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Large-scale experiment shows that nylon leaders reduce shark bycatch and benefit pelagic longline fishers

Peter Ward *, Emma Lawrence, Rebecca Darbyshire, Sheree Hindmarsh

Bureau of Rural Sciences, GPO Box 858, Canberra, ACT 2601, Australia

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Abstract

We assess the performance of wire leaders, which some jurisdictions have banned to reduce shark mortality from pelagic longline fishing. Experiments were conducted off northeastern Australia on commercial vessels that deployed equal numbers of wire and nylon monofilament leaders randomly along their longlines. Catch rates of several species, including sharks, were lower on nylon than on wire leaders, probably because those animals often escape by biting through the nylon leaders. High bite-off rates indicate that as many animals escape from nylon leaders as are caught on nylon leaders. The fate of escaped animals is not known, although large sharks are more likely to survive than are small animals. By contrast, catch rates of valuable bigeye tuna (*Thunnus obesus*) were higher on nylon than on wire leaders. Bigeye tuna are probably able to see wire leaders and avoid those hooks. The financial benefits of increased bigeye tuna catches outweigh the costs associated with banning wire leaders, such as increased rates of gear loss. Thus, banning wire leaders is an effective way of reducing shark catches that fishers should be keen to adopt.

Keywords: Bycatch mitigation; Sharks; Tuna; Billfish; Pelagic longline; Open-ocean; Catchability

1. Introduction

There is considerable concern over the ecological effects of pelagic longline fishing, which extends throughout tropical and temperate regions of the world's oceans (Lewison et al., 2004; Werner et al., 2006). The longlines are deployed in a daily operation to catch large tuna (*Thunnus* spp.) and billfish (Istiophoridae and Xiiphidae). They consist of a series of baited hooks attached to a mainline that is suspended from floating buoys. Up to 4000 hooks are deployed each day on branchlines attached to mainlines that may span 100 km of the sea surface. Fishers adjust bait, longline depth range, and the timing of operations to target particular species. For example, deep longlines (25–400 m) are typically deployed at dawn and hauled in the late afternoon – evening to catch tuna. Shallow longlines (25–175 m) with squid bait are deployed in the afternoon and hauled in the morning to catch broadbill swordfish (*Xiphias gladius*) (Ward and Hindmarsh, 2007).

Several management agencies have mandated bycatch mitigation measures, such as bird-scaring "tori" lines, to reduce the mortality of seabirds that dive for longline bait, e.g., vulnerable wandering albatross (*Diomedea exulans*) (Brothers et al., 1999; IUCN, 2006). Sea turtles, such as the leatherback (*Dermochelys coriacea*), are also threatened by pelagic longlining. Measures to reduce sea turtle interactions and mortality include large circle hooks and the deep setting of longlines (Watson et al., 2004, 2005; Gilman et al., 2006; Watson and Kerstetter, 2006).

Sharks (Elasmobranchii) are another group of vulnerable animals that interact with longlines. Concern over shark mortality has led to restrictions on landing sharks and bans on "finning", where sharks are brought on board the fishing vessel, dispatched, and the fins removed. The fins are sold at lucrative markets, while the carcass is often discarded (Gilman et al., 2008). Bans on finning and landing often result in sharks being cut free. Many of those that are released alive may survive (Moyes et al., 2006). However, fishers may also dispatch sharks to retrieve longline hooks, which limits the effectiveness of those bans in reducing shark mortality (Rose and McLoughlin, 2001). Finning is estimated to result in the mortality of 30–52 million sharks per year worldwide, much of which is attributed to pelagic and demersal longlining (Clarke et al., 2006).

* Corresponding author. Tel.: +612 6272 4163; fax: +612 6272 3882.
E-mail addresses: peter.ward@brs.gov.au, peteward@homemail.com.au (P. Ward).

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Hook type and bait may be important in reducing the incidental catch of sharks. For example, Watson et al. (2005) found that catch rates of blue shark (*Prionace glauca*) on mackerel bait were lower than those on squid bait. Gilman et al. (2008) report that some fishers avoid using certain types of bait in order to reduce shark interactions, e.g., Italian and Japanese fishers avoid using squid. Studies have reported mixed results for the effect of hook type on shark catch. Yokota et al. (2006), for example, found no significant difference in catch rates of blue shark between tuna hooks and circle hooks for two pelagic longline vessels ($p = 0.48$ and 0.43). However, Watson et al. (2005) found that blue shark catch rates were 8–9% higher on circle hooks compared to J hooks. A more effective way to reduce shark bycatch may be to ban wire leaders or “steel traces”. Fishers have used wire leaders since the 1920s to reduce the loss of longline fishing gear and hooked animals that are able to sever leaders constructed from natural or synthetic fibres. Many longline fishers began using nylon monofilament leaders in the 1980s, although several fleets have continued to use wire leaders or use wire for a proportion of their branchlines (Gilman et al., 2008; Ward and Hindmarsh, 2007). To reduce shark bycatch, Australia banned the use of wire leaders in its eastern tuna longline fishery in 2005. However, there are few published studies of the effects of wire leaders on catches, and most results are ambiguous because of small sample sizes or inappropriate experimental design. Berkeley and Campos (1988), for example, monitored one longline vessel fishing for swordfish with about 25% wire leaders and 75% nylon leaders in 13 longline operations. They reported fewer sharks on wire leaders than on nylon, but the difference was not statistically significant. Branstetter and Musick (1993) placed 50 branchlines with nylon leaders on the end of survey longlines that comprised 100 branchlines with wire leaders. Overall, catch rates of sharks were higher on the nylon leaders. However, shark catch rates in offshore waters showed the opposite pattern, with higher catch rates on wire.

Many studies of bycatch mitigation have focused on the ability of particular measures to reduce mortality of the species of concern. A more holistic approach is emerging with the broadening of studies to include the effects of mitigation on catches of other species and financial aspects of commercial fishing operations (Werner et al., 2006). This article presents results of an experiment that compares the effects of nylon and wire leaders on catch rates of various target and bycatch species taken by five commercial vessels over 16 months. It includes analyses of the financial costs and benefits of banning wire leaders. The results are also relevant to measuring the relative abundance of pelagic animals from catch and fishing effort data. For pelagic longline fisheries, abundance indices are often based on commercial catch rates or the “catch-per-unit-effort” (CPUE) that is reported as the number of animals caught per 1000 hooks. An understanding of catchability – the efficiency of the fishing gear – is critical to deriving estimates of abundance from catch rates (Bishop, 2006). It is affected by the distribution of animals and their behaviour in relation to the fishing practices and gear.

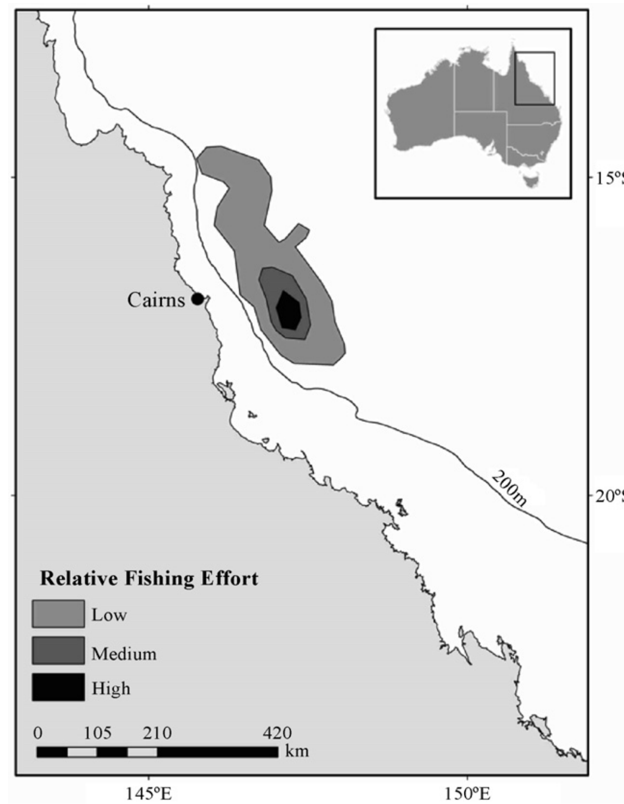

Fig. 1. Map of the study area showing the distribution and intensity of longline fishing effort.

2. Methods

We compared catches on nylon and wire leaders deployed by five commercial longline fishing vessels during September 2005–December 2006 off northeastern Australia (Fig. 1). The vessels were 18–24 m in length, with trips lasting about seven days. They targeted bigeye (*Thunnus obesus*) and yellowfin tuna (*T. albacares*) for sashimi markets.

The wire leaders used in the study were 30 cm, stainless steel, six-strand wire cable (Fig. 2). A 38 g swivel was attached to the branchline 5 m above the hook. The nylon leaders did not have a weighted swivel. They were 2 mm diameter (250–300 kg breaking strain) nylon. One longline vessel used 30 cm double nylon leaders. The nylon monofilament is a copolymer, with

Fig. 2. The wire (above) and nylon (below) leaders used in the study. Also shown is a weighted swivel.

a core of flexible nylon and an outer skin of tougher nylon. Both the nylon and wire leaders were attached to 16 m nylon monofilament branchlines constructed of the same material as the nylon leaders. All vessels used 4 mm diameter nylon monofilament mainlines and Japanese tuna hooks (55 mm total length, 28 mm bite, 27 mm gape, 10° offset). They used frozen pilchard (*Sardinops* spp.) or squid as bait. On about 9% of branchlines, crewmembers attached luminescent lightsticks 2 m above the hook.

Trained observers, contracted by the Australian Fisheries Management Authority, monitored experimental protocols and collected data on the vessels. Roughly, equal numbers of nylon and wire leaders were deployed on each longline. Crewmembers were instructed to attach the different types of leader, bait species, and lightsticks randomly along the longline. Observers regularly monitored the sequence of lightsticks, bait, and leader types during deployment. The total number of each type of leader deployed and retrieved, the number of branchlines retrieved with the leader severed, and the number of each leader type repaired after each longline operation were counted. For retained, discarded, and released animals, observers recorded the type of leader that each animal was caught on, the species, its length, time of landing, and the sequential hook number. Operational constraints, such as adverse weather and high catch rates, sometimes prevented observers collecting data on all variables described above.

Conditional logistic regression (Hosmer and Lemeshow, 1988) was used to determine whether there were statistically significant differences in catch rates between the two leader 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 and species group. The data were analyzed at the hook-level with the catch of the species being "1" if the particular leader caught the species and "0" otherwise. Hooks that caught another species and hooks without bait are treated as a zero catch for the species under consideration. Given a catch of species i, $p_{i,\mathrm{nylon}}$ is the probability that the catch was on nylon and $p_{i,\mathrm{wire}}$ is the probability that it was on wire. The odds of catching the species on wire is $p_{i,\mathrm{wire}}(1-p_{i,\mathrm{wire}})^{-1}$ and the odds of catching it on nylon is $p_{i,\mathrm{nylon}}(1-p_{i,\mathrm{nylon}})^{-1}$. The odds ratio OR_i is then:

$$\mathrm{OR}_i = \frac{p_{i,\mathrm{nylon}}(1 - p_{i,\mathrm{nylon}})^{-1}}{p_{i,\mathrm{wire}}(1 - p_{i,\mathrm{wire}})^{-1}}$$

The odds ratio is referred to as "relative catchability". A relative catchability of 1.25, for example, indicates that the odds of catching the species on nylon are 25% higher than that on wire. Conversely, a value of 0.75 indicates that the odds of catching it on nylon are 25% less than that on wire. For species that were too rare to model, we present the mean catch rate on nylon divided by that on wire as the measure of relative catchability. This is roughly equivalent to the odds ratio because the odds ratio is approximated by $p_{i,\mathrm{nylon}}/p_{i,\mathrm{wire}}$ when there is a very small probability of catching the species on any given hook (which is the case here).

We implemented the models in the *R* statistical language (R Development Core Team, 2006) using *clogit* from library *survival*. A Wald test was used to determine the significance of the leader type variable. We explored the sensitivity of estimates to double nylon leaders by fitting the model to a dataset that excluded the double nylon data.

The value of catches on the two leader types was estimated by multiplying the market price of each species (Vieira et al., 2007) by its weight and catch rate. The weights of measured animals were estimated from length–weight relationships (Froese and Pauly, 2003). Estimates of value were limited to those animals that were retained by the vessel and to species where catch rates on nylon were significantly higher than those on wire leaders ($p < 0.05$).

We used a generalized additive mixed model with a Poisson error distribution to identify variables influencing the loss rates of hooks ("bite-offs") from nylon leaders. The model included a random vessel effect to allow for correlations among the operations of each vessel.

3. Results

Observers monitored 177 longline operations consisting of 75,101 hooks (37,679 nylon leaders and 37,422 wire leaders). The vessels concentrated on a relatively small area of the western Coral Sea outside the Great Barrier Reef (Fig. 1). Longline activity was uniformly distributed throughout the 15-month study period. The vessels deployed 9 or 10 branchlines between buoys, with the maximum depth of hooks estimated to range down to about 170 m (Campbell et al., 1997). They usually deployed 500 longline hooks at dawn or dusk each day. Wire and nylon leaders attached to branchlines were stored in the same bin. Deployment lasted about 2 h on average, and then the longline was allowed to drift for about 7 h. Hauling usually commenced in the mid-afternoon or early morning and lasted about 3 h.

A runs test (Zar, 1984) at the 0.05 level of statistical significance indicated that the sequence of nylon and wire leaders was random for 80 of the 86 longline operations (93%) where observers recorded data on the sequence. However, some of the samples were heavily weighted towards one leader type, suggesting that a larger number of non-random operations may have been detected if observers had monitored the entire sequence. Regardless, data from all monitored longline operations were included in the analyses presented in this article.

The vessels caught 4,051 animals, consisting of 32 species or species groups (Table 1). Catch rates of all species combined were 13% higher on wire leaders than on nylon ($p < 0.001$). The catch rate of all bycatch species combined on nylon was almost half that on wire. For many species, including blue marlin (*Makaira nigricans*), snake mackerel (*Gempylus serpens*), and sharks, wire leader catch rates were higher than nylon catch rates.

Table 1
Summary of catches of each species on nylon and wire leaders, and estimates of relative catchability, its standard error (S.E.), and statistical significance

Scientific name	Common name	Fate[a]	Number caught		Catch rate[b]		Relative catchability[c]		
			Nylon	Wire	Nylon	Wire	Estimate	S.E.	*p*-Value[d]
Tunas and tuna-like species									
Acanthocybium solandri	Wahoo	I	32	40	0.85	1.07	0.78	0.24	0.31
Katsuwonus pelamis	Skipjack tuna	D	4	2	0.11	0.05	2.71	0.87	0.25
Thunnus alalunga	Albacore tuna	I	150	132	3.98	3.53	1.14	0.12	0.28
Thunnus albacares	Yellowfin tuna	T	838	848	22.24	22.66	0.93	0.05	0.16
Thunnus obesus	Bigeye tuna	T	255	186	6.77	4.97	1.26	0.10	0.02**
Tunas subtotal			1279	1208	33.94	32.28	1.00	0.04	0.95
Billfishes									
Istiophoridae	Unid. marlin	D	10	3	0.27	0.08	1.85	1.23	0.62
Istiophorus platypterus	Sailfish[e]	D	1	0	0.03	0.00	>1.00	–	–
Makaira indica	Black marlin	D	102	66	2.71	1.76	1.45	0.16	0.02**
Makaira nigricans	Blue marlin	D	8	29	0.21	0.77	0.27	0.40	0.00***
Tetrapturus audax	Striped marlin	D	11	19	0.29	0.51	0.55	0.38	0.12
Xiphias gladius	Broadbill swordfish	I	16	23	0.42	0.61	0.70	0.33	0.27
Billfishes subtotal			148	140	3.93	3.74	0.97	0.12	0.79
Other teleosts									
Alepisaurus spp.	Lancetfish	D	75	166	1.99	4.44	0.45	0.14	0.00****
Centrolophus niger	Rudderfish[e]	I	1	2	0.03	0.05	0.50	–	–
Coryphaena hippurus	Mahi mahi (dolphinfish)	I	151	139	4.01	3.71	1.03	0.12	0.83
Gempylus serpens	Snake mackerel	D	135	322	3.58	8.60	0.46	0.10	0.00****
Lampris guttatus	Opah (moonfish)[e]	I	1	0	0.03	0.00	>1.00	–	–
Lepidocybium flavobrunneum	Black oilfish (escolar)	I	42	38	1.11	1.02	1.17	0.23	0.48
Mola sp.	Sunfish[e]	D	0	1	0.00	0.03	0.00	–	–
Ruvettus pretiosus	Oilfish[e]	D	0	1	0.00	0.03	0.00	–	–
Sphyraena barracuda	Great barracuda	D	12	35	0.32	0.94	0.46	0.39	0.05**
Sphyraena jello	Pickhandle barracuda[e]	D	0	1	0.00	0.03	0.00	–	–
Thyrsites atun	Barracouta[e]	D	1	6	0.03	0.16	0.17	–	–
Other teleosts subtotal			418	711	11.09	19.00	0.61	0.06	0.00****
Sharks									
Alopias pelagicus	Pelagic thresher shark	D	1	13	0.03	0.35	0.08	1.04	0.01**
Alopias superciliosus	Bigeye thresher shark	D	6	5	0.16	0.13	1.07	0.63	0.91
Carcharhinus spp.	Unid. whaler sharks[f]	I	6	27	0.16	0.72	0.21	0.45	0.00****
Carcharhinus falciformis	Silky shark	I	12	20	0.32	0.53	0.61	0.37	0.18
Carcharhinus longimanus	Oceanic whitetip shark	I	3	11	0.08	0.29	0.31	0.65	0.07*
Carcharhinus tilstoni	Australian blacktip shark[e]	D	1	0	0.03	0.00	>1.00	–	–
Galeocerdo cuvier	Tiger shark	D	14	24	0.37	0.64	0.54	0.34	0.07*
Isurus oxyrinchus	Shortfin mako shark[e]	D	0	3	0.00	0.08	0.00	–	–
Sphyrna sp.	Hammerhead shark[e]	D	1	0	0.03	0.00	>1.00	–	–
Sharks subtotal			44	103	1.17	2.75	0.42	0.19	0.00****
Grand total			1889	2162	50.13	57.77	0.87	0.03	0.00****

(–) Insufficient numbers for modelling.
[a] "D" indicates bycatch species that were discarded; "T" indicates target species, and "I" indicates incidental species that were retained.
[b] Number of animals per 1000 hooks of that leader type deployed.
[c] The estimated parameter of the leader type variable from the conditional logistic regression.
[d] Statistical significance of leader type from the conditional logistic regression, indicating whether nylon and wire leader catch rates were statistically different.
[e] For species where insufficient numbers were available for modelling, relative catchability is estimated as the observed catch rate on nylon leaders divided by that on wire leaders.
[f] Observers reported 23 bronze whaler shark (*Carcharhinus brachyurus*). These have been included with unidentified whaler sharks because bronze whaler are not known from the study area. They are likely to be another species, probably silky shark.
* $0.05 \le p < 0.1$.
** $0.01 \le p < 0.05$.
*** $0.001 \le p < 0.01$.
**** $0 \le p < 0.001$.

They were higher on wire for eight of the ten shark species and significantly higher for all shark species combined ($p < 0.001$). Combined catch rates for other teleosts were also significantly higher on wire ($p < 0.001$). Catch rates of two species (bigeye tuna and black marlin, *M. indica*) showed the opposite trend; their catch rates were significantly higher on nylon ($p < 0.02$). For 12 species there was no significant difference between nylon and wire catch rates ($p > 0.10$), and a further 9 species were too rare to model.

Exclusion of data for double nylon leaders resulted in variations within ±5% of the estimate of relative catchability for most species. The double nylon data were included in the analyses presented here because they did not introduce any consistent bias into parameter estimates.

There was considerable variation in bite-off rates from nylon leaders. They ranged up to 53.3% per longline operation (mean = 5.1 ± 7.0% S.D.). By comparison, observers reported few bite-offs for wire (mean = 0.2 ± 0.6% S.D.). Season and catch rates of yellowfin tuna, snake mackerel, and sharks were significant predictors of nylon bite-offs ($p < 0.02$) (Table 2). The effect of soak time was not significant ($p > 0.05$), perhaps because most operations had a similar duration.

Observers counted repairs for 19 longline operations. Repairs included bite-offs as well as damaged or abraded leaders and branchlines. Nylon repair rates averaged 24.5 ± 15.3% S.D. per operation, compared to 14.3 ± 8.8% S.D. for wire leaders.

4. Discussion

We first consider the underlying mechanisms that are responsible for the differences in catchability among species and speculate on the fate of animals that escape from nylon leaders. Financial costs and benefits of the two leader types are then compared and improvements to the study's design are identified.

The analyses show that the relative catchability of leader types varies among species. Catch rates of bigeye tuna on nylon, for example, were 26% higher than those on wire (Fig. 3). Catch rates of many species, including sharks, snake mackerel, lancetfish (*Alepisaurus* sp.), and wahoo (*Acanthocybium solandri*), show the opposite tendency; they were higher on wire. Before the study commenced, fishers indicated that those latter species were responsible for severing nylon leaders. The mixed model showed that bite-off rates rose with the increased local abundance of sharks and snake mackerel (Table 2). We conclude that the catch rates of species with sharp teeth, such as sharks and snake mackerel, are lower on nylon because the animals are able to sever the leader and escape.

Table 2
Results of a generalized additive mixed model of bite-off rates for nylon leaders

Term	Estimate	Standard error	p–Value
Intercept	−4.0265	0.1395	0.0000
Season: spring	−0.3737	0.1620	0.0226
Season: summer	−0.1602	0.1736	0.3577
Season: winter	−1.1259	0.2796	0.0001
Yellowfin tuna	0.0114	0.0023	0.0000
Sharks	0.0748	0.0130	0.0000
Snake mackerel	0.0206	0.0026	0.0000

Variables that did not have a statistically significant effect on bite-offs ($p > 0.05$) included soak time, deployment time, bigeye tuna catch rates, and lancetfish (*Alepisaurus* spp.) catch rates.

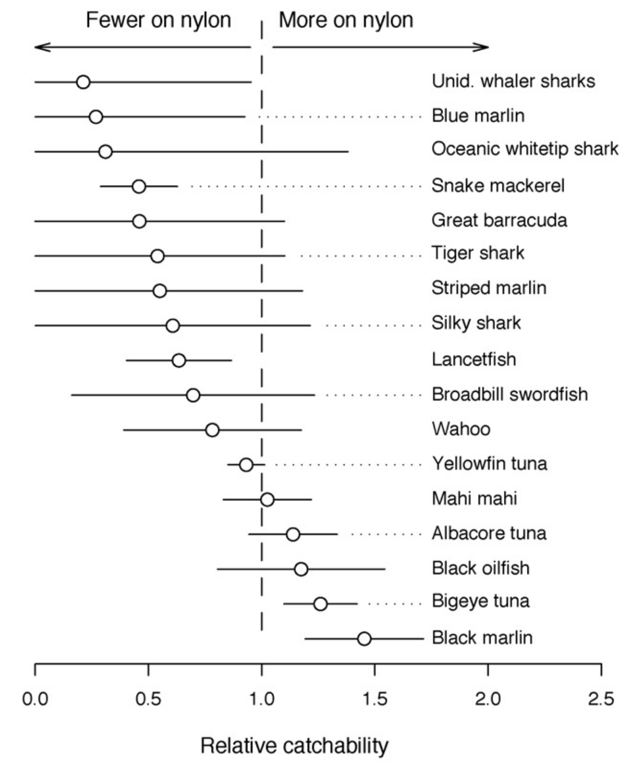

Fig. 3. Comparison of the effects of leader type on the relative catchability of the 17 most frequently caught species or species groups. Relative catchability is the estimated parameter of the leader type variable in conditional logistic regressions (circles) and 90% confidence intervals for the estimate (horizontal lines).

We present an estimate of relative catchability for all sharks combined because several species were too rare to model (Table 1). However, relative catchability probably varies among shark species. The heavily serrated teeth of tiger shark (*Galeocerdo cuvier*), for example, are more likely to sever nylon than the smooth, needle-like teeth of species like bigeye thresher shark (*Alopias superciliosus*). The position of hooking will also be important. Circle hooks almost always embed in the corner of the jaw (Prince et al., 2002; Skomal et al., 2002). Consequently, the leader will be less exposed to abrasion. Nylon catch rates are more likely to be similar to wire catch rates when circle hooks are used. By contrast, J-shaped hooks, like those used in the present study, often embed in the throat or gut (Kerstetter and Graves, 2006). The leader will be exposed to abrasion against the teeth. J-shaped hooks on nylon leaders are therefore expected to have higher bite-off rates than circle hooks on nylon leaders.

In contrast to sharks, tuna have small conical teeth (Collette and Nauen, 1983) that we hypothesise to be less effective in severing nylon leaders. Mesopelagic species, like bigeye tuna, have excellent vision (Brill et al., 2005). We hypothesize that catch rates of bigeye are lower on wire leaders because the animals are often able to see the wire and avoid baited hooks attached to those leaders.

The results suggest that banning wire leaders will reduce catches of blue marlin, but increase black marlin catches for longline operations with similar attributes to those analyzed in this study. The differences in catchability might be due to behavioral differences between the two species. Recreational anglers report that blue marlin have a violent reaction to hooking, which might result in the abrasion and severing of leaders. Black marlin however tend to be more docile when hooked. Fishery managers considering the banning of wire leaders will need to balance the beneficial effects on blue marlin and adverse effects on black marlin, as both species are important to anglers. Swordfish also respond violently to hooking. Although the differences with leader type were not statistically significant in the present study ($p > 0.27$), wire catch rates might be higher than nylon catch rates, especially at higher latitudes where large swordfish are more frequently encountered (DeMartini, 1999).

The similar catch rates of yellowfin tuna on the two leader types might indicate that this species is unable to detect wire leaders and unable to sever nylon leaders. However, catches on nylon leaders are the product of two independent processes: elevated catchability of nylon due to its low visibility; and increased loss rates due to animals severing leaders. Hooking rates of yellowfin tuna might actually be higher on nylon, but landings may be reduced by losses, resulting in similar catch rates between the two leader types.

Bite-offs may also mask the increased catchability of nylon for other species. Subtracting nylon catch rates from wire catch rates for species where wire catch rates were higher gives an overall loss rate of 11.6 animals per 1000 hooks. By contrast, observers reported bite-offs at a rate of 5.14% or 51.4 per 1000 hooks. The discrepancy between loss rates and bite-off rates is due to nylon leaders elevating catchability for many species, but many animals subsequently escape by severing the leader. The high bite-off rate indicates that as many animals escape from nylon leaders as are caught on nylon leaders.

The species composition of animals that are lost through bite-offs might be obtained by multiplying the bite-off rate by the difference between catch rates on the two leader types. For example, the difference between wire and nylon catch rates is 2.5 per 1000 hooks for lancetfish. This is 21% of the wire-nylon differential for all animals (11.6 per 1000 hooks). Multiplying 21% by the bite-off rate (51.4 per 1000 hooks) gives a loss rate of 10.9 lancetfish per 1000 hooks. The same method can be use to estimate the loss rates of other species where wire catch rates exceeded nylon catch rates. However, this estimation method does not take into account animals that might bite-off more than one hook during a longline operation. Furthermore, the loss rate of each species is likely to be overestimated because the method omits the seven species where nylon catch rates exceeded wire catch rates. At least some of those omitted species are likely to be lost, but their elevated catchability on nylon leaders probably masked those losses. Regardless, it is clear that large numbers of snake mackerel, lancetfish, great barracuda (*Sphyraena barracuda*), and blue marlin must escape from nylon leaders. The development of leader materials that combine the advantages of nylon (low visibility) and wire (resistance to abrasion) would increase catches of target species and financial returns, but it would also increase bycatch levels.

Fishers retained or discarded about half of the sharks caught during the study. Banning wire leaders is an effective way of reducing the number of sharks landed and will reduce shark mortality in fisheries where sharks are retained or dispatched before they are discarded. However, the benefits of wire leader in reducing mortality are unclear because the fate of animals that sever the leader and escape is unknown. Several shark species seem to be robust to the stresses associated with being hooked. For example, 83% of the 163 sharks that observers monitored during the study were alive, with most classified at the top of the scale ("alive and vigorous"). Moyes et al. (2006) studied the post-release survival of blue sharks caught on commercial longlines and brought on board the vessel. They used biochemical analyses of blood ($N = 33$) and pop-up satellites archival tags (PSATs; $N = 11$). From the biochemical analyses, they predicted a 95% survival rate; the PSATs had a 100% survival rate (mean 116 ± 96 days of deployment). Furthermore, fishers and observers often report catching sharks with several longline hooks embedded in their jaws. In contrast to sharks, we did not find any reports of fishers catching small species like lancetfish embedded with hooks from past encounters with longlines. Mortality rates may be high for small, fragile species that escape, or their recapture rates might be low because of high rates of natural mortality, dispersion, or relatively large population sizes.

High bite-off rates, like those observed in this study, are common in pelagic longline fisheries. Multiplying the estimated bite-off rate by the number of hooks reported by Australian vessels in logbooks indicates that hundreds of thousands of hooks are lost from the nylon leaders each year. Multiplying the bite-off rate by estimates of global longlining effort (Lewison et al., 2004) suggest that many millions of hooks must be lost worldwide. There is a need to quantify the level of cryptic mortality associated with bite-offs and to introduce measures to mitigate it.

In contrast to the uncertain survival rates of animals lost from nylon leaders, there is information on survival rates of animals caught on wire leaders. Observers reported that 80% of the snake mackerel were dead. Few animals are released alive. Fishers often dispatch sharks caught on wire leaders so that they can safely retrieve hooks or they may cut the branchline leaving the hook embedded in the shark with a trailing leader. On the other hand, some fishers believe that wire leaders provide better control over live sharks, allowing them to bring the animal alongside the vessel where they can remove the hook. They prefer to use wire leaders with weighted swivels—nylon leaders may part when an animal is being hauled, sometimes resulting in the swivel rapidly recoiling and injuring crewmembers.

The estimated value of the catch taken on the two leader types shows a financial incentive for fishers to use nylon leaders. The increased value resulting from the elevated catchability of bigeye tuna outweighs losses associated with the reduced catchability of sharks. The annual value of the bigeye tuna and shark catch landed by a typical longline vessel deploying only nylon leaders is about USD20,000 higher than that of a typical vessel using all wire leaders (Table 3). Nylon leaders cost about USD12,000

Table 3
Summary of the weight and value of retained species that had significantly different catch rates on the two leader types ($p < 0.02$)

Product	Mean dressed weight (kg)[a]	Annual catch (kg)[b]		Unit price (USD/kg)[c]	Annual value (USD)[d]	
		Nylon	Wire		Nylon	Wire
Bigeye tuna	20.7	14,005	10,285	$6.69	$93,710	$68,823
Shark carcass	29.5	838	1,918	$1.54	$1,291	$2,954
Shark fins	1.4	41	94	$57.75	$2,372	$5,429
Total	–	14,884	12,298	–	$97,373	$77,206

[a] Whole weight derived from observer length measurements and length–weight relationships (Froese and Pauly, 2003) then converted to dressed weight by dividing by 1.2077 for bigeye tuna and 1.320 for shark carcass. Weight of shark fins estimated as 4.9% of shark dressed weight (Cortes and Neer, 2006).

[b] Product of the mean number of hooks reported in official logbooks of the vessels involved in the study in 2006 (91,700 hooks), dressed weight, catch rate on that leader type, and the proportion of the species retained.

[c] Bigeye tuna and shark carcass price (Vieira et al., 2007) and shark fin prices (G. Heilman, pers. comm.) converted from Australian dollars (AUD) to US dollars (USD) using a 1.00AUD:0.77 USD exchange rate.

[d] Estimated value of the catch of bigeye tuna and sharks landed by a typical longline vessel in 2006 derived by multiplying the unit price by the annual catch on each leader type.

more to replace or repair each year (Table 4), which reduces the financial benefit of using nylon to about USD8000. Variations in retention practices will influence these conclusions. Fishers involved in this study chose not to land commercially valuable striped marlin (*Tetrapturus audax*), and landed less than half of their shark catch because of regulations and operational considerations, e.g., some sharks were too large or dangerous to bring on board. Furthermore, the analyses do not include safety issues or the cost of the labour involved in repairing branchlines and replacing hooks or subsequent reductions in time available for fishing.

Three improvements could be made to the study so that conclusions are applicable to longline fisheries in other regions. First, future work should compare leaders with the same weighting regime. In our study, fishers attached 38 g weighted swivels to the wire leaders, but not to the nylon leaders. The buoyancy of the wire will also be slightly different to that of the nylon. An experiment by G. Robertson (pers. comm.) showed that branchlines with a 100 g swivel reach a depth of 10 m in 38 s on average compared to 44 s for branchlines with a 60 g swivel. The difference in sinking rates increased with depth over the experiment's depth range (1–15 m). This suggests that for the shallowest leaders in our study, the nylon leaders would take about 15 s longer than the wire leaders to reach their maximum depth (∼30 m). The deepest nylon leaders might take about 2 min longer to reach their maximum (∼170 m). However, this is likely to have a small effect on catchability because of the long soak time of baited hooks (about 9 h on average). The two leader types might also reach different maximum depths, although currents and the weight of adjacent branchlines will also affect the maximum depth.

Table 4
Estimated costs (US dollars) of replacing lost hooks and repairing damaged branchlines for the two leader types on a typical longline vessel

Component	Nylon	Wire
Hooks and leaders		
Bite-off rate (%)	5.1	0.2
Unit cost (US$)	0.62	0.85
Annual cost[a] (US$)	2,929	125
Branchlines		
Repair rate (%)	19.8	14.4
Unit cost (US$)	1.93	1.93
Annual cost[a] (US$)	34,982	25,472
Total annual cost (US$)	37,911	25,597

[a] Unit cost and bite-off rate (or repair rate) multiplied by the mean number of hooks reported in logbooks of the vessels involved in the study in 2006 (91,700 hooks).

A second improvement to the study is the construction of leaders. The nylon leaders consisted of a single strand of nylon, like those used by many other fleets (Ward and Hindmarsh, 2007). One of the vessels in the study used two strands of nylon, although this was found not to change results. Historically, several longline fleets have used braided "multifilament" nylon leaders that have been shown to have lower catchability than nylon, presumably because of their higher visibility (Stone and Dixon, 2001). The results of the experiment may be confounded by the effects of leader visibility on catchability and the effects of leader durability on loss rates. A better approach to estimating relative catchability would be to deploy leaders constructed from the same nylon of varying visibility determined by dyes mixed with the nylon. Separate experiments might then compare the performance of opaque nylon and wire leaders.

A third improvement to the study is the exploration of the effects of light and soak time on relative catchability. Higher nylon loss rates are likely for longer operations than those in this study, as there will be more time for leaders to be abraded. This effect could be investigated with time–depth recorders that provide the actual time when each animal is hooked. We also hypothesized that catch rates of bigeye tuna were lower on wire leaders because these animals are sometimes able to see the wire and consequently avoid those baited hooks. According to this hypothesis, relative catchability should decline to unity at night when vision is less important for locating baited hooks. To test this prediction, we separately modeled longline operations that occurred entirely during the day and those that occurred entirely at night. The analyses contradicted our predictions; relative catchability was not significant for the day operations ($p > 0.620$), but nylon catch rates were significantly higher at night ($p < 0.034$). These results warrant further investigation although they might be affected by the reduced number of observations available for analysis ($N = 123$ bigeye).

Regardless of these suggested improvements to the study, the comparison of the performance of nylon and wire leaders is valid for this particular fishery because this is the gear deployed by commercial vessels involved in the Australian fishery.

5. Conclusions

The analyses show the benefits of banning wire leaders. It substantially reduces catches of sharks and other bycatch species. At least some sharks that sever the nylon escape and survive, although the fate of other bycatch species is unknown. By increasing the catchability of bigeye tuna, nylon increases financial returns. The increased returns outweigh the costs of replacing and repairing damaged gear.

The results also have important implications for assessments of target and non-target species. Global declines in shark populations may not be as severe as suggested by Baum et al. (2003) if the switch to nylon by many longline vessels during the 1980s resulted in large declines in shark catchability and if the mortality rates of escaped sharks are relatively low. Conversely, declines in bigeye tuna will be larger than currently estimated if the switch to nylon leaders by many vessels in the 1980s resulted in the increased catchability indicated by the analyses.

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References

Baum, J.K., Myers, R.A., Kehler, D.G., Worm, B., Harley, S.J., Doherty, P.A., 2003. Collapse and conservation of shark populations in the northwest Atlantic. Science 299, 389–392.

Berkeley, S.A., Campos, W.L., 1988. Relative abundance and fishery potential of pelagic sharks along Florida's east coast. Mar. Fish. Rev. 50, 9–16.

Bishop, J., 2006. Standardizing fishery-dependent catch and effort data in complex fisheries with technology change. Rev. Fish Biol. Fisher. 16, 21–38.

Branstetter, S., Musick, J.A., 1993. Comparison of shark catch rates on longlines using rope-steel (Yankee) and monofilament gangions. Mar. Fish. Rev. 55, 4–9.

Brill, R.W., Bigelow, K.A., Musyl, M.K., Fritsches, K.A., Warrant, E.J., 2005. Bigeye tuna (*Thunnus obesus*) behavior and physiology and their relevance to stock assessments and fishery biology. Int. Comm. Cons. Atl. Tunas (ICCAT) Coll. Vol. Sci. Pap. LVII, 142–161.

Brothers, N.P., Cooper, J., Lokkeborg, S., 1999. The Incidental Catch of Seabirds by Longline Fisheries: A Worldwide Review and Technical Guidelines for Mitigation, vol. 937. FAO Fisheries Circular, Rome, FAO, p. 100.

Campbell, R., Whitelaw, W., Mc-Pherson, G. 1997. Domestic longline fishing methods and the catch of tunas and non-target species off north-eastern Queensland. Report to the Eastern Tuna and Billfish Fishery Management Advisory Committee. Australian Fisheries Management Authority (AFMA), Canberra.

Clarke, S.C., McAllister, M.K., Milner-Gullan, E.J., Kirkwood, G.P., Michielssens, C.G.J., Agnew, D.J., Pikitch, E.K., Nakano, H., Shivji, M.S., 2006. Global estimates of shark catches using trade records from commercial markets. Ecol. Lett. 9, 1115–1126.

Collette, B.B., Nauen, C.E. 1983. FAO Species Catalogue Vol. 2 Scombrids of the World: An Annotated and Illustrated Catalogue of Tunas, Mackerels, Bonitos and Related Species Known to Date. FAO Fisheries Synopsis No. 125, Vol. 2. FIR/S125 Vol. 2. United Nations Development Programme, FAO, Rome, 137 pp.

Cortes, E., Neer, J.A., 2006. Preliminary reassessment of the validity of the 5% fin to carcass weight ratio for sharks. Int. Comm. Cons. Atl. Tunas (ICCAT) Coll. Vol. Sci. Pap. LIX, 1025–1036.

DeMartini, E. 1999. Size-at-maturity and related reproductive biology. In: DiNardo, G.T. (Ed.), Proceedings of the Second International Symposium on Swordfish in the Pacific Ocean. Southwest Fisheries Science Center Administrative Report NOAA-TM-NMFS-SWFSC-263. National Marine Fisheries Service, Honolulu, pp. 161–169.

Froese, R., Pauly, D. 2003. Fishbase (available at http://www.fishbase.org, accessed April 2007).

Gilman, E., Zollett, E., Beverly, S., Nakano, H., Shiode, D., Davis, K., Dalzell, P., Kinan, I., 2006. Reducing sea turtle bycatch in pelagic longline gear. Fish Fish. 7, 2–23.

Gilman, E., Clarke, S., Brothers, N., Alfaro-Shigueto, J., Mandelman, J., Mangel, J., Peterson, S., Piovano, S., Thomson, N., Dalzell, P., Donoso, M., Goren, M., Werner, T., 2008. Shark interactions in pelagic longline fisheries. Marine Policy 32, 1–18.

Hosmer, D.W., Lemeshow, S., 1988. Applied Logistic Regression. John Wiley & Sons Inc., New York.

IUCN (2006). IUCN Redlist. (available at http://www.iucnredlist.org accessed 1 August 2007).

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

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

Moyes, C.D., Fragoso, N., Musyl, M.K., Brill, R.W., 2006. Predicting Postrelease Survival in Pelagic Fish. Trans. Am. Fish. Soc. 135, 1389–1397.

Prince, E.D., Ortiz, M., Venizelos, A., 2002. A comparison of circle and "J" hook performance in recreational catch and release fisheries for billfish. Am. Fish. Soc. Symp. 30, 66–79.

R Development Core Team (2006). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0 (available at http://www.R-project.org. accessed December 2006).

Rose, C., McLoughlin, K. 2001. Review of shark finning in Australian fisheries. Final Report to the Fisheries Resources Research Fund. Bureau of Rural Sciences, Canberra.

Skomal, G.B., Chase, B.C., Prince, E.D., 2002. A comparison of circle and straight hooks relative to hooking location, damage and success while catch and release fishing for Atlantic bluefin tuna. Am. Fish. Soc. Symp. 30, 57–65.

Stone, H.H., Dixon, L.K., 2001. A comparison of catches of swordfish, *Xiphias gladius* and other pelagic species from Canadian longline gear configured with alternating monofilament and multifilament nylon gangions. Fish. Bull. 99, 210–216.

Vieira, S., Wood, R., Galeano, D., 2007. Australian Fisheries Surveys Report 2006. ABARE Report Prepared for the Fisheries Resources Research Fund. Australian Bureau of Agricultural and Resource Economics, Canberra.

Ward, P., Hindmarsh, S., 2007. An overview of historical changes in the fishing gear and practices of pelagic longliners, with particular reference to Japan's Pacific fleet. Rev. Fish Biol. Fish. 17, 501–516.

Watson, J.W., Bergmann, C.E., Shah, A., Foster, D., Epperly, S., 2004. Evaluation of 18/0 Circle Hook in the Gulf of Mexico Tuna Fishery. National Marine Fisheries Service, Southeast Fisheries Center, Pascagoula, MS, p. 14.

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

Watson, J., Kerstetter, D.W., 2006. Pelagic longline fishing gear: a brief history and discussion of research efforts to improve selectivity and sustainability. Mar. Technol. Soc. J. 40, 5–10.

Werner, T., Kraus, S., Read, A., Zollett, E., 2006. Fishing techniques to reduce the bycatch of threatened marine animals. Mar. Technol. Soc. J. 40, 50–68.

Yokota, K., Kiyota, M., Minami, H., 2006. Shark catch in a pelagic longline fishery: Comparison of circle and tuna hooks. Fish. Res. 81, 337–341.

Zar, J.H., 1984. Biostatistical Analysis, second ed. Prentice Hall International, New Jersey, p. 718.