, rather the ICCAT (Recommendation 2006–09) has encouraged the use of circle hooks to minimize post-release mortality of blue and white marlins.

4.7. Conclusions

The emphasis on hook trials in shallow-set longline fisheries has been prompted by the necessity to reduce sea turtle interaction modifying gear depth deeper than 100 m to reduce billfish rates which appear to be at least an order of magnitude greater than in deep-set tuna fisheries (Gilman et al., 2007). Large circle hooks maintained target species catches in this study with demonstrated conservation benefits for billfish, sharks and several other species. Large circle hooks show promise in reducing bycatch, although there is economic concern in the Hawaii-based tuna longline sector of lost revenue due to lower catch rates of incidental species such as yellowfin tuna and billfishes that are often retained and marketed. Additional methods to reduce non-target catches include catch (Beverly et al., 2009) and reducing the duration of the longline soak time to increase survival (Poisson et al., 2010). Deploying large circle hook types should be considered within our evolving conservation tool box to mitigate the longline capture of non-target species.

Acknowledgements

We thank captains and crews of the Hawaii-based commercial longline vessels and the Pacific Islands Regional Observer Program. Russell Ito and Diosdado Gonzales provided economic revenue data. William Walsh, Yonat Swimmer, Steve Beverly, Tom Graham and David Kerstetter reviewed earlier versions of the article.

Appendix A. Statistical comparison of catch rates (Generalized Linear Mixed Modeling, GLMM) among tuna, offset and non-offset circle hooks for 18 species caught in the Hawaii-based tuna longine fishery. GLMM coefficients are estimates of catchability between tuna hooks with values greater than 1.0 indicating higher catchability with circle hooks.

Species	AIC	Circle hook with offset coefficient (95% CI)	Circle hook without offset coefficient (95% CI)	Significant
Bigeye tuna	13,073.2	0.962 (0.877–1.050)	1.061 (0.977–1.145)	Yes
Yellowfin tuna	6506.8	0.721 (0.529–0.911)	0.985 (0.800–1.170)	Yes
Wahoo	4143.7	0.766 (0.568–0.968)	0.755 (0.519–0.992)	No
Albacore	2049.6	0.767 (0.468–1.072)	0.539 (0.178–0.900)	No
Skipjack tuna	3811.1	0.739 (0.512–0.970)	1.041 (0.796–1.286)	Yes
Striped marlin	4364.0	0.702 (0.491–0.917)	0.486 (0.291–0.682)	Yes
Spearfish	3941.7	0.635 (0.428–0.847)	0.389 (0.137–0.641)	No
Swordfish	2260.5	0.567 (0.285–0.855)	0.469 (0.164–0.773)	No
Blue marlin	1830.6	0.577 (0.188–0.972)	0.831 (0.492–1.170)	No
Blue shark	11,077.2	0.849 (0.766–0.933)	0.808 (0.723–0.893)	No
Bigeye thresher	1904.8	0.571 (0.167–0.982)	0.888 (0.527–1.249)	No
Pelagic stingray	1953.8	0.305 (0–0.703)	0.315 (0–0.642)	No
Dolphinfish	9791.8	0.574 (0.462–0.687)	0.511 (0.393–0.630)	No
Opah	4491.0	0.751 (0.568–0.937)	0.730 (0.548–0.911)	No
Sickle pomfret	6956.4	0.805 (0.657–0.956)	0.726 (0.572–0.880)	No
Longnose lancetfish	12,829.2	0.773 (0.701–0.845)	0.690 (0.618–0.762)	Yes
Escolar	5804.6	0.929 (0.774–1.087)	0.688 (0.528–0.849)	Yes
Snake mackerel	6021.0	0.360 (0.205–0.518)	0.302 (0.124–0.480)	No

Appendix B. Stepwise model selection for catch rates based on Generalized Linear Mixed Modeling (GLMM).

Variable	AIC	df	*P*-value	Variable	AIC	df	*P*-value	Variable	AIC	df	*P*-value
Bigeye tuna				Yellowfin tuna				Wahoo			
Hooks	13,130.6	3		Hooks	6613.8	3		Hooks	4247.8	3	
Lat_Lon	13,078.0	9	4.88E−12	Lat_Lon	6510.0	9	0	Lat_Lon	4189.5	9	3.55E−13
Quarter	13,071.4	12	5.80E−03	Quarter	6514.8	12	0.7	Vessel	4157.7	24	1.20E−07
Hook type	13,074.0	14	5.00E−01	Hook type	6512.4	14	0.1	Hook type	4143.4	26	1.10E−04
Albacore				Skipjack tuna				Striped marlin			
Hooks	2113.1	3		Hooks	3884.4	3		Hooks	4488.9	3	
Lat_Lon	2069.5	9	3.41E−10	Lat_Lon	3822.8	9	7.53E−14	Hook type	4430.5	5	2.71E−14
Quarter	2057.3	12	4.08E−04	Hook type	3823.6	11	0.2	Lat_Lon	4386.2	11	2.56E−10
Hook type	2050.1	14	3.59E−03	Quarter	3814.3	14	1.58E−E−03	Quarter	4382.5	14	2.00E−02
				Vessel	3813.2	29	0.01	Vessel	4368.2	29	1.02E−04
Spearfish				Swordfish				Blue marlin			
Hooks	4104.9	3		Hooks	2330.2	3		Hooks	1847.0	3	
Lat_Lon	4028.9	9	1.11E−16	Lat_Lon	2290.4	9	2.12E−09	Hook type	1839.1	5	2.66E−03
Hook type	3956.3	11	0	Hook type	2259.4	11	2.49E−08	Lat_Lon	1830.9	11	2.51E−03
Vessel	3949.1	26	1.22E−03								
Quarter	3948.4	29	8.00E−02								

Appendix B (*Continued*)

Variable	AIC	df	*P*-value	Variable	AIC	df	*P*-value	Variable	AIC	df	*P*-value
Blue shark				Bigeye thresher				Pelagic stingray			
Hooks	11,267.6	3		Hooks	1997.3	3		Hooks	2100.6	3	
Lat_Lon	11,134.8	9	0	Lat_Lon	1909.3	9	0	Hook type	2014.4	5	
Hook type	11,094.8	11	2.85E−10	Hook type	1907.5	11	6.00E−02	Lat_Lon	1961.7	11	0
Quarter	11,075.8	14	1.46E−05					Quarter	1951.5	14	5.02E−12
Dolphinfish				Opah				Sickle pomfret			
Hooks	10,076.8	3		Hooks	4572.1	3		Hooks	7000.6	3	
Hook type	9862.6	5	0	Lat_Lon	4515.7	9	8.62E−13	Hook type	6981.8	5	1.12E−05
Lat_Lon	9831.4	11	1.08E−07	Hook type	4501.2	11	9.42E−05	Lat_Lon	6964.6	11	5.88E−05
Quarter	9801.6	14	8.67E−08	Quarter	4489.0	14	4.12E−04	Quarter	6959.2	14	9.22E−03
Vessel	9791.6	29	4.60E−04					Vessel	6955.4	29	3.63E−03
Longnose lancetfish				Escolar				Snake Mackerel			
Hooks	13,427.6	3		Hooks	5854.1	3		Hooks	6394.2	3	
Lat_Lon	13,000.4	9	0	Quarter	5826.6	6	2.58E−07	Hook type	6051.4	5	0
Hook type	12,842.2	11	0	Hook type	5814.5	8	3.26E−04	Lat_Lon	6021.2	11	1.60E−07
Vessel	12,832.2	26	4.54E−04	Lat_Lon	5810.2	14	1.00E−02				
Quarter	12,832.2	29	1.00E−01								

References

Beverly, S., Curran, D., Musyl, M., Molony, B., 2009. Effects of eliminating shallow hooks from tuna longline sets on target and non-target species in the Hawaii-based pelagic tuna fishery. Fish. Res. 96, 281–288.

Bigelow, K., Musyl, M., Poisson, F., Kleiber, P., 2006. Pelagic longline gear depth and shoaling. Fish. Res. 77, 173–183.

Brodziak, J., Piner, K., 2010. Model averaging and probable status of North Pacific striped marlin, *Tetrapturus audax*. Can. J. Fish. Aquat. Sci. 67, 793–805.

Brothers, N., Cooper, J., Lokkeborg, S., 1999. The incidental catch of seabirds by long-line fisheries: worldwide review and technical guidelines for mitigation. In: FAO Fish. Circ. 937. Food and Agriculture Organization of the United Nations, Rome, 100 p.

Camiñas, J.J., Báez, X.V., Real, R., 2006. Differential loggerhead by-catch and direct mortality due to surface longlines according to boat strata and gear type. Sci. Mar. 70, 661–665.

Campana, S., Joyce, W., Manning, M., 2009. Bycatch and discard mortality in commercially caught blue sharks *Prionace glauca* assessed using archival satellite pop-up tags. Mar. Ecol. Prog. Ser. 387, 241–253.

Chaloupka, M., Parker, D., Balazs, G., 2004. Modeling post-release mortality of pelagic loggerhead sea turtles exposed to the Hawaii-based longline fishery. Mar. Ecol. Progr. Ser. 280, 285–293.

Cooke, S., Suski, C., 2004. Are circle hooks an effective tool for conserving marine and freshwater recreational catch-and release fisheries? Aquat. Conserv.: Mar. Freshw. Ecosyst. 14, 299–326.

DeMartini, E., Uchiyama, J., Humphreys, R., Sampaga, J., Williams, H., 2007. Age and growth of swordfish (*Xiphias gladius*) caught by the Hawaii-based pelagic longline fishery. Fish. Bull. 105, 356–367.

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. Manage. 28, 500–506.

FAO Fisheries Department, 2009. Guidelines to Reduce Sea Turtle Mortality in Fishing Operations. FAO, Rome, 128 p.

Gilman, E., Boggs, C., Brothers, N., 2003. Performance assessment of an underwater setting chute to mitigate seabird bycatch in the Hawaii pelagic longline tuna fishery. Ocean Coast. Manage. 46, 985–1010.

Gilman, E., Brothers, N., Kobayashi, D., 2005. Principles and approaches to abate seabird by-catch in longline fisheries. Fish Fish. 6, 35–49.

Gilman, E., Zollett, E., Beverly, S., Nakano, H., Davis, K., Shiode, D., Dalzell, P., Kinan, I., 2006. Reducing sea turtle bycatch in pelagic longline fisheries. Fish Fish. 7, 1–22.

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.

IATTC, 2008. Workshop on turtle bycatch mitigation for longline fisheries: experimental design. Special Report 17, 50 pp.

ICCAT, 2006. Report of the 2006 ICCAT Billfish stock assessment. SCRS/2006/012 Col. Vol. Sci. Pap. ICCAT 60 (5), 1431–1546.

ICCAT, 2009. ICCAT: Report of the 2009 sailfish assessment. SCRS/2009/012, 117 p.

Kerstetter, D., Graves, J., 2006. Effects of circle versus J-style hooks on target and non-target species in a pelagic longline fishery. Fish. Res. 80, 239–250.

Kerstetter, D., Pacheco, J., Hazin, F., Travassos, P., Graves, J., 2006. Preliminary results of circle and J-style hook comparisons in the Brazilian pelagic longline fishery. Col. Vol. Sci. Pap. ICCAT 60 (6), 2140–2147.

Kim, S., Moon, D., Boggs, C., Koh, J., An, D., 2006. Comparison of circle hook and J hook catch rate for target and bycatch species taken in the Korean tuna longline fishery. J. Kor. Soc. Fish. Technol. 42, 210–216.

Kim, S., Moon, D., An, D., Hwang, S., Kim, Y., Bigelow, K., Curran, D., 2008. Effects of hook and bait types on bigeye tuna catch rates in the tuna longline fishery. Kor. J. Ichthy. 20, 105–111.

Lewison, R., Freeman, S., Crowder, L., 2004. Quantifying the effects of fisheries on threatened species: the impact of pelagic longlines on loggerhead and leatherback sea turtles. Ecol. Lett. 7, 221–231.

Manly, B., 2007. Randomization Bootstrap and Monte Carlo Methods in Biology, 3rd ed. Chapman & Hall/CRC, New York, 455 pp.

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

Minami, H., Yokota, K., Kiyota, M., 2006. Effect of circle hooks and feasibility of de-hooking devices to reduce incidential mortality of sea turtles in the Japanese longline fishery. Working paper EB WP-9 presented at the Second Regular Session of the Scientific Committee, Western and Central Pacific Fisheries Commission, http://www.wcpfc.int/doc/eb-wp-9/japanese-research-activities-reduce-incidental-mortality-sea-turtles-tuna-longline-fishe.

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.

Piovano, S., Simona, C., Giacoma, C., 2010. Reducing longline bycatch: the larger the hook, the fewer the stingrays. Biol. Cons. 143, 261–264.

Poisson, F., Gaertner, J.-C., Taquet, M., Durbec, J.-C., Bigelow, K., 2010. Effects of lunar cycle and fishing operations on longline-caught pelagic fish: fishing performance, capture time, and survival of fish. Fish. Bull. 108, 268–281.

R Development Core Team, 2008. 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.

Read, A., 2007. Do circle hooks reduce the mortality of sea turtles in pelagic longlines? A review of recent experiments. Biol. Conserv. 135, 155–169.

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. Aquat. Conserv.: Mar. Freshw. Ecosyst. 20, 428–436.

Sasso, C., Epperly, S., 2007. Survival of pelagic juvenile loggerhead turtles in the open ocean. J. Wildl. Manage. 71, 1830–1835.

Serafy, J., Kerstetter, D., Rice, P., 2009. Can circle hook use benefit billfishes? Fish Fish. 10, 132–142.

Steel, R., Torrie, J., 1980. Analysis of covariance. In: Principles and Procedures of Statistics: A Biometrical Approach. McGraw-Hill, New York, pp. 401–437.

Swimmer, Y., Arauz, R., Wang, J., Suter, J., Musyl, M., Bolanos, A., Lopez, A., 2010. Comparing the effects of offset and non-offset circle hooks on catch rates of fish and sea turtles in a shallow longline fishery. Aquat. Conserv.: Mar. Freshw. Ecosyst. 20, 445–451.

Walsh, W., Bigelow, K., Sender, K., 2009. Decreases in shark catches and mortality in the Hawaii-based longline fishery as documented by fishery observers. Mar. Coast. Fish.: Dyn. Manage. Ecosyst. Sci. 1, 270–282.

Ward, P., Epe, S., Kreutz, D., Lawrence, E., Robins, C., Sands, A., 2009. The effects of circle hooks on bycatch and target catches in Australia's pelagic longline fishery. Fish. Res. 3, 253–262.

Watson, J., Epperly, S., Foster, D., Shah, A., 2005. Fishing methods to reduce sea turtle mortality associated with pelagic longlines. Can. J. Fish. Aquat. Sci. 62, 965–981.

Yokota, K., Minami, H., Kiyota, M., 2006. Measurement-points examination of circle hooks for pelagic longline fishery to evaluate effects of hook design. Bull. Fish. 17, 83–102.