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EFFECTS OF 16/0 CIRCLE HOOKS ON PELAGIC FISH CATCHES IN THREE SOUTH PACIFIC ALBACORE LONGLINE FISHERIES

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ABSTRACT

The present study tested the effects of using large 16/0 circle hooks on catch rates in three pelagic longline fisheries in the South Pacific Ocean. Large (16/0) circle hooks were tested against a variety of smaller hooks already in use by longline vessels in American Samoa, Cook Islands, and New Caledonia. The majority of these fleets use a mix of hook sizes, including circle hooks that are smaller than a 16/0 circle hook. Vessels alternated hooks throughout every set, maintaining a 1:1 ratio of 16/0 circle hooks to their existing hooks. Information on catch by hook size, fish lengths, and condition at gear retrieval was collected. In total, 4912 fishes of 33 species were observed on 145,982 hooks from 67 sets. In the Cook Islands fishery, there was no significant difference in catch by hook type for two main target species, but there was an increase in catchability for swordfish, *Xiphias gladius* (Linnaeus, 1758). In the New Caledonia fishery, there was no significant difference in catch by hook size for any species. In the American Samoa fishery, 16/0 circle hooks did not significantly affect the catch of albacore, *Thunnus alalunga* (Bonnaterre, 1788), but did significantly reduce the catch of skipjack tuna, *Katsuwonus pelamis* (Linnaeus, 1758), dolphinfish, *Coryphaena hippurus* (Linnaeus, 1758), and wahoo, *Acanthocybium solandri* (Cuvier, 1832). For all locations, catch rates on 16/0 circle hooks were nominally lower, but not always significant for smaller pelagic species.

Reducing rates of interaction with protected and non-target species of concern has been identified as a fisheries management priority in the United States and has garnered worldwide interest (e.g., Kerstetter and Graves 2006, FAO 2009). Pelagic longline fishing has been identified specifically as a threat to protected sea turtle and seabird populations globally (Brothers et al. 1999, Lewison et al. 2004) and there is concern that some non-target species are currently being overfished in North Pacific Ocean longline fisheries (Brodziak and Piner 2010).

A myriad of types, sizes, and shapes of hooks are used within longline fisheries globally (Gilman et al. 2006). Circle hooks (Fig. 1) are generally defined as circular or oval in shape and have a point that is perpendicular to a shank that curves inward and is less exposed than conventional tuna and J-hooks where the point is parallel to the shank (Cooke and Suski 2004, Yokota et al. 2006, Serafy et al. 2009). In addition to shape effects, overall size (i.e., minimum width) has also been indicated as a factor influencing catchability (Curran and Bigelow 2011), with the minimum width being greater in circle hooks vs similar sized J- or tuna style hooks.

The objective of the present study was to quantify the effects of size 16/0 circle hooks in commercial albacore longline fisheries in the South Pacific Ocean that are presently using circle hooks (Fig. 1) and other types of hooks that are <16/0 (i.e., minimum width <4.4 cm). The South Pacific albacore catch in 2009 was 66,996 t and was the highest in history (OFP 2010). Most (97%) of the South Pacific albacore catch is captured by longline fisheries including the Chinese-Taipei and China distant-water fleets and vessels that operate within their nation's exclusive economic zone

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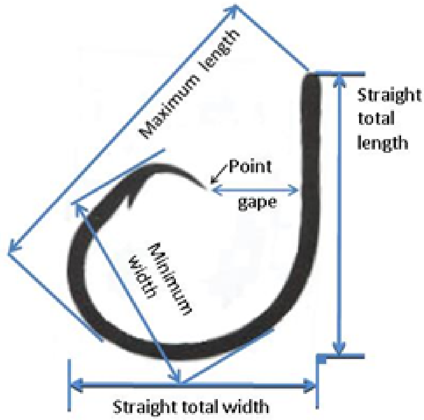

Figure 1. Measurement terminology of a circle hook [modified from fig. 1 in Curran and Bigelow (2011)].

in various Pacific Island countries between 10°S and 25°S. Since 2000, the longline catch has increased, largely as a result of the development of small-scale longline fisheries in Pacific Island countries including American Samoa, Cook Islands, Fiji, French Polynesia, New Caledonia, Samoa, and Tonga (OFP 2010).

Simple and relatively inexpensive gear modifications, such as the use of large circle hooks and a shift in bait from squid to fish in shallow-set (<100 m) longline fisheries have been shown to be an effective tool to mitigate sea turtle takes in US swordfish longline fisheries in the Atlantic and Pacific Oceans (Swimmer et al. 2005, Gilman et al. 2007, Read 2007). Despite the demonstrated efficacy of large circle hooks to mitigate sea turtle takes, studies comparing circle hook catchability and direct mortality rates of target and non-target species to other hook types in pelagic fisheries have often yielded conflicting and variable results. Two meta-analyses (Cooke and Suski 2004, Serafy et al. 2009) tested the performance of circle hooks and J-hooks for species-specific capture efficiency (i.e., catchability), mortality rate, and injury caused by hooking and bleeding. In 28 studies of marine recreational fisheries, circle hooks showed an overall tendency for lower fish mortality (Cooke and Suski 2004). A quantitative review (Serafy et al. 2009) of istiophorid-focused circle hook studies provided 30 species-specific comparisons of circle hooks vs J-hooks in recreational rod-and-reel and commercial fisheries and found 13 instances where significant differences between hook types were found. However, no significant differences in catch rates were found for four billfish species. This review concluded that without evidence of negative effects from the use of circle hooks, there was a scientific basis for their promotion when considering billfish fisheries. Consistent with this contention, a recent study in the Hawaii-based tuna longline fishery found that catch rates on circle hooks were significantly lower for 16 species compared to Japanese-style tuna hooks and suggested a potential catch reduction of 29.2%–48.3% for billfishes and 17.1%–27.5% for sharks if 18/0 circle hooks were adopted throughout the Hawaii-based fleet (Curran and Bigelow 2011). Differing results among circle hook studies have led some researchers (e.g., Cooke and Suski 2004, Read 2007) to conclude that fishery managers should only promote circle hooks when appropriate scientific data from fishery-specific rigorous field experiments supports their use. Serafy et al.

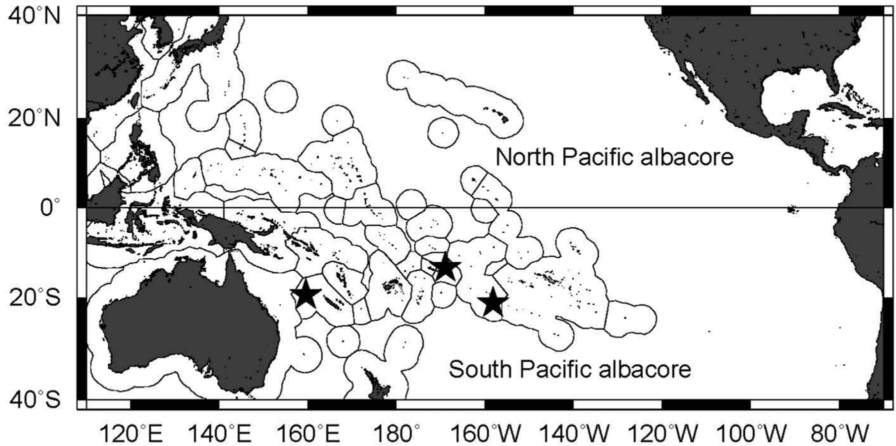

Figure 2. Three study locations (stars) and exclusive economic zones of Pacific Island countries. From left to right (approximately 160°E to 160°W) these are New Caledonia, American Samoa, and Cook Islands.

(2009) took issue with this conclusion. They argued that this stance is counter to the precautionary approach and making testing a pre-condition for a gear change would delay benefits for species known to be overfished, threatened, or endangered.

In the present study, we evaluated circle hooks in three domestic Pacific Island fisheries for catchability of target, incidental (retained non-target), and bycatch (discarded) species; size selectivity; and condition (dead or alive upon gear retrieval). We investigated the operational viability of each fishery to adopt 16/0 circle hooks.

Materials and Methods

Vessel Protocols.—A single cooperative fishing vessel was used in each of three locations (off Cook Islands, New Caledonia, and American Samoa; Fig. 2) to alternate 16/0 circle hooks (hereafter referred to as "16C") with their existing complement of hooks [hereafter referred to as "<16C" (Table 1, Fig. 3)]. As part of the cooperative nature of the study, vessel operators were given the option of choosing from several types of 16C (i.e., offset or non-offset and ringed or non-ringed). All participants chose to test offset hooks and one (New Caledonia) opted to test ringed hooks. During longline operations, vessel crews alternated hook types along an entire longline set and for all sets during the field trials. To ensure that the first hook after a float would alternate by hook type, crews were encouraged to deploy an odd number of hooks between floats. To minimize sources of variation, no change was made to any other gear or operational characteristics. Vessel captains chose how, when, and where they fished and were also allowed to retain, discard, and sell their fish in their normal manner. Branchline snaps were either painted or marked with 10-cm cable ties to allow for easy identification of the terminal hook type and corresponding fish catch.

In all three locations, the 16C used were stainless steel 5° offset circle hooks (Fig. 3). The gape of the 16C measured 2.4 cm and the minimum width measured 4.4 cm (Table 1). In the Cook Islands, the vessel's <16C consisted of at least 11 different types and sizes of hook making it impractical to keep track of all hook categories, but most (>80%) were equivalent to a 13/0 circle hook with a gape of 1.8 cm and a minimum width of 3.8 cm (Table 1) and all were smaller than the 16C. In New Caledonia, the vessel's <16C were sized 15/0 non-ringed stainless steel circle hooks, and the vessel owner insisted we use a ringed 16C in this location. In

Table 1. Dimensions of 16/0 circle hook (16C) and dimensions of hooks (<16C) in use by the cooperating vessels during the field trials. Terminology is after Curran and Bigelow (2011).

Location	All	Cook Islands	New Caledonia	American Samoa
Nominal size	16/0	13/0	15/0	14/0
Gape (cm)	2.5	1.6	1.8	2.0
Minimum width (cm)	4.4	3.3	3.9	3.8

American Samoa, the vessel's <16C were size 14/0 stainless steel circle hooks with a 5° offset. The gape of the 14/0 hooks measured 2.0 cm and the minimum width measured 3.8 cm (Table 1). The <16C, normally used by the cooperating fishing vessels, were considered by the investigators to be the average hooks used in their respective fisheries (Fig. 2). To ensure a 1:1 ratio of 16C to <16C throughout the trials, additional gear was provided to enable a vessel to replace lost and damaged gear while fishing. All locations used 60–80 g Pacific sardines (*Sardinops sagax* Jenyns, 1842) for bait. In American Samoa, bait were hooked into the body anterior to the dorsal fin, but in the Cook Islands and New Caledonia bait were hooked by a single pass of the point of the hook completely through the head or eye socket. All three vessels used standard commercial pelagic longline techniques as described in Suzuki et al. (1997) employing all monofilament gear (3.6 mm mainline) and deploying from 21 to 31 2.0-mm branchlines at 5-s intervals between consecutive floats.

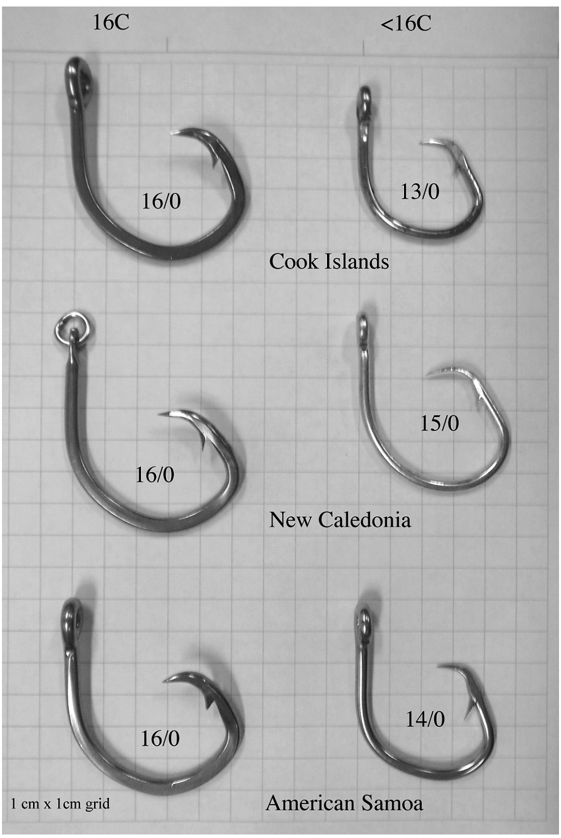

Figure 3. Lateral view of 16/0 circle hooks (16C) and the smaller (<16C) used in 3 locations during field trials (1 cm × 1 cm grid).

Observer Protocols.—All data were collected by the authors in New Caledonia and American Samoa, but in the Cook Islands, one author accompanied and trained an observer from the Cook Islands Ministry of Marine Resources on the first trip and that observer then collected data from the three additional trips. Information was collected using standardized forms and procedures on all catch identified by species, hook type, sequential hook number between two floats, condition (recorded as alive or dead at the time of gear retrieval with any physiological responsiveness being categorized as alive), catch disposition (retained, discarded), length measurements (lower jaw fork length), bait retention (full, partial, none) at retrieval on hooks without catch, daily tally of the numbers of each type of hook deployed, and the crew's ability to alternate hook types. During the first set of any trip, the entire gear deployment procedure was monitored to qualitatively note any differences in crew methods as a result of using different hook types. Temperature depth recorders (TDR) were placed midway between floats at least once on all sets to record fishing depths and mean depth of deepest hook was estimated by computing the mean depth of the TDR depth trace during the gear soak period (data from the first and last 2 hrs of deployment were excluded from analysis).

Statistical Methods.—A randomization test (Manly 2007) was used to assess catchability differences between hook types, following recommendations on methods used to assess 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 is straightforward with minimal assumptions, and the method used (Curran and Bigelow 2011) 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. The null hypothesis is that there would be no difference in catch between paired hook types and the test statistic (*S*) was the mean difference in catch between hook types by species and by individual longline set. Data were randomized and resampled 10,000 times and then scored for whether or not the resampled *S* value was equal to or greater than the observed *S* value.

The chi-square test (χ^2) was used to compare differences in condition (alive or dead) on longline retrieval. Odds ratios were calculated to determine the relative increase in survival for 16C compared to <16C for all locations combined. For each species, if an odds ratio

$$\frac{(alive_{16C})/(dead_{16C})}{(alive_{<16C})/(dead_{<16C})}$$

had a value >1.0, then higher survival occured on 16C than on <16C. A total of 14 species (target species and species with a total catch of 31 or more individuals) were chosen for all analyses (Table 2).

Results

Fishing Gear and Catches.—In total, 4912 fishes of 33 species were caught on 145,982 hook observations from 67 sets within the three fisheries (Tables 2, 3). In American Samoa, operations were conducted within an area ranging from 11°S to 16°S and 168°W to 170°W, and all catch was delivered frozen to the American Samoa cannery. In the Cook Islands, operations were conducted within 30 nmi of the island of Rarotonga (21°14´S, 159°46´W). The Cook Islands vessel marketed all fish fresh on a weekly basis in the Cook Islands through a retail market owned by the vessel company. In New Caledonia, fishing ranged from 19°S to 20°S and 159°E to 160°E. The New Caledonia-based vessel marketed fresh fish to buyers for sale in New Caledonia or for transshipment to France. Mean depth of deepest hook for all sets combined ranged from 158 to 327 m and was location specific, reflecting the different operational methodologies used in the three study locations (Table 3).

Table 2. Statistical comparison (randomization test) and total catch by hook type for target species and other species where more than 30 individuals were caught on experiments alternating 16/0 circle hooks (16C) and a vessel's smaller hooks (<16C) for three South Pacific Ocean locations. Bold indicates $P < 0.05$.

		American Samoa			Cook Islands			New Caledonia		
Species	Common name	<16C	16C	*P*	<16C	16C	*P*	<16C	16C	*P*
Tunas										
Thunnus alalunga (Bonnaterre, 1788)	Albacore	1,143	1,122	0.8962	25	36	0.2263	86	76	0.6518
Thunnus obesus (Lowe, 1839)	Bigeye tuna	63	73	0.5263	12	9	0.5740	1	2	0.7287
Katsuwonus pelamis (Linnaeus, 1758)	Skipjack tuna	190	101	**0.0109**	5	2	0.4442	6	3	0.4015
Thunnus albacares (Bonnaterre, 1788)	Yellowfin tuna	306	293	0.8439	7	8	0.9028	2	3	0.7512
Billfishes										
Xiphias gladius Linnaeus, 1758	Swordfish	2	2	0.9345	14	30	**0.0130**			
Makaira nigricans Lacépède, 1802	Blue marlin	9	6	0.3450	1	4	0.9214			
Tetrapturus angustirostris Tanaka, 1915	Shortbill spearfish	26	6	**0.0005**	1	5	0.8847			
Other										
Coryphaena hippurus Linnaeus, 1758	Dolphinfish	59	47	0.0178	25	36	0.2519	17	14	0.8494
Acanthocybium solandri (Cuvier, 1832)	Wahoo	148	77	**0.0026**	5	6	0.8843	12	11	0.9191
Bycatch (*n* >30)										
Prionace glauca (Linnaeus, 1758)	Blue shark	54	42	0.3798	1	5	0.1723	23	12	0.1444
Pteroplatytrygon violacea (Bonaparte, 1832)	Pelagic stingray	27	17	0.0729	4	0		1	2	0.7639
Lepidocybium flavobrunneum (Smith, 1845)	Escolar	102	30	**0.0001**				3	2	0.8468
Alepisaurus ferox Lowe, 1833	Longnose lancetfish	56	29	**0.0040**	1	0		38	26	0.3327
Sphyraena barracuda (Edwards, 1771)	Great barracuda	31	14	**0.0020**				7	1	0.2051

Other species with catches ≤30 individuals: snake mackerel, *Gempylus serpens* Cuvier, 1829, silky shark, *Carcharhinus falciformis* (Müller and Henle, 1839), sickle pomfret, *Taractichthys steindachneri* (Doderlein, 1833), shark unidentified Chondrichthyes, black marlin, *Makaira indica* (Cuvier, 1832), shortfin mako shark, *Isurus oxyrinchus* Rafinesque, 1810, oceanic white-tip shark, *Carcharhinus longimanus* (Poey, 1861), opah, *Lampris guttatus* (Brünnich, 1788), sailfish, *Istiophorus platypterus* (Shaw, 1792), bigeye thresher shark, *Alopias superciliosus* (Lowe, 1841), pelagic thresher shark, *Alopias pelagicus* (Nakamura, 1935), slender mola, *Ranzania laevis* (Pennant, 1776), hammerjaw, *Omosudis* lowii Günther, 1887, pomfret unidentified Bramidae, striped marlin, *Kajikia audax* (Philippi, 1887), pelagic puffer, *Lagocephalus lagocephalus* (Linnaeus, 1758), gray reef shark, *Carcharhinus amblyrhynchos* (Bleeker, 1856), and sharptail mola, *Masturus lanceolatus* (Lienard, 1840).

Table 3. Operational characteristics and summary results of the three fisheries in the hook trials.

Location	American Samoa	Cook Islands	New Caledonia	Totals
Vessel length (m)	27	18	25	
Longline fishing type	Deep day	Shallow night	Deep day	
Target species	Albacore	Tunas, swordfish	Albacore	
<16C hook type(s)	14/0 SS circle no ring	approximately 13/0 (11 types/sizes)	15/0 SS circle no ring	
16C hook type	16/0 SS no ring	16/0 SS no ring	16/0 SS ringed	
Sets	43	19	5	67
Total hooks	108,036	27,538	10,408	145,982
Hooks per set	2,512	1,449	2,082	
Hooks per float	29	21	31	
Depth of deepest hook	267	158	327	
Species	28	20	18	
Total fishes	4,181	374	357	4,912

Catch Rates (Catchability).—*American Samoa.*—Nominal catch per unit effort (CPUE) for all fishes caught was 37.9 fish per 1000 hooks. Albacore represented 54% of the overall catch by number. The CPUE was the highest for albacore (20.6 for <16C and 20.1 for 16C). Yellowfin tuna (*Thunnus albacares*, see Table 2 for species authorities) CPUE was the next highest (5.5 for <16C and 5.4 for 16C). All other species showed much lower catch rates. Randomization tests indicated that 16C had significantly lower catch rates for three retained species (skipjack tuna, *Katsuwonus pelamis*, shortbill spearfish, *Tetrapturus angustirostris*, and wahoo, *Acanthocybium solandri*) and also had lower catch rates for discarded escolar (*Lepidocybium flavobrunneum*), longnose lancetfish (*Alepisaurus ferox*), and great barracuda (*Sphyraena barracuda*, Table 2).

Cook Islands.—Nominal CPUE for all fishes was 13.6 fish per 1000 hooks. Albacore and dolphinfish (*Coryphaena hippurus*) each represented 17.3% of the total catch by number with identical CPUEs of 2.2 fish per 1000 hooks and identical catch numbers by respective hook type (25 by <16C and 36 by 16C). Swordfish was the third largest component of catch (12.3%) with a CPUE of 1.5 fish per 1000 hooks. Randomization tests did not indicate a significant reduction in catch for any species, but did indicate significantly higher catch rates with 16C for swordfish (Table 2).

New Caledonia.—Nominal CPUE for all fishes was 34.3 fish per 1000 hooks. Albacore comprised 43% of the total catch by number with a CPUE of 15.6 fish per 1000 hooks. Discard species such as longnose lancetfish (CPUE of 6.1 fish per 1000 hooks) and blue shark, *Prionace glauca* (CPUE of 3.4 fish per 1000 hooks), were the next largest components of total catch. Randomization tests were not significant for all species analyzed (Table 2).

Size Selectivity.—Among the 11 species tested across all locations combined, there were significant differences in the fork length of fish caught by 16C vs <16C hooks for bigeye and yellowfin tuna ($P < 0.01$, Table 4).

Condition at Retrieval.—Condition at retrieval (alive upon gear retrieval) varied considerably among the 14 species analyzed (Table 5). The percentage of fish identified as alive at retrieval was significantly higher on 16C compared to <16C for blue

Table 4. Mean fork length (cm) ± standard deviation by hook type for 11 fish species and results of one-way ANOVA on length frequencies by hook type. There were no lengths recorded for blue shark, pelagic stingray, and escolar. 16C = 16/0 circle hook, <16C = 13/0, 14/0, and 15/0 circle hooks. Bold indicates $P < 0.05$.

Species	16C	<16C	*F*-value ($P > \|F\|$)
Tunas			
Albacore	94.8 ± 5.43 (*n* = 1,146)	94.4 ± 5.93 (*n* = 1,165)	2.857 (*P* = 0.091)
Bigeye tuna	109.6 ± 22.33 (*n* = 82)	93.3 ± 20.15 (*n* = 78)	24.001 (***P* < 0.001**)
Skipjack tuna	67.6 ± 5.91 (*n* = 89)	66.2 ± 7.37 (*n* = 177)	3.047 (*P* = 0.082)
Yellowfin tuna	99.3 ± 21.42 (*n* = 275)	94.0 ± 18.00 (*n* = 268)	8.609 (***P* = 0.003**)
Billfishes			
Swordfish	157.1 ± 38.05 (*n* = 15)	154.1 ± 40.34 (*n* = 28)	0.107 (*P* = 0.745)
Blue marlin	179.8 ± 29.45 (*n* = 10)	179.7 ± 25.58 (*n* = 3)	0.002 (*P* = 0.966)
Shortbill spearfish	152.0 ± 16.58 (*n* = 6)	139.1 ± 23.37 (*n* = 7)	1.510 (*P* = 0.245)
Other			
Dolphinfish	98.7 ± 15.53 (*n* = 89)	99.4 ± 16.41 (*n* = 98)	0.054 (*P* = 0.816)
Wahoo	122.8 ± 14.25 (*n* = 84)	121.7 ± 15.25 (*n* = 150)	0.339 (*P* = 0.561)
Bycatch (*n* > 30)			
Longnose lancetfish	130.9 ± 23.44 (*n* = 14)	118.9 ± 25.44 (*n* = 14)	1.438 (*P* = 0.241)
Great barracuda	104.7 ± 20.81 (*n* = 4)	105.1 ± 13.23 (*n* = 11)	0.013 (*P* = 0.911)

marlin, *Makaira nigricans* (χ^2 test: $P = 0.006$), and pelagic stingray, *Pteroplatytrygon violacea* ($P < 0.001$), and significantly lower for swordfish ($P = 0.004$), shortbill spearfish ($P < 0.001$), blue shark ($P = 0.002$), and wahoo ($P < 0.001$).

Operational Viability of Adopting the Use of 16/0 Circle Hooks.—All three vessel crews were able to incorporate 16/0 circle hooks into their fishing operations with minimal alteration to their normal methodologies. All vessels used an audible timer during gear deployment and no alteration of timing or baiting methods by hook type was observed during gear deployment. Bait retention did not differ significantly (full, partial, none) by hook type and there were no qualitative observations that the use of 16C added time to gear retrieval or fish handling operations. During the trials, all crews and captains indicated that the adoption of 16C in their respective fisheries would not have a deleterious effect on their daily operations (DC and SB, pers obs).

Discussion

The present study examined catchability (catch rate by hook type), condition (alive or dead at retrieval), and the viability of using 16/0 circle hooks in South Pacific pelagic longline fisheries. This study focused on three locations that all target albacore in South Pacific waters, but are operationally, culturally, and commercially distinct from each other. Although there is a paucity of circle hook research information in these three locations, the consistency of results for albacore catchability from these three disparate fisheries indicates broad applicability to other albacore longline fisheries throughout the South Pacific. The cooperative nature of the study precluded the larger monitoring efforts originally targeted for the Cook Islands where after the initial trip, the vessel owner wanted to switch all of his hooks to 16/0 circle hooks and only agreed to allow three more observed trips before discontinuing the study. In New Caledonia, an observer was successfully trained on the first trip and expected to continue the study, but the project was then abandoned by the observer's employer.

Table 5. Effect of hook type on condition (survival at retrieval) for 14 fish species and all locations combined. 16C = 16/0 circle hook, <16C = 13/0, 14/0, and 15/0 circle hooks. Bold indicates $P < 0.05$.

	Percent survival		Percent survival		
Species	16C	Total fish (*n*)	<16C	Total fish (*n*)	Odds ratio (*P*-value)
Tunas					
Albacore	21.52	1,199	19.63	1,228	1.10 (0.645)
Bigeye tuna	47.62	84	40.74	81	1.17 (0.168)
Skipjack tuna	3.03	99	4.19	191	0.72 (0.499)
Yellowfin tuna	42.35	307	41.86	301	1.01 (0.922)
Billfishes					
Swordfish	25.00	32	12.50	16	2.00 (**0.004**)
Blue marlin	36.36	11	55.56	9	0.65 (**0.006**)
Shortbill spearfish	54.55	11	14.81	27	3.68 (**< 0.001**)
Other					
Dolphinfish	71.13	97	66.99	103	1.06 (0.360)
Wahoo	26.02	342	6.17	162	4.22 (**< 0.001**)
Bycatch (*n* > 30)					
Blue shark	79.41	68	67.11	76	1.18 (**0.002**)
Pelagic stingray	5.26	19	15.63	32	0.34 (**< 0.001**)
Escolar	21.88	32	20.75	106	1.05 (0.786)
Longnose lancetfish	12.28	57	11.34	97	1.08 (0.774)
Great barracuda	66.67	15	57.89	38	1.15 (0.063)

Catchability and Condition Comparisons.—There were no significant catchability differences between hook types for albacore in any location; however, randomization tests indicated that in American Samoa 16/0 circle hooks reduced the catchability of three incidental (skipjack tuna, shortbill spearfish, and wahoo) and three bycatch species (escolar, longnose lancetfish, and great barracuda). Randomization results from the Cook Islands and New Caledonia were not significant for both target and bycatch species, except for an increase in catchability of swordfish by 16/0 circle hooks in the Cook Islands. The failure to detect catchability differences in these two locations may be a result of the relatively small sample sizes for most species analyzed. Comparing previous hook efficiency studies to our results is problematic as other studies have been based in different fisheries, often tested many variables such as several hook types and baits simultaneously leading to confounding results, and also were constrained by small sample sizes leading to inconclusive statistical analyses. In contrast to our results of no significant difference in catchability by hook size for albacore, a previous study by Ward et al. (2009) tested four sizes of circle hooks (13/0–18/0) on 10 trips in an Australia-based longline fishery targeting tunas and swordfish and used conditional logistic regression models (Hosmer and Lemeshow 1988) to analyze the results. Overall, Ward et al. (2009) found an increase in catchability for albacore, yellowfin tuna, black oilfish (reported as *Lepidocybium flavobrunneum*), and striped marlin for all circle hook sizes combined compared to Japanese tuna hooks. However, these results may be confounded by combined results from different test hook sizes: out of 76 total longline sets, 56 tested 14/0 circle hooks and only 4 (4096 hooks) tested 16/0 circle hooks against 3.4 sun (approximately 14/0) Japanese tuna hooks. Although our results indicate that introducing a 16/0 circle hook into the South Pacific longline fisheries would not reduce catch rates of target species, the use of an even larger circle hook (18/0, minimum width 4.9 cm) may reduce catchability of albacore and other marketable species in other pelagic longline fisheries in the Pacific Ocean. A study testing 18/0 circle hooks (Curran and Bigelow 2011) against 3.6 sun (minimum width 3.1 cm) Japanese tuna hooks (1182 sets) and against 9/0 (minimum width 3.9 cm) J-hooks (211 sets) in the Hawaii-based tuna longline fishery yielded results that were consistent with ours, indicating that a larger hook reduces catch rates of skipjack tuna, shortbill spearfish, longnose lancetfish, and escolar. Curran and Bigelow (2011) also found that the use of 18/0 circle hooks compared to tuna hooks may cause a significant reduction in catch rates of many other targeted and discarded species such as albacore (33.6%), billfish (29.2%–48.3%), and pelagic sharks (17.1%–27.5%).

Our results are consistent with the hypothesis that an increase in overall hook size up to 16/0 (as measured by minimum width) causes a reduction in catchability of smaller-mouthed pelagic species. Such size and shape effects have been shown to be a factor in reducing sea turtle interactions (Gilman et al. 2005), and recent research on pelagic species indicates that a larger minimum width relates to a smaller probability of ingestion and reduces catchability of smaller mouthed species such as dolphinfish and pelagic stingray (Curran and Bigelow 2011). Piovano et al. (2010) compared 16/0 circle hooks to J-hooks in the Mediterranean and found approximately 80% reduction in pelagic stingray catches; and in the Atlantic, Pacheco et al. (2011) found approximately 89% reduction in pelagic stingray ray catch on 18/0 circle hooks compared to J-hooks. Circle hooks have been shown to increase hooking survival of sea turtles (Sales et al. 2010) and billfishes (Kerstetter and Graves 2006, Diaz 2008) by showing a tendency to become lodged in the jaw as opposed to passing into the gills or gut before the hook sets. The hooks tested in the present study varied in size and not shape, thus any effect on survival at retrieval should also be a result of minimum width effects. There was a significant decrease in survival on 16C hooks for blue marlin and pelagic stingray, but these results were based on a relatively small number of samples. Our results show an increase in hooking survival on 16/0 circle hooks for four species and direct survival odds ratios above 2.0 for shortbill spearfish and wahoo, but there is a paucity of similar studies utilizing 16/0 circle hooks in the Pacific Ocean to compare these findings and the results may also be conflated with overall catchability effects.

Size Selectivity.—We detected significant differences in size selectivity for bigeye and yellowfin tuna on 16/0 circle hooks, but not for any other species. Our results indicate that the use of 16/0 circle hooks in the South Pacific would cause an increase in the number of larger bigeye and yellowfin tuna caught. Kerstetter and Graves (2006) found size-selectivity differences for yellowfin tuna and dolphinfish, but they also indicated that seasonality may have been a factor in their results. Seasonality may also have been an issue in our results as all three locations were sampled during relatively short time frames (<3 mo). In contrast to our results, Curran and Bigelow (2011) did not find any evidence of size-selectivity differences for bigeye and yellowfin tuna on 18/0 hooks compared with 3.6 sun tuna hooks or 9/0 J-hooks, but did detect size selectivity significance for skipjack tuna, swordfish, and blue marlin. The catch rates of these three species were relatively low in our study, thus our sample size may be too low to detect differences.

Operational Viability of a Fishery to Adopt Use of 16/0 Circle Hooks.—Several criteria must be considered when implementing gear modifications in a fishery (Gilman et al. 2003). Ideally, a measure reduces bycatch, does not increase interactions with protected species, requires minimal amount of alteration of established fishing practices, proves practical and safe, increases or maintains fishing efficiency, and remains enforceable. Introducing 16/0 circle hooks into the South Pacific commercial longline fisheries would meet most of these criteria. The cost of a 16/0 circle hook (approximately US$0.50) is higher than the cost of a 14/0 circle hook (approximately US$0.35), but this single change to the existing gear would not otherwise alter current fishing practices or costs. All three vessels kept about 3000 hooks on board, thus a one-time change to 16/0 circle hooks would cost one of these vessels approximately US$1500. A new hook usually lasts for multiple trips and even several seasons, but replacement costs for lost and damaged hooks would be higher for 16/0 circle hooks, especially if a vessel encounters high shark bycatch and has to replace hundreds of hooks on a single trip. The reduction in catch of some bycatch species may increase fishing efficiency. Qualitatively, there were no observed operational or safety issues during the study, and all concerns that the fishermen originally expressed regarding bait retention were alleviated over the course of the study as all participants indicated a willingness to use 16/0 hooks in future operations. There was no decrease in fishing efficiency for albacore, but there was a reduction in marketable shortbill spearfish in American Samoa. There were no interactions with birds, sea turtles, or marine mammal species during the study. The three fisheries in the study operate under different management regimes, but all are regulated, have observer programs to monitor the fisheries, and possess enforcement entities that could potentially ensure compliance if 16/0 circle hooks were mandated.

In summary, the introduction of large circle hooks into shallow-set pelagic longline fisheries was originally instigated to reduce sea turtle interactions in fisheries that caught sea turtles on an order of magnitude greater than deep-set tuna fisheries (e.g., Watson et al. 2005, Gilman et al. 2007). The success of implementing large circle hooks in shallow-set fisheries has also prompted research into their use in deep-set tuna fisheries to mitigate sea turtle takes and to reduce bycatch (Curran and Bigelow 2011). Other studies have also examined simple gear modifications to ensure that all hooks descend below 100 m (Beverly et al. 2009) and to reduce soak time to increase survival at retrieval (Poisson et al. 2010). All of these mitigation techniques should be evaluated within individual fisheries independently and in concert. The use of 16/0 circle hooks in South Pacific commercial longline fisheries appears to be one of several methods that could be adopted with minimal cost burdens and without major deleterious effects on albacore catch rates.

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