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Catchability of target and non-target species by circle hook size in the Hawaii and American Samoa tuna longline fisheries

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Abstract:

Models were used to compare catchability (catch rate, number of fish per 1,000 hooks) as a function of hook size for a number of retained (target and non-target) and bycatch (discarded) species in two longline fisheries. Observer data from tuna longline fisheries in Hawaii and American Samoa were used to investigate catchability for 22 species in the Hawaii fishery and 16 species for the A. Samoa fishery. Generalized linear models (GLMs) were used to estimate catchability based on circle hook sizes, with comparisons for sizes 14/0 vs 15/0, 14/0 vs 16/0 and 15/0 vs 16/0 for the Hawaii fishery, and 13/0 vs 14/0 for the A. Samoa fishery.

The results from the Hawaii fishery are more robust than the A. Samoa fishery as the Hawaii fishery monitored ~8 times (25.8 million) more hooks than the A. Samoa fishery (3.3 million hooks). In Hawaii, there was a significant increase in catchability with larger hook size for 11 of 13 retained species, including bigeye tuna (*Thunnus obesus*), the primary target species. There were numerous species that were not affected by hook sizes, including two bycatch shark species, oceanic whitetip shark (*Carcharhinus longimanus*) and silky shark (*C. falciformis*). Of the eight species of bycatch, catchability was higher on larger hooks only for blue sharks (*Prionace glauca*). There was a significant decrease in catchability between 14/0 and larger hooks for five bycatch species, including shortfin mako shark (*Isurus oxyrinchus*), bigeye thresher (*Alopias superciliosus*), and pelagic stingray (*Pteroplatytrygon violacea*).

In A. Samoa, there was a significant increase in catchability for the target species, albacore (*T. alalunga*) as well as for five of eight retained species between hook sizes 13/0 and 14/0. No catchability effects were found for three of the eight retained species. Catchability in a number of retained species had no effect with hook size. With regards to bycatch species, larger (14/0) hooks were associated with higher catchability of pelagic stingray, blue shark, oceanic whitetip shark, silky shark, as well as a lower catchability for snake mackerel (*gempylus serpens*).

This study provides empirical evidence to suggest that for a tuna fishery in the Pacific Ocean, adoption of a larger hook could provide increased catchability of retained species while simultaneously serving as a conservation tool by decreasing catchability of a majority of bycatch species. With the exception of higher catchability of blue shark, the primary elasmobranch species caught, larger hook size implementation could reduce overall discards.

Introduction:

The National Marine Fisheries Service (NMFS) Pacific Islands Fisheries Science Center initiated an analysis on retained (target and non-target) and discarded bycatch species catchability by hook size in response to the WCPFC14 paragraph 362: *"The Commission tasks SC14 and TCC14 to evaluate the expected effects of several potential sea turtle management scenarios, including, but not limited to, ones in which vessels in all longline fisheries in the Convention Area are required to: (1) use either large circle hooks or whole finfish for bait; (2) use large circle hooks and whole finfish for bait; or (3) use any other combination of mitigation methods identified by the SC as being potentially effective. The SC may consider a range of specifications for large circle hooks. SC's evaluation should focus on expected effects on sea turtle interactions and mortalities and on target and bycatch species catch rates. TCC's evaluation should focus on implementation and compliance implications, as well as SIDS implementation considerations. Based on the evaluations, SC14 and TCC14 will provide any appropriate advice or recommendations to WCPFC15 with respect to improving CMM 2008-03."*

The Hawaii longline fishery typically targets bigeye tuna (*Thunnus obesus*), retains other non-target species and discards bycatch species. There were 11 species that were retained more than 90% of the time; two species had moderate (56-59%) retention, and nine bycatch species with low (0-10%) retention (Tables 1–2). The A. Samoa fishery typically targets south Pacific albacore (*T. alalunga*), retains other non-target species and bycatch species. There were six species that were kept more than ~90% of the time, two species had moderate (60-68%) retention and eight bycatch species with low (<1%) retention (Tables 1–2).

Large circle hooks have been increasingly used as a conservation measure in U.S. fisheries that aim to promote sustainable fisheries and minimize interactions with protected species, yet concern has been raised regarding potential changes in species' catchability as a response to these regulations. The aim of this investigation is to better understand the impacts of circle hook sizes on catchability of retained and bycatch species. This information is necessary in order to predict catch rates if size requirements were to be implemented as part of circle hook regulations in longline fisheries. In particular, the reference to a hook's "minimum width" (Figure 1) has been associated with differential catchability, yet this is largely anecdotal and has not been empirically evaluated.

Despite the demonstrated benefits to protected species such as sea turtles, fisheries managers and industry have concerns that an expanded use of large circle hooks, either voluntarily or mandated, may inadvertently have negative impacts on retained species, depleted shark stocks and other protected species such as sea turtles and marine mammals. This study addresses these concerns with regard to fish species. In all U.S. commercial longline fisheries, use of circle hooks is mandated, yet the size of the hook is variable and often mandated only by a minimum size.

Since January 2013, the NMFS Pacific Islands Regional Office fisheries observer program has recorded data that allow for the estimation of circle hook sizes used on each set in both the Hawaii and A. Samoa tuna longline fisheries. Prior to January 2013, observers noted the predominant hook type with no clarification on what percentage a particular size represents on a given set. Observers also recorded a suite of biological data on all catch, both retained and bycatch species that were caught on each hook size. Table 3 includes circle hook sizes with its associated minimum width. This analysis assesses differences in catchability or relative catch rates as a function of hook size for a number of retained (target and non-target) and bycatch species.

Methods:

This analysis was conducted on longline sets from two tuna fisheries from January 2013 to April 2018 that had 100% of one hook size reported. These included circle hook sizes 13/0, 14/0, 15/0 and 16/0 for the Hawaii fishery and 13/0, 14/0 and 15/0 for the A. Samoa fishery. Analysis of size 13/0 hooks in Hawaii and size 15/0 hooks in A. Samoa were excluded due to a paucity of representative trips. A total of 10,245 and 1,153 longline sets were analyzed from Hawaii and A. Samoa, respectively (Table 4).

Generalized Linear Models (GLMs) were used to compare catchability of the most common species captured, which was determined if the average catch rate was at or above 0.20 fish per set. Despite not meeting this criterion, silky (*Carcharhinus falciformis*) and oceanic whitetip (*C. longimanus*) sharks were also included given the conservation concerns for these species. There were a total of 22 species considered for the Hawaii fishery and 16 species for the American Samoa fishery. Catchability as a function of circle hook sizes included 14/0 vs 15/0, 14/0 vs 16/0 and 15/0 vs 16/0 for the Hawaii fishery and 13/0 vs 14/0 for the A. Samoa fishery.

For each species, GLMs predicts mean catch (μ_i) as number of individuals using two categorical and two continuous variables with a log link:

$$\log(\mu_i)=N_i+H_i+T_i+B_1Lat_i+B_2Lat_i^2+B_3Lat_i^3+B_4Lon_i+B_5Lon_i^2+B_6Lon_i^3+log(E_i)$$

where N is the mean local abundance; H, hook size effect; T, time (year:quarter) effect; Lat and Lon are third order (cubic) effects of latitude and longitude and offset E is the number of hooks deployed during longline set i. The GLMs were fitted in R (version 3.4.4. for Linux) and considered a negative binomial response distribution. Model selection was conducted by AIC and log likelihood tests. 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.

Results:

Hawaii

Convergence of the GLMs was achieved for all species. The time effect was often the initial entrant in the model, followed by the spatial effect and hook size. The GLM coefficients are illustrated in Table 5 and Figure 2 for retained species and Table 6 and Figure 3 for bycatch species. Significance is assigned 'Yes' or 'No' in Table 4 by comparing 14/0 vs 15/0, 14/0 vs 16/0 and 15/0 vs 16/0 hook sizes. Tables 5–6 and Figures 2–3 illustrate mean effects and 95% confidence intervals of the 15/0 and 16/0 hooks in comparison with a 14/0 with a value of 1.0 from the GLM. There is a significant effect between hooks sizes if a 95% CI doesn't overlap with the value of 1.0 (14/0 hook). There is a significant effect between 15/0 and 16/0 if the 95% CIs don't overlap.

Target species. There was a significant increase in bigeye tuna catchability between the 14/0 and 15/0 hooks (20.3% increase), 14/0 and 16/0 hooks (21.7% increase) and no significant effect between 15/0 and 16/0 hooks (Table 5).

Significant increase in catchability with larger hooks. There was a significant increase in catchability with larger hook size for 11 of the 13 retained species (Table 5). The increase in catchability for the 11 retained species averaged 17.3% (range=4.1–51.3%) between 14/0 and 15/0 hooks and averaged 34.1% (range=7.6–124.7%) between 14/0 and 16/0 hooks. There was no significant increase in catchability with larger hook size for eight of nine bycatch species, with the exception of blue shark (*Prionace glauca*) which was found to significantly increase between 14/0 and 16/0 hooks (14.1%) and 15/0 and 16/0 hooks (11.0%).

No significant increase in catchability with larger hooks. There were five species with no significant difference in catchability between any hook size, including two retained species, dolphinfish (*Coryphaena hippurus*) and sickle pomfret (*Taractichthys steindachneri*), and three bycatch species, oceanic whitetip shark, silky shark and knifetail pomfret (*Taractes rubescens*).

Significant decrease in catchability with larger hooks. There was a significant decrease in catchability between 14/0 and larger hooks for five species (Table 5, shortfin mako shark [*Isurus oxyrinchus*], bigeye thresher [*Alopias superciliosus*], pelagic stingray [*Pteroplatytrygon violacea*], longnose lancetfish [*Alepisaurus ferox*] and snake mackerel [*Gempylus serpens*]). The decrease in catchability between 14/0 and 15/0 hooks averaged 12.8% (range=3.3–19.5%). While there was a significant decrease in catchability between 14/0 and 15/0 hooks and there was an unexpected result of no significant difference between 14/0 and 16/0 for four species.

Fish size. Relationships between hook sizes and lengths were tested for 13 species that are usually retained (Table 5). F-tests indicated significant differences ($P < 0.01$, Table 7) for seven species. The mean length differences were relatively small (<2 cm FL). There were no significant differences in lengths for four billfish species and opah (*Lampris guttatus*).

American Samoa

Convergence of the GLMs was achieved for all species. Similar to the Hawaii fishery, the time effect was often the initial entrant in the model, followed by the spatial effect and hook size. Tables 5–6 and Figure 4 illustrates the mean effects and 95% confidence intervals of the 14/0 hooks in comparison with a 13/0 with a value of 1.0 from the GLM. There is a significant effect between hooks sizes if a 95% CI doesn't overlap with the value of 1.0 (13/0 hook). The CIs for the coefficients for the A. Samoa fishery are much wider than the Hawaii fishery as there was less effort observed in A. Samoa (3,302,562 hooks) than in Hawaii (25,882,977 hooks).

Target species. There was a significant increase of 50.3% in albacore catchability between the 13/0 and 14/0 hooks (Table 5).

Significant increase in catchability with larger 14/0 hooks. There was a significant increase in catchability with 14/0 hooks for five of the eight species that are retained (Table 5). The increase in catchability for the five retained species averaged 44.2% (range=25.1–79.3%). There was a significant increase in catchability with 14/0 hooks for six of eight bycatch species, including blue shark, oceanic whitetip, silky shark, pelagic stingray, lancetfish, and longfin escolar (*Scombrolabrax heterolepsis*). The increase in catchability for bycatch species averaged 46.7% (range=23.6–66.6).

No significant increase in catchability with larger 14/0 hooks. There were four species with no significant difference in catchability with 13/0 and 14/0 hooks, three retained species (Table 5, wahoo(*Acanthocybium solandri*), blue marlin (*Makaira nigricans*) dolphinfish, and escolar (*Lepidocybium flavobrunneum*) a bycatch species (Table 6).

Significant decrease in catchability with larger 14/0 hooks. There was a significant decrease in catchability with 14/0 hooks of 36.6% for snake mackerel (Table 6).

Fish size. Relationships between hook sizes and lengths were tested for five retained species (Table 8). F-tests indicated significant differences ($P < 0.01$, Table 8) for four species. The mean length differences were relatively small (<3 cm FL).

Discussion:

Numerous studies conducted in Pacific longline fisheries have demonstrated that use of relatively large circle hooks and fish bait can both reduce interaction rates with sea turtles as well as improve their chances of survival if interactions occur (Minami et al. 2006, Boggs and Swimmer 2007, WCPFC 2017). Workshops aimed to analyze observer data from international longline fleets within the Pacific Ocean used empirical models to conclude that four sea turtle species benefitted when using circle hooks size 16/0 or larger (WCPFC 2017). Given the growing evidence for the conservation benefits of circle hook use to sea turtles; their use in global fisheries has been suggested as a means to further reduce threats to sea turtle populations. In addition to the shape of the hook, the size has also been identified to play a role in reducing sea turtle catch, especially for smaller animals with a more limited gape.

The potential for expanded use of large circle hooks has raised concerns from both fisheries managers and industry on retained species, depleted shark stocks and protected species such as sea turtles and marine mammals. Potential impacts of large circle hooks include changing the vulnerability, or catchability, of fishing gear on a species- or size- specific basis and are therefore important for stock assessments and improved bycatch mitigation.

There are two methods to assess catchability in hook types and/or hook sizes. The preferred method is to conduct controlled trials whereby hooks types/sizes are sequentially alternated on a longline set. An alternative method is to statistically compare catchability from longline sets that use unique hook types/sizes, which is the approach of the current study. Longline trials are preferred to estimate catchability of hook type or size as catchability is eliminated due to vessel effects such as operational differences (e.g. depth of longline hooks) between vessels. In this study, catchability is assumed to be the same among vessels and catchability varies due to time, location and hook sizes.

Meta-analysis is potentially useful to estimate catchability; however, the analyses generically consider hook type and do not consider hook size which can alter catchability. Additionally, there are many nuances in fisheries data that are not easily captured in a meta-analysis, resulting in an over-simplification of both methods and results, thereby limiting the value of a single interpretation.

Hawaii

Analysis from the Hawaii fishery indicated a significantly higher catchability of nearly all retained catch on larger (15/0 and 16/0) compared to smaller (14/0) circle hooks and a reduction of bycatch for all species with the exception of blue shark, which were found to have a higher catchability on larger hooks. This study had positive results for shark species of concern such as oceanic whitetip and silky shark as there was no significant differences in catchability among hook sizes.

Circle hook minimum width is usually characterized as 3.8 cm for 14/0, 3.8–4.0 cm for 15/0 and 4.4 cm for 16/0 hooks (WCPFC 2017). Controlled field trials in the same Hawaii fishery tested very large 18/0 circle hooks (minimum width 4.9 cm), 3.6 sun Japan tuna (minimum width 3.1 cm) and 9/0 J-hooks (minimum width 3.9 cm, Curran and Bigelow 2011). Large circle hooks had greater effects on catch rates than on fish size selectivity and fish survival. There was no significant difference in catchability for bigeye and skipjack tuna (*Katsuwonus pelamis*) among any hook type. However, generalized linear mixed models (GLMMs) indicated that catchability on large circle hooks were significantly lower for 16 and 8 species compared to tuna and J-hooks, respectively. Curran and Bigelow (2011) contended that reduced catchability is a function of 18/0 circle hook shape, where the minimum width (4.9 cm) was 57% greater than the Japanese tuna hook and 25% wider than the J-hook (3.9 cm). In contrast to hooks of smaller minimum width, the large 18/0 circle hooks have conservation potential for use in the world's pelagic tuna longline fleets for some highly migratory species, with catchability reductions of 29.2–48.3% for billfish species and 17.1–27.5% for sharks (Curran and Bigelow 2011). However, there is concern in the tuna fishery that implementation of 18/0 hooks would reduce the economic value as the fishery usually retains yellowfin tuna and billfish (Curran and Bigelow 2011).

Results from the 18/0 circle deep-set trials presented were similar to when 18/0 circle hooks were implemented in 2004 for the Hawaii shallow-set fishery that targets swordfish. Prior to this time, terminal gear consisted primarily of size 9 J hooks. Analysis of data before and after the regulations indicated that blue shark catch rates declined by 28.8% after 2004 when there was mandated use of large circle hooks (Walsh et al. 2009). Additionally, there were additional significant reductions of oceanic white tip, bigeye thresher (*Alopias superciliosus*) and crocodile sharks after the regulations. This analysis is complicated by the fact that the changes in hook and bait types were confounded, as the regulations also required a change from squid to fish bait.

In a more recent analysis of the Hawaii shallow set data, which includes an additional eight years of data (with 100% observer coverage of the fleet), Swimmer and Barcelo (in prep) also found a significant reduction in nominal blue shark capture rates, which was also attributed to the changes in terminal gear as a combination of factors such as hook type, bait and leader material.

The higher capture rate of blue sharks on circle hooks compared to tuna hooks in this study differs from another study in the N. Pacific investigating catch rates as a function of hook sizes, including 3.8 sun, 4.3 sun, 5.2 sun (Yokota, et al., 2006).

However, higher capture rates as function of circle hooks has been found in several studies in the Atlantic Ocean (Sales, et al., 2010; Watson, et al., 2005, see review Reinhardt et al. 2017). Hook type and size, bait type (fish, squid), leader material and even ocean basin may play a role in shark capture rates. More research is needed to understand the single factor effects of capture risk.

American Samoa

Analysis from the A. Samoa fishery indicates a significantly higher catchability from size 13/0 to 14/0 hooks for five of the eight species that are retained. All four species of tuna, including the predominately caught and targeted albacore, as well as bigeye, yellowfin, and skipjack, all had higher catchability on the larger hook. These findings are similar to those presented by Ward et al. (2009) who found an increase in catchability for albacore and yellowfin tuna when comparing catch among relatively large circle hooks (sizes were grouped) to Japanese tuna hooks. However, these results may be confounded by the experimental methods that limit interpretation of actual size differences.

In comparing our results with a study of south Pacific albacore fisheries, Curran and Beverly (2012) conducted field trials testing catch rates as a function of circle hook sizes in A. Samoa, New Caledonia, and the Cook Islands. Catchability of a variety of species were compared among large (16/0) circle hooks (4.4 cm minimum width) and a variety of smaller circle hooks (3.3–3.9 cm minimum width) traditionally used in the fishery. Results from the three fisheries were based on 145,982 hook observations from 67 sets and suggested there was no significant catchability differences between hook types for albacore in any location. For A.Samoa there was reduced catchability for three retained species (skipjack tuna, shortbill spearfish, and wahoo) and three bycatch species (escolar, longnose lancetfish, and great barracuda). We are uncertain what could explain the different findings in relatively similar study scenarios.

There was higher catchability for species of concern such as oceanic whitetip and silky shark; however, GLMs were applied to relatively low sample sizes, 789 for silky shark and 300 for oceanic whitetip shark. There was no significant difference in catchability between 13/0 and 14/0 hooks for three retained species, wahoo, blue marlin and dolphinfish.

Conclusion:

Larger hook sizes resulted in higher catchabilty for both target and retained species in a bigeye tuna and albacore Pacific longline fisheries; however the current maximum hook sizes in use are 16/0 in Hawaii and 14/0 in A. Samoa. In general, the results from the Hawaii fishery are more robust than the A. Samoa fishery as the Hawaii fishery monitored eight times (25.8 million) more hooks than the A. Samoa fishery (3.3 million hooks). Therefore, this study provides higher confidence in the findings of the Hawaii data set.

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Table 1. Summary statistics for retained species in the Hawaii and American Samoa tuna longline fisheries. Catch is number of individuals retained and brackets are the percentage of catch kept. Parentheses are catch per unit effort (CPUE) per 1,000 hooks.

Species	Hawaii Catch (CPUE) from 10,245 sets				American Samoa Catch (CPUE) from 1,153 sets		
	Catch (% kept)	Circle 14/0	Circle 15/0	Circle 16/0	Catch (% kept)	Circle 13/0	Circle 14/0
Bigeye tuna *Thunnus obesus*	128,424 [93.2]	39,570 (4.39)	78,102 (5.27)	10,752 (5.26)	3,768 [89.3]	928 (0.89)	2,840 (1.26)
Yellowfin tuna *Thunnus albacares*	23,067 [90.8]	5,971 (0.66)	15,151 (1.02)	1,945 (0.95)	10,968 [94.3]	4,149 (3.97)	6,819 (3.02)
Wahoo *Acanthocybium solandri*	14,416 [94.6]	4,688 (0.52)	8,427 (0.57)	1,301 (0.63)	3,114 [89.9]	907 (0.89)	2,207 (0.96)
Albacore *Thunnus alalunga* Hawaii – N. Pacific stock, A. Samoa – S. Pacific stock	5,433 [98.6]	1,581 (0.18)	3,262 (0.22)	590 (0.29)	41,405 [98.9]	10,509 (10.06)	30.896 (13.68)
Skipjack tuna *Katsuwonus pelamis*	21,485 [90.0]	5,361 (0.59)	12,952 (0.87)	3,172 (1.55)	6,536 [95.5]	1,790 (1.71)	4,746 (2.10)
Striped marlin *Kajikia audax*	9,113 [94.4]	3,025 (0.33)	5,332 (0.36)	756 (0.37)			

Spearfish *Tetrapturus angustirostris*	11,340 [90.3]	3,564 (0.39)	6,690 (0.45)	1,086 (0.53)			
Swordfish *Xiphias gladius*	5,558 [58.7]	1,835 (0.20)	3,228 (0.22)	495 (0.24)			
Blue marlin *Makaira nigricans*	2,889 [96.7]	943 (0.10)	1,718 (0.12)	228 (0.11)	703 [68.1]	296 (0.30)	407 (0.18)
Dolphinfish *Coryphaena hippurus*	41,796 [91.1]	15,284 (1.69)	23,069 (1.55)	3,443 (1.68)	562 [89.8]	136 (0.13)	426 (0.19)
Opah *Lampris guttatus*	12,642 [95.5]	3,813 (0.42)	7,721 (0.52)	1,108 (0.54)			
Sickle pomfret *Taractichthys steindachneri*	46,018 [97.4]	17,565 (1.95)	24,985 (1.69)	3,468 (1.70)			
Escolar *Lepidocybium flavobrunneum*	31,148 [56.2]	9,915 (1.10)	18,315 (1.23)	2,918 (1.43)			
Great barracuda *Sphyraena barracuda*					834 (59.8)	198 (0.19)	636 (0.28)

Table 2. Summary statistics for typical bycatch (discarded) species in the Hawaii and American Samoa tuna longline fisheries. Catch is number of individuals retained and brackets are the percentage of catch kept. Parentheses are catch (# individuals) per unit effort (1,000 hooks) (CPUE).

Species	Hawaii (CPUE) from 10,245 sets				American Samoa (CPUE) from 1,153 sets		
	Catch (% kept)	Circle 14/0	Circle 15/0	Circle 16/0	Catch (% kept)	Circle 13/0	Circle 14/0
Blue shark *Prionace glauca*	52,363 [0.0]	17,260 (1.91)	30,733 (2.07)	4,370 (2.14)	1,743 [0.0]	731 (0.70)	1,012 (0.45)
Oceanic whitetip shark *Carcharhinus longimanus*	821 [0.1]	307 (0.03)	466 (0.03)	48 (0.02)	300 [0.0]	97 (0.09)	203 (0.09)
Silky shark Carcharhinus *falciformis*	618 [0.17]	280 (0.03)	300 (0.02)	38 (0.02)	789 [0.2]	259 (0.2)	530 (0.2)
Shortfin mako shark *Isurus oxyrinchus*	3,347 [10.1]	1,158 (0.13)	1,896 (0.13)	293 (0.14)			
Bigeye thresher *Alopias superciliosus*	6,215 [0.40]	2,794 (0.31)	2,951 (0.20)	470 (0.23)			
Pelagic stingray *Pteroplatytrygon violacea*	2,736 [3.3]	1,072 (0.12)	1,473 (0.10)	191 (0.09)	6,340 [0.1]	2,437 (2.33)	3,903 (1.73)
Knifetail pomfret *Taractes rubescens*	3,137 [0.82]	1,029 (0.11)	1,893 (0.13)	215 (0.11)			
Longnose lancetfish *Alepisaurus ferox*	139,681 [0.0]	51,959 (5.76)	75,363 (5.08)	12,539 (6.13)	2,207 [0.0]	9990 (0.95)	1,217 (0.54)

Escolar *Lepidocybium flavobrunneum*					3,627 [0.5]	994 (0.95)	2,633 (1.16)
Longfin escolar *Scombrolabrax heterolepsis*					3,194 [0.1]	1,335 (1.27)	1,859 (0.82)
Snake mackerel *Gempylus serpens*	58,808 [2.5]	23,733 (2.63)	31,061 (2.09)	5,014 (2.43)	605 [0.7]	167 (0.16)	438 (0.19)

Table 3. Minimum dimensions and circle hooks sizes. From Western and Central Pacific Fisheries Commission (2017).

Circle Hook size	**Minimum Dimension**
Offset 13/0	3.5 cm
Offset 14/0	3.8 cm
Offset 15/0	3.8–4.0 cm
Offset 16/0	4.4 cm
Offset 18/0	4.9 cm

Table 4. Summary statistics for circle hooks used in the Hawaii and American Samoa tuna longline fisheries.

	Hawaii				American Samoa		
	Total	14/0	15/0	16/0	Total	13/0	14/0
Trips	758	272	428	58	42	8	34
Sets	10,245	3,638	5,748	839	1,153	319	834
Hooks	25,882,977	9,018,678	14,819,799	2,044,500	3,302,562	1,043,731	2,258,831

Table 5. Statistical comparison among circle hook sizes on catchability (Generalized Linear Modeling, GLM) of retained species caught in the Hawaii and American Samoa-permitted tuna longline fisheries. GLM coefficients are estimates of catchability between circle hook sizes with values greater than 1.0 indicating higher catchability.

	Hawaii					Samoa	
Species	Coefficient (95% CI)		Statistically different			Coefficient (95% CI)	Statistically different
	15/0	16/0	14/0 vs 15/0	14/0 vs 16/0	15/0 vs 16/0	14/0	13/0 vs 14/0
Bigeye tuna	1.203 (1.163-1.244)	1.217 (1.147-1.293)	Yes	Yes	No (*p*=0.64)	1.503 (1.254-1.800)	Yes
Yellowfin tuna	1.321 (1.240-1.408)	1.362 (1.220-1.523)	Yes	Yes	No (*p*=0.25)	1.389 (1.128-1.707)	Yes
Wahoo	1.131 (1.075-1.189)	1.227 (1.123-1.340)	Yes	Yes	No (*p*=0.07)	1.075 (0.942-1.227)	No (*p*=0.30)
Albacore Hawaii – North Pacific stock, A. Samoa – South Pacific stock	1.111 (0.962-1.282)	1.311 (1.033-1.661)	No (*p*=1.0)	Yes	No (*p*=0.30)	1.275 (1.139-1.426)	Yes
Skipjack tuna	1.513 (1.407-1.627)	2.247 (1.994-2.536)	Yes	Yes	Yes	1.251 (1.008-1.550)	Yes
Striped marlin	1.074 (1.006-1.146)	1.076 (0.959-1.208)	Yes	No (*p*=0.25)	No (*p*=0.94)		
Spearfish	1.122 (1.058-1.190)	1.437 (1.297-1.591)	Yes	Yes	Yes		
Swordfish	1.041 (0.972-1.114)	1.167 (1.035-1.313)	No (*p*=0.33)	Yes	No (*p*=0.13)		
Blue marlin	1.110 (1.012-1.218)	1.154 (0.975-1.363)	Yes	No (*p*=0.06)	No (*p*=0.96)	1.090 (0.873-1.361)	No (*p*=0.44)
Dolphinfish	1.044 (0.988-1.103)	0.978 (0.887-1.079)	No (*p*=0.16)	No (*p*=0.97)	No (*p*=0.24)	1.200 (0.837-1.720)	No (*p*=0.36)

Opah	1.133 (1.073-1.197)	1.262 (1.149-1.387)	Yes	Yes	No (*p*=0.07)		
Sickle pomfret	0.995 (0.947-1.045)	0.997 (0.913-1.090)	No (*p*=0.88)	No (*p*=0.43)	No (*p*=0.80)		
Escolar	1.154 (1.103-1.206)	1.291 (1.195-1.395)	Yes	Yes	Yes		
Great barracuda						1.793 (1.390-2.317)	Yes

Table 6. Statistical comparison among circle hook sizes on catchability (Generalized Linear Modeling, GLM) of typical bycatch (discarded) species caught in the Hawaii and American Samoa tuna longline fisheries. GLM coefficients are estimates of catchability between circle hook sizes with values greater than 1.0 indicating higher catchability.

	Hawaii					Samoa	
Species	Coefficient (95% CI)		Statistically different			Coefficient (95% CI)	Statistically different
	15/0	16/0	14/0 vs 15/0	14/0 vs 16/0	15/0 vs 16/0	14/0	13/0 vs 14/0
Blue shark	1.028 (0.995-1.062)	1.141 (1.077-1.210)	No (*p*=0.08)	Yes	Yes	1.386 (1.171-1.647)	Yes
Oceanic whitetip shark	1.024 (0.874-1.213)	0.836 (0.601-1.164)	No (*p*=0.83)	No (*p*=0.24)	No (*p*=0.26)	1.647 (1.153-2.372)	Yes
Silky shark	1.011 (0.788-1.300)	0.618 (0.360-1.043)	No (*p*=0.98)	No (*p*=0.06)	No (*p*=0.14)	1.666 (1.23-2.261)	Yes
Shortfin mako shark	0.915 (0.842-0.996)	0.949 (0.819-1.098)	Yes, lower	No (*p*=0.64)	No (*p*=0.58)		
Bigeye thresher	0.833 (0.753-0.921)	1.065 (0.883-1.283)	Yes, lower	No (*p*=0.57)	No (*p*=0.06)		
Pelagic stingray	0.839 (0.764-0.921)	0.910 (0.763-1.082)	Yes, lower	No (*p*=0.30)	No (*p*=0.31)	1.236 (1.095-1.395)	Yes
Knifetail pomfret	1.079 (0.977-1.191)	1.014 (0.841-1.220)	No (*p*=0.14)	No (*p*=0.74)	No (*p*=0.45)		
Longnose lancetfish	0.967 (0.938-0.997)	1.013 (0.960-1.070)	Yes, lower	No (*p*=0.59)	No (*p*=0.07)	1.344 (1.197-1.577)	Yes
Escolar						1.013 (0.868-1.180)	No (*p*=0.86)
Longfin escolar						1.525 (1.293-1.802)	Yes
Snake mackerel	0.805 (0.769-0.842)	0.899 (0.829-0.976)	Yes, lower	Yes, lower	No (*p*=0.06)	0.634 (0.322-0.952)	Yes. lower

Table 7. Mean length (cm FL or cm EFL, ±1 standard deviation) by hook type for 13 species in the Hawaii-permitted longline fishery and results of one-way ANOVA on length frequencies by hook type.

Species	Mean length ± S.D				Significance of mean difference (Tukey HSD)		
	14/0	15/0	16/0	*F*-value (*P*>|*F*|)	14/0−15/0	14/0−16/0	15/0-16/0
Bigeye tuna	111.0±22.39 (n=12,554)	110.3±22.71 (n=25,102)	111.0±22.67 (n=3,481)	6.05 (*P*=0.002)**	*P*=0.003**	*P*=0.998	*P*=0.137
Yellowfin tuna	113.7±26.39 (n=1,958)	113.1± 24.50 (n=4,849)	116.9±24.36 (n=636)	5.76 (*P*=0.003)*	*P*=0.999	*P*=0.006**	*P*=0.002**
Albacore	105.9±8.7 (n=548)	97.3±16.27 (n=1074)	106.4±6.59 (n=182)	99.6 (*P*<0.001)***	*P*<0.001***	*P*=0.881	*P*<0.001***
Skipjack tuna	70.7±7.74 (n=1,675)	70.8±6.68 (n=4,191)	71.8±5.74 (n=1,003)	11.02 (*P*<0.001)***	*P*=0.551	*P*<0.001***	*P*<0.001***
Wahoo	126.2±15.98 (n=1,568)	125.4±15.76 (n=2,702)	128.1±15.31 (n=430)	5.38 (*P*=0.004)**	*P*=0.406	*P*=0.051	*P*=0.003**
Swordfish	111.5±47.52 (n=538)	112.6±48.06 (n=891)	112.0±46.44 (n=136)	0.09 (*P*=0.910)			
Striped marlin	138.3±21.02 (n=1,053)	138.3±21.88 (n=1,755)	138.1±20.01 (n=261)	0.011 (*P*=0.989)			
Blue marlin	172.24±30.95 (n=306)	169.3±29.92 (n=588)	164.1±25.66 (n=68)	2.33 (*P*=0.098)			
Spearfish	134.3±10.68 (n=1,118)	134.5±10.75 (n=1,989)	135.4±8.97 (n=349)	2.02 (*P*=0.133)			
Opah	98.9±10.39 (n=1,277)	99.7±10.97 (n=2,478)	99.1±10.63 (n=361)	2.06 (*P*=0.127)			
Sickle pomfret	58.1±8.85 (n=5,685)	58.6±9.29 (n=8,197)	58.8±8.29 (n=1,092)	4.99 (*P*=0.007)**	*P*=0.017*	*P*=0.047*	*P*=0.593
Escolar	78.4±18.00 (n=2,827)	77.3±17.61 (n=4.893)	78.4±16.00 (n=744)	3.03 (*P*=0.051)			
Mahimahi	85.3±13.58 (n=4,962)	87.1±14.00 (n=7,460)	86.8±14.58 (n=1,137)	21.82 (*P*<0.001)***	*P*<0.001***	*P*=0.008**	*P*=0.769

*** 0≤*P*<0.001, ** 0.001≤*P*<0.01, * 0.01≤*P*<0.05

Table 8. Mean length (cm FL or cm EFL, ±1 standard deviation) by hook type for 5 species in the American Samoa-permitted longline fishery and results of one-way ANOVA on length frequencies by hook type.

Species	13/0	14/0	*F*-value (*P*>|*F*|)
Bigeye tuna	88.6±25.04 (n=281)	91.7±22.23 (n=914)	6.8 (*P*=0.002)**
Yellowfin tuna	102.6±16.12 (n=1,296)	99.7±20.21 (n=2,207)	25.6 (*P*<0.001)***
Albacore	94.7±4.51 (n=3,498)	93.3±5.95 (n=10,273)	173 (*P*<0.001)***
Skipjack tuna	65.9±6.63 (n=566)	67.0±6.95 (n=1,523)	9.5 (*P*<0.001)***
Wahoo	117.4±14.89 (n=293)	119.0±14.62 (n=809)	2.8 (*P*=0.09)

*** 0≤*P*<0.001, ** 0.001≤*P*<0.01, * 0.01≤*P*<0.05

Table 9. Previous hook trials in the Pacific Ocean examining effects of hook size on catchability of fish species.

Author	Hook sizes	Species	Effort (hooks) in hook trials	Findings
Curran and Bigelow 2011	18/0 circle (4.9 cm) vs. Japan tuna (3.6 sun [3.1 cm]) vs. size J 9/0 (3.9 cm).	18 retained and bycatch species. Species with minimum catch had 350 individuals	1393 sets (2,773,427 hooks); 1182 sets were circle hooks vs. tuna hooks and 211 sets were circle hooks vs. J-hooks.	no significant catchability difference for bigeye and skipjack tunas between circle and tuna hooks. significant lower catchability for 16 species on circle hooks compared to tuna hooks. no significant catchability difference for ten species between circle and J-hooks. significant lower catchability for eight species on circle hooks compared to J-hooks.

Curran and Beverly 2012	16/0 circle (4.4 cm) vs. smaller circle hooks (3.3-3.9 cm)	14 retained and bycatch species. Retained species with a minimum catch of 20 individuals. Bycatch species with a minimum catch of 30 individuals.	67 sets with 145,982 hooks	no significant catchability difference for albacore in any location. For A.Samoa there was reduced catchability for three retained species (skipjack tuna, shortbill spearfish, and wahoo) and three bycatch species (escolar, longnose lancetfish, and great barracuda).
Ward et al. 2009*	Circle hooks (sizes 13/0 to 18/0) vs J Tuna sun hooks (2.8- 3.6 cm)	28 species	76 sets with 95,150 hooks	significant catchability difference for albacore and crocodile shark No significant catchability difference for blue shark
Walsh et al. 2009	Mostly J9, vs C 18	Blue shark		Significant reduction after regulations in Hawaii shallow set regulations of 18/0 circle hook and fish bait
Minami et al. 2006	3.8-sun tuna hook vs. 4.3 and 5.2-sun (~ 18/0) circle hooks	Loggerhead Tuna species	52 sets with 48,600 hooks	Larger (5.2 cm) hooks resulted in fewer turtle captures No significant effect catchability difference for swordfish or bigeye tuna on any hook size. Significant difference for billfish on 5.2 sun hooks, but low sample size

Yokota et al. 2006	3.8 sun and wider cicle hooks (4.3 and 5.2 cm)	Blue shark	52 sets with 48,600 hooks	No significant catchability difference for blue shark

* Note flawed study with wide range of circle hooks. Also, sample sizes in crocodile sharks is <10.

Figure 1. Circle hook dimensions.

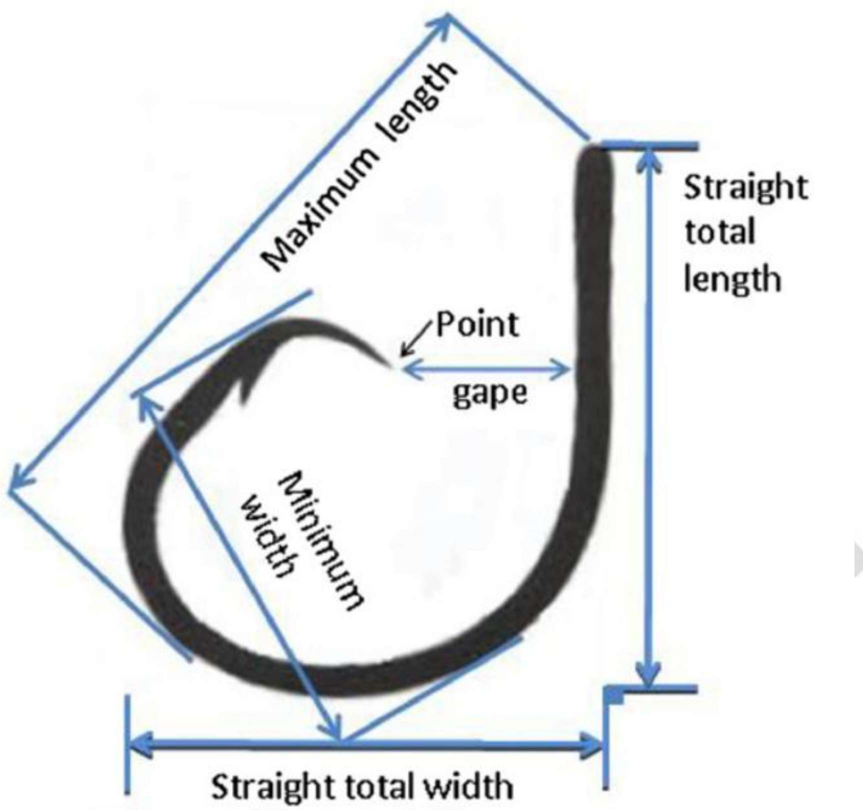

Figure 2. Comparison of circle hook catchability for 11 species usually kept in the Hawaii tuna longline fishery. Mean catchability (circles) is the exponent of the GLMM estimated parameters by hook size and horizontal lines are the 95% confidence intervals around the estimate. The value of 1.0 corresponds to the catchability of size 14/0 circle hooks. Red is the catchability of size 15/0 circle hooks and blue is the catchability of size 16/0 circle hooks.

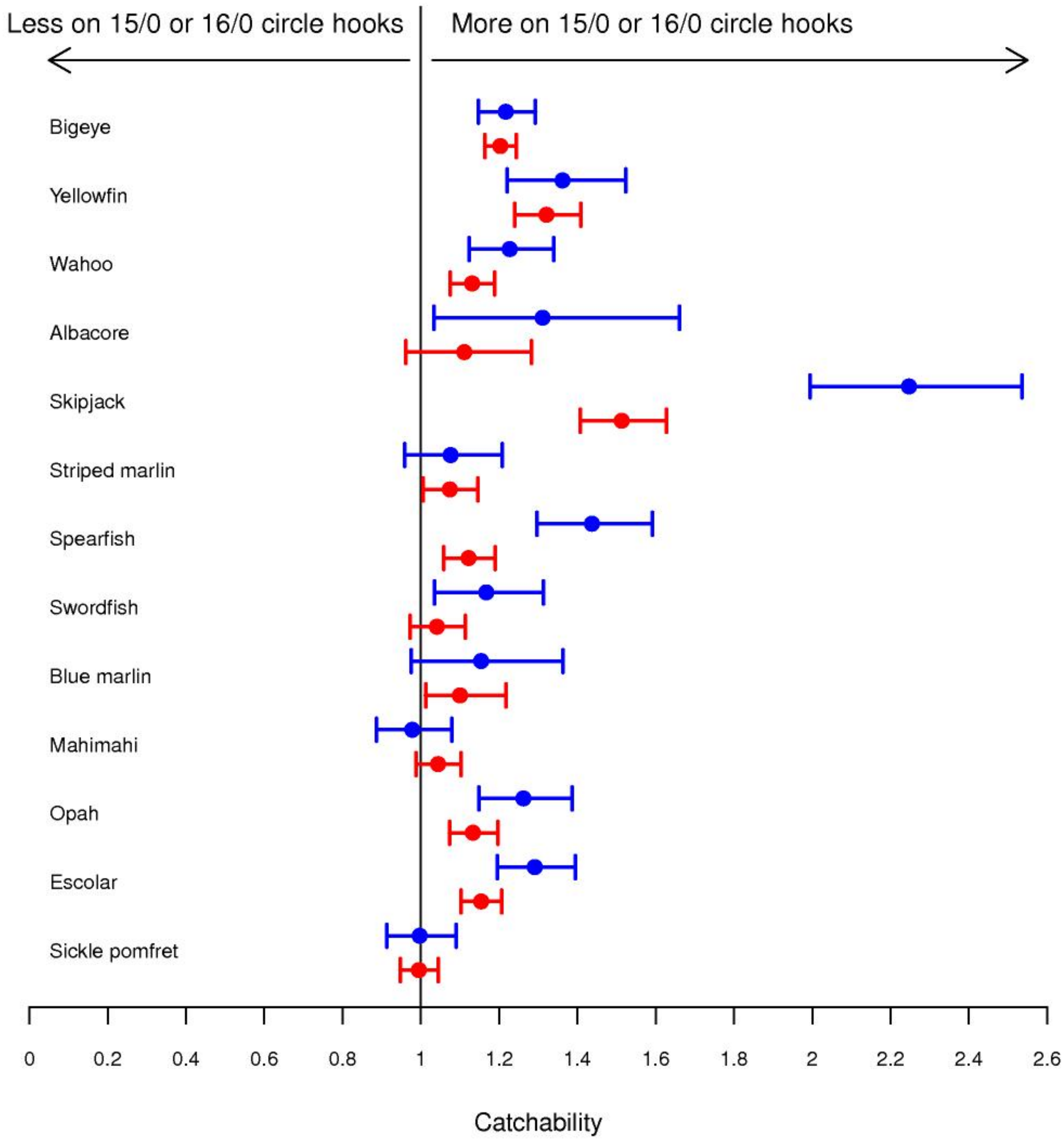

Figure 3. Comparison of circle hook catchability for 11 species usually discarded in the Hawaii tuna longline fishery. Mean catchability (circles) is the exponent of the GLMM estimated parameters by hook size and horizontal lines are the 95% confidence intervals around the estimate. The value of 1.0 corresponds to the catchability of size 14/0 circle hooks. Red is the catchability of size 15/0 circle hooks and blue is the catchability of size 16/0 circle hooks.

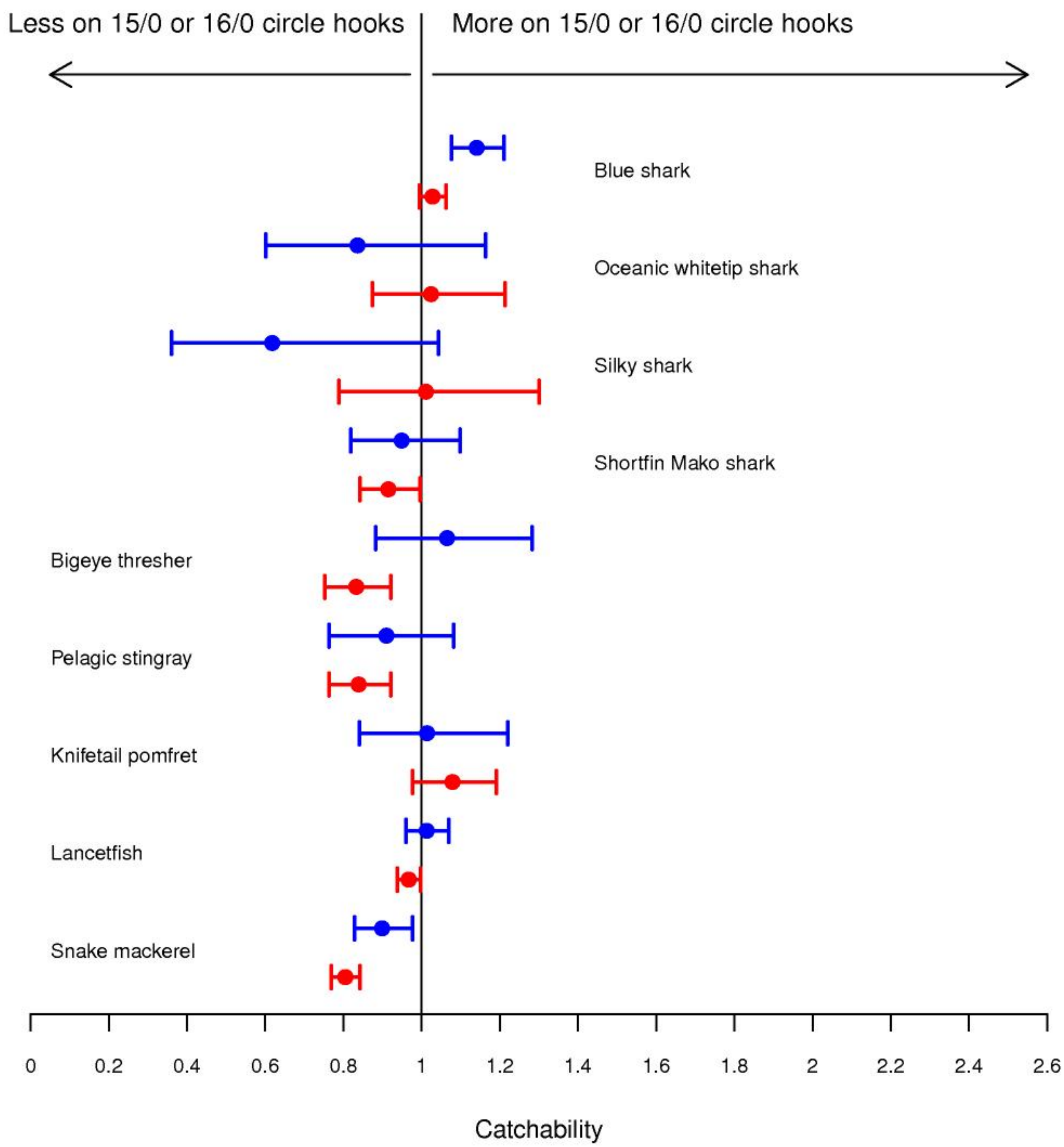
Less on 15/0 or 16/0 circle hooks
More on 15/0 or 16/0 circle hooks
Blue shark
Oceanic whitetip shark
Silky shark
Shortfin Mako shark
Bigeye thresher
Pelagic stingray
Knifetail pomfret
Lancetfish
Snake mackerel
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
Catchability

Figure 4. Comparison of circle hook catchability for 16 species usually kept or discarded in the American Samoa tuna longline fishery. Mean catchability (circles) is the exponent of the GLMM estimated parameters by hook size and horizontal lines are the 95% confidence intervals around the estimate. The value of 1.0 corresponds to the catchability of size 13/0 circle hooks. Blue is the catchability of size 14/0 circle hooks.