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IMPLEMENTATION OF BYCATCH MITIGATION MEASURES IN AUSTRALIA'S PELAGIC LONGLINE FISHERIES: THE EFFECTS OF CIRCLE HOOKS ON TARGET AND NON-TARGET CATCHES

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Implementation of bycatch mitigation measures in Australia's pelagic longline fisheries

The effects of circle hooks on target and non-target catches

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Summary

Circle hooks reduce marine turtle mortality

Reports of unacceptable catch levels of marine turtles resulted in the closure of major United States (US) longline fisheries in the Pacific and Atlantic Oceans in 2001. Subsequent research demonstrated that large circle hooks and whole fish baits can significantly reduce longline catch rates and associated mortality of turtles. The US fisheries reopened in 2005 with stringent mitigation measures, including the use of large circle hooks and whole fish bait. More recently, the US is moving to ban imports of broadbill swordfish and other pelagic species from countries where longliners do not use acceptable mitigation measures, such as those required under US domestic legislation. These restrictions might eventually apply to Australia's Eastern Tuna and Billfish Fishery (ETBF), although interactions with turtles are quite rare here. Rather than investigating the efficacy of circle hooks in reducing turtle mortality, this study focused on the effects of circle hooks on catches of other non-target species and target species.

Large-scale experiment

We conducted experiments during 2005–08 to test the effects of circle hooks on longline catches. The experiments involved ETBF longliners fishing primarily for yellowfin tuna, bigeye tuna and swordfish. Crewmembers alternated similar-sized circle hooks and control hooks along each longline. The control hooks were Japanese tuna hooks that ETBF longliners traditionally used. Observers monitored hook deployment and recorded the hook type, species, life status, hooking position and length of each animal caught. The experimental design, combined with the large sample size (> 95 000 hooks), provided a substantial dataset for investigating the relative performance of circle hooks.

Elevated catch rates

For most species, catch rates on circle hooks exceeded those on tuna hooks. Overall catch rates on circle hooks were about 25 per cent higher than those on tuna hooks. The elevated catch rates were statistically significant for several commercially targeted species, including albacore tuna, yellowfin tuna, black oilfish, striped marlin and swordfish.

Other factors mask circle hook effects

Variations in catch rates between longliners, trips and operations were often larger than the differences attributed to hook type. The effects of circle hooks on catch rates were masked by other factors, such as fluctuations in the availability and catchability of the different species, which were in turn driven by local environmental conditions, subtle differences in fishing gear and fishing practices and species' distribution and abundance. For commercial longliners, the development of techniques to cope with variations in those factors may have a greater impact on catches and financial returns than switching to circle hooks.

Similar body size

For most species, there was no difference in the average size caught on the different hook types. Bigeye and yellowfin tuna caught on circle hooks were slightly smaller than those caught on tuna hooks, but these differences were not statistically significant. The difference was statistically significant for striped marlin. Striped marlin caught on tuna hooks were on average 10 kilogram larger than those caught on circle hooks. It is unclear how hook type affects the size of striped marlin caught on longlines.

Improved financial returns

In addition to being statistically significant, the differences in catch rates were large enough to affect catch levels of most species and financial returns. The superior catch rates of circle hooks mean that financial returns will be maximised with a complete switch to circle hooks rather than replacing existing hooks over a long period. The cost of converting to circle hooks is relatively small because additional fishing gear is not required and the cost of circle hooks has dropped to within about 5 per cent of that of tuna hooks. All else being equal, the adoption of circle hooks should result in increased catches and financial returns across the fleet and over time. These predictions relate only to the longliners participating in our study. Other longliners and fishery sectors will have different mixes of species, which could result in different catch rates and financial returns than those predicted by these results.

Inconclusive results for marine turtles

The study was not designed to investigate the efficacy of circle hooks in reducing marine turtle bycatch because turtle interactions are quite rare in the ETBF. Four turtles were caught during the study: three on circle hooks and one on a tuna hook. Crewmembers released three of these turtles alive. The other was a green turtle, which was jaw-hooked on a circle hook. It was dead on retrieval, possibly because it was hooked at the deepest part of the longline and drowned. The small number of turtle interactions precludes reliable conclusions being drawn on the merits of circle hooks in reducing turtle interactions and mortality in the ETBF. It is also noteworthy that studies of circle hooks elsewhere in the world have shown that they can reduce interaction rates and mortality of marine turtles during longline fishing.

Elevated catch rates of sharks and marlin

Catch rates of most shark species were higher on circle hooks. The elevated catch rates may be of concern to fishery managers because most species of pelagic sharks are considered to be at risk of longlining—they are slow-growing, long-lived and have small litter sizes. Similarly, the adoption of circle hooks might contradict international moves to limit fishing mortality of striped marlin unless there were commensurate reductions in fishing effort or the introduction of other measures to limit striped marlin catches. An unknown factor is the ultimate fate of these animals. The effect of elevated catch rates may be irrelevant if, for example, more animals come to the boat but are then successfully released alive using recommended release techniques.

Similar survival rates

Circle hooks are considered to be effective in reducing bycatch mortality because they are more likely to lodge in the jaw. By contrast, tuna and “J” hooks are believed to lodge in other locations, including the throat and stomach, as well as the jaw. Counter to expectations, most species had an equal or significantly lower probability of being alive on circle hooks compared to tuna hooks in our study. Analyses of hooking location partly explain these unexpected results. Regardless of hook type, most animals were hooked in the lip or jaw. Very few were hooked in locations that were likely to be fatal such as the throat, gills or stomach. The differences between our results and the accepted paradigm might be related to the fact that many of the circle hooks used in this study were relatively small.

Large hooks and bait not fully investigated

The results are only relevant to the circle hooks used in the study (mainly size 13/0 and 14/0). The large 16/0 and 18/0 circle hooks used in the US might have quite different effects on catches to those indicated by our study. Many ETBF fishers were resistant to using the very large 18/0 circle hooks that the US mandates. The common reason given by fishers was that the size of bait used in the ETBF was too small to conceal large hooks. Fishers were resistant to using large fish baits instead of the squid, small mackerel and live bait that they normally deploy. Their reasons included problems with availability, costs and affects on catch rates of target species. There is growing evidence that bait type and size strongly influence catch rates through the attraction of target species and bait loss rates. The results from one fishing trip showed large variations in catch rates between squid and live bait.

Management implications

In taking an ecosystem-based approach to decision-making, fishery managers and stakeholders need to consider the wider implications of bycatch mitigation measures, such as the measure’s effects on other species, industry’s economic performance and occupational health and safety issues. Numerous mitigation measures have been trialled to determine their efficacy in reducing marine turtle bycatch in longline fisheries. Circle hooks are one mitigation measure that are generally considered effective in reducing the catch of marine turtles by longlines. Our results suggest that the adoption of small circle hooks by ETBF longliners will not be detrimental to financial returns, at least for longliners targeting yellowfin and bigeye tuna at mid latitudes off eastern Australia. Other studies suggest that circle hooks provide benefits by reducing marine turtle mortality. On the other hand, those benefits need to be balanced against predicted increases in the mortality of striped marlin and pelagic sharks in a fishery where marine turtle interactions are rare. We cannot predict how large circle hooks and large fish bait might affect the catch levels of bycatch and financial returns for target species. Fishery managers will need to deal with these issues regardless of whether the US mandates circle hooks for exporters. During the study there was widespread adoption of circle hooks, partly as a result of the introduction of techniques to target albacore.

Acknowledgements

This research project was funded by the Natural Heritage Trust (NHT). The Fisheries Resources Research Fund (FRRF) funded the feasibility fishing trials. Ocean Watch Australia, the Australian Fisheries Management Authority (AFMA) and Australian Bureau of Agricultural and Resource Economics (ABARE) provided additional contributions to the program in the form of staff time, meeting venues and equipment. We are particularly grateful for the support provided by Wez Norris and Trysh Stone (AFMA). Richard Curtotti (ABARE) provided advice on analyses of expenditure and revenue. We are particularly grateful for the thorough work of AFMA observers, especially Steve Hall, and the assistance provided by skippers, crewmembers and vessel owners, especially Paul, Michael and Nick Williams.

Introduction

Background

Bycatch mitigation is a response to a growing awareness of the wider, ecosystem effects of fishing and the vulnerability of some species to fishing. Several bycatch mitigation measures have been implemented in Australia's pelagic longline fisheries and more are being considered. These include tori lines, weighted swivels and night-operations to reduce seabird mortality, banning shark-finning and nylon leaders for shark survival, use of release equipment and introduction of circle hooks (Figure 1) to reduce turtle bycatch. In addition to reducing the impact on threatened, endangered and protected (TEP) species, mitigation measures also affect catches of target and other non-target species. In taking an ecosystem-based approach to decision-making, fishery managers and stakeholders need to know the wider implications of mitigation measures, such as their effects on other species and the industry's economic performance.

Reports of unacceptable catch levels of marine turtles lead to the closure of major US longline fisheries in the Pacific and Atlantic Oceans in the late 1990s. Subsequent research has shown that large circle hooks and large mackerel baits significantly reduce longline catch rates of turtles (Falterman & Graves 2004; Watson et al. 2004; Bolton and Bjorndal 2005). In 2004, the US fisheries reopened with stringent mitigation measures including the use of large circle hooks and mackerel bait.

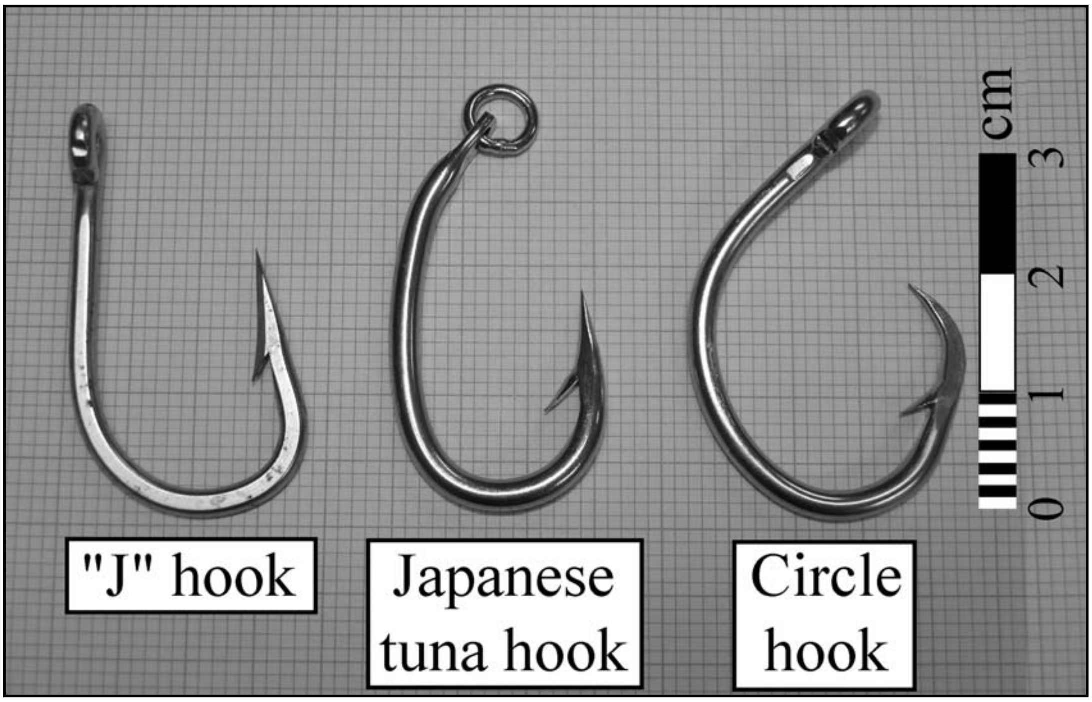

Figure 1. "J" hook, Japanese tuna hook and circle hook.

The US is moving to ban imports of swordfish and other pelagic species from countries where longliners do not use acceptable mitigation measures, as required under US legislation for their domestic fleet. This trade restriction is expected to be similar to that imposed on Australia's prawn trawl fisheries in the late 1990s, leading to the implementation of turtle-excluder devices (TEDs) and bycatch-reduction devices (BRDs).

Past reviews suggest that marine turtle interactions are rare in the ETBF, with annual catches amounting to around 200 turtles (Robins et al. 2003, 2007). Since then, fishing activity has declined from 12.4 million hooks in 2001 to 8.4 million hooks in 2007 and measures have been adopted to improve the survival of released turtles (e.g. de-hooking devices and dip nets). Observer data show that most turtles are released alive, with very few dead at the time of longline retrieval. For 2005/06, Dambacher and Moeseneder (2006) estimated from observer data that the ETBF interacted with 244 turtles. From July 2005 to June 2006, observers monitored 0.507 million longline hooks in the ETBF (6.7 per cent of total effort) and reported 13 turtles interactions with no fatalities. This suggests sea turtle interactions have remained low. However, we caution against raising these numbers to fishery-wide catch rates or catch levels because of the need to adjust for heterogeneity in the distribution and nature of longlining activities and observer coverage.

Previous studies have found varying results for the effects of circle hooks on catch rates and sizes of target fish species compared to other hook types (Appendix A). Some studies have demonstrated higher catch rates of target species on circle hooks than "J" hooks (e.g. Falterman and Graves 2002; Kerstetter and Graves 2006a) while other studies have demonstrated either no significant difference in catch rates between hook types (e.g. Nakano et al. 2004; Hall 2005) or reduced catch rates on circle hooks than "J" hooks (e.g. Boggs 2003; Kim et al. 2006).

Circle hooks are one method that has been considered to reduce the incidental catch of marine turtles on pelagic longlines. However, the effect of circle hooks on catches of target and other non-target species vary significantly among fisheries.

The present study is the third stage of a larger project. Stage I, which was funded by the Fisheries Resources Research Fund (FRRF), proved the feasibility of the experimental approach subsequently used by the project. Stage II compared the effects of wire and nylon leaders on longline catches (Ward et al. 2008). The present project (Stage III) quantifies the effects of circle hooks on longline catches.

Project Objectives

The study aimed to compare catch rates and size of animals caught on circle hooks, compared to tuna hooks, commonly used by pelagic longliners operating in Australia's ETBF. Specific objectives included the following:

1. quantify the effects of hook type and bait type on catches of target and non-target species
2. estimate the costs and benefits of the introduction of those mitigation measures in terms of the landed value of the catch and variations in the mortality of non-target species
3. facilitate the adoption of mitigation measures in the Eastern and Western Tuna and Billfish Fisheries.

Methods

Experimental design

We used the results of feasibility fishing trials in 2005 (Stage I) to estimate the sample size required for given levels of precision and to test the feasibility of the experimental design. Ward et al. (2006) describe the longline fishing gear and methods used in those trials, the results of which are included in the present report. Including the feasibility trials, the circle hook study involved 16 trips on longliners where circle hooks were alternated with tuna hooks along the longline. Crewmembers deployed equal numbers of circle and tuna hooks on each longline. To facilitate the alternating sequence of hook types, crewmembers stored branchlines with the different hook types in separate bins. Where a shortage of one hook type occasionally occurred, the longline segments with only one hook type were not included in results or analyses presented in this report.

For operations that used an even number of hooks-between-floats it was necessary to adjust the sequence so that the same hook type was not always in the same position along the longline (Figure 2).

(a) Odd number of hooks-between-floats

Hook no.	F	1	2	3	4	5	6	7	F	1	2	3	4	5	6	7	F	1	2	3
Hook type		C	T	C	T	C	T	C		T	C	T	C	T	C	T		C	T	C

(b) Even number of hooks-between-floats

Hook no.	F	1	2	3	4	5	6	F	1	2	3	4	5	6	F	1	2	3	4	5
Hook type		C	T	C	T	C	T		T	C	T	C	T	C		C	T	C	T	C

Figure 2. Alternating sequence of circle hooks (“C”) and tuna hooks (“T”) between floats (“F”) along longline segments with (a) an odd number of hooks-between-floats, and (b) an even number of hooks-between-floats.

Additional trips by Vessels E and F involved the random deployment of the two hook types in equal quantities. The data from those trips could not be included in the comparisons of catch rates for the two hook types that are presented in this report.

Table 1. Summary of project fishing trips.

Trip code	Vessel name	Port	Departure date	Target species	No. of ops[a]	No. of hooks[a]	Size of circle hook
A1	Vessel A	Mooloolaba	12/07/05	swordfish	4	4 096	16/0
B1	Vessel B	Evans Head	19/09/05	yellowfin, bigeye	4	3 830	13/0
C1	Vessel C	Mooloolaba	23/09/05	swordfish	5	5 138	14/0
D1	Vessel D	Mooloolaba	30/01/07	swordfish	12	18 076	18/0
E1	Vessel E[b]	Cairns	04/08/07	yellowfin	0	0	14/0
F1	Vessel F[b]	Sydney	11/02/07	albacore	0	0	14/0
G1	Vessel G	Mooloolaba	19/10/07	bigeye, swordfish	6	8 150	14/0
G2	Vessel G	Mooloolaba	02/11/07	bigeye, yellowfin	5	6 870	14/0
G3	Vessel G	Mooloolaba	20/11/07	yellowfin, bigeye, swordfish	6	7 320	14/0
G4	Vessel G	Mooloolaba	17/01/08	bigeye	4	4 440	14/0
G5	Vessel G	Mooloolaba	09/02/08	bigeye	3	4 210	14/0
G6	Vessel G	Mooloolaba	23/02/08	swordfish, bigeye	4	4 600	14/0
G7	Vessel G	Mooloolaba	29/03/08	bigeye, yellowfin, swordfish	6	7 090	14/0
G8	Vessel G	Mooloolaba	22/04/08	bigeye, yellowfin	6	7 570	14/0
G9	Vessel G	Mooloolaba	03/05/08	bigeye, yellowfin	6	7 640	14/0
G10	Vessel G	Mooloolaba	05/06/08	bigeye, yellowfin	5	6 120	14/0
				Total	**76**	**95 150**	

[a]Excludes longlining operations where the alternating circle – tuna hook design was not undertaken.

[b]Data not included in analyses of catch rates because those trips involved the random deployment of circle and tuna hooks rather than the alternating sequence.

Fishing gear and practices

The project involved seven commercial longliners, with Vessel G responsible for 10 of the 16 trips. Longliners involved in the project were typical ETBF longliners, which deploy around 1200 hooks per day and fish for around 107 days per year on average. Longliners involved in the project were around 20 metre long and used nylon monofilament longline fishing gear. Most trips lasted 7–10 days. The catch was stored on ice, in ice slurry or in refrigerated brine. Most trips targeted yellowfin and bigeye tuna off south-eastern Queensland (Figure 3). The vessels deployed 10–12 branchlines between floats, with the maximum depth of hooks estimated to range from 30–170 metre (Campbell et al., 1997).

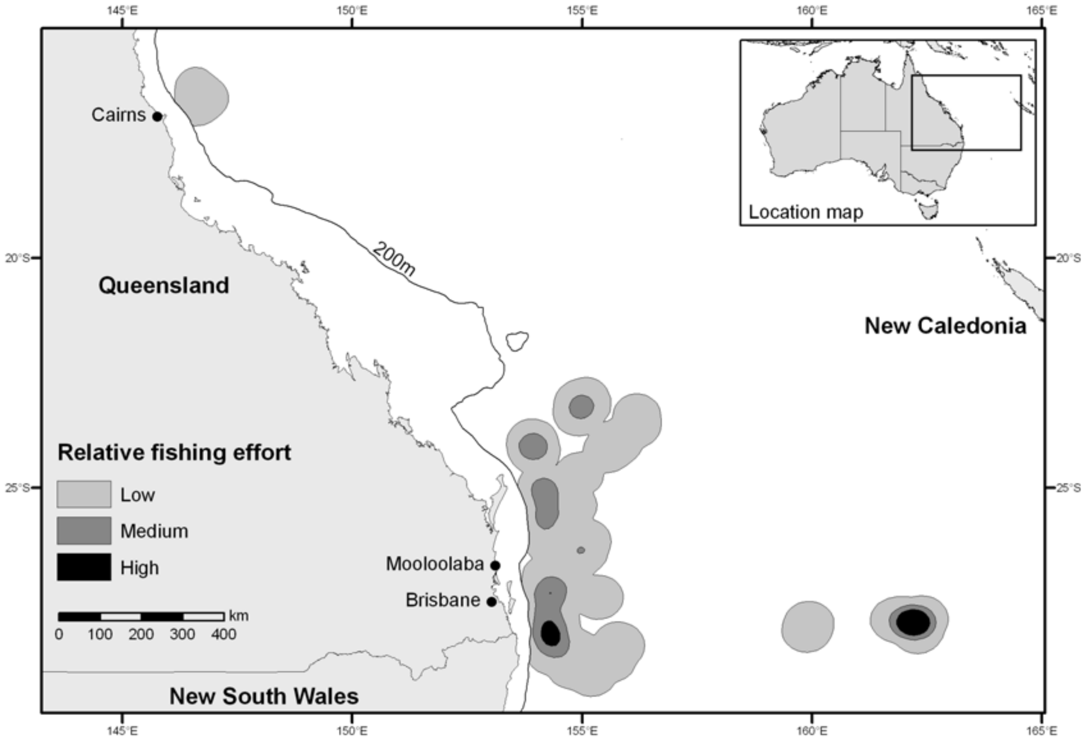

Figure 3. Map of the study area showing the distribution and intensity of longline fishing activity by project longliners.

The number of branchlines between floats is a rough indicator of the depth range of longline hooks. Vessels A, C and D targeted swordfish. They deployed tuna hooks with 6–8 branchlines between floats. Vessel F targeted albacore tuna with tuna hooks with pilchard bait attached to deep longlines (about 30 branchlines between floats). Vessel G usually targeted tuna with 10–12 branchlines between floats and tuna hooks, but used a deep depth range (30 branchlines between floats) in 6 of the 46 longline operations.

Most of the longliners used squid as bait, with some operations involving a mixture of squid and pilchard. Vessel B used live yellowtail scad and blue mackerel.

Longline deployment commenced around dusk and retrieval commenced around dawn for about half of the 76 longline operations (“night sets”). The other operations were “day sets” where deployment commenced at dawn and retrieval commenced during the afternoon (Figure 4). Longlines were counter-retrieved. The soak time of individual hooks ranged from about 6–18 hours.

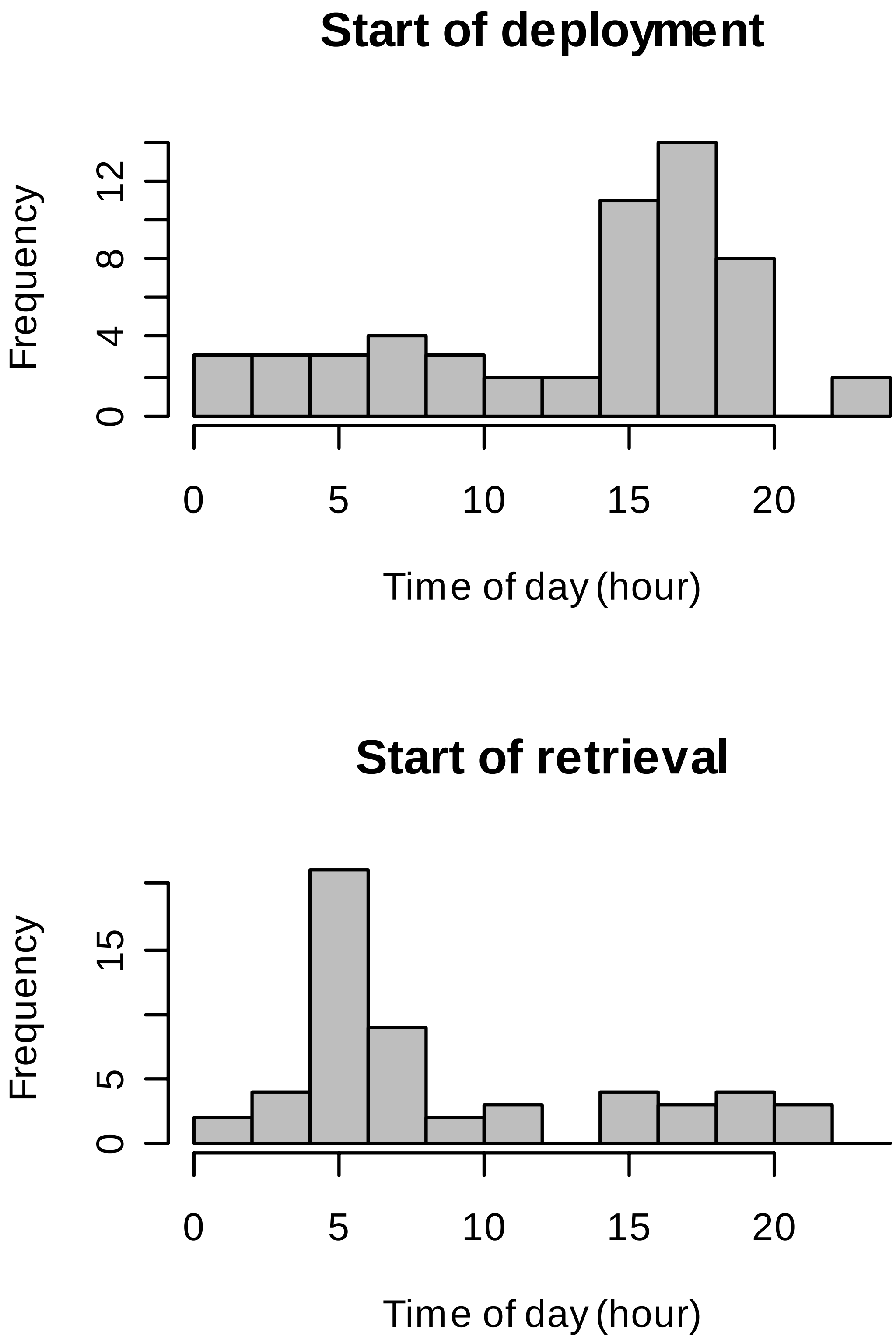

Figure 4. Histogram of deployment and retrieval start times for longline operations undertaken by the project. All times are Eastern Australian Standard Times.

The circle hooks were relatively small; 13/0 or 14/0 stainless steel with a 5 degree offset. Two longliners deployed larger 16/0 and 18/0 circle hooks. We also distributed several hundred larger 16/0 and 18/0 circle hooks for several longliners to trial. The tuna hooks were a similar size to the circle hooks. They were 2.8–3.5 sun-size stainless steel with a ring and 5 degree offset. We matched the hooks used by Vessel A with 16/0 Wonyang Maruto stainless-steel circle hooks and the hooks used by Vessel D with 18/0 OPI stainless-steel circle hooks.

For each vessel, all branchlines were constructed of the same materials and were the same dimensions. Branchlines and leaders consisted of 1.6–1.8 millimetre (~220 kilogram breaking strain) clear nylon monofilament attached to a 60 gram stainless steel or brass leaded swivel and a 2.0 metre leader. Different colours of tubing (or the presence–absence of tubing) were placed at the clip or "snap" end of the branchline to help observers determine the type of hook on each branchline. Crewmembers attached branchlines to the mainline with 130–140 millimetre stainless steel snaps. The hooks, snaps and swivels were attached to the monofilament with 1.7–2.0 millimetre aluminium or alloy crimps. The total length of branchlines was about 20 metre.

Data collection

During longline deployment, observers counted the number of each hook type deployed. They regularly collected data on the sequence of other variables during deployment, such as bait type and lightsticks (Appendix E and F). We used a runs test to verify that the sequence of those variables was random with respect to hook type.

During longline retrieval, observers attempted to identify the species, measure the length and record the life status, hook number, location of hooking and hook type for all animals caught. This included animals that were lost or cut-free during branchline retrieval. For many catches, observers also recorded the presence of lightsticks and bait type. At the end of longline retrieval observers counted the number of each hook type that had been bitten off and number of branchlines replaced.

Observers also recorded details of each vessel's fishing gear and operations, such as its position, start and finish times of longline deployment and hauling, and branchline lengths.

Data analysis

We used length – dressed weight relationships to estimate the weight of each animal measured by observers. The landed value of each animal was estimated by multiplying its estimated weight by the average price of that species and trip that vessel owners supplied from sales receipts for 10 trips.

The matched pair approach used in analysing catch rates assumes that a vacant hook followed the hook that caught each animal. Unfortunately, we did not instruct observers to record the status of every hook as it was retrieved. The convention that we adopted was to compare the hook with a catch and the next hook retrieved (the status of the preceding hook was ignored). We removed from the catch rate analysis any catches that were consecutive. Consecutive catches were defined as those where the same species occurred on consecutive hooks within 3 minutes on the alternative hook type. We assumed that catches where observers did not record the hook number were not consecutive. This rule excluded 30 catches of the 2547 catches available for analysis.

Conditional logistic regression models (Hosmer and Lemeshow 1988) were used to determine whether there were statistically significant differences in catch rates between the two hook types. Conditional logistic regression allows the simplification of the linear predictor so that covariates that are constant within the experiment can be ignored. This simplifies the interpretation of results and avoids the model selection process. The advantage of using a conditional likelihood in this analysis is that covariates that are common to hooks (e.g. season, location) within a longlining operation do not appear in the conditional probabilities. It overcomes the problem of not having detailed information about all the characteristics associated with each operation.

Separate models were estimated for each species or species group. The data were analysed at the hook-level with the catch of the species being "1" if the particular hook caught the species and "0" otherwise. Hooks that caught another species, hooks where the hook type was not reported and hooks without bait were treated as a zero catch for the species under consideration. Given a catch of species *i*, $p_{i,C}$ is the probability that the catch was on a circle hook and $p_{i,T}$ is the probability that it was on a tuna hook. The odds of catching the species on a tuna hook is $p_{i,T}(1-p_{i,T})^{-1}$ and the odds of catching it on a circle hook is $p_{i,C}(1-p_{i,C})^{-1}$. The odds ratio OR_i is then:

$$OR_i = \frac{p_{i,C}\left(1-p_{i,C}\right)^{-1}}{p_{i,T}\left(1-p_{i,T}\right)^{-1}}$$

We refer to this odds ratio as "relative catchability". A relative catchability of 1.25 indicates that the odds of catching the species on a circle hook is 25 per cent higher than that on a tuna hook. Conversely, a value of 0.75 indicates that the odds of catching it on a circle hook is 25 per cent less than that on a tuna hook.

We implemented the models in the *R* statistical language (*R* Development Core Team 2006) using *clogit* from the library *survival*. A Wald test was used to determine the significance of the hook type variable. We tested the sensitivity of estimates to hook size by comparing results for a dataset that included all circle hooks and a reduced dataset, which was limited to operations that deployed circle hooks smaller than size 18/0.

For each species, we used generalised linear models (GLMs) with a binomial error distribution to explore the effects of variables on longline catches and the performance of the two hook types:

$$p_{i,j} = \beta_0 + \beta_1 H_{i,j} + \beta_2 L_{i,j} + \beta_3 T_i + \beta_4 Q_i + \beta_5 M_i + \beta_6 D_i + \beta_7\left(H_{i,j}L_{i,j}\right) + \beta_8\left(H_{i,j}T_i\right) + \beta_9\left(H_{i,j}M_i\right)$$

where, $p_{i,j}$ is the presence of the species, $H_{i,j}$ is the hook type (circle or tuna hook) and $L_{i,j}$ is the presence of a lightstick on hook *j* and T_i is the time of day (day or night), Q_i is the three-month quarter, M_i is the moon phase and D_i is the longline depth of longline operation *j*. The depth categories were shallow (< 8 hooks per float), regular (8–16 hooks per float) and deep (> 16 hooks per float). Interaction terms are in parentheses. The β_j are estimated parameters. We fitted the models separately to the data for each species.

Observers reported the life status of each animal brought to the vessel on a six-point scale (dead and damaged, dead in rigour, dead and flexible, just alive, alive sluggish and alive and vigorous). We collapsed those data into two categories: alive or dead. We used Fisher's Exact test to check for differences in life status and hook type. For each species, Fisher's Exact test was used to test the statistical significance of the odds ratio *OR*:

$$OR = \frac{p_C\left(1-p_C\right)^{-1}}{p_T\left(1-p_T\right)^{-1}}$$

where, p_C is the probability of the species being alive on a circle hook and p_T is the probability of it being alive on a tuna hook. An odds ratio greater than one indicates that the species is more likely to be alive on circle hooks, and vice versa for estimates less than one. We tested the sensitivity of estimates to all circle hooks and small circle hooks (size 16/0 or smaller) by comparing results for the combined dataset (operations that deployed tuna hooks and all circle hooks) and the reduced dataset (those that deployed tuna hooks and circle hooks only).

Observers reported the location where each animal was hooked. We collapsed those data into eight categories (Figure 5). Fisher's Exact test was used to test for differences in the location of hooking with hook type.

We used Student’s *t*-tests to check for differences in average lengths and bite-off rates between circle and tuna hooks. The level of statistical significance was set at $\alpha = 0.05$ for two-tailed tests.

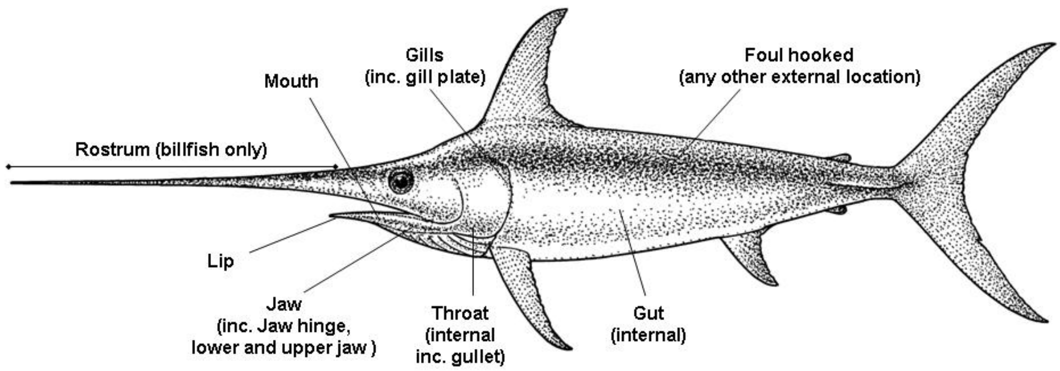

Figure 5. The eight categories used in analysing hooking locations.

Results

Bait type

The project compared the performance of live bait (yellowtail scad) and dead squid bait on one longline trip that deployed small circle hooks and tuna hooks. For both hook types, catch rates of target species were much higher on squid than live bait (Table 2). We considered the sample size to be too small to support a rigorous statistical analysis. Skippers attributed this to the timing of operations—squid is far more effective at night during the full moon periods that occurred during this particular trip.

Table 2. Summary of catches for four longline operations according to bait type. Each operation deployed about 1000 hooks, including 250–300 circle hooks. Estimates include animals that were released or discarded. A "+" indicates that catch rates were higher on live bait than on dead squid, and vice versa for a "–".

Species	**Number caught**		
	Unknown	**Squid**	**Live**
Target			
bigeye tuna	0	6	0
swordfish	2	23	1
yellowfin tuna	0	8	5
striped marlin	0	2	0
Byproduct			
albacore tuna	3	53	47
mahi mahi	0	3	2
escolar	1	3	2
Ray's bream	0	1	0
Bycatch			
mako shark	1	0	0
shortbill spearfish	0	2	0
blue marlin	0	1	0
skipjack tuna	0	0	1
sunfish	0	1	0
pufferfish	0	0	0
lancetfish	1	39	34
Total	**8**	**142**	**92**

Catch rates

Data for 95 150 hooks were analysed, consisting of 47 575 circle hooks and 47 575 tuna hooks. The sensitivity analyses gave very similar results for the conditional logistic regressions fitted to data for tuna hooks and small circle hooks only (the "reduced dataset") and for tuna hooks and all circle hooks (Table 3). For eight species, the model fitted the combined dataset, but could not converge on a solution for those species in the reduced dataset. Conversely, the model fitted the reduced dataset for three species (silky shark, opah and wahoo), but could not fit the

Table 3. Model estimates of the effects of hook type on the relative catchability of 29 species. The estimated parameter of the hook type variable from each conditional logistic regression is presented along with its standard error (SE) and the p-value for a test of the estimate's significance. The models were fitted to longline operations that compared catches on tuna hooks and small circle hooks and tuna hooks and all circle hooks combined.

Species	Tuna hooks and small circle hooks only				Tuna hooks and all circle hooks			
	Estimate	SE	p-value		Estimate	SE	p-value[a]	
Shortnose lancetfish	–	–	–		4.000	1.120	0.210	
Blue marlin	–	–	–		4.000	1.120	0.210	
Dusky shark	–	–	–		3.000	1.150	0.340	
Sunfish	–	–	–		2.000	0.548	0.210	
Snake mackerel	1.500	0.527	0.440		1.620	0.449	0.280	
Wahoo	1.500	0.913	0.660		–	–	–	
Silky shark	1.330	0.540	0.590		–	–	–	
Longnose lancetfish	1.150	0.379	0.710		1.140	0.228	0.570	
Mahi mahi	0.992	0.125	0.950		0.942	0.115	0.610	
Bigeye tuna	0.932	0.133	0.600		0.907	0.118	0.410	
Hectors lanternfish	0.733	0.281	0.270		0.867	0.268	0.590	
Pelagic stingray	–	–	–		0.833	0.606	0.760	
Swordfish	0.750	0.175	0.100	·	0.831	0.120	0.120	
Shortbill spearfish	1.500	0.913	0.660		0.800	0.671	0.740	
Black oilfish	0.820	0.120	0.096	·	0.790	0.101	0.019	*
Yellowfin tuna	0.796	0.141	0.110		0.780	0.125	0.047	*
Bigeye thresher	0.500	1.220	0.570		0.750	0.764	0.710	
Blue shark	1.110	0.317	0.750		0.745	0.214	0.170	
Opah	0.636	0.483	0.350		–	–	–	
Shortfin mako	0.667	0.645	0.530		0.636	0.483	0.350	
Albacore tuna	0.574	0.122	0.000	***	0.616	0.107	0.000	***
Striped marlin	0.421	0.421	0.040	*	0.600	0.298	0.087	○
Great barracuda	–	–	–		0.500	1.220	0.570	
Manta ray	–	–	–		0.500	1.220	0.570	
Skipjack tuna	0.333	1.150	0.340		0.333	1.150	0.340	
Oceanic whitetip	–	–	–		0.333	0.816	0.180	
Tiger shark	0.200	1.100	0.140		0.167	1.080	0.097	○
Crocodile shark	0.111	0.745	0.003	**	0.138	0.533	0.000	***

[a]Statistical significance of a two-sided Wald test, indicating whether the estimate was significantly different to one (no effect):

*** $0 \le p < 0.001$
** $0.001 \le p < 0.01$
* $0.01 \le p < 0.05$
○ $0.05 < p < 0.1$

combined dataset for those species. In both cases, the lack of convergence is likely due to the relatively small number of observations and high variability in the response. For most species, the reduced dataset produced coefficients in the same direction and often at a similar level. For two species (shortbill spearfish and blue shark) the estimated coefficients for the hook type were in the opposite direction, but those coefficients were not statistically significant. The confidence intervals for the hook type variable for most species were broader for the reduced dataset largely because of the smaller number of observations available for modelling. We chose to combine data for all circle hook sizes for the analyses throughout this report.

Catch rates for circle hooks exceeded those on tuna hooks for all species combined. Circle hooks produced statistically significant increases in catch rates for crocodile shark, albacore tuna, yellowfin tuna and black oilfish ($p < 0.05$; Figure 6). The elevated catchability of striped marlin, tiger shark, blue shark and swordfish was marginally significant ($0.05 < p < 0.10$). Few species showed elevated catchability on tuna hooks, and none of those differences were statistically significant. Relative catchability was well-estimated for several species, but there was no significant difference in catchability (e.g. mahi mahi, bigeye tuna). Other species were too rare or their catch rates were too variable for relative catchability to be reliably estimated (e.g. skipjack tuna, dusky shark).

The generalised linear models (GLMs) gave very similar results to the conditional logistic regressions (Table 4), and showed that some variables may influence the effects of hook type on catch rates of some species.

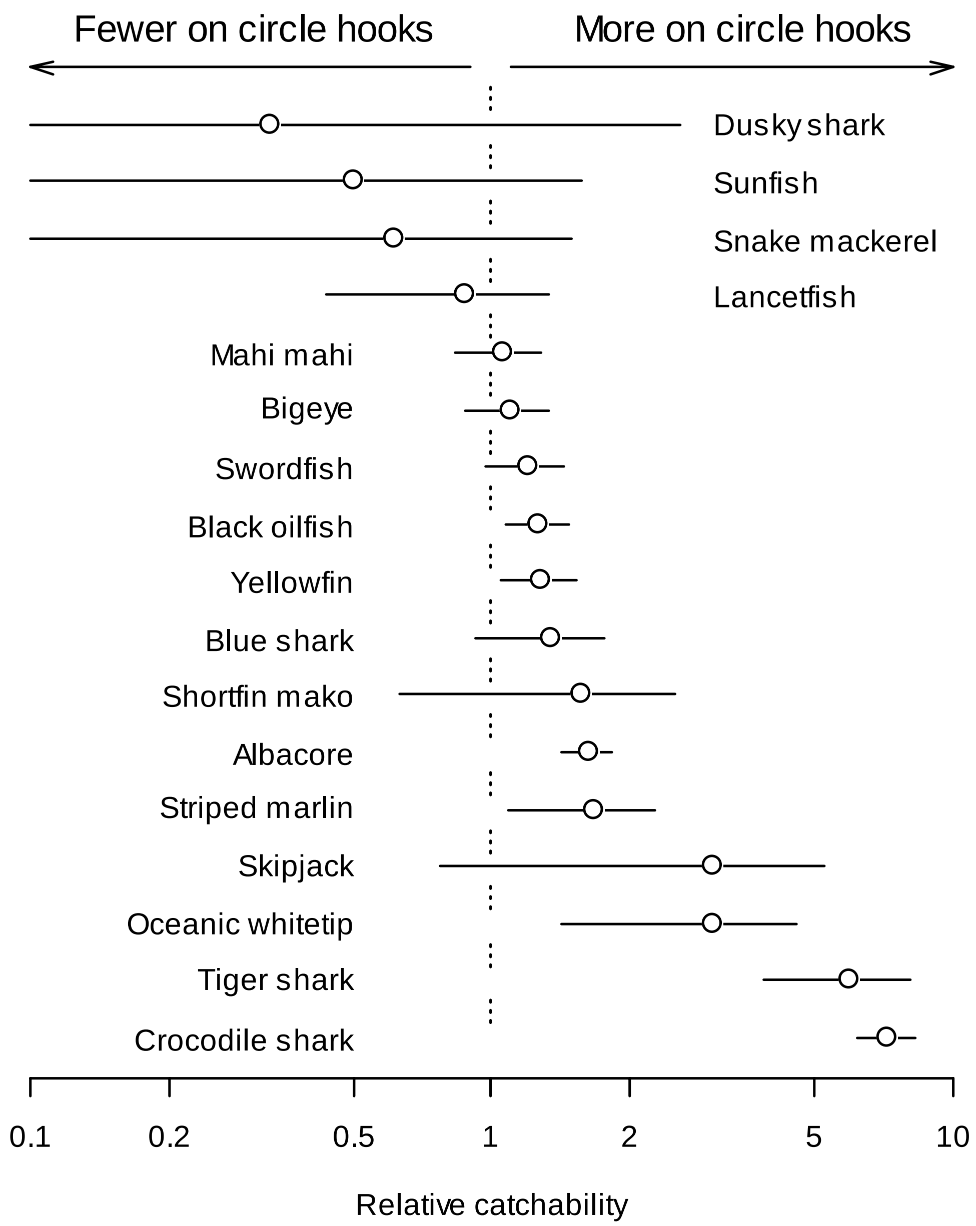

Figure 6. Comparison of the effects of hook type on the relative catchability of 18 frequently caught species. Relative catchability is the estimated parameter of the hook type variable in conditional logistic regressions (circles). Horizontal lines are 95 per cent confidence intervals for the estimate.

Species composition

Observers identified a total of 47 species. Seven species caught on circle hooks were not caught on tuna hooks. Seven species caught on tuna hooks were not caught on circle hooks. It is noteworthy that six of the seven tiger sharks were taken on circle hooks. The other differences in species composition are unlikely to be significant because of the small number of animals involved (<5 animals per species).

Seabird interactions

Seabirds (mainly shearwaters and occasionally albatrosses and petrels) were sometimes associated with longline setting and hauling, but none were hooked during our study.

Marine turtle interactions

Four marine turtles were caught during the study. An olive Ridley turtle was hooked through the tongue by a tuna hook and it was successfully dehooked and released healthy after a period of observation. The other three turtles were all jaw hooked on circle hooks. An olive Ridley turtle was landed and successfully dehooked and released. A large green turtle was dehooked while still in the water and swam away strongly. A small green turtle was retrieved dead. This turtle probably drowned because hooking occurred midway between two floats where the longline would sink too deep for the turtle to reach the sea surface to breath.

Table 4. Parameter estimates from generalised linear models used to explore the interaction between the effects of hook type and other variables on catches of four species. Coefficients that are statistically significant ($p < 0.05$) are in bold font.

Variable	Yellowfin	Albacore	Bigeye	Black oilfish
(Intercept)	**–8.1702**	**–6.5144**	**–6.9760**	**–5.5643**
hookTypeT	–0.7815	**–1.3950**	–0.1492	–0.4781
LightstickY	**0.7417**	**0.3390**	0.3585	–0.1364
SetstartNight	**–0.8476**	–0.2493	–0.3393	**–0.5543**
Season2	**2.6498**	**1.8507**	**1.4720**	**2.0328**
Season3	**1.9151**	**3.4089**	**0.7984**	**1.5271**
Season4	**1.2712**	**1.1094**	–0.3606	**–2.1377**
Moon2	–0.6841	–0.0310	0.1792	**0.6011**
Moon3	–0.2579	**1.0799**	0.0457	–0.0722
Moon4	**–0.9644**	0.1642	**–0.5059**	**0.5156**
Depthregular	**1.0767**	**–1.0379**	**0.9236**	**–0.6810**
Depthshallow	**1.8079**	**–1.0625**	–0.4143	0.1961
hookTypeT:LightstickY	0.1788	0.4164	0.0847	–0.0575
hookTypeT:SetstartNight	0.4884	–0.0644	0.1942	–0.1659
hookTypeT:Moon2	0.2081	–0.1105	**0.9779**	0.4271
hookTypeT:Moon3	0.3878	0.5550	0.4307	0.6072
hookTypeT:Moon4	0.3440	0.0673	**0.9700**	0.3878
hookTypeT:Depthregular	–0.0582	0.3896	–0.9060	0.1422
hookTypeT:Depthshallow	–0.5818	0.5549	0.2837	–0.4532

Size composition

There was no significant difference between the average length of fish caught on circle and tuna hooks, except for striped marlin which were smaller on average on circle hooks than those caught on tuna hooks (Table 5). The difference in average length is equivalent to striped marlin on circle hooks being about 10 kilogram smaller on average.

Table 5. Summary statistics for the average length of the seven most frequently caught species on each hook type. All lengths are fork lengths except for swordfish and striped marlin lengths, which are lower jaw – fork lengths. Statistical significance is indicated according to the scheme given in the footnote to Table 3.

Species	No. measured		Average length (cm)			p-value	
	Circle	Tuna	Circle	Tuna	C–T		
Black oilfish	165	129	90.0	89.2	0.9	0.7153	
Swordfish	140	112	136.4	136.6	–0.2	0.9720	
Mahi mahi	152	152	117.1	117.7	–0.6	0.5948	
Albacore tuna	93	48	89.2	90.1	–0.9	0.5469	
Bigeye tuna	114	97	128.6	130.4	–1.8	0.4354	
Yellowfin tuna	142	130	121.5	123.7	–2.1	0.3794	
Striped marlin	28	16	187.6	197.1	–9.5	0.0474	*

Life status

Many species were too rare to assess differences in life status between hook types. Some frequently caught species demonstrated no significant difference in life status between hook types, e.g., albacore, yellowfin and bigeye tuna (Table 6). For the full dataset, swordfish and striped marlin were significantly more likely to be alive when caught on tuna hooks compared to circle hooks. Similarly, swordfish were significantly more likely to be alive on tuna hooks for the reduced dataset. However, albacore tuna were significantly more likely to be alive when caught on circle hooks than tuna hooks.

Table 6. Effect of hook type on the life status of each species reported by observers. Estimates are shown for the reduced dataset (operations that deployed tuna hooks and small circle hooks only) and the combined dataset (tuna hooks and all circle hooks). The estimated odds ratio is the probability of a live animal being caught on a circle hook compared to the probability of it being caught on a tuna hook. Grey shading highlights estimates that indicate that live animals were more likely on circle hooks (estimate > 1.000). Statistical significance is indicated according to the scheme given in the footnote to Table 3.

Species	Tuna hooks and all circle hooks			Tuna hooks and small circle hooks only		
	estimate	p-value		estimate	p-value	
Silky shark	0.1462	0.1333		0.1582	0.1421	
Striped marlin	0.1693	0.0259	*	0.2988	0.1678	
Bigeye thresher	0.2247	0.4857		0.0000	0.4000	
Shortbill spearfish	0.2952	0.5238		0.5477	1.0000	
Wahoo	0.4142	1.0000		0.7746	1.0000	
Swordfish	0.4177	0.0013	**	0.5000	0.0334	*
Blue shark	0.6558	1.0000		1.1723	1.0000	
Yellowfin tuna	0.7415	0.2398		1.3169	0.3138	
Albacore tuna	0.7822	0.5042		2.9088	0.0406	*
Ray's bream	0.8128	1.0000		0.5484	0.6648	
Bigeye tuna	0.8646	0.6199		0.9988	1.0000	
Mahi mahi	0.9713	1.0000		0.9467	1.0000	
Black oilfish	1.1718	0.5096		1.2514	0.3597	
Longnose lancetfish	1.2466	0.7792		0.4353	0.2067	
Shortnose lancetfish	1.6565	1.0000		–	–	
Shortfin mako shark	4.0744	0.1809		2.5068	0.6000	

Location of hooking

Most animals were hooked through the lip (Figure 7). This was the case for animals caught on both circle and tuna hooks. There was no significant difference between hooking location and hook type for any of the 10 species with sufficient data for statistical analysis (Table 7). The difference was marginally significant for silky shark. Silky shark was the only species with a higher number of animals hooked elsewhere—most of the silky shark caught on tuna hooks were hooked through the lip. Many swordfish and mahi mahi were hooked in the throat, but these were still less than the number hooked through the lip.

Table 7. Summary of Fisher Exact tests of differences in the location of hooking between hook types. Statistical significance is indicated according to the scheme given in the footnote to Table 3.

Species	No. observed		p-value	
	circle	tuna		
Albacore tuna	119	42	0.8112	
Bigeye tuna	131	110	0.9722	
Blue shark	7	10	1.0000	
Mahi mahi	167	153	0.7940	
Silky shark	7	9	0.0870	○
Black oilfish	171	149	0.1950	
Striped marlin	26	11	0.4445	
Swordfish	85	67	0.5476	
Yellowfin tuna	118	95	0.2635	
Other sharks	22	7	0.4502	

Bite-offs

Observers counted the number of branchlines retrieved with the hook missing in 23 longlining operations that deployed circle and tuna hooks. On average, 1.49 per cent of circle hook branchlines were retrieved with the hook missing compared to an average of 1.53 per cent for tuna hooks. The average bite-off rates of tuna hooks were not significantly greater than that of circle hooks ($p = 0.389$).

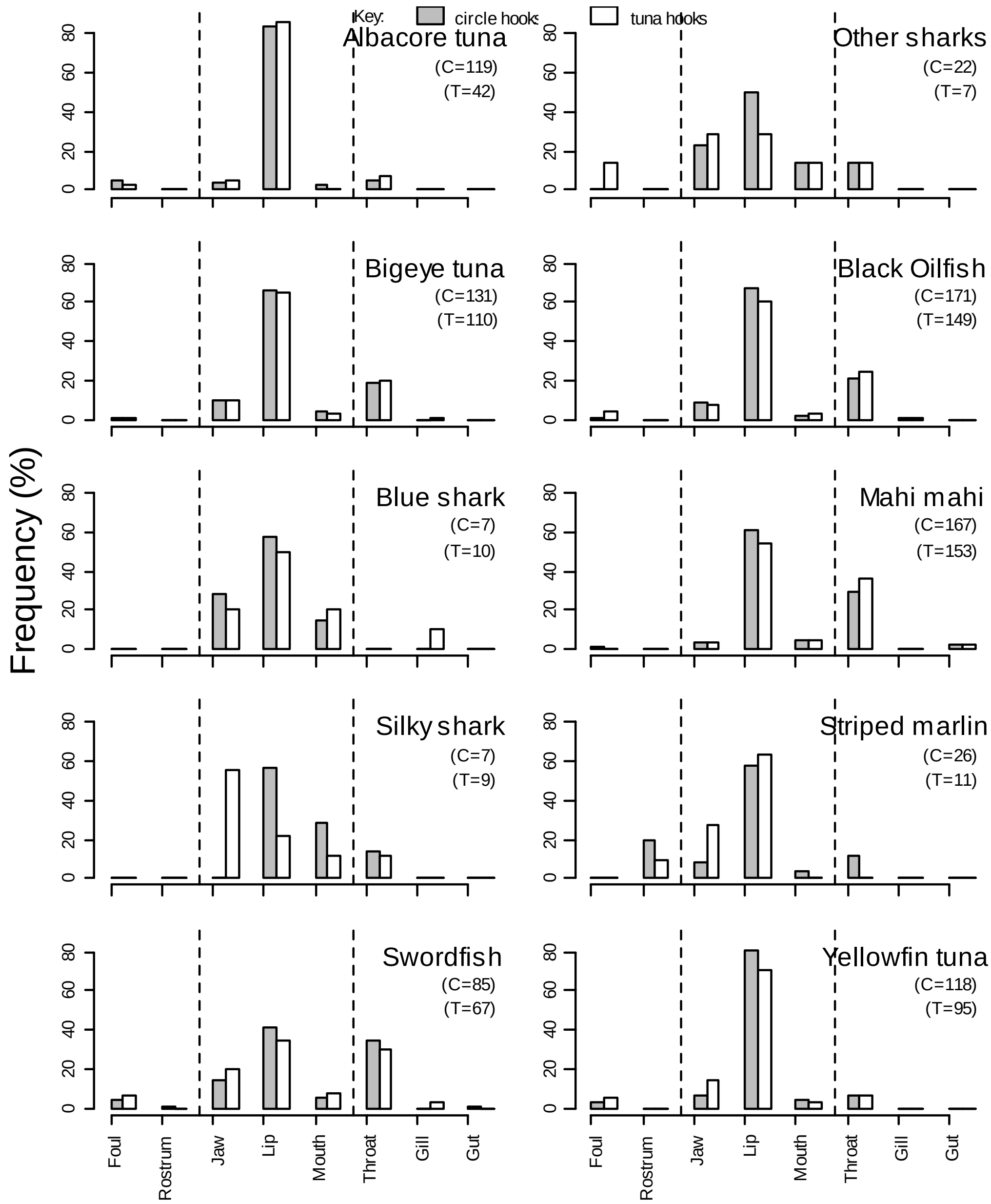

Figure 7. Frequency histograms of the location of hooking reported for each species by observers for each hook type. The number of observations is indicated for circle hooks ("C") and tuna hooks ("T").

Landed value

Multiplying the estimated total weight of each species by their average landed value provides a rough guide to the relative value of catches taken by circle and tuna hooks (Table 8). Bigeye and yellowfin tuna were the most valuable species. The elevated catch rates of bigeye tuna and swordfish on circle hooks were largely responsible for the total value of all retained species for circle hooks exceeding that of tuna hooks by about 20 per cent. Variations in catch rates of the two hook types among species and trips resulted in considerable variability in financial performance among trips (Table 9). Note that our estimates of revenue do not include the value of shark carcasses and fins, which were a small fraction of total revenue during the study.

Costs

During the study, materials to construct a single longline branchline cost $4.21. Each circle hook cost $0.78 on average or 25 per cent of the total cost of branchline materials (Table 10). The branchline materials are usually identical for either hook type, so our comparison of costs can be limited to hook prices. The price of 14/0 circle hooks ($0.70–0.84 each) was comparable to that of similar sized 2.8–3.5 Sun tuna hooks ($0.68–0.77 each) that were popular amongst ETBF longliners during the study. The slightly higher cost is due to the extra amount of steel required for manufacturing circle hooks (Craig Bath, pers. comm., 30 May 2008). Assuming that the circle hooks are $0.78 each and tuna hooks are $0.74[2], it would cost an extra $1011 for an average ETBF longliner to completely switch over to 14/0 circle hooks in the first year (Table 11). By May 2008, 14/0 circle hooks accounted for over 95 per cent of all longline hook sales in the main ETBF port of Mooloolaba (Craig Bath, pers. comm., 30 May 2008).

Vessel owners would maximise their financial returns by completely switching over to circle hooks rather than replacing existing hooks over a long period. It would cost just over $1000 to replace all existing longline hooks (1249 hooks for an average longliner) with circle hooks. However, that outlay would be recouped within about 3–4 operations if catch rates are increased at the levels suggested by our study. By contrast, it would take more than 12 months to achieve that level of financial return if owners replaced existing hooks with circle hooks through natural attrition.

At over $1.09 each, 18/0 circle hooks were significantly more expensive than the 14/0 tuna hooks that many ETBF longliners used. In the first year, it would cost an extra $65 119 for an average ETBF longliner to completely switch over to 18/0 circle hooks. It would cost an extra $4 million for the entire ETBF fleet to switch over to 18/0 circle hooks, with the annual cost of replacing hooks being an extra $56 274. It is noteworthy that 12/0 “J” hooks, which were popular in the past, are more expensive ($1.27 each) than 18/0 circle hooks.

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[2] These prices are the average price paid for those hooks during the study. Prices were about 5 per cent higher in May 2008 (Craig Bath, pers. comm., 30 May 2008), but the $0.04 differential between circle and tuna hooks remained.

Table 8. Estimated catch weights, average weights, prices and total value of each species retained by project longliners on circle hooks ("C") and tuna hooks ("T"). Weights are processed weights derived from length measurements. These estimates are limited to the 10 trips where market prices were reported and they do not include the value of shark carcasses and fins.

Species	Total number			Total weight (kg)			Average weight (kg)			Average	Total value ($)		
	Circle	Tuna	C–T	Circle	Tuna	C–T	Circle	Tuna	C–T	price ($/kg)	Circle	Tuna	C–T
Bigeye tuna	135	114	21	6 028	5 365	540	44.7	47.1	–2.4	$12.91	$90 798	$81 384	$9 414
Swordfish	86	70	16	2 564	2 151	322	29.8	30.7	–0.9	$8.26	$23 283	$17 734	$5 550
Striped marlin	26	12	14	1 714	931	794	65.9	77.6	–11.7	$5.04	$9 092	$3 818	$5 273
Albacore tuna	123	43	80	1 791	594	1 108	14.6	13.8	0.7	$1.90	$4 532	$1 443	$3 089
Wahoo	3	4	–1	45	49	8	15.0	12.2	2.8	$2.00	$90	$102	–$12
Mahi mahi	168	154	14	1 815	1 700	95	10.8	11.0	–0.2	$5.20	$9 684	$9 081	$602
Yellowfin tuna	120	95	25	4 539	4 027	261	37.8	42.4	–4.6	$9.77	$48 716	$44 282	$4 433
Total	**661**	**492**	**169**	**18 496**	**14 816**	**3 128**	**28.0**	**30.1**	**-2.1**	**–**	**$186 195**	**$157 844**	**$28 361**

Table 9. Estimated catch weights, average weights, prices and total value of catch retained for 10 trips by project longliners on circle hooks ("C") and tuna hooks ("T"). Weights are processed weights derived from length measurements. These estimates do not include the value of shark carcasses and fins.

Trip	Total number			Total weight (kg)			Average weight (kg)			Total value ($)		
	Circle	Tuna	C–T	Circle	Tuna	C–T	Circle	Tuna	C–T	Circle	Tuna	C–T
S1	56	29	27	1 208	587	621	21.6	20.3	1.3	$8 763	$4 421	$4 342
S2	56	54	2	1 348	1 273	75	24.1	23.6	0.5	$7 140	$8 579	–$1 439
S3	62	52	10	1 852	2 066	–214	29.9	39.7	–9.9	$16 561	$18 108	–$1 547
S4	36	37	–1	658	736	–78	18.3	19.9	–1.6	$5 348	$6 120	–$772
S5	23	14	9	480	379	101	20.9	27.1	–6.2	$3 627	$4 155	–$528
S6	38	30	8	1 194	753	441	31.4	25.1	6.3	$14 511	$8 637	$5 874
S7	101	84	17	2 747	2 099	648	27.2	25.0	2.2	$27 415	$19 329	$8 085
S8	70	60	10	2 478	2 441	36	35.4	40.7	–5.3	$27 606	$32 035	–$4 429
S9	156	89	67	4 927	2 874	2 053	31.6	32.3	–0.7	$60 919	$36 196	$24 723
S10	63	43	22	1 579	1 585	–6	25.1	36.9	–11.8	$14 305	$20 265	–$5 960
Total	**661**	**492**	**171**	**18 471**	**14 793**	**3 975**	**27.9**	**30.1**	**–2.1**	**$186 195**	**$157 845**	**$28 349**

Table 10. Estimated cost of materials required to construct 1000 longline branchlines with circle hooks.

Item	Quantity	Unit price	Total cost
Circle hooks	1000	$0.78	$784
Nylon monofilament	20	$64.22	$1 284
Crimps	4	$26.44	$106
Tubing	1	$38.39	$38
Leaded swivels	1000	$0.90	$897
Branchline clip	1000	$1.10	$1 100
		Total	**$4 210**

Table 11. Estimated cost of ETBF longliners switching over to circle hooks. All estimates are based on averages derived from 2007 logbook data and a price of $0.78 for each circle hooks and $0.74 for a tuna hook.

Hook type	No. of hooks		Cost
Estimated cost of an average longline			
Circle hooks	1 289	$0.78	$1011
Tuna hooks	1 289	$0.74	$950
		Difference	**$61**
Estimated cost to an average longline for one year			
Circle hooks[a]	109	$0.78	$86
Tuna hooks[b]	109	$0.74	$81
		Difference	**$5**

[a]Based on the average bite-off rate of 1.49 per cent for circle hooks per operation observed on project longliners.

[b]Based on the average bite-off rate of 1.53 per cent for tuna hooks per operation observed on project longliners.

Project staff and crewmembers assembled the branchlines. About 66 man-hours were required to construct 1000 branchlines. It is difficult to place a value on the labour involved in commercial longliners adopting circle hooks because crewmembers are not specifically paid for that task. They usually construct fishing gear while in port or while the longliner is in transit between ports and fishing grounds. Furthermore, the adoption of circle hooks is likely to involve the progressive replacement of damaged gear rather than the complete construction of a new set of gear.

Observers reported no problems in attaching bait to circle hooks, including the one trip that deployed live bait. Neither were there any problems in deploying or retrieving the hooks. Crewmembers remarked that the hooks were easier to remove from animals than tuna hooks.

Discussion

Target and byproduct species

For most species, catch rates on circle hooks exceeded those on tuna hooks. The differences were significant or marginally significant for several target and byproduct species, including albacore tuna, yellowfin tuna, black oilfish, striped marlin and swordfish. In addition to being statistically significant, the differences in catch rates were large enough to affect catch levels of most species and, consequently, financial returns. The widespread adoption of circle hooks would most likely result in increased catches and financial returns across the fleet and over time, as well as ensuring continued access to US markets.

The sensitivity analyses showed that combining small and large circle hook data made very little difference to the results, other than reducing uncertainty in estimates of the effects of hook type and increasing the number of species that could be estimated. Nevertheless, the performance of small and large circle hook is likely to vary over the range of species and types of longlining activities. Dedicated field-based trials would also be required to quantify the effects of tuna and “J” hooks on longline catches.

Variations in catch rates between trips and operations were often larger than differences attributed to hook type. We conclude that hook type significantly affects longline catch rates, but those effects are not as influential as other factors, such as fluctuations in the availability of target species, local environmental conditions and subtle differences in fishing gear and fishing practices. For commercial operators, the development of techniques and strategies to cope with variations in those factors will have a greater impact on catches and financial returns than switching to circle hooks.

The generalised linear models showed that some variables may influence the effects of hook type on catch rates of some species. For example, the catchability of bigeye tuna on tuna hooks was greater for moon phases 2 (first quarter) and 4 (last quarter). There are many plausible explanations for the effects of those variables on the performance of the two hook types. For example, the way that bigeye tuna attack prey during moon phases 2 and 4 may be different to their behaviour at other times, resulting in the observed differences in hook performance. In interpreting these results, we need to be mindful that the models tested a very limited number of explanatory variables. Regardless, analyses like these, combined with research on causal effects, will be useful for predicting the effects of circle hooks for longlining operations similar to those sampled by our study. We might predict, for example, that adoption of circle hooks by longliners targeting swordfish over the full moon will result in a greater differential in bigeye tuna catch rates than indicated by the simple comparison of the performance of circle and tuna hooks.

It is important to note that estimates of financial returns relate only to the longliners involved in our study and only to the style of operations, areas and seasons that they encompassed. Other longliners are likely to have quite different mixes of species, which would result in very different returns in relation to hook types. Longliners fishing exclusively for swordfish, for example, might experience no great variation in returns if they were to switch to circle hooks.

Life status will affect the quality of catches and consequently the unit value of landed species. Live animals are fresher and may be less likely to suffer damage by sharks and other marine life. Animals that are alive when brought onboard tend to fetch higher prices than those that are dead on longlines for long periods. Striped marlin was shown to less likely be alive on circle hooks. Unfortunately, we were unable to match individual animals with the price that it fetched at market so that the effects of life status on price could not be tested.

Stock status

In view of uncertainty over the status of striped marlin in the south-western Pacific, the Western and Central Pacific Fisheries Commission (WCPFC) has directed that there be no increase in fishing mortality rates for that stock (WCPFC 2006). The elevated catch rates of striped marlin on circle hooks were marginally significant. The adoption of circle hooks might therefore contradict the management measure unless there were commensurate reductions in fishing effort or introduction of other measures to reduce catches. Currently, the ETBF is developing a harvest strategy and introducing a fishing effort cap that will limit striped marlin catches.

Our results also have implications for stock assessments and harvest strategies that rely on commercial catch and effort data. Those data will need to be adjusted or "standardised" for the effects of hook type on longline catchability. The abundance of albacore and yellowfin tuna, for example, will be overestimated if the adoption of circle hooks in recent years is not taken into account.

Bycatch

Elevated catch rates of several bycatch species on circle hooks may be of concern to fishery managers. Pelagic sharks are considered to be a group at risk of longlining because most species are slow-growing and long-lived, with low reproductive potential. Catch rates of some shark species were considerably higher on circle hooks. Although not statistically significant because of the small sample size, it is noteworthy that six of the seven tiger sharks caught during the study were caught on circle hooks and 8 of the 10 oceanic whitetips were caught on circle hooks. The differences in crocodile shark catch rates were statistically significant, with the catch rates on circle hooks almost double those on tuna hooks. An ecological risk assessment (ERA) classified oceanic whitetip, tiger and crocodile shark as being at medium risk from fishing in the ETBF (Webb et al. 2007). Currently, ETBF management regulations include a 20 shark trip limit. Catches of all shark species during this study were well within the trip limit for every trip.

Body size

Although our estimates indicate that several species, such as bigeye and yellowfin tuna, were on average smaller on circle hooks, those results were not statistically significant ($p > 0.05$). The differences in average size were significant for striped marlin, but it is unclear how hook type affects the size composition of longline catches.

Variations in catchability and selectivity also have important implications for stock assessments and harvest strategies that rely on longline catch and size data. An assessment or harvest strategy for example, might attribute a reduction in average size to an increase in exploitation rates, whereas such a change might actually be due to the introduction of new hook patterns.

Survival

The design of circle hooks is believed to greatly increase the likelihood of animals being hooked in the jaw (Falterman and Graves 2002; Cooke and Suski 2004; Kerstetter and Graves 2006a). By contrast, it has been noted in the literature that tuna and “J” hooks can lodge in other locations, including the stomach and throat. Similar conclusions have been drawn on the hooking of billfish by recreational anglers (Domeier et al. 2003; Horodysky and Graves 2005). However, our results showed seven species with a significantly *lower* probability of being alive on circle hooks than tuna hooks. No species had a significantly higher probability of being alive on circle hooks than tuna hooks. More detailed analyses are required to determine the causes of those differences and the interactions of other factors, including soak time, body size and hooking location.

Hooking location is likely to influence life status; stomach and throat hooked animals are less likely to be alive at the time of longline retrieval than are jaw-hooked animals. In our study, most animals were hooked in the lip or jaw, regardless of hook type. Very few were hooked in locations that were likely to be fatal such as the throat, gills or stomach.

One possible explanation for the predominance of lip and jaw hooking in this study may be the way many fish species tend to interact with longline bait and hooks. Fish such as tuna and swordfish tend to hit the bait at speed and continue swimming until the line tightens and the hook engages. The hook has little time to be swallowed and embed in the throat or stomach. It is more likely to embed in the side of the jaw.

The comparison of life status on circle and tuna hooks showed two species with a significantly *lower* probability of being alive on circle hooks than tuna hooks. For the combined dataset, swordfish and striped marlin were significantly less likely to be alive when caught on circle hooks than tuna hooks. No species had a significantly higher probability of being alive on circle hooks compared to tuna hooks. This is opposite to what the jaw-hooking hypothesis would predict and the reasons for these differences are unclear given that there was no significant difference in hooking location between the species.

We expected bite-off rates to be higher for tuna hooks than circle hooks because it is generally believed that tuna hooks are more likely to be swallowed, leaving the leader exposed to abrasion by the animal’s teeth. However, the results do not support this hypothesis. We found no significant difference in bite-off rates between circle and tuna hooks. The similar bite-off rates between circle and tuna hooks is likely to be due to the low incidence of stomach and throat-hooking for both hook types. It might also reflect the relatively low encounter rates with sharp-toothed animals, such as sharks and snake mackerel, during the study. A stronger difference in bite-off rates might be expected in areas and at times when those sorts of animals are more active. For example, Ward et al (2008) reported bite-off rates of 5.1 per cent for tuna hooks on nylon leaders off North Queensland compared to 1.5 per cent in our study.

Another hypothesis that has been proposed in other trials around the world is that there is no difference between catchability on circle and tuna hooks. It has been hypothesised that the observed difference in catch rates is the result of differences in bite-off rates. The idea is that tuna hooks are more likely to hook in the stomach so the leader would be exposed to abrasion by the animal’s teeth and more likely to be bitten off. Alternatively, this deep-hooking may result in death, with dead animals more likely to be removed by large scavengers (Ward et al 2004, 2008). However, our analyses of survival rates and hooking positions do not indicate that animals are more likely to be deep-hooked and dead on tuna hooks.

Bait and hook size

We could not directly compare the performance of small and large circle hooks. Generally, we would expect larger hooks to increase “selectivity”; they may be less effective in catching very small animals, but not affect catches of larger animals. For industry, the increased cost associated with needing to use larger bait to conceal those larger hooks may be significant. During our study, skippers indicated that squid bait cost about $1.80/kilogram. Small (150 g) squid bait that could be used on 14/0 circle hooks, but 250–300 gram squid bait would be required for 18/0 circle hooks, which would greatly increase bait costs. Fishers who rely on live bait would also be resistant to using hooks larger than 14/0. Of 6797 operations where fishers reported bait type in their logbooks in 2007, 16 per cent used all live bait or a combination of live and dead bait.

The experiment that compared the performance of dead squid and live bait was limited to one longlining trip (2200 hooks). However, results indicated striking differences in the performance of bait type, both for target and non-target species. Skippers also suggested that there was a strong interaction between bait type and other factors, particularly lunar phase. It is not possible to draw firm conclusions from the bait experiment because of the small sample size and the lack of statistical analysis. There is a need to undertake further experiments on the effects of hook size and bait size and species on longline catches.

Conclusions

Our study demonstrated that circle hooks resulted in elevated catch rates for most species compared to similar-sized tuna hooks. Variations in catch rates between longliners, trips and operations were often larger than differences attributed to hook type. The effects of circle hooks on catch rates are likely to be masked by other factors, such as fluctuations in the availability and catchability of the different species, which were in turn driven by local environmental conditions, subtle differences in fishing gear and fishing practices and species' distribution and abundance. For commercial longliners, the development of techniques and strategies to cope with variations in those factors may have a greater impact on catches and financial returns than switching to circle hooks.

The differences in catch rates were large enough to affect financial returns. The cost of converting to 14/0 circle hooks is relatively small because no additional fishing gear is required. The superior catch rates of circle hooks mean that financial returns are maximised with a complete switch to circle hooks rather than replacing existing hooks over a long period. These predictions relate only to the longliners participating in our study. Other longliners will have different mixes of species, which could result in different catch rates and financial returns than those predicted by these results.

The small number of turtle interactions precludes reliable conclusions being drawn on the merits of circle hooks in reducing turtle interactions and mortality in the ETBF. It is also noteworthy that studies of small circle hooks elsewhere in the world have shown that they can reduce interaction rates and mortality of marine turtles from longline fishing. We did not investigate the effects of large 16/0 and 18/0 circle hooks and large fish bait on catch rates, financial returns and bycatch.

Catch rates of several shark species were higher on circle hooks. The elevated catch rates may be of concern because most species of pelagic sharks are considered to be at risk of longlining. Similarly, the adoption of circle hooks might contradict international moves to limit fishing mortality of striped marlin unless there were commensurate reductions in fishing effort or the introduction of other measures to limit striped marlin catches.

In our study, most species had an equal or significantly lower probability of being alive on circle hooks compared to tuna hooks. Analyses of hooking location partly explain these unexpected results. Regardless of hook type, most animals were hooked in the lip or jaw. Very few were hooked in locations that are likely to be fatal such as the throat, gills or stomach. The differences between our results and the accepted paradigm might be related to the fact that many of the circle hooks used in this study were relatively small.

Fishery managers and stakeholders need to consider the wider implications of bycatch mitigation measures, such as the measure's effects on other species and the industry's economic performance. Numerous mitigation measures have been trialled to determine their efficacy in reducing marine turtle bycatch in longline fisheries. Circle hooks are one mitigation measure that are generally considered effective in reducing the catch of marine turtles by longlines. Our results suggest that the adoption of small circle hooks will not be detrimental to the financial returns of longliners targeting yellowfin and bigeye tuna off eastern Australia.

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Appendix A. Review of circle hooks experiments in pelagic longline fisheries

The capture of marine turtles in pelagic longline fisheries is a growing international concern (FAO 2004). Of the seven marine turtle species found worldwide, six are endangered (IUCN 2006) . Globally, the loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) turtle species are most commonly caught by pelagic longlines. Hawksbill (*Eretmochelys imbricata*), green (*Chelonia mydas*), Olive Ridley (*Lepidochelys olivacea*) and Kemp's Ridley (*Lepidochelys kempii*) turtles are also incidentally captured (Robins et al. 2007).

Pelagic longlines consist of a series of baited hooks, each attached to a branchline. The branchlines, also called "snoods" or "gangions", are attached at regular intervals along a mainline that is suspended from floats at the sea surface. Longlines can range in size from small-scale, locally-based vessels, to modern industrialized distant-water fleets. The longlines deployed by large, distant-water longliners can span hundreds of kilometres of the sea's surface and consist of 3000–4000 baited hooks. They are usually deployed and retrieved within 24-hours (Ward 1996). Shorter longlines, with fewer hooks are more commonly used by locally-based vessels. The sparse and patchy spatial distribution of fish, diurnal cycles in their feeding activity, and distance from port usually necessitate 24-hour operations, regardless of catch rates or vessel size. This method of fishing mainly targets tuna (*Thunnus* species) and billfishes (swordfish, marlin, etc.).

In the late 1990s, the North-East Distant Fishery (NED) in the North Atlantic Ocean, which includes the Grand Banks, was identified as having unacceptable levels of turtle bycatch. Scientists concluded that the fishery jeopardised the continued existence of loggerhead and leatherback turtles. Consequently, this fishery was partially closed in 2000 and completely closed in 2001 (National Marine Fisheries Service 2004b, Read 2007). An extensive co-operative NMFS and industry research program which started in the NED in 2001 found that circle hooks in conjunction with whole fish bait significantly reduced the catch of marine turtles and decreased the rate of deep-hooking in loggerheads (Watson et al. 2005). Consequently, the NED was reopened in 2004 with a suite of turtle mitigation measures, including:

- Possess onboard and/or use 18/0 or larger circle hooks with an offset not exceeding 10 degrees,
- Use only whole Atlantic mackerel and squid bait,
- Only use hooks offset by the manufacturer,
- Carry and use marine turtle release equipment, and
- Comply with specified marine turtle handling and release protocols (National Marine Fisheries Service, 2004b).

Similar measures were imposed on the rest of the US Atlantic Longline fleet on 5 August 2004 (Fairfield 2008).

Increasing awareness of turtle interactions in pelagic longline fisheries also led the US to close their Hawaiian swordfish fishery in 2001. The Hawaiian fishery was reopened in 2004, with strict regulations to reduce marine turtle capture including the mandatory use of large circle hooks with fish bait, restricted annual effort, limits on the number of turtles that can be incidentally caught (16 leatherbacks or 17 loggerheads) and 100 per cent observer coverage (National Marine Fisheries Service 2004a). The swordfish fishing season was closed early in 2006 when target levels for turtle bycatch were reached. This was believed to be as a result of increasing effort and not as a result of increasing loggerhead catch rates (Gilman et al 2006a). The fishery reopened in 2007 and during that year interactions occurred with five leatherbacks and 15 loggerheads. As of 15 July 2008, there has been two interactions with leatherbacks and none with loggerheads (National Marine Fisheries Service 2008).

The US has moved to ban imports of swordfish and other pelagic species from countries where longline vessels do not use acceptable mitigation measures, as required under US legislation, for their domestic fleet (Federal Register, United States 2007, Federal Register, United States 2008). This trade embargo would be similar to that imposed on Australia's prawn trawl fisheries in the late 1990s and is expected to impact most, if not all, longline fishing nations either directly, or indirectly, through market changes.

The Western and Central Pacific Fisheries Commission made the following recommendation in relation to reducing the capture and injury of marine turtles in fishing gear at the Second Regular Session of the Scientific Committee, Manila, 2006:

'Scientific experiments should be undertaken testing a range of mitigation techniques to determine appropriate mitigation measures for a particular fishery or area. Research should also continue to be focused on the development and implementation of improved mitigation measures and turtle handling and release method'.

What is a circle hook?

Circle hooks differ from conventional J-style hooks in that the point of the hook is perpendicular to the shank (Figure 1). By contrast, the point is parallel to the shank in the "J" hook. The shank is shortened in circle hooks compared to "J" hooks, making the entire hook almost circular in shape. In some circle hooks, the point may be oriented down towards the bend in the hook (Cooke and Suski 2004). Japanese tuna hooks are an intermediate style of hook (Figure 1). They are more rounded than a "J" hook, however, unlike a circle hook; the point of the Japanese tuna hook is still perpendicular to the shank. It is believed the Japanese tuna hook works more like a "J" hook than a circle hook (Robins et al. 2007).

Because of their design, circle hooks more frequently hook fish in the jaw rather than deep-hooking (e.g. in the stomach, oesophagus or pharynx) (Cooke and Suski 2004). The inward point of the circle hook allows fish to swallow the hook, without it hooking internal organs. As the fish attempts to swim away, the hook is pulled out of the oesophagus or throat, if swallowed, to the side of the mouth where the point of the hook catches on the flesh or bones of the jaw and pivots outwards. Tension on the line pulls the hook over the jaw and rotates as the fish moves. The rounded design prevents the hook from "backing out" of the wound and will hold a fish, even on slack lines (Cooke and Suski 2004).

The effects of circle hooks on marine turtle catches

The first comprehensive trials evaluating the efficacy of circle hooks in reducing turtle bycatch during commercial longline operations were conducted by Watson et al. in the Grand Banks area of the US Atlantic pelagic fishery (Watson et al. 2002, Watson et al. 2003a; Watson et al. 2003b; Shan et al. 2004; Watson et al. 2004b; Watson et al. 2005). The results of experiments conducted between 2001 and 2003 showed that 18/0 circle hooks significantly reduced turtle bycatch when compared to standard 9/0 "J" hooks, without impacting on catch rates of swordfish. Loggerhead captures were significantly reduced when large circle hooks were used with mackerel bait. Similarly, leatherback interactions were reduced on large circle hooks baited with mackerel (Appendix B). The rate of hook ingestion by loggerhead turtles was also reduced using circle hooks, with 27 per cent of loggerheads caught on circle hooks swallowing the hook compared to 69 per cent of the loggerheads caught on "J" hooks (Watson et al. 2005).

Bolten and Bjorndal (2005) conducted trials in the Azores longline fishery in late 2003 to evaluate the effects of gear modification on marine turtle bycatch in the swordfish fishery. Three hook types were alternated along longlines: 16/0 and 18/0 circle hooks and 3.6 millimetre Japanese tuna hooks. Use of tuna hooks was terminated after 27 sets because of high levels of turtle bycatch and a high proportion of turtles being hooked in the throat. Results show the Japanese tuna hook caught significantly more turtles than the two circle hooks. Fewer turtles were caught using the 18/0 circle hook compared to the 16/0 circle hook (Appendix B). They also found that "J" hooks and Japanese tuna hooks had a significantly higher rate of throat hooking in turtles when each hook was compared to circle hooks ($p<0.0001$). Marine turtles that are hooked in the throat are assumed to have higher rates of mortality than those that are hooked elsewhere (Bolten and Bjorndal 2005).

Results from the Hawaii-based swordfish fishery also show a significant reduction in catch rates of both loggerheads and leatherbacks on pelagic longlines after the mandatory use of large circle hooks and fish bait (Gilman and Kobayashi 2007; Dalzell and Gilman 2006). In their review, Boggs and Swimmer (2007) provide preliminary results for experiments in Uruguay, Brazil and in the Mediterranean Sea comparing catch rates of marine turtles on circle and "J" hooks (Appendix B). In all three studies mentioned, "J" hooks caught a larger percentage of marine turtles than circle hooks, however statistical tests have not been conducted for two of the experiments and sample sizes are quite small. Also in the tuna and mahi mahi fisheries of Ecuador Largacha et al (2005) reported that circle hooks were found to reduce turtle interactions by 44–88 per cent in the tuna fishery (18/0 and 16/0) and 16–37 per cent in the mahi mahi fishery (15/0 and 14/0) with less harmful hookings on circle hooks. In contrast, MRAG Ltd et al (2008) reported that turtle catch in three European surface longline fisheries was not significantly different between circle hooks (16/0 and 18/0) and "J" hooks. They found, however, that bait type (squid versus mackerel) did have an effect on turtle catch.

For internally-hooked turtles (primarily hard shelled-turtles), circle hooks are believed to be more effective because there may be:

- A reduction in the probability of a marine turtle being caught on a hook due to the inability of the turtle to swallow the large size of the hook — obviously a hook bigger than a turtle's mouth will not be so readily taken (Gilman et al. 2005; Watson et al. 2005; Boggs and Swimmer 2007).

- Reductions in the severity of the hooking event as circle hooks will more often mouth-hooked and not deep-hooked (Watson et al. 2003b; Bolten and Bjorndal 2005; Gilman et al. 2005; Dalzell and Gilman 2006; Swimmer et al. 2006; Boggs and Swimmer 2007).
- The use of large circle hooks may result in fewer turtles being released with terminal tackle still attached (Dalzell and Gilman 2006).

For externally-hooked and/or entangled turtles (primarily leatherbacks), there may be a reduction in the probability of a marine turtle becoming foul-hooked following the interaction event (Boggs and Swimmer 2007). This is believed to be due to:

- The tendency of circle hooks not to foul hook the flipper or shoulder of the animal as it swims into and past the gear, because of the direction of the barb of the hook (Robins et al. 2007).
- The shorter distance between the tip of the barb and the shank of the hook (minimum inner width) may prevent the flipper from sliding into the hook and the turtle becoming snagged (Robins et al. 2007).

Effects of circle hooks on other species

The use of circle hooks can reduce the incidental capture of, and damage to marine turtles, but their effect on catch rates of other species varies. Several studies have reported improved catch rates of other species on circle hooks while others report no difference or decreases in catches as a result of the use of circle hooks.

Watson et al. (2005) found an increase in swordfish catch rates using circle hooks with mackerel bait; however catches of bigeye were significantly lower on circle hooks (Appendix C). In the yellowfin tuna fishery in the Caribbean, there was a significant difference in catch rates of target species between circle and "J" hooks. Catch rates were 2.5 times higher using large circle hooks compared to "J" hooks (Falterman and Graves 2002). Similarly, Kerstetter and Graves (2006a) found the use of circle hooks resulted in a significantly higher catch rate for yellowfin tuna compared to "J" hooks in the US Atlantic coastal pelagic fishery (Appendix C). They also observed overall catch rates of all species combined were significantly reduced on sets where mackerel was used as bait (as opposed to squid) in the spring Gulf of Mexico/Caribbean fishery. There was no significant difference in catches of swordfish between the two baits in the spring fishery (Kerstetter and Graves 2006a). A comparison of circle and "J" hooks in the Venezuelan pelagic longline fishery revealed that the catch rate for all species combined, including yellowfin tuna, was significantly higher on circle hooks compared to "J" hooks (Falterman and Graves 2002). Watson et al. (2004a) compared catch rates of yellowfin tuna caught on 16/0 with 18/0 circle hooks in the Gulf of Mexico tuna fishery. They found a significant reduction in the catch rate of yellowfin on the larger circle hooks compared to smaller circle hooks.

Preliminary results from a number of experiments currently being conducted in longline fisheries around the world, including Italy, Brazil and Indonesia, indicate no difference in catch rates of target species between circle and "J" hooks (Boggs and Swimmer 2007, Appendix C). However, statistical tests have not yet been conducted in most of these studies. Boggs (2006) notes catch rates of bigeye tuna on circle hooks are “at least as good” as those on tuna hooks in the Hawaiian swordfish longline fishery (Appendix C).

Other studies have found negative impacts of circle hooks on catch rates of several target species. In the Hawaiian swordfish fishery, Boggs (2003) evaluated the effectiveness of circle hooks at catching target species based on the ratio of swordfish and tuna caught on circle hooks compared to those caught on “J” hooks. He found circle hooks to be only 40 per cent as effective as “J” hooks at catching swordfish and 94 per cent as effective at catching tuna. Experiments comparing circle hooks and Japanese tuna hooks in the Korean longline fishery showed no significant difference in catch rates among the hook types (Kim et al. 2006). However there was a significant difference in catch rates between the tuna hook and the large circle hook for all target species (tuna and billfish) combined (Appendix C). Largarcha et al. (2005) found no significant difference in catch rates of target species between tuna hooks and two sizes of circle hooks in the Ecuador tuna longline fishery. These results however are confounded by a number of factors including time of day, hook style and material and bait. Minami et al. (2006) examined the effects of circle hooks on catch rates of turtles and target species in the Japanese longline fishery of the western north Pacific. The use of circle hooks had little effect on catch rates of tuna, but large circle hooks had a negative effect on billfish catch rates when compared to tuna hooks (Appendix C). Trials in the western Mediterranean reported that there were significantly higher catches of swordfish on “J” hooks compared with circle hooks (MRAG Ltd et al 2008).

The effects of circle hooks on catch rates of non-target species are largely unknown; however a few studies have compared catch rates of sharks on circle versus “J” hooks. Bolten and Bjorndal (2005) compare catch rates of blue sharks on offset versus non-offset hooks, circle hooks versus “J” hooks and tuna hooks, and different sizes of circle hooks over a three-year period in the Azores. The results vary between years and hook types. Watson et al. (2005) observed increased catch rates of blue shark when circle hooks baited with squid were compared to “J” hooks (Appendix C). They noted that these results may not be representative because during hauling, sharks that were deep-hooked on lines with monofilament leaders may have bitten the line and escaped. Similarly, Yokota et al. (2006) found circle hooks had no effect on mitigating shark bycatch in the Japanese longline fishery. Boggs (2006) found that shark catch was not higher on circle hooks compared to tuna hooks in the Hawaiian swordfish longline fishery.

The effects of circle hooks on catches of seabirds and marine mammals have not been studied widely (Robins et al. 2007; Read 2007). However, observer data from the US Atlantic pelagic longline fishery suggests the catch rate of seabirds was six times higher on “J” hooks compared to circle hooks (ICCAT 2007).

Effect of hook type on fish size

In their review, Cooke and Suski (2004) examined 14 studies that assessed the size of various recreational fish species caught on circle and “J” hooks. They found no significant difference in the size of fish caught by the two hook types. Similarly, Kerstetter and Graves (2006a) detected no significant difference in the mean length of swordfish caught on circle hooks compared to “J” hooks in the US Atlantic coastal pelagic longline fishery. By contrast, they found that yellowfin caught on circle hooks were significantly longer than those caught on "J" hooks (Appendix C). Mean size of yellowfin caught on circle hooks was 116 (SD±9) cm FL compared to 111 (SD±7) cm FL for those caught on "J" hooks.

Few studies have examined the effect of hook size on the size of fish caught in pelagic longline fisheries. Watson et al. (2004a) report a significant reduction by weight of marketable yellowfin tuna caught on 18/0 circle hooks compared to 16/0 circle hooks in the Gulf of Mexico tuna longline fishery. Boggs and Swimmer (2007) provide preliminary results from hook trials in Brazil that show similar weights of individual swordfish caught on both "J" hooks and circle hooks. MRAG Ltd et al (2008) report that trials in three European surface longline fisheries in the Mediterranean and the Atlantic found that hook type (circle versus "J" hook) did not impact on swordfish catch rates.

The effect of hook type on the size of fish caught in pelagic longline fisheries requires further investigation.

Hook-related injuries and mortality of fish

Cooke and Suski (2004) conducted a review of studies examining the effectiveness of circle hooks, mainly in recreational catch-and-release fisheries. They found that circle hooks were more likely to hook fish in the jaw than "J" hooks. Furthermore, circle hooks were less likely to deep-hook fish than "J" hooks. Overall, mortality rates were lower on circle hooks compared to "J" hooks (Cooke and Suski 2004). Similarly, Kerstetter and Graves (2006a) found that 82 per cent of yellowfin caught on circle hooks were hooked in the jaw. Falterman and Graves (2002) noted that 95 per cent of fishes caught on circle hooks were hooked in the jaw compared to only 57 per cent caught on "J" hooks.

Cooke and Suski (2004) also noted that the use of circle hooks was less likely to cause bleeding compared to "J" hooks and that bleeding was generally related to lower survival. Similarly, Skomal et al. (2002) observed that wounds to the jaw, palate and body in Atlantic bluefin tuna (*Thunnus thynnus*) resulted in minimal bleeding while hook wounds to the pharynx and oesophagus lead to severe bleeding. They concluded that the ability of circle hooks to hook in the jaw more frequently than "J" hooks would result in less physical damage to the fish. However, a number of studies have reported damage to the eye or eye socket of fish hooked on circle hooks (Horodysky and Graves 2005; Kerstetter and Graves 2006b).

In the North Atlantic recreational fishery for white marlin (*Tetrapturus albidus*), Horodysky and Graves (2005) attached pop-up satellite archival tags to marlin caught on "J" hooks (n=21) and circle hooks (n=20) to estimate post-release survival. Survival was significantly higher (P<0.01) for marlin caught on circle hooks (100 per cent survival) compared to "J" hooks (65 per cent survival). An extension of this research by Graves and Horodysky (2008) evaluated post-release survival using pop-up satellite archival tags of white marlin following capture on three different styles of circle hooks. They concluded that there was no significant difference in the incidence of deep hooking, hook-induced trauma, or post-release survival among the fish caught on the different styles of circle hooks and that post-release survival was significantly higher for all three circle hooks combined compared with the J hook tested during the previous study (P<0.0001).

In a similar study, Domeier et al. (2003) compared the effectiveness and associated mortality of circle hooks and "J" hooks for striped marlin (*Tetrapturus audax*). They found no significant difference in mortality rates between circle hooks and "J" hooks (Yates' P=0.55, n=122), but deep-hooking was 2.5 times higher on "J" hooks compared to circle hooks. Furthermore, five times as many fish were observed bleeding from the gill cavity when caught on "J" hooks compared to circle hooks (Domeier et al. 2003).

Other marine turtle bycatch mitigation measures

The reasons why marine turtles are attracted to and consequently become hooked or entangled in, commercial fishing gear are not well known. It may be related to the fact that marine turtles are mostly visual predators (Southwood et al. 2007 and references therein). For example, Southwood et al. (2007) found that loggerheads had a limited ability to locate squid bait in total darkness. Wang et al. (2007) conducted laboratory studies with captive-reared juvenile loggerheads and wild-caught post hatchling loggerheads to examine the response of these turtles to chemical lightsticks and LED lights. They found that the captive-reared and wild-caught loggerheads were attracted to glowing green, blue and yellow lightsticks and orange LED lights and were not attracted to the inactive lightsticks used as a control. The authors note the limitations of laboratory experiments and suggest that field studies be conducted to test the hypothesis that the use of lightsticks can increase marine turtle bycatch. They also suggest that modifications to lightsticks to reduce their attractiveness to turtles (e.g. use of shades or use of certain wavelengths outside the turtle's vision), should be tested as a possible mitigation measure.

Other studies have trialled chemical deterrents as a means of reducing turtle bycatch on longlines. Southwood et al. (2007) found that chemical modification of squid bait with 2-phenylethanol or skin secretions from a tiger shark (*Galeocerdo cuvier*), did not alter the feeding behaviour of loggerheads. Similarly, Swimmer et al. (2006) exposed green turtles and two species of tuna (yellowfin and skipjack) to squid marinated in a variety of pungent substances including garlic, cilantro, chilli, wasabi, lemon, squid ink and noxious secretions from the sea hare *Aplysia* spp. They found that all of the modified baits were eaten by nearly all of the animals.

Altering the depth of longline gear, so that longline hooks fish deeper depths, has also been suggested as a method of reducing marine turtle bycatch by longlines (Løkkeborg 2004, Gilman et al. 2006b). In an analysis of observer data from the Secretariat of the Pacific Community (SPC), the Oceanic Fisheries Program found that catch rates of marine turtles were an order of magnitude higher on shallow-set longlines (<100 metre) compared to deep-set longlines (150–300 metre) (SPREP 2001). An analysis of observer data from the Hawaiian longline fishery show that shallowest hooks in a set, those closest to the floats, caught significantly more leatherbacks and loggerheads than the hooks in other positions in the set. These results imply that either the shallowest hooks are more likely to catch turtles or that the floats attract turtles (Kleiber and Boggs 2000). The US has regulated the depth of the deepest part of a longline basket, the length of branchlines and the setting location for the shallowest branchlines (Federal Register, United States 2001).

Beverly (2004) reports on trials of a deep-setting technique to reduce bycatch in pelagic longline fisheries. The method involves weighting the mainline so that an entire basket fishes below the critical depth of 100 metres. This is achieved by suspending the fishing portion of the line by 50 metre section of mainline. Trials in the Australian pelagic longline fishery found that the weighted gear typically fished depths of 120–340 metres while the normal gear fished depths of 40–200 metres. Nominal catch rates were slightly improved for weighted gear. The US has regulated the depth of the deepest part of a longline basket, the length of branchlines and the setting location for the shallowest branchlines (Federal Register, United States 2001).

Shiode et al. (2005) tested a mid-water float system for adjusting the depth at which longlines hook fish. Three different settings were trialled with either zero, one or two floats attached at points along the mainline. On the control set (no float attached), the distance between the deepest and shallowest hooks was 55.1 metre compared to 26.2 metre for the one float set and 4.9 metre in the two float set. There was also no significant reduction in the sinking speed of hooks and branchlines with midwater floats compared to conventional lines (no midwater floats). This method could allow greater adjustment of longline depth to target the swimming depth of target species without the addition of a lot of extra gear. However, the effect of the altered gear on the catch of turtles and target species was not examined.

A number of other mitigation measures to reduce marine turtle bycatch in longline fisheries have been trialled with varying results. These include the use of blue-dyed bait (Laurs et al. 2001), use of fish bait as opposed to squid (Watson et al. 2005), moving the branchline away from the float line (Dalzell and Gilman 2006), minimising gear soak during the day (Watson et al. 2005), bait type (Watson et al. 2005, Rueda et al. 2006), area and seasonal closures (NMFS 2004a), hook modifications (Beverly and Chapman 2007, Hataway and Mitchell 2002, Boggs and Swimmer 2007), acoustic deterrents (Bartol and Kettem 2006) and the use of stealth fishing gear (Boggs 2003, Johnsen 2006).

Appendix B. Summary of experiments examining effect of circle hooks on marine turtle bycatch in pelagic longline fisheries.

Statistically significant results are in bold.

Fishery	Bait used	Sample size	Experimental hook type	Control hook type	Turtle Species	Results	Reference
US Atlantic pelagic longline – North-west Atlantic	Mackerel	427,382 hooks	18/0 10º offset circle	9/0 "J" hook 20–25º offset baited with squid	Loggerhead	Reduced catch rates by 90% (CI=70–97%, ***p*<0.001**) compared to control	Watson et al. (2005)
					Leatherback	Reduced catch rates by 65% (CI=36–81%, ***p*<0.007**) compared to control	
			9/0 "J" hook 20–25º offset		Loggerhead	Reduced catch rates by 71% (CI=42–86%, ***p*<0.0005**) compared to control	
					Leatherback	Reduced catch rates by 66% (CI=37–81%, ***p*<0.006**) compared to control	
	Squid		18/0 0º offset circle		Loggerhead	Reduced catch rates by 86% (CI=73–93%, ***p*<0.001**) compared to control	

Fishery	Bait used	Sample size	Experimental hook type	Control hook type	Turtle Species	Results	Reference
			10º offset circle		Leatherback	Reduced catch rates by 57% (CI=34–72%, ***p*<0.0001**) compared to control	
Swordfish longline fishery – Azores Phase 1 (2000)	Squid	138, 121 hooks	16/0 circle hook 9/0 offset "J" hook	9/0 non offset "J" hook	Loggerhead	No significant difference in catch rates among the 3 hook types (p>0.05) although the lower number of turtles caught on offset "J" hook approaching significance (p=0.0509)	Bolten & Bjorndal (2005)
Swordfish longline fishery – Azores Phase 2 (2001)	Squid	88, 150 hooks	16/0 circle hook 18/0 circle hook	9/0 non offset "J" hook	Loggerhead	No significant difference in catch rates among 3 hook types (p>0.05) although the higher number of turtles caught on 16/0 circle hooks approaching significance (p=0.0539)	Bolten & Bjorndal (2005)
Swordfish longline fishery –	Squid	75, 511 hooks	16/0 offset circle hook	16/0 circle hook	Loggerhead	No significant difference in catch rates among the 3 hook types (p>0.05)	Bolten & Bjorndal

Fishery	Bait used	Sample size	Experimental hook type	Control hook type	Turtle Species	Results	Reference
Azores Phase 3 (2002)			18/0 offset circle hook				(2005)
Swordfish longline fishery – Azores Phases 4A and 4B (2003)	Squid	4A: 40,838 hooks 4B: 73,579 hooks	16/0 non offset circle	No control used	Loggerhead	4A: CPUE = 1.91 4B: CPUE = 0.63	Bolten & Bjorndal (2005)
			18/0 non offset circle			4A: CPUE = 1.18 4B: CPUE = 0.41 Fewer turtles were caught with 18/0 compared to 16/0 for 4A and 4B combined (Friedman χ^2=4.8, df=1, p=0.029).	
			3.6mm Japanese tuna hook			4A: CPUE = 4.55 4B: terminated because of high catch rates For 4A the tuna hook caught **significantly more turtles** than other hook types (Friedman χ^2=19.38, df=2, **p=0.0001**).	

Fishery	Bait used	Sample size	Experimental hook type	Control hook type	Turtle Species	Results	Reference
Japanese longline fishery – Western North Pacific	Squid	48,600 hooks	4.3 *sun* circle hook	3.8 *sun* tuna hook	Loggerhead	**No significant difference** in hooking rates between 4.3 circle hook and tuna hook (Wilcoxin signed-rank test, **p=0.9263**)	Minami et al. (2006)
			5.2 *sun* circle hook			Large circle hooks **significantly reduced** hooking rates compared to tuna hooks (Wilcoxin signed-rank test, **p=0.0088**)	
Hawaiian swordfish longline fishery	Squid used pre-regulations Fish used post-regulation	4,260,380 hooks 1,282,748 before intro of circle hooks 2,977,632 after intro of circle hooks	18/0 10º offset circle hooks with fish bait	9/0 "J" hook with squid bait	Loggerhead	Circle hooks **significantly reduced** capture rates of loggerheads compared to "J" hooks - **90% reduction**	Gilman & Kobayashi (2007)
					Leatherback	Circle hooks **significantly reduced** capture rates of leatherbacks compared to "J" hooks – **85% reduction**	
Hawaiian swordfish longline fishery	Squid used pre-regulations Fish used post-regulation		18/0 10º offset circle hooks with fish bait	9/0 "J" hook with squid bait	Loggerhead	Circle hooks **significantly reduced** capture rates of loggerheads compared to "J" hooks - **90% reduction**	Dalzell & Gilman (2006)
					Leatherback		

Fishery	Bait used	Sample size	Experimental hook type	Control hook type	Turtle Species	Results	Reference
Ecuador tuna longline fishery	Squid	20, 570 hooks	16/0 circle hook		Marine turtles combined	16/0 circle hooks **significantly reduced** marine turtle hooking rates compared to tuna hook (44% reduction, p=0.139, p(sign)=0.087)	Largarcha et al. (2005)
Ecuador tuna longline fishery	Squid	20, 570 hooks	18/0 circle hook		Marine turtles combined	18/0 circle hooks **significantly reduced** marine turtle hooking rates compared to tuna hook (89% reduction, p=0.019, p(sign)=0.062)	Largarcha et al. (2005)
Ecuador mahi mahi longline fishery	Unknown	32, 200 hooks	14/0 circle hook	4/0 or 5/0 “J” hook or 7/0 tuna hook	Marine turtles combined	14/0 circle hooks reduced marine turtle hooking rates by 37% compared to “J” hook (preliminary data only, no statistical tests conducted)	Largarcha et al. (2005)
Ecuador mahi mahi longline fishery	Unknown	32, 200 hooks	15/0 circle hook	4/0 or 5/0 “J” hook or 7/0 tuna hook	Marine turtles combined	15/0 circle hooks reduced marine turtle hooking rates by 16% (preliminary data only, no statistical tests conducted)	Largarcha et al. (2005)
Italian shallow-set swordfish longline fishery – Mediterranean Sea	Frozen mackerel	20, 000 hooks	16/0 10º offset circle hook	20º offset “J” hook	Marine turtles combined (N=17)	Circle hooks caught **significantly less** (17.6%) turtles compared to “J” hooks (82.4%).	Boggs & Swimmer (2007)

Fishery	Bait used	Sample size	Experimental hook type	Control hook type	Turtle Species	Results	Reference
Brazil longline	Mackerel	16, 500 hooks	18/0 10º offset circle hook	9/0 “J” hook	Marine turtles combined (N=30)	Circle hooks caught 34% of marine turtles compared to 66% caught on “J” hooks – no statistical test conducted	Boggs & swimmer (2007)
Uruguay longline	Unknown	37, 968 hooks	18/0 10º offset circle hook	9/0 “J” hook	Marine turtles combined (N=29)	Circle hooks caught 38% of marine turtles compared to 62% on “J” hooks – no statistical test conducted	Boggs & Swimmer (2007)
Greek longline in eastern Mediterranean	Squid and mackerel	60,000 hooks	18/0 10º offset circle hook 16/0 circle hook	Size 2 “J” hook	Loggerhead (N=1); Leatherback (N=1) not analysed	40%, 36% and 24% of loggerheads caught were on “J” hooks, 18/0 circle hooks and 16/0 circle hooks respectively. But the differences were found to be **not significant** (**p**>**0.01**).	MRAG et al (2008)
Spanish longline in western Mediterranean	Squid and mackerel	71,100 hooks	18/0 10º offset circle hook 16/0 circle hook	“J” hook no 2	Loggerhead (N=77); leatherback (N=0) not analysed		
Spanish distant water longline in south-east Atlantic Ocean	Squid and mackerel	44,705 hooks	18/0 10º offset circle hook 16/0 circle hook	16/0 10º offset “J” hook	Loggerhead (N=36); leatherback (N=9) not analysed		

Appendix C. Summary of experiments examining effects of circle hooks on other non-target and target species.

Statistically significant results are in bold.

Fishery	Bait used	Sample size	Experimental hook type	Control hook type	Species	Results	Reference
US Atlantic pelagic longline – North-west Atlantic	Mackerel	427,382 total hooks 142,000 control hooks Approx. 71,000 of each treatment hook	18/0 10º offset circle	9/0 "J" hook 20–25º offset baited with squid	Swordfish	Catch rates **increased** by 30% (CI=14–46%, ***p*<0.001**) compared to control	Watson et al. (2005)
					Bigeye	Catch rates **reduced** 81% (CI=49–100%, ***p*<0.001**) compared to control	
					Blue shark	Catch rates **reduced** 31% (CI=27–35%, ***p*<0.001**) compared to control	
			9/0 "J" hook 20–25º offset		Swordfish	Catch rates **increased** by 63% (CI=46–81%, ***p*<0.001**) compared to control.	
					Bigeye	Catch rates **reduced** 90% (CI=58–100%, ***p*<0.0001**) compared to control	
					Blue shark	Catch rates **reduced** 40% (CI=36–43%, ***p*<0.001**) compared to control	
	Squid		18/0 0º offset circle		Swordfish	Catch rate **reduced** 33% (CI=19–46%, ***p*<0.001**) compared to control	
					Bigeye	Catch rates increased 26% but increase was not significant (*p*=0.1463)	

Fishery	Bait used	Sample size	Experimental hook type	Control hook type	Species	Results	Reference
US Atlantic pelagic longline – North-west Atlantic	Squid	142,000 control hooks set	18/0 0º offset circle	9/0 “J” hook 20–25º offset baited with squid	Blue shark	Catch rates **increased** by 8% (CI=2–14%, ***p*<0.0073**) compared to control	Watson et al. (2005)
		Approx. 71,000 of each treatment hook set	18/0 10º offset circle		Swordfish	Catch rate **reduced** 29% (CI=14–44%, ***p*=0.002**) compared to control	
					Bigeye	Catch rates increased 26% but increase was not significant (*p*=0.1463)	
					Blue shark	Catch rates **increased** 9% (CI=3–16%, ***p*=0.0030**) compared to control	
Caribbean-Venezuelan pelagic longline fishery	Mostly live bigeye scad	5480 total hooks 9 sets Trip 1 6 sets Trip 2	14/0 circle hooks (Trip 1) – manually offset 16/0 circle hooks (Trip 2) – manually offset	7/0 “J” hooks	Yellowfin tuna	CPUE on circle hooks **significantly higher** than that of “J” hooks (*p*=0.026) No significant difference in mean length of tuna between circle and “J” hooks	Falterman & Graves (2002)
US Atlantic coastal pelagic longline fishery -	Squid	39 sets Autumn season	16/0 0º offset circle hooks	9/0 10º offset “J” hooks	Yellowfin tuna	CPUE on circle hooks significantly higher than that of “J” hooks (t value=2.47, *P*=0.018)	Kerstetter & Graves (2006a)

Fishery	Bait used	Sample size	Experimental hook type	Control hook type	Species	Results	Reference
		30,600 total hooks across the two seasons				Yellowfin caught on circle hooks significantly longer than those caught on "J" hooks (N=39, *P*=0.009)	
	Squid and Mackerel	46 sets Spring season 30,600 total hooks across the two seasons			Swordfish	No significant difference in swordfish catch rates between circle and "J" hooks. No significant difference in swordfish catch rates between baits. No significant difference in mean lengths of swordfish between circle and "J" hooks.	
Gulf of Mexico tuna fishery	Sardine	29,570 total hooks	18/0 0º offset circle hooks	16/0 0º offset circle hook	Yellowfin tuna (N=597)	CPUE on 16/0 circle hooks **significantly higher** compared to 18/0 circle hooks (***p*=0.0025**).	Watson et al. (2004a)

Fishery	Bait used	Sample size	Experimental hook type	Control hook type	Species	Results	Reference
Hawaiian pelagic longline fishery	Unknown	78,071 total hooks 95 sets	18/0 0º offset circle hooks Only 20% of branchlines were equipped with circle hooks	0º offset "J" hook	Swordfish	Circle hooks only 40% as effective as "J" hooks at catching swordfish (no statistical significance stated)	Boggs (2003)
					Tuna	Circle hooks 94% as effective as "J" hooks at catching swordfish (no statistical significance stated)	
Korean tuna longline fishery – eastern Pacific Ocean	Sardine, jack mackerel, squid, herring, chub mackerel and milkfish	62,464 total hooks	C15 10º offset circle hooks	4/0 Japanese tuna hook	Tuna and billfish (all species combined)	No significant difference in catch rates of target species combined among 3 hook types (χ^2= 5.76, p=0.06). There was a significant difference in catch rates between the "J" hook and the 18/0 circle hook (χ^2=5.3, p=0.02).	Kim et al. (2006)
			C18 10º offset circle hooks				
Japanese longline fishery – Western North Pacific	Squid	48,600 total hooks	4.3 *sun* circle hook	3.8 *sun* tuna hook	Bigeye tuna (N=11)	No significant difference in catch rates between 3 hook types	Minami et al. (2006)
Japanese longline fishery – Western North Pacific	Squid	48,600 total hooks	5.2 *sun* circle hook	3.8 *sun* tuna hook	Swordfish (N=34) and striped marlin	Large circle hooks had a negative impact on billfish catch rates (statistical significance not stated)	Minami et al. (2006)

Fishery	Bait used	Sample size	Experimental hook type	Control hook type	Species	Results	Reference
					(N=17)		
Japanese longline fishery – Western North Pacific	Squid	48,600 total hooks	4.3 *sun* circle hook	3.8 *sun* tuna hook	Blue shark	No significant difference in catch rates between 3 hook types	Yokota et al. (2006)
			5.2 *sun* circle hook				
Ecuador tuna longline fishery	Squid	20, 570 total hooks	16/0 circle hooks	9/0 or 10/0 tuna hook	All target species combined	Catch rates of target species reduced by 6% on 16/0 circles compared to tuna hooks. Not a significant difference (*p*=0.102)	Largarcha et al. (2005)
			18/0 circle hooks			Catch rates of target species reduced 10% on 18/0 circles compared to tuna hooks. Not a significant difference (*p*=0.156)	
Ecuador mahi mahi longline fishery	Unknown	32, 200 hooks set	14/0 circle hooks	4/0 or 5/0 “J” hook or 7/0 tuna hook	Mahi mahi	14/0 circle hooks reduced catch rates by 30% compared to “J” hooks – no statistical test conducted	Largarcha et al. (2005)
			15/0 circle hooks			15/0 circle hooks reduced catch rates by 36% compared to “J” hooks – no statistical tests conducted	

Fishery	Bait used	Sample size	Experimental hook type	Control hook type	Species	Results	Reference
Hawaii swordfish longline fishery	Squid used pre-regulations Fish used post-regulation		18/0 10º offset circle hook with fish bait	9/0 "J" hook with squid bait	Swordfish	Catch rates of swordfish **significantly increased** (16%) on circle hooks compared to "J" hooks	Dalzell & Gilman (2006)
					Combined tuna species	Catch rates of tunas were **significantly reduced** (50%) on circle hooks compared to "J" hooks	
					Shark	Catch rates of sharks were **significantly reduced** on circle hooks compared to J hooks	
Italian shallow-set swordfish longline fishery	Frozen mackerel	20, 000 hooks	16/0 10º offset circle hook	20º offset "J" hook	Swordfish	Circle hooks caught 48% of swordfish. "J" hooks caught 52%. No statistical test conducted.	Boggs & Swimmer (2007)
Brazil longline	Mackerel	16, 500 hooks	18/0 10º offset circle hook	9/0 "J" hook	Swordfish	60 swordfish caught on circle hooks, 65 caught on "J" hooks – no statistical test conducted	Boggs & Swimmer (2007)
					Tuna	Catch rates for tuna species were similar for both hook types	
Indonesian tuna longline fishery – Bali	Unknown	54, 000 hooks	16/0 circle hook	Tuna hook	All target species	Circle hooks caught 12% more target catch with 14.63% less discards compared to tuna hooks	Boggs & Swimmer (2007)
Hawaiian swordfish longline fishery	Unknown	546, 808 hooks	18/0 circle hook	3.6 sun tuna hook	Bigeye tuna	Catch rates of bigeye on circle hooks were just as good as those on tuna hooks	Boggs (2006)
					Shark	Shark catch was not higher on circle hooks	

Fishery	Bait used	Sample size	Experimental hook type	Control hook type	Species	Results	Reference
Swordfish longline fishery – Azores Phase 1 (2000)	Squid	138, 121 hooks	16/0 circle hook 9/0 offset "J" hook	9/0 "J" hook	Blue shark	No significant difference between non-offset "J" hook and circle hook (*p*=0.26) Off-set "J" hook caught **significantly fewer** sharks **(*p*<0.001)**	Bolten & Bjorndal (2005)
Swordfish longline fishery – Azores Phase 2 (2001)	Squid	88, 150 hooks	16/0 circle hook 18/0 circle hook	9/0 "J" hook	Blue shark	No significant difference between 16/0 and 18/0 circle hook (*p*=0.43) Non-offset "J" hook caught **significantly fewer** sharks than circle hooks **(*p*<0.001)**	Bolten & Bjorndal (2005)
Swordfish longline fishery – Azores Phase 3 (2002)	Squid	75, 511 hooks	16/0 offset circle hook 18/0 offset circle hook	16/0 circle hook	Blue shark	Catch rates were **significantly different** among the 3 hook types (*p*=0.0001)	Bolten & Bjorndal (2005)
Swordfish longline fishery – Azores Phase 4A	Squid	40, 838 hooks	16/0 circle hook 18/0 circle hook	3.6 mm Japanese tuna hook	Blue shark	Catch rates were **significantly different** among the 3 hook types (*p*=0.0008)	Bolten & Bjorndal (2005)
Swordfish longline fishery – Azores	Squid	73, 579 hooks	16/0 circle hook	18/0 circle hook	Blue shark	No significant difference between circle hooks (*p*=0.81)	Bolten & Bjorndal

Fishery	Bait used	Sample size	Experimental hook type	Control hook type	Species	Results	Reference
							(2005)
Phase 4B							
Greek longline in eastern Mediterranean	Squid and mackerel	60,000 hooks	18/0 10º offset circle hook	Size 2 "J" hook	Swordfish	Swordfish catch rates by number were greatest in the western Mediterranean, where there were **statistically significant** hook effects (highest catches rates being on "J" hooks) (**p**>**0.01**).	MRAG et al (2008)
			16/0 circle hook				
Spanish longline in western Mediterranean	Squid and mackerel	71,100 hooks	18/0 10º offset circle hook	"J" hook no 2			
			16/0 circle hook				
Spanish distant water longline in south-east Atlantic Ocean	Squid and mackerel	44,705 hooks	18/0 10º offset circle hook	16/0 10º offset "J" hook			
			16/0 circle hook				

Appendix D. Observer instructions

Refer to standard AFMA briefing material.

Set

1. With the skipper and crew, agree on the **configuration** of the gear before each set, e.g., alternating circle and tuna hooks with a squid bait on every branchline and a lightstick on every second branchline. Enter the details of the configuration(s) in the Hook Monitoring Data sheet.
2. In the Hook Monitoring Data sheet **describe** the bait (size, species), lightstick and hook (their standard tuna hook as well as the circle hook). Obtain a sample of a leader with circle hook and one with their standard hook and forward to Canberra.
3. Regularly **monitor** the set to check that the configuration is being adhered to.

Haul

1. On the Biological Data Sheet Record the **species**, **length**, **life status**, **hook number, hook type** and **bait** for all animals caught, both retained and discarded, target and non-target catch. Make sure that this data can be linked to the record of hook number, etc in your Hook Monitoring Data sheet.
2. In the comments section of the Biological Data sheet also record **where** the animal was hooked, e.g., jaw, mouth, gut, foul-hooked. Report whether there are any problems with **releasing sharks** from circle hooks. Pay particular attention to the identification of **turtles** and **seabirds**. **Retain** any dead seabirds.
3. Record the number of each hook type **lost** and the number of branchlines **replaced** per longline operation.
4. Report any **problems** that the crew may have with circle hooks or the experimental design. Note any techniques or innovations that might be used to improve catch rates on the circle hooks. Consider how the experimental design might be improved and anything that might be affecting the performance of the different hooks that is not being accounted for.
5. Take a camera (preferably digital and waterproof) and take **photos** of the vessel, gear, deck work, placement of hook in landed fish and action shots of fish in the water and being landed.

Landing

We need to determine the impact of circle hooks on the economics of longline operations. To do this, we need you to collect data on the relative costs and financial returns of circle hooks compared with the vessel’s standard hooks. If possible, please attempt to collect the following data in the days or weeks after each trip:

1. Where possible, record the **weight** of each fish on the Biological Data sheet.
2. Where possible, record on the Biological Data sheet the **price** that the fish eventually fetched at market and the name of the market.

Appendix E. Example datasheets

OBSERVER LONGLINE HOOK MONITORING DATA

Obs name:	Kreutz		Vessel	Malibu			Project	CIRCLE HOOK		Beacon no.		1
Set no.	2		Shot date:	14	7	05	Start shot time:	20	35	Pag	1 of	3
										Trip ID	K	1

Basket code		← Hook number (set								
		9	8	7	6	5	4	3	2	1
A	hook type	C	T	C	T	C	T	C	T	C
	bait type	S	S	S	M	M	M	S	S	S
	lightstick	Y	-	Y	-	Y	-	Y	-	Y
B	hook type	T	C	T	C	T	C	T	C	T
	bait type	S	S	S	M	M	M	S	S	S
	lightstick	Y	-	Y	-	Y	-	Y	-	Y
C	hook type									
	bait type									
	lightstick									

Use spare columns to define the gear, e.g.,
C=13/0 circle S/S C-1 hook
T=3.8mm tuna hook
S=200 g squid
M=150 g blue mackerel

(only 2 configurations used)

Float no.	Time hh	Time mm	Basket code	1	2	3	4	5	6	7	8	9
1	6	23	B	0	0	0	1	0	0	0	1	1
2	6	28	A	1	1	Y01						
3	6	33	B	0	0	0	0	0	0	0	0	1
4	6	38	A	B01				Y02				
5	6	43	B		1	1	0	0	0	0	0	0
6	6	48	A	0	0	0	0	1	1	1	0	0
7	6	53	B	0	0	0	1	1	1	0	0	0
8	6	58	A	0	0	U01						
9	7	4	B	0	0	0	1	0	0	0	1	1
10	7	10	A	0	0	A01	A02					
11												
12												
13												
14												
15												
16												
17												
18												
19												
20												
21												
22												
23												
24												
25												
26												
27												
28												
29												
30												

Hook number (haul sequence) →

Use spare columns to define your species codes, e.g.,
Y=yellowfin tuna
B=bigeye tuna
U=blue shark
S=swordfish
A=albacore tuna

and any comments, e.g., "125 cm YFT caught on float #10, but hook number unkown"

0 = bait missing, 1 = intact, 2 = branchline missing, 3 = branchline bitten off, 4 = branchline tangled

Float #1 was last float set: Y/N

OBSERVER LONGLINE HOOK MONITORING DATA

Obs name:	Kreutz	Vessel	Malibu
Set no.	2	Shot date:	14 7 05

Project	CIRCLE HOOK	Beacon no.	1
Start shot time:	20 35	Page 1 of	3
		Trip ID	K 1

Float no.	Time hh	Time mm	Basket code	Hook number (haul sequence) → 1	2	3	4	5	6	7	8	9	10
1	6	23	B	0	0	1	1	1	0	0	0	1	
2	6	28	A	0	0	YFT CSL							
3	6	33	B	1	1	1	1	0	BET TSL				
4	6	38	A	1	1	1	0	1	0	0	1	1	
5	6	43	B	0	0	1	0		YFT TSL			YFT CML	
6	6	48	A					0	0	1	1	1	
7	6	53	B	0	1	0	0	1	0	1	1	1	
8	6	58	A	1	0	1	0	0	0	1	1	1	
9	7	4	B	1	1	1	0	1	0	1	1	1	
10													
11													
2													
3													
4													
5													
6													
7													
8													
9													
0													
1													
2													
3													
4													
5													
6													
7													
8													
9													
0													

0 = bait missing, 1 = intact, 2 = branchline missing, 3 = branchline bitten off, 4 = branchline tangled

Float #1 was last float set: Y/N

Appendix F. Estimated value of each species retained by project longliners

Values are in Australian dollars. Weights are processed weights derived from length measurements.

Albacore tuna

Trip	Total number			Total weight (kg)			Average weight (kg)			Average	Total value ($)		
	Circle	Tuna	C–T	Circle	Tuna	C–T	Circle	Tuna	C–T	price ($/kg)	Circle	Tuna	C–T
G1	16	3	13	188	39	149	11.7	13.0	–1.3	$1.60	$301	$62	$238
G2	2	1	1	38	14	24	19.2	14.0	5.1	$1.60	$61	$22	$39
G3	3	2	1	41	26	15	13.7	12.9	0.8	$1.50	$62	$39	$23
G4	1	0	1	12	0	12	12.3		12.3	$1.50	$18	$0	$18
G5	13	6	7	177	75	102	13.6	12.4	1.2	$1.50	$265	$112	$153
G6	1	2	–1	13	31	– 19	12.7	15.7	–3.0	$1.80	$23	$57	–$34
G7	15	6	9	198	78	120	13.2	13.0	0.2	$1.44	$285	$113	$172
G8	18	5	13	268	66	202	14.9	13.2	1.7	$1.50	$402	$99	$303
G9	22	7	15	357	102	255	16.2	14.6	1.6	$5.98	$2 137	$612	$1 525
G10	32	11	21	493	165	312	15.4	15.0	0.4	$1.99	$979	$327	$651
Total	**123**	**43**	**80**	**1 791**	**594**	**1 197**	**14.6**	**13.8**	**0.7**	**$1.90**	**$4 532**	**$1 443**	**$3 089**

Bigeye tuna

Trip	Total number			Total weight (kg)			Average weight (kg)			Average	Total value ($)		
	Circle	Tuna	C–T	Circle	Tuna	C–T	Circle	Tuna	C–T	price ($/kg)	Circle	Tuna	C–T
G1	4	1	3	158	31	127	39.4	31.2	8.2	$10.50	$1 656	$327	$1 329
G2	2	1	1	0	41	– 41	0.0	40.8	–40.8	$7.60	$0	$310	–$310
G3	11	4	7	396	122	275	36.0	30.4	5.6	$11.90	$4 717	$1 448	$3 269

Trip	Total number			Total weight (kg)			Average weight (kg)			Average	Total value ($)		
	Circle	Tuna	C–T	Circle	Tuna	C–T	Circle	Tuna	C–T	price ($/kg)	Circle	Tuna	C–T
G4	0	1	–1	0	83	– 83	0.0	82.6	–82.6	$16.50	$0	$1 363	–$1 363
G5	6	8	–2	212	304	– 92	35.3	38.0	–2.7	$13.28	$2 817	$4 043	–$1 227
G6	6	7	–1	283	272	11	47.2	38.9	8.3	$17.66	$5 001	$4 809	$191
G7	21	11	10	1 103	506	596	52.5	46.0	6.5	$13.80	$15 212	$6 985	$8 227
G8	20	27	–7	901	1 515	– 615	45.0	56.1	–11.1	$14.32	$12 893	$21 695	–$8 802
G9	50	31	19	2 267	1 404	863	45.3	45.3	0.0	$17.29	$39 205	$24 286	$14 919
G10	15	23	–6	620	1 075	– 361	41.3	46.7	–5.4	$14.99	$9 298	$16 117	–$6 819
Total	**135**	**114**	**23**	**6 028**	**5 365**	**664**	**44.7**	**47.1**	**–2.4**	**$12.91**	**$90 798**	**$81 384**	**$9 414**

Mahi mahi

Trip	Total number			Total weight (kg)			Average weight (kg)			Average	Total value ($)		
	Circle	Tuna	C–T	Circle	Tuna	C–T	Circle	Tuna	C–T	price ($/kg)	Circle	Tuna	C–T
G1	8	8	0	98	100	– 1	12.3	12.5	–0.2	$5.90	$580	$589	–$9
G2	36	35	1	374	372	1	10.4	10.6	–0.3	$4.80	$1 793	$1 787	$6
G3	23	15	8	285	175	110	12.4	11.6	0.7	$5.50	$1 567	$961	$606
G4	21	28	–7	165	273	– 108	7.8	9.7	–1.9	$5.50	$905	$1 501	–$596
G5	2	0	2	17	0	17	8.4	0.0	8.4	$5.00	$84	$0	$84
G6	15	13	2	167	152	15	11.1	11.7	–0.6	$5.25	$878	$800	$77
G7	34	35	–1	382	406	– 25	11.2	11.6	–0.4	$5.47	$2 088	$2 224	–$136
G8	6	9	–3	73	102	– 29	12.1	11.3	0.8	$5.50	$400	$561	–$161
G9	16	10	6	177	107	70	11.1	10.7	0.4	$5.50	$974	$588	$386
G10	7	1	6	75	13	62	10.8	13.0	–2.2	$5.50	$415	$72	$343
Total	**168**	**154**	**14**	**1 815**	**1 700**	**115**	**10.8**	**11.0**	**–0.2**	**$5.20**	**$9 684**	**$9 081**	**$602**

Trip	Total number			Total weight (kg)			Average weight (kg)			Average	Total value ($)		
	Circle	Tuna	C–T	Circle	Tuna	C–T	Circle	Tuna	C–T	price ($/kg)	Circle	Tuna	C–T

Striped marlin

Trip	Total number			Total weight (kg)			Average weight (kg)			Average	Total value ($)		
	Circle	Tuna	C–T	Circle	Tuna	C–T	Circle	Tuna	C–T	price ($/kg)	Circle	Tuna	C–T
G1	1	1	0	39	82	– 44	38.6	82.5	–43.9	$5.60	$216	$462	–$246
G2	6	3	3	505	215	290	84.2	71.6	12.6	$3.50	$1 767	$751	$1 016
G3	6	5	1	422	433	– 12	70.3	86.7	–16.4	$3.90	$1 645	$1 690	–$45
G4	2	2	0	118	118	0	58.9	58.8	0.1	$5.34	$629	$628	$2
G5	1	0	1	67	0	67	67.2	0.0	67.2	$5.08	$341	$0	$341
G6	0	1	–1	0	64	– 64	0.0	63.9	–63.9	$4.50	$0	$288	–$288
G7	1	0	1	59	0	59	58.8	0.0	58.8	$6.25	$367	$0	$367
G8	4	0	4	231	0	231	57.8	0.0	57.8	$6.36	$1 470	$0	$1 470
G9	4	0	4	279	0	279	69.8	0.0	69.8	$9.29	$2 594	$0	$2 594
G10	1	0	1	12	0	12	12.2	0.0	12.2	$5.04	$62	$0	$62
Total	**26**	**12**	**14**	**1 714**	**931**	**783**	**65.9**	**77.6**	**–11.7**	**$5.04**	**$9 092**	**$3 818**	**$5 273**

Swordfish

Trip	Total number			Total weight (kg)			Average weight (kg)			Average	Total value ($)		
	Circle	Tuna	C–T	Circle	Tuna	C–T	Circle	Tuna	C–T	price ($/kg)	Circle	Tuna	C–T
G1	26	16	10	646	335	311	24.8	20.9	3.9	$8.90	$5 746	$2 981	$2 766
G2	0	2	–2	0	22	– 22	0.0	11.1	–11.1	$6.50	$0	$144	–$144
G3	8	14	–6	222	725	– 504	27.7	51.8	–24.1	$7.20	$1 596	$5 223	–$3 627
G4	10	6	4	270	292	– 22	27.0	48.6	–21.7	$9.01	$2 430	$2 629	–$199

Trip	Total number			Total weight (kg)			Average weight (kg)			Average	Total value ($)		
	Circle	Tuna	C–T	Circle	Tuna	C–T	Circle	Tuna	C–T	price ($/kg)	Circle	Tuna	C–T
G5	1	0	1	14	0	14	14.4	0.0	14.4	$8.33	$120	$0	$120
G6	14	6	8	626	137	489	44.7	22.8	21.9	$11.09	$6 939	$1 518	$5 421
G7	7	8	–1	115	182	– 67	16.4	22.7	–6.3	$7.11	$817	$1 290	–$473
G8	13	13	0	505	404	101	38.9	31.1	7.8	$8.59	$4 340	$3 470	$870
G9	3	4	–1	30	55	– 25	10.1	13.8	–3.8	$6.05	$183	$335	–$152
G10	4	1	3	148	19	129	37.1	19.3	17.8	$7.49	$1 112	$145	$967
Total	**86**	**70**	**16**	**2 564**	**2 151**	**413**	**29.8**	**30.7**	**–0.9**	**$8.26**	**$23 283**	**$17 734**	**$5 550**

Wahoo

Trip	Total number			Total weight (kg)			Average weight (kg)			Average	Total value ($)		
	Circle	Tuna	C–T	Circle	Tuna	C–T	Circle	Tuna	C–T	price ($/kg)	Circle	Tuna	C–T
G1	0	0	0	0	0	0	0.0	0.0	0.0	0	$0	$0	$0
G2	2	2	0	32	29	3	16.2	14.5	1.7	$2.00	$65	$58	$7
G3	0	0	0	0	0	0	0.0	0.0	0.0	0	$0	$0	$0
G4	0	0	0	0	0	0	0.0	0.0	0.0	0	$0	$0	$0
G5	0	0	0	0	0	0	0.0	0.0	0.0	0	$0	$0	$0
G6	0	0	0	0	0	0	0.0	0.0	0.0	0	$0	$0	$0
G7	1	2	–1	13	22	– 10	12.5	11.1	1.5	$2.00	$25	$44	–$19
G8	0	0	0	0	0	0	0.0	0.0	0.0	0	$0	$0	$0
G9	0	0	0	0	0	0	0.0	0.0	0.0	0	$0	$0	$0
G10	0	0	0	0	0	0	0.0	0.0	0.0	0	$0	$0	$0
Total	**3**	**4**	**–1**	**45**	**49**	**– 4**	**15.0**	**12.2**	**2.8**	**$2.00**	**$90**	**$102**	**–$12**

Trip	Total number			Total weight (kg)			Average weight (kg)			Average	Total value ($)		
	Circle	Tuna	C–T	Circle	Tuna	C–T	Circle	Tuna	C–T	price ($/kg)	Circle	Tuna	C–T
Yellowfin tuna													
Trip	Total number			Total weight (kg)			Average weight (kg)			Average	Total value ($)		
	Circle	Tuna	C–T	Circle	Tuna	C–T	Circle	Tuna	C–T	price ($/kg)	Circle	Tuna	C–T
G1	1	0	1	54	0	54	53.9	0.0	53.9	$4.90	$264	$0	$264
G2	8	10	–2	363	580	– 216	45.4	58.0	–12.5	$9.50	$3 453	$5 506	–$2 053
G3	11	12	–1	484	608	– 123	44.0	50.6	–6.6	$14.40	$6 975	$8 747	–$1 773
G4	2	0	2	83	0	83	41.5		41.5	$16.47	$1 366	$0	$1 366
G5	0	0	0	0	0	0	0.0		0.0	$6.45	$0	$0	$0
G6	2	1	1	119	83	36	59.3	82.7	–23.4	$14.10	$1 671	$1 166	$506
G7	22	22	0	872	877	– 5	39.6	39.9	–0.2	$9.89	$8 620	$8 674	–$54
G8	9	6	3	500	383	117	55.5	63.9	–8.3	$16.21	$8 100	$6 210	$1 890
G9	61	37	24	1 831	1 200	631	30.0	32.4	–2.4	$8.64	$15 827	$10 375	$5 452
G10	4	7	–3	210	310	– 100	52.5	44.3	8.2	$11.61	$2 440	$3 604	–$1 164
Total	**120**	**95**	**25**	**4 539**	**4 027**	**512**	**37.8**	**42.4**	**–4.6**	**$9.77**	**$48 716**	**$44 282**	**$4 433**

Appendix G. Prices of longline fishing gear purchased during the project

Item	Quantity	Unit price	Total price
1.7mm single alloy Crimp x 1 000pcs	1	$20.35	$20.35
Crimp A Single E 2mm x1000pcs	4	$26.40	$105.60
Crimp E Single 2mm 1000 pcs	3	$23.10	$69.30
E-crimps to suit 1.8mm mono (1000 pcs)	3	$23.10	$69.30
Crimp Alum 2.0mm ID x 1000pcs	4	$33.00	$132.00
		$26.44	*ave.
Hook Circle 14/0 C-1 (4.5mm)	600	$0.84	$501.60
Hook Circle 14/0 C-1 (4.5mm)	100	$0.84	$83.60
Hook Circle 18/0 DC w/o ring	280	$1.71	$477.40
Hook Circle 16/0 DC w/o ring	100	$1.38	$137.50
OPI Hook Circle Offset 18/0	1500	$1.10	$1 650.00
16/0 Maruto style S/S circle hooks	1000	$0.98	$979.00
16/0 C-1 style S/S circle hooks	1000	$0.87	$869.00
Hook SS Circle 16/0	1000	$0.70	$704.00
13/0 circle hook S/S C-1	1000	$0.75	$748.00
		$0.93	*ave.
Tuna Hook K 3.4 (with ring)	1000	$0.77	$770.00
Tuna Hook D 2.8 4.5mm Wire	1000	$0.74	$737.00
2.8 D-Type Tuna Hook	600	$0.68	$409.20
		$0.74	*ave.
1.8mm Blue Japanese Supa Nylon Branchline 1000 metre hank	6	$48.62	$291.72
Shibahira 1.80mm (220 kg B/S) x 1000 m	20	$86.90	$1 738.00
Branchline Clear Jap SupaNy1.6	1	$41.25	$41.25
Branchline Blue Jap SupaNy1.8	1	$48.62	$48.62

Item	Quantity	Unit price	Total price
Branchline Clear Jap SGupaNy1.6	24	$48.62	$1 166.88
1.6mm Mono Branchline	8	$41.25	$330.00
1.8mm x 1 000mtr clear mono	20	$48.62	$972.40
Shibahira 1.80mm (220 kg B/S) x 1000 m	30	$82.50	$2 475.00
		$64.22	*ave.
Swivel Stainless Leaded 60g	1000	$0.87	$869.00
Clip 2.8x100Jap VNch SS SBLSvl	1000	$1.38	$1 375.00
Clip UGA Vnotch 3.5x145 SS Swv	750	$1.49	$1 113.75
Snaps 2.8 x 100 GBL Jap	200	$1.54	$308.00
		$1.24	*ave.
Swivel Stainless Leaded 60g	50	$0.87	$43.45
Swivel Stainless Leaded 60g	750	$0.79	$594.00
60 gram rubber coated leaded swivel (Brass)	700	$1.01	$708.40
		$0.90	*ave.
Tubing Coils Red anti-chafe	2	$43.45	$86.90
Tubing Coils Clear anti-chafe	3	$43.45	$130.35
Luminous Sleeves-8cm x 250pcs	3	$23.65	$70.95
Protector tube to suit mono	1	$43.45	$43.45
Deep fish tub with lid	1	$63.09	$63.09
Tube snood clear x 200 m	2	$33.00	$66.00
		$38.39	*ave.

*Average unit prices are weighted averages.