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RESEARCH PAPER

Effects of pelagic longline hook size on species- and size-selectivity and survival

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Abstract Pelagic fisheries can have profound effects on ecosystem structure and functioning, affecting ecosystem services, including fisheries production, and threaten vulnerable bycatch species. Controlling hook size could manage the species- and size-selectivity and survival of target and incidental catch. To test this hypothesis, we conducted experimental pelagic longline fishing in the western tropical Pacific testing a control hook and two hooks with wider minimum widths. Data such as catch, length and condition were fit to response-specific Bayesian geo-additive generalized additive and linear mixed regression models. Model fits were assessed using posterior predictive check tests. Catch rates of both retained and discarded species were significantly higher on medium hooks. Target tuna species were significantly larger and had significantly higher at-vessel survival rates on wider hooks. Significantly larger billfishes, also market species, were caught on narrowest hooks. These effects of hook width on length and survival, however, are a much smaller determinant of economic value of the catch than effects on catch rates. If input controls are limiting, then, relative to medium hooks, continued use of narrowest hooks would maintain current economic viability without causing a significant increase in discard catch levels, including of vulnerable sharks. If market species output controls are limiting, because the ratio of retained to discarded catch on medium hooks was greater than on narrowest hooks, medium hooks would generate lower discard levels. Further research assessing single-factor effects of longline hook width is needed to support robust meta-analyses that account for fishery-specific effects.

Keywords Bycatch · Hook width · Longline · Selectivity · Tuna

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Introduction

Fisheries directly impact target species, and can affect evolutionary processes, associated and dependent species, habitats, trophic food web structure and processes and functionally-linked systems (Cox et al. 2002; Pikitch et al. 2004; Ward and Myers 2005).

Sustaining target production levels of principal market species by marine capture fisheries requires the persistence of a selected state of an ecosystem. Managing fishery effects across manifestations of biodiversity, from effects on genotypes to communities within a system, is required to maintain a desired ecosystem state, as well as to reduce the risk of population extirpations and species extinctions per se (Sainsbury et al. 2000; Link 2002).

Fisheries that target species with r-selected life history characteristics such as relatively high fecundity, including tuna and tuna-like species (Scombroidei) and billfishes (Xiphioidei), can have large impacts on incidentally caught species with K-selected life-history strategies, including seabirds, sea turtles, marine mammals, elasmobranchs and some bony fishes. Their populations can decline over short periods and are slow to recover from large declines (Hall et al. 2000; Stevens et al. 2000). Changes in fishing methods and gear can increase selectivity to mitigate the bycatch of at-risk taxa, one element of managing fisheries via an ecosystem approach (Hall 1996; Gilman 2011).

Of a large suite of variables demonstrated to significantly affect catch and survival rates of pelagic longline fisheries, four terminal tackle gear elements have been the focus of research and management measures to mitigate unwanted bycatch of sea turtles, seabirds, marine mammals, elasmobranchs and some teleosts. These are hook shape, hook narrowest (minimum) width, bait type and leader material (Gilman and Hall 2015; Clarke et al. 2014; Gilman et al. 2016a; Gilman and Huang 2017). Despite this focus, there is limited understanding of single-factor effects of pelagic longline hook minimum width. Few previous studies that assessed the effect of hook size employed designs that did not have simultaneous variability in additional terminal tackle factors that also significantly explain catch rates, at-vessel mortality rates, anatomical hooking position and length (Gilman et al. 2016a; Gilman and Huang 2017). Due to effects on species- and size-selectivity and at-vessel survival rates, controlling hook minimum width can enable meeting objectives for managing fishery effects on target and bycatch species.

To address this priority research gap, we tested the single-factor effect of hook minimum width on catch and at-vessel survival rates, mean length and length frequency distribution. The study also assessed the effect of hook minimum width on anatomical hooking position, an indicator of the severity of injury, and on bite-off rates. Findings have implications for the management of regional and global pelagic longline fisheries. However, as with many gear technology bycatch mitigation methods, optimal hook size could be fishery specific (Gilman et al. 2016a). Due to spatial differences in length frequency distributions, the effects of hook minimum width on species-specific catch rates and mean lengths, especially for species that do not have relatively small mouth dimensions, may vary between fisheries. As a result, prescribing a minimum hook width for an individual fishery needs to account for the fishery-specific species and size selectivity of different sized hooks (Erzini et al. 1998; Curran and Beverly 2012; Gilman et al. 2016a).

Methods

Study design and data collection

Research fishing trips were conducted between 8 February and 19 November 2016 within the Republic of Palau Exclusive Economic Zone (EEZ) and high seas adjacent to the EEZs of Palau, Federated States of Micronesia and Indonesia in the western tropical Pacific Ocean, between 3–8°N and 132–139°E. The research was conducted on two pelagic longline fishing vessels that have fished in Palau, Federated States of Micronesia and Republic of the Marshall Islands to target bigeye and yellowfin tunas (*Thunnus obesus* and *T. albacares*, respectively). F/V Shen Lian Cheng 901 conducted the first 10 trips of the experiment. Engine problems required use of a second vessel, F/V Hua Nan Yu 769, for the final two trips.

Three different sized hooks manufactured by OPI used in the experiment were 14/0 (manufacturer code OPI00491), 16/0 (OPI00493) and 18/0 (OPI00494) stainless steel, forged (the wire at the bend of the hook is slightly compressed and flattened, i.e., flat-shanked), ringed, 10°–15° reversed offset circle hooks. The offset is ‘reversed’, meaning that the point and front of the hook bends to the left when looking towards the shank from the front of the hook, with the eye of the hook at the top and bend of the hook at the bottom. Table 1 summarizes measurements of minimum widths and other dimensions of the three hooks used in the experiments. Hook ‘minimum width’

Table 1 Dimensions of three reversed offset, forged circle hooks manufactured by OPI used in the study, mean (± 95% CI) of a random sample of 15 hooks of each size. Wire diameter was measured at a round section of the shank below the ring (not the forged, flattened section)

Hook model	Minimum width (cm)	Wire diameter (mm)	Gape (mm)
14/0	3.6 (± 0.08)	3.6 (± 0.09)	22.0 (± 0.47)
16/0	4.3 (± 0.06)	4.8 (± 0.10)	25.3 (± 0.40)
18/0	5.2 (± 0.07)	5.0 (± 0.03)	25.7 (± 0.80)

refers to the narrowest dimension of a hook (Supplemental Material Fig. S1). The vessels that participated in the study conventionally use the OPI 14/0 circle hook. Relative to the conventional (control) hook, the 16/0 and 18/0 hooks had 19% and 44% larger minimum widths, respectively. Hereafter we refer to the 14/0 hook as small or narrowest, 16/0 as medium and 18/0 as large or widest.

Three colors of cable ties were attached to the snaps of branchlines to facilitate the observer's identification of the hook type. The crew alternated the order of the three hooks during the initial set of each trip (e.g., small, medium, large, small, etc.). For the first set of each trip, the vessel used a number hooks between two floats (a basket) not divisible by three in order to vary the placement (hook number) and number of each hook type within a basket. The order of coiling branchlines into tubs and deployment of the three hooks was randomly mixed during subsequent sets of each trip. This study design was selected in order to avoid systematic differences in the distribution of the three hook types within and between baskets of a set, thus avoiding uncontrolled simultaneously variable factors (e.g., vertical and geo-spatial distribution, soak duration, time-of-day of soak and movement through the water column during setting and hauling, reviewed in Gilman and Hall 2015) from systematically affecting catch rates of the three hook types. At the end of each set, the observer recorded the order of hook types of a sample of ca. 350 hooks in each tote. We used the DescTools package for R (Signorell et al. 2016) to perform set-specific Wald-Wolfowitz test for runs (Wackerly et al. 1986) for each sampled hook order series by set in order to test the hypothesis of randomness, that there was no significant difference between the number (size classes) of runs of each of the three hook types after the first set. During each trip, in order to maintain the same number of branchlines with each hook type, an attempt was made to replace all lost and damaged branchlines.

Other gear design and fishing methods were standardized to minimize confounding factors between the three treatments. The research vessel set the gear in the morning at a mean local time of 5:03am (± 12 min 95% CI), deploying an average of 21.5 (± 0.3 hooks 95% CI) hooks between two floats with shallowest and deepest hooks soaking at depths of about 63 m (± 4 m 95% CI, N = 84) and 186 m (± 9 m 95% CI, N = 73), respectively (data from Star-Oddi milli-L depth temperature archival tags Time Depth Recorder measurements, with an accuracy of ± 4 m). The maximum soak duration (the duration between the first hook entering the water during setting to the last hook retrieved during gear haulback) was a mean of 17.1 h (± 0.7 h 95% CI). A mean of 1709 hooks were deployed per set (± 91 hooks 95% CI). As pelagic longline leader material can have a significant effect on species-specific catch and survival rates (Clarke et al. 2014; Gilman and Hall, 2015; Gilman et al. 2016a), the vessels used monofilament polyamide (nylon) leaders of a standardized color (clear) and diameter (1.8 mm). Branchlines had 45 g swivels located about 1 m from the hook. Only one bait type (whole sardine, *Sardinops* spp., mean weight of 125 g ± 23 g SD, N = 25) and method for threading the bait onto the hook (single threading) was used due to evidence of effects on catch and survival rates of bait type, size and method for threading (Clarke et al. 2014; Gilman et al. 2016a; Gilman and Huang 2017).

Researchers recorded set-level information on the date and time of the start and end of sets and hauls, latitude and longitude at the start and end of sets and hauls, number of hooks observed, and number of bite-offs by hook type. A bite-off is when the terminal tackle of the branchline (hook and section of branchline) was missing upon gear haulback. Researchers also recorded the following information for each caught organism: Hook size; species; at-vessel condition (alive or dead at haulback before being handled by crew); length (measured to the nearest cm, lower jaw to fork in mouth for billfishes; upper jaw to fork in tail for other teleosts and sharks; total width between tips of wings for rays; and straight carapace length for turtles); hooked, entangled or both; anatomical hooking position (foul hooked externally in the body, hooked in the mouth, or deeply hooked internally in the throat or deeper); and fate (retained vs. discarded).

Data analyses

Analyses of effects of hook minimum width on catch rates, bite-off rates, anatomical hooking position, and at-vessel survival rates were conducted for bigeye (*Thunnus obesus*) and yellowfin (*T. albacares*) tunas; long snouted lancetfish (*Alepisaurus ferox)*; blue (*Prionace glauca*), pelagic thresher (*Alopias pelagicus*) and silky (*Carcharhinus falciformis*) sharks; pelagic stingray (*Pteroplatytrygon violacea*); and combined billfishes (blue marlin *Makaira nigricans*, black marlin *M. indica*, Indo-Pacific sailfish *Istiophorus platypterus*, shortbill spearfish *Tetrapturus angustirostris*, striped marlin *T. audax*, swordfish *Xiphias gladius*).

These seven species and one group made up 87% of the number of caught organisms. Bigeye and yellowfin tunas were included as they were the target species and composed the two largest components of both the total and retained catch. Billfishes, combined to provide an adequate sample size, were included because as a group this was the third largest component of the retained catch. Long snouted lancetfish was the largest component of non-retained teleosts, third largest component of non-retained species, and fifth largest component of the total catch. The three shark species selected for inclusion in analyses were the three largest components of the total shark catch. Blue shark was the third largest component of the total catch and largest component of the non-retained catch. There were insufficient sample sizes for other captured shark species. Pelagic stingray was the predominant ray species captured (98% of rays), second largest component of the non-retained catch, and fourth largest component of the total catch. Effect of hook minimum width on the length of the catch by species was assessed for billfishes, bigeye tuna and yellowfin tuna, these being the only group/species with sufficient length data sample sizes.

Despite employing a balanced and randomized study design, there was still statistically significant unexplained heterogeneity for hook minimum width nested within set. We therefore fit data to models that explicitly accounted for potentially significant explanatory variables to explore approaches to reduce this unexplained variance.

We used a Bayesian inferential procedure to fit a range of geo-additive generalized additive mixed regression models (Gilman et al. 2016b) to the set-specific catch rates (number of fish caught per set). The models were fit using the Stan computation engine with NUTS sampling (Stan Development Team 2016; Carpenter et al. 2017) via the brms package for R (Bürkner In Press). These models were implemented using weakly informative regularizing priors (Gelman et al. 2008; Park and Casella 2008) with posterior samples sourced from five chains and 50 k iterations after a warmup of 2000 iterations. The best-fit model for catch rate determined using leave-one-out cross-validation (Vehtari et al. 2017) was a Bayesian geo-additive GAMM with negative binomial likelihood (Aitkin et al. 2010).

The response variable was catch rate given six predictors (species, minimum hook width, season, soak duration, time of day of the start of the set, geo-referenced location of the location of the start of the set), log(number of hooks) was used as an offset with set as the random effect. An explicit interaction term between species and hook width was also included. The model fit was then displayed using the ggplot2 package for R (Wickham 2016) and evaluated using graphical posterior predictive checking procedures (Gelman et al. 2014) via the bayesplot package for R (Gabry 2016). The four posterior predictive check tests for the best-fit Bayesian GAMM with negative binomial likelihood were density overlay, maximum prediction and two summary statistics (mean, standard deviation), and all reflected adequate model fit (Supplemental Material Fig. S2).

Around 64% of the 2424 modeled replicates (where one replicate is defined here as the catch of one of the eight species/group on one of the three hook types for each of the 101 sets) had zero catch. This apparent excess of zeros was adequately accounted for by the covariates included in the best-fit model with negative binomial likelihood-posterior predictive check tests and leave-one-out cross-validation supported the negative binomial geo-additive GAMM model over a geo-additive zero-inflated Poisson GAMM model with the same covariates. Only species and minimum hook width were significant predictors of catch rates. While expected catch rates increased nonlinearly with increasing soak time, this effect was highly uncertain and consequently of limited explanatory power.

We then also used a Bayesian inferential procedure to fit a range of generalized linear mixed regression models to the fish catch-at-length data. The length models were fit and implemented employing similar methods as for catch rates, described above. The best-fit model, determined, again, using leave-one-out cross-validation, was a Bayesian GLMM with lognormal likelihood with set as the random effect. The model fit was displayed using the ggplot2 package for R and evaluated using graphical posterior predictive checking procedures (Gelman and Hill 2007; Chambert et al. 2014; Gelman et al. 2014) via the bayesplot package for R. The four posterior predictive check tests for the best-fit Bayesian GLMM with lognormal likelihood were density overlay, maximum prediction and two summary statistics (mean, standard deviation), and all reflected adequate model fit (Supplemental Material Fig. S3). We then used the evidence ratio of alternative hypotheses (Burnham et al. 2011; Morey et al. 2016) to determine the evidentiary strength of parameter-specific comparisons, such as how many times more likely is it that the expected mean length is larger for yellowfin tuna caught on large hooks than caught on medium hooks.

A Bayesian inferential procedure was used to fit a range of generalized linear mixed regression models to bite-off rate data. The bite-off rate models were fit and implemented employing the same methods as for catch rates, described above. The best-fit model for the bite-off rate determined using leave-one-out cross-validation was a Bayesian GLMM with negative binomial likelihood with observation level random effect to account for over-dispersion (Harrison, 2014). This was a much better model fit than models with either Poisson likelihood with observation-level random effect or a zero-inflated Poisson likelihood. The response variable was bite-off rate (number of bite-offs per set) given two predictors (minimum hook width, season), log(number of hooks) as an offset and set as a random effect in addition to the observation-level random effect. The model fit was displayed and evaluated using the same approach as for the catch rate model, described above.

We also fitted a range of generalized linear mixed regression models (GLMMs) to anatomical hooking position data (binary hooking position: internally hooked in the esophagus and deeper, or externally hooked in the jaw, mouth and foul hooked in the body). The models were fit within a fully Bayesian inferential framework as outlined above for catch rates. The best-fit model for the anatomical hooking position rate determined using leave-one-out cross-validation was a GLMM with Bernoulli likelihood. The response variable was internal hooking rate (number internally hooked per total captured) given two predictors (species, minimum hook width), with fishing set as the random effect.

We used a Bayesian inferential procedure to fit a range of generalized linear mixed regression models to at-vessel condition data (binary survival status: alive or dead). The at-vessel survival models were fit and implemented employing the same methods as for catch rates, described above. The best-fit model for survival rate determined using leave-one-out cross-validation was a Bayesian GLMM with Bernoulli likelihood (Aitkin et al. 2010). The response variable was the survival rate given three predictors (species, minimum hook width, anatomical hooking position) and with set as the random effect. The model fit was displayed and evaluated using the same approach as for the catch rate model, described above. As conducted for the catch-at-length analyses, we then used the evidence ratio of alternative hypotheses to determine the evidentiary strength of parameter-specific comparisons.

Convergence diagnostics such as the effective posterior sample size and the Gelman-Rubin statistic (Rhat < 1.01) reflected convergence of all best-fit Bayesian models used in each study component (Gelman and Hill 2007).

Results

Testing for hypothesis of randomized order of hook type

The Wald-Wolfowitz test for runs found that 89% of sets did not have a significantly different number of runs of the three hook types, suggesting that they were in randomized order. In the remaining 11% of sets, there were significantly more runs of one hook size than expected. There was no evidence that hooks became increasingly or decreasingly non-randomly ordered as the sets proceed within a trip, suggesting that there was no systematic process biasing the order of hooks. The 11% of sets that showed significant non-random hook order may have been due to chance.

Catch rates

There were 12 fishing trips comprising 101 sets and 172,091 hooks. Figure 1 presents catch rates by hook size from fitting combined catch data to a Bayesian geo-additive GAMM with negative binomial likelihood. There was a significant difference in expected catch rates between the medium and large hooks (significantly higher on medium), but not between the small and medium or between the small and large hooks (Fig. 1a). Catch rate increased with increasing soak duration, but the effect of soak duration was not significant (Fig. 1b).

Figure 2 shows expected catch rates by hook size from fitting data from individual species and combined billfishes to a Bayesian geo-additive GAMM with negative binomial likelihood. In general, the shark and tuna species had higher expected catch rates on the medium minimum width hook than on both the small and large hooks, with a similar but less certain effect for billfishes and long snouted lancetfish. There was a significantly higher bigeye tuna catch rate on medium versus large hooks and the yellowfin tuna catch rate on medium hooks was significantly higher than on either small or large hooks. The blue shark catch rate on small hooks was significantly lower than on both medium and large hooks. Silky and pelagic thresher shark catch rates were significantly higher on medium than large hooks.

Figure 3 presents catch rates by hook size from fitting data for pooled retained species (bigeye and yellowfin tunas, all billfishes [blue, black and striped marlins; Indo-Pacific sailfish; shortbill spearfish and swordfish], > 94% was retained) and combined non-retained (released alive and discarded dead) species (long snouted lancetfish; blue, pelagic thresher and silky sharks, pelagic stingray, < 0.3% was retained). Mean catch rates for both retained and non-retained species were significantly higher on the medium hook than on both the small and large hooks (Fig. 3). The retained species catch rate was lower and non-retained species catch rate higher on large hooks relative to small hooks, however, the differences were not significant (Fig. 3).

Length

Based on the best-fit Bayesian lognormal GLMM regression, significantly larger yellowfin tuna were caught on the largest hook relative to the small and

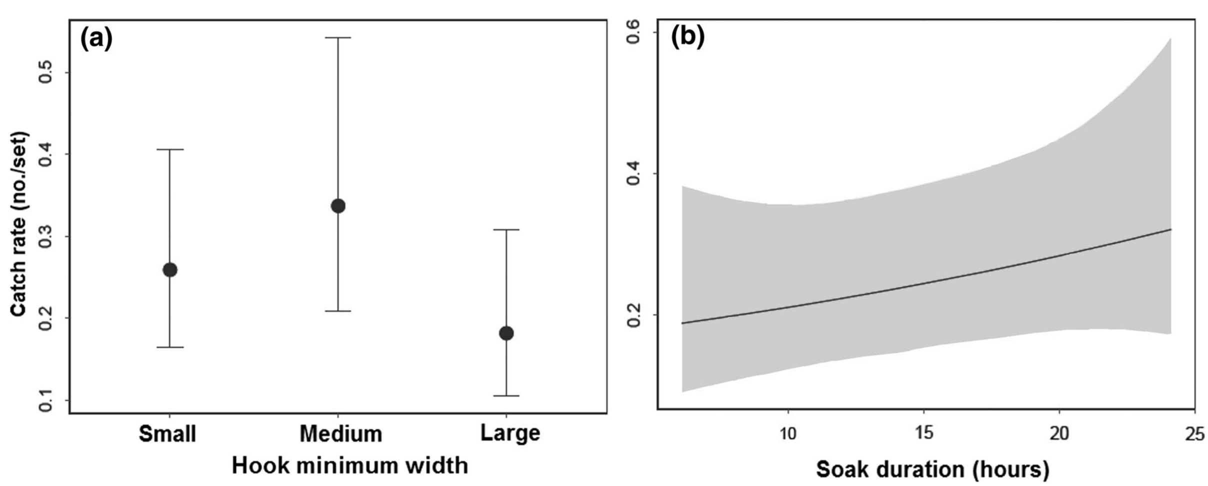

Fig. 1 Catch rate and 95% uncertainty intervals for **a** the effect of hook minimum width, and **b** effect of soak duration, from fitting catch data for combined bigeye and yellowfin tunas, billfishes, long snouted lancetfish, blue shark, pelagic thresher shark, silky shark and pelagic stingray to a Bayesian geo-additive GAMM with negative binomial likelihood

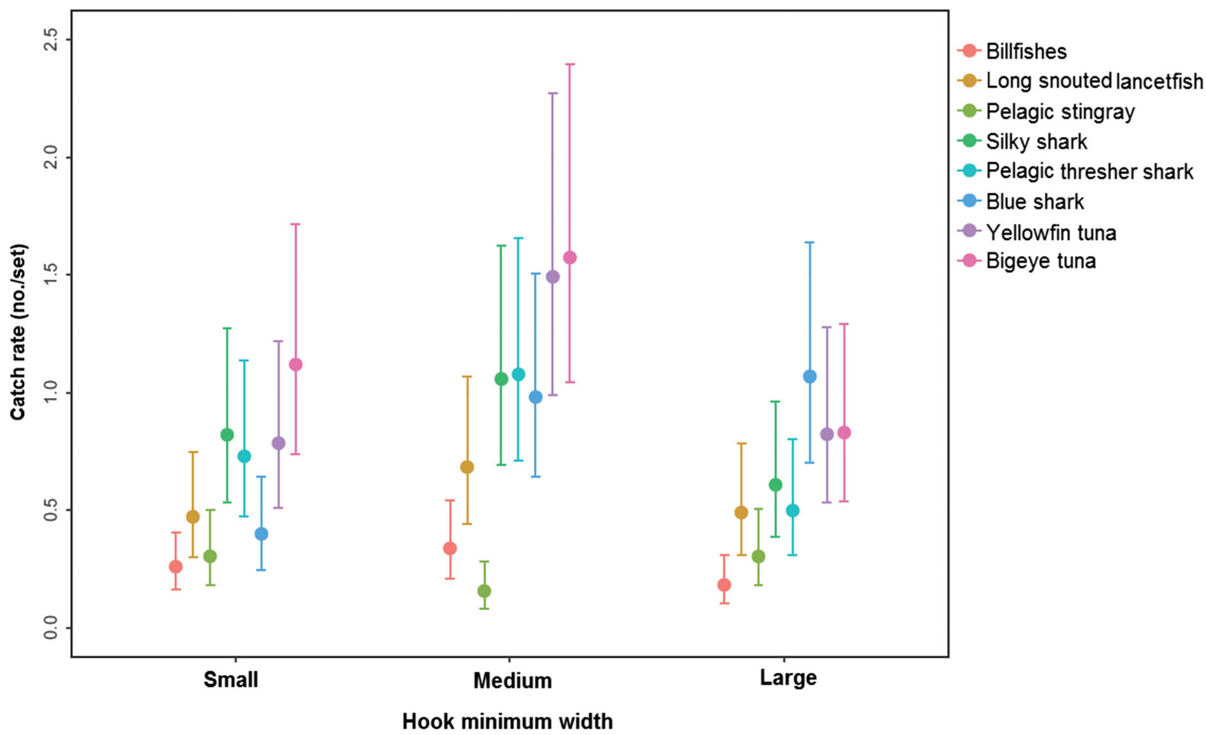

Fig. 2 Catch rate and 95% uncertainty intervals from fitting catch data by individual species and combined billfishes to a Bayesian geo-additive GAMM with negative binomial likelihood

medium hooks, with no significant difference in mean length between the small and medium hooks (Fig. 4). Based on the evidence ratio of alternative hypotheses, the large hook was 9.6 times more likely to capture larger mean length yellowfin tuna than the medium hook, and there was 90% certainty that larger yellowfin were caught on the large versus medium sized hook. Yellowfin tuna mean length was 111 cm (± 12 SD, N = 132), 111 cm (± 14 SD, N = 207), and 117 cm (± 12 SD, N = 57) on the small, medium and large hooks, respectively. The highest frequency of captures on all three hook sizes was for the length range of 100–119 cm.

A similar effect of hook minimum width on mean length was apparent for bigeye tuna as observed for yellowfin tuna, but with larger uncertainty of the effect (Fig. 4). The large hook was 7.1 times more likely to capture larger mean length bigeye tuna than the medium sized hook, and there was 88% certainty that larger bigeye were caught on the large versus medium sized hook. Bigeye tuna mean length was 130 cm (± 16 SD, N = 105), 130 cm (± 16 SD, N = 142), and 133 cm (± 14 SD, N = 77) on the small, medium and large hooks, respectively. The highest frequency of captures on all three hook sizes was for the length range of 120–139 cm.

There was also large uncertainty of the effect of hook size on billfishes mean length, where larger billfishes were caught on the smallest hook (Fig. 4). The small hook was 9.2 times more likely to capture larger mean length billfishes than the medium sized hook, and there was > 99% certainty that larger billfishes were caught on the large versus medium sized hook. Billfishes mean length was 184 cm (± 26 SD, N = 20), 176 cm (± 31 SD, N = 32), and 173 cm (± 19 SD, N = 14) on the small, medium and large hooks, respectively. The highest frequency of captures on small hooks was for the length range of 180–199 cm, and on medium and large hooks was for the length range of 160–179 cm.

Bite-off rate

Missing hooks, assumed to be from bite-offs during the gear soak, made up 0.0056 of the total number of observed hooks, and 0.0049, 0.0056 and 0.0063 of

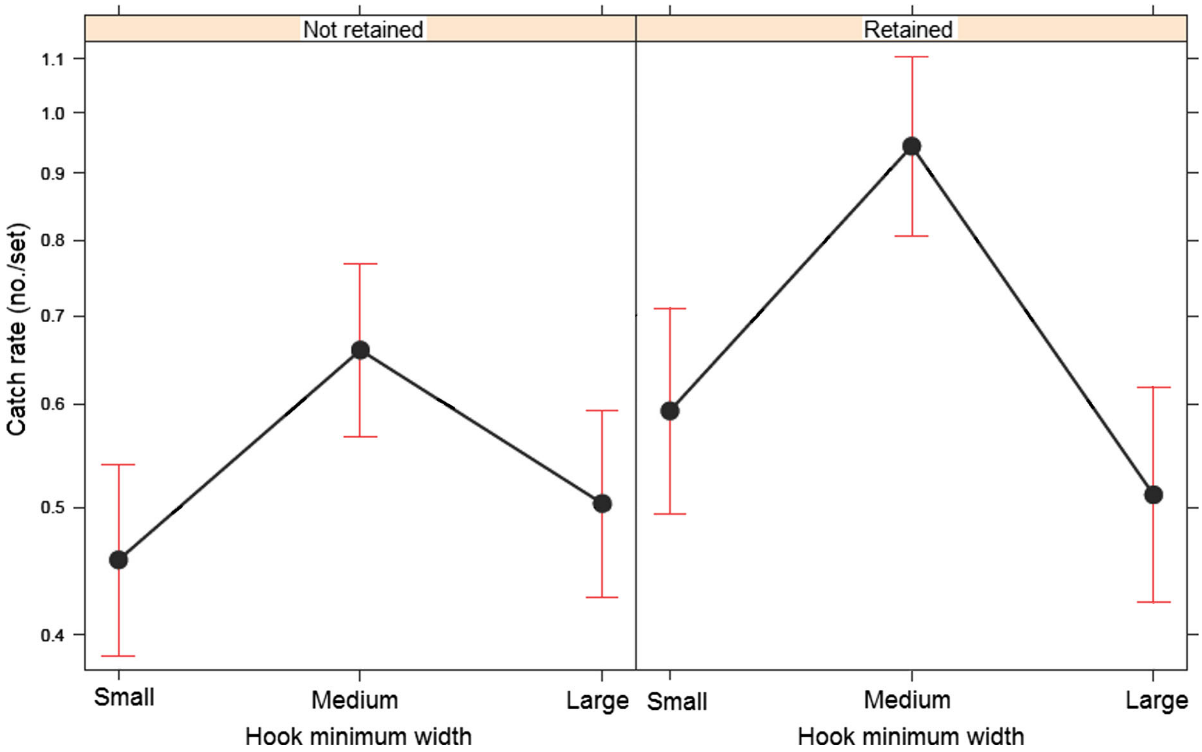

Fig. 3 Catch rate and 95% uncertainty intervals from fitting catch data by retained and non-retained species to a Bayesian geo-additive GAMM with negative binomial likelihood

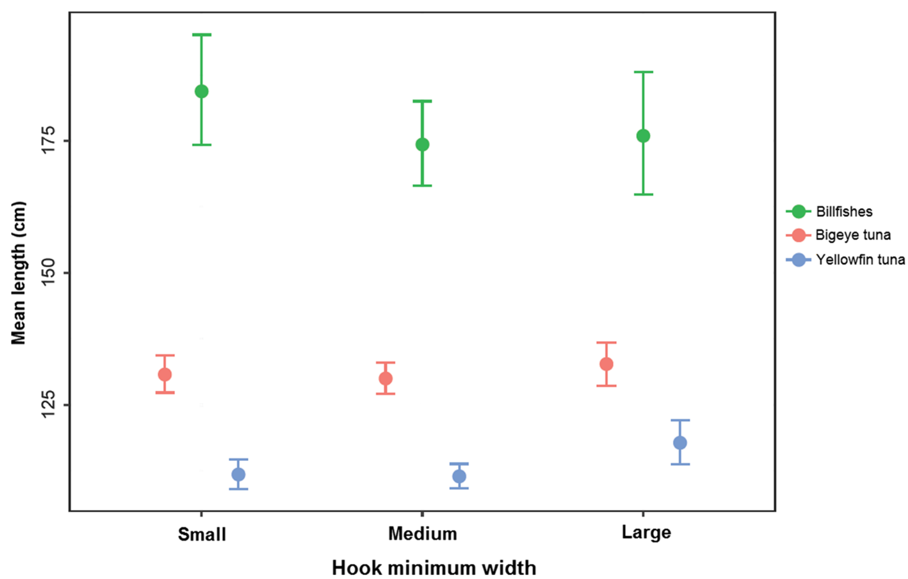

Fig. 4 Effect of hook minimum width on mean lengths and 95% uncertainty intervals of bigeye and yellowfin tunas and combined billfishes from fitting length data to a Bayesian geo-additive GLMM with lognormal likelihood

small, medium and large hooks, respectively. Based on fitting bite-off and hook width data to a Bayesian GLMM with negative binomial likelihood, expected bite-off rates increased with increasing hook size. Bite-off rates were 0.67 per set ± 0.35 95% uncertainty interval, 0.79 per set ± 0.42 95% uncertainty interval, and 0.89 per set ± 0.46 95% uncertainty interval for the small, medium and large hooks, respectively. The effect was highly uncertain due to the small number of bite-off records (Fig. 5). There was no support for a model with any meaningful difference in bite-off rate between medium and large hook width (Bayesian $P = 0.002$).

Anatomical hooking positions and at-vessel survival rates

There was a significantly higher deep-hooking rate of billfishes on the medium hook than on small and large hooks, with no significant difference between the small and large hooks (Fig. 6). There was no significant effect of hook minimum width on expected deep-hooking rate for any of the seven assessed species.

The effect of hook width and anatomical hooking position on at-vessel survival rates is presented in Fig. 7. Based on the best-fit Bayesian GLMM regression, externally hooked yellowfin tuna had a significantly higher mean survival rate with increasing hook size. The difference was marginally significant for externally hooked yellowfin on medium versus large hooks (46% certainty), while there was large certainty with the other two mean survival rate comparisons for

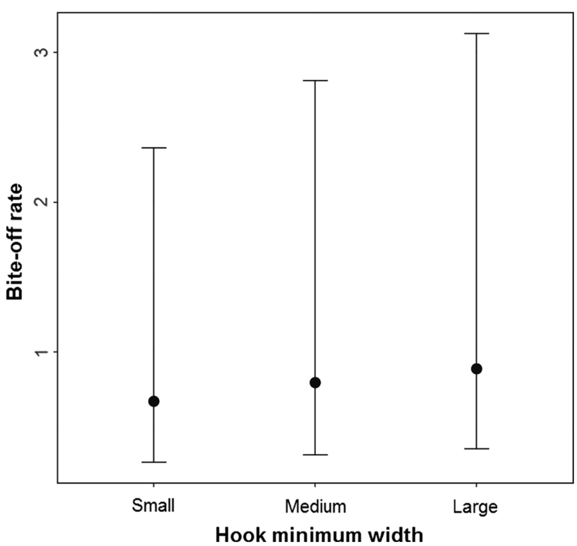

Fig. 5 Effect of hook minimum width on expected bite-off rate and 95% uncertainty intervals when fitting bite-off data to a Bayesian geo-additive GLMM with negative binomial likelihood

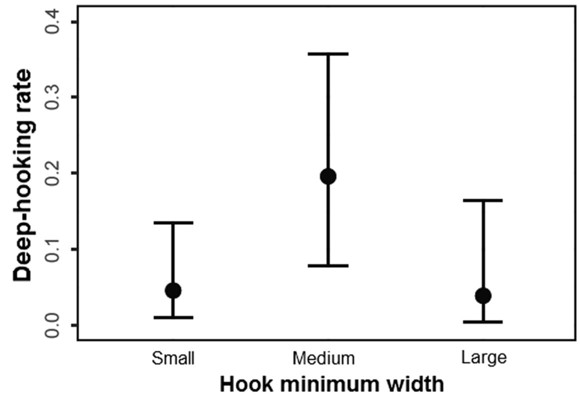

Fig. 6 Effect of hook minimum width on billfishes' expected deep-hooking rate and 95% uncertainty intervals from fitting anatomical hooking position data to a GLMM with Bernoulli likelihood

externally hooked yellowfin tuna (small vs. medium, small vs. large). Externally hooked bigeye tuna had a significantly higher survival rate on the large hook relative to the other two hooks, and externally hooked pelagic thresher sharks had a significantly lower expected survival rate on the medium hook relative to the other two hooks. No definitive conclusions can be drawn on the effect of hook minimum width on survival rates when deeply-hooked for any of the seven species or billfishes group due to extremely small sample sizes. In general, for all seven species and billfishes, for each hook size, mean survival rates were lower when deeply-hooked than when externally hooked.

Discussion

Due to effects on species- and size-selectivity and survival rates, pelagic longline hook minimum width can enable meeting objectives for managing fishery effects on target and bycatch species (Cortez-Zaragoza et al. 1989; Erzini et al. 1998; Scharf et al. 2000; Ménard et al. 2006; Bachiller and Irigoien 2013). Catch rates of both retained and discarded species were significantly higher on medium hooks. Target tunas were significantly larger and had significantly higher at-vessel survival rates on wider hooks, while significantly larger billfishes were caught on narrowest hooks. However, given the small difference in mean lengths and survival rates of bigeye and yellowfin

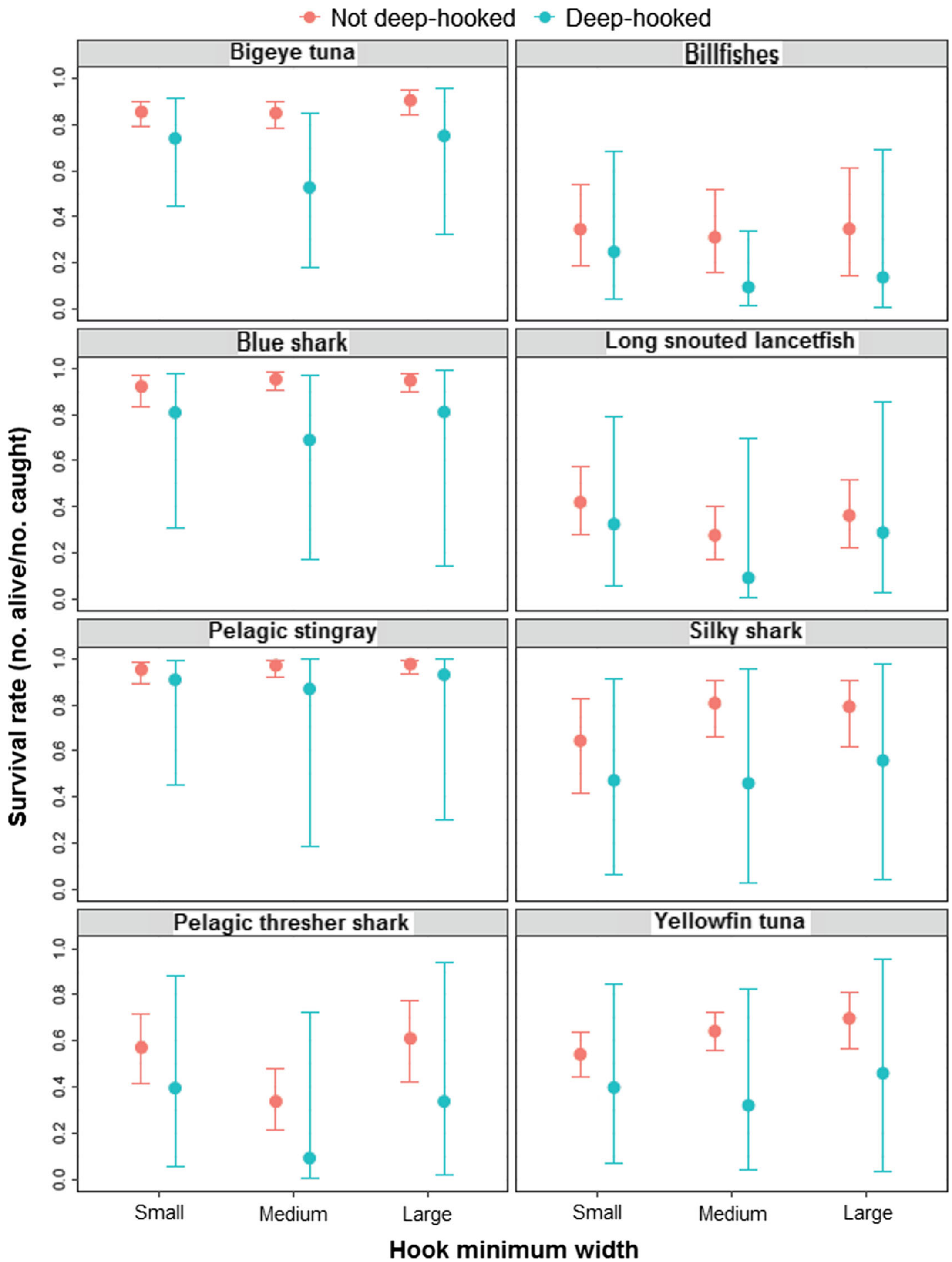

Fig. 7 Effect of hook minimum width and anatomical hooking position on expected at-vessel survival rates and 95% uncertainty intervals by individual species and combined billfishes when fitting at-vessel condition data to a Bayesian geo-additive GLMM with Bernoulli likelihood

tunas by hook size, and small contribution of billfishes to the catch, the effect of hook minimum width on length selectivity and at-vessel survival is likely a smaller effect on the economic value of the catch than the effect of hook width on catch rates. The selection of a minimum hook width that achieves an acceptable balance of catch rates and levels of market and discarded species depends on the design of the management framework.

Hook minimum width effect on catch rates

Only six previous studies tested the single factor effect of pelagic longline hook minimum width on catch rates, survival rates, anatomical hooking position or length (Bolten and Bjorndal 2006; Yokota et al. 2006; Piovano et al. 2010; Stokes et al. 2011; Curran and Beverly 2012; Pacheco 2013). These studies did not have confounding variability introduced into experimental designs by using multiple types of hook shapes, bait types or leader materials.

Comparing findings on the effect of minimum hook width on catch rates from the present study with findings of these six previous studies reveals that the effect can be fishery- and species-specific. Supplemental Material Section S1 reviews the mechanisms underlying the effects of hook minimum width on species selectivity, as well as causes of variability in these effects among fisheries and between species. Curran and Beverly (2012) observed a significantly higher swordfish catch rate on a wider 16/0 circle hook than on narrower circle hooks. But inconsistent with the findings here, Curran and Beverly (2012) found significantly lower catch rates of shortbill spearfish and long snouted lancetfish on the wider 16/0 circle hook, and no significant effect of circle hook size on bigeye and yellowfin tuna and blue marlin catch rates. Two studies observed no significant difference in blue shark catch rates between two sizes of circle hooks (Yokota et al. 2006; Curran and Beverly 2012), while we observed a significant difference between the small and medium circle hooks, but not between the medium and large circle hooks. Curran and Beverly (2012) found no significant effect between a 16/0 circle hook and narrower circle hooks on pelagic stingray catchability, consistent with the findings here, but Piovano et al. (2010) found significantly lower pelagic stingray catch rates on wider versus narrower J hooks. The length frequency distribution of a species that overlaps with a fishery, the difference in minimum widths of hooks being compared, and the difference in the hook widths relative to the species' range of mouth dimensions determine if hooks of different widths have different catch rates for a species in a particular fishery. In general, across fisheries, hook size is more likely to consistently affect catch rates of species with relatively small mouths (Supplemental Material Section S1).

Catch risk of hard shelled sea turtles has been observed in previous studies to decline with increasing hook minimum width (Gilman and Huang 2017). However, with only four captured sea turtles, the sample size in this experiment was too small to assess an effect of hook size on catch rate. The non-standardized sea turtle catch rate (0.02/1000 hooks) was typical of deep-set pelagic longline fisheries, where most hooks soak below the mixed-layer depths where hard shelled turtles, and to a lesser degree leatherback sea turtles, predominantly occur (FAO 2010; Shillinger et al. 2011).

No marine mammals or seabirds were captured during the experiment. Seabird interactions with longline fisheries occur primarily at higher latitudes and marine mammal captures (mainly odontocetes, but also pinnipeds in coastal fisheries) are rare events in most pelagic longline fisheries, including in the Palau and Marshall Islands locally-based longline fisheries (Molony 2005; Gilman et al. 2014, 2015). No previous studies assessed the single factor effect of hook minimum width on catch rates of seabirds or marine mammals (Clarke et al. 2014; Gilman and Hall 2015). For seabirds, a few studies assessed effects of hook type with simultaneous variability in hook shape and size. Two studies observed that wider circle hooks had lower seabird catch rates than narrower J-shaped hooks (Hata 2006; Li et al. 2012). Two other studies found no significant difference in albatross catch rates between wider circle and narrower J-shaped hooks (Domingo et al. 2012; Gilman et al. 2016b).

For Palau and other pelagic longline fisheries of the western tropical Pacific Ocean that use 14/0 circle hooks to target bigeye and yellowfin tunas (e.g., Federated States of Micronesia, Republic of the Marshall Islands, Gilman et al. 2014; Collinson and Gascoigne 2015), the selection of a hook size that provides an acceptable balance of catch rates and levels of market and discard species depends largely on the design of the management framework. If an input control is limiting, for example where the Parties to the Nauru Agreement longline vessel day scheme caps longline effort in some Pacific Island countries (PNA 2015), then, given a fixed level of effort, continued use of the conventional small hook would maintain current economic viability while avoiding a large, significant increase in catch of discarded species, including vulnerable blue, pelagic thresher and silky sharks, that would occur with the medium hook. Alternatively, if an output control for one or more market species is limiting, because the ratio of retained catch to discarded catch on the medium hook was greater than that of the small hook, the medium hook would result in a lower catch level of non-retained fishes, including sharks. A fishery with a bycatch threshold, such as an annual cap on the number of captured sharks or a shark catch rate limit, which would require substantially higher at-sea observer coverage than currently occurs in most global pelagic longline fisheries (Gilman et al. 2013), could allow the catch sector to select their preferred hook and other fishing gear designs and fishing methods to achieve the bycatch threshold.

Relative to the medium sized hook, the large hook resulted in a large and significantly lower catch rate of retained species and a relatively smaller, significantly lower catch rate of discarded species. The conventionally used small hook was an advantage for both achieving higher catch of market species and lower catch of discarded species relative to the widest hook, however, the difference in catch rates between smallest and largest hooks was not significant.

Hook minimum width effect on size selectivity

Findings for bigeye and yellowfin tunas, which were consistent with Curran and Beverly (2012), indicate that larger and potentially more valuable yellowfin and bigeye tunas were caught on the large circle hook than narrower hooks. These species made up > 80% of the total retained catch. Also consistent with Curran and Beverly (2012), larger billfishes were caught on the smallest hook. Billfishes, however, were only 7.5% of the total retained catch. Given the small difference in mean lengths of bigeye and yellowfin tunas caught on the large versus two narrower hooks (ca. 7 cm for yellowfin, 3 cm for bigeye), and minimal contribution of billfishes to the catch, the effect of hook minimum width on length selectivity is very likely a much smaller effect on the total value of the catch than is the effect of hook minimum width on catch rates.

The lack of a large length selectivity effect by hook minimum width observed here for bigeye and yellowfin tunas and billfishes is likely due to there being a relatively narrow range in lengths of the catch within fish species, and small differences in the sizes of the hooks (Erzini et al. 1998). Underlying mechanisms for the effects of hook size on length are discussed in detail in Supplemental Material Section S1.

Hook minimum width effect on bite-off rates

The lack of a significant difference in bite off rates between the three hook sizes, and low bite-off rate for all three hook sizes, suggests that bite-offs was not an important mechanism underlying the effect of circle hook minimum width on catch rates and mean length. Species with sharp teeth, including sharks and some teleosts, can sever monofilament leaders and escape (Ward et al. 2008; Afonso et al. 2012). However, likely due to the use of circle hooks, sharks caught in this study were very rarely deeply hooked ($< 0.5\%$). Circle hooks tend to catch in the corner of the mouth (except, for example, for thresher sharks and leatherback sea turtles, which tend to get foul hooked regardless of hook shape) (Cooke and Suski 2004; Curran and Beverly 2012; Epperly et al. 2012). Unlike mouth-hooked organisms, deeply-hooked catch can reach monofilament leaders with their teeth and are more likely to bite through it.

Hook minimum width effect on anatomical hooking position

The tendency for circle hooks to lodge in the corner of the mouth in species that are caught by ingesting hooks may have been a larger effect on anatomical hooking position than hook minimum width. The higher deep-hooking rate on the medium versus large hook for combined billfishes may have been due to the large hook being too large to be swallowed into the esophagus and more deeply (Cooke et al. 2005; Stokes et al. 2011; Yokota et al. 2012). It is unclear, however, why there was a higher billfish deep-hooking rate on the medium versus small hook. Previous studies reported four findings on the effect of pelagic longline hook minimum width on anatomical hooking position. No significant effect was observed for pelagic stingrays (Piovano et al. 2010). This is consistent with the observation here that no pelagic stingrays were deeply hooked regardless of hook size (> 94% were mouth hooked, the remainder foul-hooked). Cooke et al. (2005) found that deep hooking of bluegills (*Lepomis macrochirus*) in a recreational freshwater fishery occurred on smaller but not larger circle hooks. Bolten and Bjorndal (2006) observed no significant effect on loggerhead sea turtles, while Stokes et al. (2011) observed a significantly higher odds of loggerheads attempting to ingest narrower hooks.

Effect of hook minimum width and anatomical hooking position on at-vessel survival rates

Findings on variables that significantly affect at-vessel survival could identify opportunities to increase the probability of survival of organisms that escape from the gear before retrieval, and organisms that are caught alive and released by the crew. These findings also may enable improving the quality and value of retained species. Market species that are alive when retrieved may be of higher quality and more valuable than those retrieved dead (Cramer et al. 1981; Nobrega et al. 2014).

The effect of hook size on at-vessel survival rate may be related to the effect of hook minimum width on size selectivity (Supplemental Material Section S1.4). The observed higher survival rate of bigeye and yellowfin tunas caught on the large hook may have been due to larger individuals caught on the larger hook being less sensitive to the stress of capture (Broadhurst et al. 2006). Thus, the large circle hook may produce more valuable, larger and better condition bigeye and yellowfin tuna catch than smaller hooks. However, given the relatively small difference in at-vessel mean survival rates for bigeye and yellowfin tunas for the three hook widths, the effect of hook narrowest width on catch rates is likely a larger effect on the value of the catch than the effect on survival rates. While it is unclear why the externally hooked pelagic thresher sharks (which are most often foul hooked in the tail) had a significantly lower expected survival rate on medium hooks, this finding indicates that the smallest hook benefits pelagic threshers by producing a lower at-vessel mortality rate relative to the medium hook. Curran and Beverly (2012) observed significant effects of hook minimum width on at-vessel survival rates for blue marlin, swordfish, shortbill spearfish, wahoo, pelagic stingray and blue shark.

Although small sample sizes for deep hooking prevented drawing definitive conclusions, the observation that mean survival rates for deeply hooked fishes were lower than for externally hooked fishes is consistent with the understanding that externally hooked organisms have a lower at-vessel mortality rate and likely higher probability of pre-catch and post-release survival relative to those that are deeply hooked (Cooke and Suski 2004; Horodysky and Graves 2005; Campana et al. 2009; Pacheco et al. 2011). For billfishes, there was a significantly higher deep-hooking rate on medium versus small and large hooks, indicating that a larger proportion of caught billfishes would be deeply hooked and possibly dead, and thus potentially of lower quality and value, when caught on the medium circle hook.

Conclusions and research priorities

Unsustainable fishing mortality is a widespread driver of change and loss of global marine biodiversity that can shift ecosystems away from a state that sustains target production levels (Pauly et al. 2005; Leadley et al. 2010). Bycatch in pelagic longline fisheries threatens some populations of at-risk taxa (e.g., Lewison et al. 2004; Clarke et al. 2014; Gilman and Huang 2017). Due to effects on species- and size-selectivity and at-vessel survival, controlling pelagic longline hook minimum width can enable meeting objectives for managing fishery effects on target and bycatch species.

Findings here on the single factor effect of pelagic longline hook minimum width can contribute to improving the sustainability of fishery effects on both target and incidentally caught bycatch species, elements of ecosystem-based fisheries management (Gilman et al. 2017). Some shark and tuna species had significantly higher expected catch rates on the medium hook than the small and large hooks. Mean catch rates of combined retained marketable species of tunas and billfishes as well as of combined non-retained species were significantly higher on the medium hook than on both the small and large hooks. The narrow control hook both achieved higher catch of market species and lower catch of discarded species relative to the widest hook, however, the difference was not significant. Significantly larger mean lengths of yellowfin and bigeye tunas were caught on the largest hook, there were significantly higher externally hooked bigeye and yellowfin tuna at-vessel survival rates on larger hooks, and significantly larger billfishes were caught on the smallest hook. However, given the small difference in mean lengths and survival rates of bigeye and yellowfin tunas by hook size, and small contribution of billfishes to the catch, the effect of hook minimum width on length selectivity and at-vessel survival is likely a smaller effect on the economic value of the catch than the effect of hook width on catch rates. The small length selectivity effect of hook minimum width was likely due to compressed length frequency distributions of these species at the fishing grounds and relatively small differences in hook widths relative to the range of sizes of mouth dimensions. A lack of a significant difference in bite off rates between the three hook sizes and low rate of severed hooks for all three hooks suggests that bite-offs were not an important mechanism underlying the effect of circle hook minimum width.

The selection of a minimum hook width that achieves an acceptable balance of catch rates and levels of market and discarded species depends on the design of the management framework. For example, if an input control is limiting then, given a fixed level of effort, continued use of the control hook would maintain the current economic viability of the fishery without causing a large and significant increase in catch level of discarded species, including vulnerable sharks, which would occur with use of the medium hook. Alternatively, if an output control for target species is limiting, because the ratio of retained to discarded catch on the medium hook was greater than that of the control hook, use of the medium hook would result in lower discard levels than the control hook. We assessed catch rates, length and at-vessel condition of retained species to infer the effect of hook minimum width on value of the catch; evaluation of ex-vessel value of the catch by hook type would provide an improved understanding of anticipated economic consequences of hook size.

The effect of hook minimum width on species-specific catch rates and mean length, especially for species with relatively large mouth dimensions, may vary between fisheries due to spatial differences in length frequency distributions as well as due to differences between the width of two hooks being compared (Supplemental Material Section S1.2) (Erzini et al. 1998; Curran and Beverly 2012; Yokota et al. 2006, 2012). Prescribing a minimum hook width therefore needs to account for potential fishery-specific effects on species- and size-selectivity as well as possible tradeoffs between at-risk taxa (Gilman et al. 2016a).

There is a small body of literature documenting the single factor effects of pelagic longline hook minimum width (Bolten and Bjorndal 2006; Yokota et al. 2006; Piovano et al. 2010; Stokes et al. 2011; Curran and Beverly 2012; Pacheco 2013). More research on effects of hook minimum width, and other pelagic longline gear components that enable increased selectivity to avoid at-risk bycatch species while maintaining economically viable catch rates of market species, are needed in multiple fisheries and regions. Once there is a sufficient number of studies designed to assess the single factor effect of pelagic longline hook minimum width, meta- and sensitivity analyses, due to the larger sample sizes plus the number of studies, with moderators to account for fishery-specific effects, would provide estimates with increased precision and accuracy over estimates from individual studies, with increased statistical power to detect an effect (e.g., Musyl et al. 2011; Gilman et al. 2016a).

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