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The influence of wire leaders and shark lines on shark bycatch in pelagic longline fisheries

A review and implications for the IOTC

Brooke D’Alberto, Heather Patterson and Don Bromhead

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Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES)
GPO Box 858 Canberra ACT 2601
Telephone 1800 900 090
Web agriculture.gov.au/abares

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We acknowledge the Traditional Custodians of Australia and their continuing connection to land and sea, waters, environment and community. We pay our respects to the Traditional Custodians of the lands we live and work on, their culture, and their Elders past and present.

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Executive Summary

This paper provides a detailed review of the global scientific research and evidence pertaining to the influence of wire leaders and shark lines, upon the catch rates and mortality of pelagic shark species caught by longline fisheries targeting tuna and swordfish. It discusses the implications of the review findings for future potential Indian Ocean Tuna Commission (IOTC) shark conservation measures. The review considered evidence from scientific fishing trials/surveys, commercial fishery data analyses, and predictive modelling approaches. The review highlights a number of consistent and relevant findings, specifically:

1. Experimental fishing trials/surveys, designed to look at leader material effects, and focussed on pelagic longline fisheries targeting tuna or swordfish, have consistently determined that monofilament leaders result in significantly lower at-vessel catch rates of pelagic sharks (grouped) and of specific shark species (most commonly shortfin mako *Isurus oxyrinchus* and blue shark *Prionace glauca*, but also pelagic thresher *Alopias pelagicus* and oceanic whitetip shark *Carcharhinus longimanus*), with the precise outcomes differing depending on species, trial, and sampling numbers. Shark lines were not assessed in those trials.
2. A number of these trials inferred from bite-off data that the difference in at-vessel catch rate was due to bite-offs on monofilament lines, allowing sharks to escape after initial hooking, and that actual catch rates between leader types, at the point of bait being taken, were likely similar.
3. A number of the trials found that catch rates of at least one or more target tuna and billfish species were higher on monofilament than wire leaders. None of these studies found that target species at-vessel catch rates were significantly lower on monofilament leaders.
4. Analyses of observer catch rates data in the Pacific provides strong evidence that prohibiting the use of shark lines can significantly reduce the mortality of some shark species, in situations where the use of shark lines is common.
5. Predictive modelling research conducted in the Pacific determined that banning both shark lines and wire traces in the WCPFC Area had the potential to reduce fishing mortality by 30.8% and 40.5% for silky sharks and oceanic whitetip sharks respectively in that region (Harley et al. 2015, Bigelow & Carvahlo, 2021).

While research clearly indicates the potential of measures prohibiting wire leaders and shark lines to reduce pelagic shark mortality, the degree to which a reduction would occur in the IOTC depends on the current level of use of these gears in IOTC, which is uncertain and requires further investigation. However, prohibition of these gears can strengthen current IOTC shark conservation measures by either reducing future mortality (where use of these gears is common) or preventing future increases in shark mortality due to increased use of these gears (if current use is low). Current IOTC shark conservation measures include provisions banning retention of thresher sharks (Family *Alopiidae*) and oceanic whitetip shark. While these measures will clearly help to reduce mortality of these species, their efficacy is dependent on the proportion of sharks alive and healthy at haul and their survivability post release. A prohibition on the use of shark lines and wire leader, if adopted by IOTC, would further strengthen IOTC measures by reducing initial capture rates (shark line prohibition) and increase escapement post capture (wire leader prohibition), resulting in reduced overall mortality. They would also reduce fishing mortality across a broader range of pelagic shark species. Such provisions would be consistent with IOTC Scientific Committee (SC) advice pertaining to the need to reduce mortality of shortfin mako, silky shark (*Carcharhinus falciformis)* and oceanic whitetip shark. This paper provides three recommendations pertaining to a) prohibiting the use of wire leaders and

shark lines; b) making collection of branch line material data mandatory and c) acquiring additional information on wire leader and shark line use in IOTC fisheries for IOTC Working Party in Ecosystems and Bycatch (WPEB) consideration.

1 Purpose

This paper was developed in direct response to a request by the IOTC Commission (IOTC, 2023a) for scientific advice pertaining to technical and mitigation measures to strengthen the conservation of sharks[1]. The primary purpose of this paper is to provide a detailed review of the global scientific research and evidence pertaining to the influence of longline leader material (specifically wire leaders and monofilament leaders) and shark lines, upon the catch rates and mortality of pelagic shark species caught by longline fisheries targeting tuna and swordfish. It reviews which national and regional fisheries management bodies are already implementing measures to control the use of wire leaders and shark lines, and discusses the implications of the review findings for potential future IOTC measures to strengthen the conservation of sharks.

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[1] The term “sharks” refers to Chondrichthyes (sharks, rays, skates, and chimeras) for the purposes of this report, as defined by the Food and Agriculture Organisation (FAO)

2 Background

At the global scale, it is well recognised that many shark species are facing substantial population declines due to overfishing (Dulvy et al. 2021). Bycatch of sharks can pose a significant challenge for their conservation and management and is a major concern for the sustainability of fisheries (Alverson et al. 1994; Kennelly 2007). The need to reduce fishing mortality and bycatch of sharks has been widely recognised in domestic and international fisheries (Dulvy et al. 2021; FAO 1999).

At the IOTC scale, a lack of appropriate and representative fisheries data pertaining to shark bycatch in IOTC fisheries has prevented robust stock assessment of these species, with the majority of attempted assessments unable to reliably determine status. The exception is for blue shark which is assessed to be not overfished and not subject to overfishing (IOTC, 2023b).

The IOTC SC provides species summaries containing scientific advice to the IOTC Commission on seven key pelagic shark species interacting with IOTC fisheries. In these summaries, the SC has highlighted that six of those species are of global conservation concern, based on the International Union for Conservation of Nature (IUCN)'s Red List of Threatened Species (IOTC, 2023b). The SC has also noted outcomes of an ecological risk assessment (ERA) of the vulnerability of shark species to IOTC fisheries (Murua et al. 2018), highlighting those species which have relatively high vulnerability to longline, purse seine and gillnet fisheries in the IOTC Area. On the basis of IUCN and ERA assessments and other available fisheries data and information, the SC has formulated scientific advice to the Commission for each species. This advice includes recommending that the Commission implement additional measures to reduce fishing mortality of shortfin mako (*Isurus oxyrinchus)*, as well as the need for the Commission to take mitigation measures to reduce at-vessel and post release mortality of silky shark and oceanic whitetip sharks. The latter advice includes the consideration of potential gear modifications in longline fleets targeting tuna and swordfish (IOTC, 2023b).

Concerns among some IOTC member countries over the need for stronger management measures to reduce mortality of pelagic sharks in IOTC fisheries led to the Commission considering a proposal to adopt a strengthened shark conservation measure at its 27th Session in May 2023 (IOTC 2023a). The proposal (IOTC-2023-S27-PropR *On the conservation of sharks caught in association with fisheries managed by IOTC*) submitted by the Maldives, aimed to combine the five existing shark resolutions (Resolutions 12/09, 13/05, 13/06, 17/05 and 18/02) into one. In doing so, it also included a range of changes to existing resolutions, including two new "mitigation" provisions prohibiting the use of wire leaders and shark lines by longline vessels (IOTC 2023a). Leaders are lines used to connect hooks to the remainder of the branchlines (which connect to the mainline). Wire leaders are used to prevent the loss of fish with sharp teeth and typically used in fisheries that target and/or retain sharks (Vega and Licandeo, 2009; Watson et. al. 2005). This is in contrast to nylon monofilament leaders (hereafter referred to as *monofilament leaders*) which allow such species to "bite-off" and escape. Shark lines place baited hooks near the surface by attaching branch lines directly to floats instead of the mainline, and large pieces of tuna or incidental catch are often used as bait (Piovano & Gilman 2017). The use of these shallow hooks off the mainline are specifically targeted at catching sharks (Bromhead et al. 2012).

The inclusion of these prohibitions in the proposal is based on scientific evidence from research studies conducted around the world that nylon monofilament leaders used by longline vessels result in significantly lower at-vessel catch rates and lower overall fishing mortality of pelagic shark than do wire leaders (which are commonly used in some fisheries) (e.g Afonso et al. 2012; Scott et al. 2022; Ward et al. 2008; Vega & Licandeo, 2009). This is due to sharks being able to bite-off and escape from longlines using monofilament leaders, in contrast to wire leaders which prevent bite-offs and escapement, leading to higher mortality. Studies have also indicated neutral or sometimes positive impacts on target tuna and swordfish catch rates using monofilament lines (e.g. Afonso et al. 2012; Berkeley & Campos 1988; Vega & Licandeo, 2009; Ward et al. 2008). There is also strong evidence that prohibiting the use of shark lines can significantly reduce the mortality of some shark species (Bromhead et al. 2012, Bromhead et al. 2013, Harley et al. 2015, Bigelow & Carvahlo, 2021).

However, following discussions on the issues of shark lines, wire leaders and fins naturally attached as approaches to reduce the impacts of IOTC fisheries on elasmobranchs (p70, IOTC 2023a), the Commission determined that it lacked clear advice from the IOTC SC regarding the conservation and management of elasmobranch populations in the IOTC area of competence. Subsequently the Commission (p71, IOTC 2023a): -

“*REQUESTED the relevant Working Parties and IOTC Scientific Committee, at its 26th session, to review the latest science and best practices in other oceans and, in collaboration with the Compliance Committee as appropriate, provide advice to the Commission at S28 on technical and mitigation measures to strengthen the conservation of sharks. In particular, advice on vulnerable species such as oceanic whitetip sharks, whale sharks and thresher sharks, and how to reduce the impact of tuna fisheries, including the following:*

- *the use of wire trace as branch lines or leaders and the use of branch lines running directly off the longline floats or drop lines, known as shark lines; and*
- *the application of fins naturally attached requirements to improve monitoring of elasmobranchs, prevention of the practice of shark finning, full utilization of caught sharks and effective monitoring of compliance with existing conservation and management measures.*

This paper was developed in direct response to the above Commission request, and specifically the request pertaining to wire trace and shark lines. It aims to provide a detailed review of the global scientific research and evidence pertaining to the influence of longline leader material (specifically wire leaders and monofilament leaders) and shark lines, upon the catch rates and mortality of pelagic shark species caught by longline fisheries targeting tuna and swordfish. The paper includes a brief review of which national and regional fisheries management bodies are already implementing measures to control the use of wire leaders and shark lines. Finally, it discusses the implications of the review findings for potential future IOTC measures to strengthen the conservation of sharks, and provides two recommendations.

3 Research review

Changes to fishing gear configurations have the potential to decrease fishing interactions, minimise injury and reduce mortality for bycatch species in commercial fisheries. In pelagic longline fisheries specifically, catch rates and mortality of both target species and shark bycatch have been demonstrated to be influenced by the type of leader type and construction (Afonso et al. 2011; Afonso et al. 2012; Bigelow & Carvalho, 2021; Bromhead et al. 2012; Harley et al. 2015; Scott et al. 2022; Ward et al. 2008; Vega & Licandeo, 2009) and the presence or absence of shark lines (Bigelow & Carvalho, 2021; Bromhead et al. 2012; Harley et al. 2015).

The following sections provide a review of the influence of leader material (focussed mainly on wire leader versus monofilament) and construction, as well as the use of shark lines, upon shark “at haul” catch rates and mortality, based on three different types of published studies:

- Experimental fishing trials designed to assess leader type/construction effects,
- Analyses of commercial fishing catch rate data (logbook or observer data), and
- Predictive modelling research assessing future likely changes in catches, catch rates and mortality.

3.1 Experimental designed fishing trials

3.1.1 Catch rates

Wire vs Monofilament leader

Several studies have systematically tested the differences in catch-per-unit-effort (CPUE) between leader material (wire vs. monofilament) through paired or alternate gear trials (Afonso et al. 2012; Santos et al. 2017; Scott et al. 2022; Ward et al. 2008; Vega & Licandeo, 2009). The results of these trials including outcomes of statistical analyses are provided in Table 1. In all studies reviewed, wire leaders have been found to have higher at-vessel catch rates and mortality of one or more pelagic sharks, compared to monofilament leaders.

In the Australian tuna and billfish fishery off eastern Australia, Ward et al. (2008) conducted an experimental fishing trial, that deployed equal numbers of wire and monofilament leaders randomly along the mainlines. They found that the catch rates of sharks (combined) were significantly higher on wire leaders compared to monofilament leaders (Table 1). The catch rates for pelagic thresher shark, oceanic whitetip sharks and tiger sharks (*Galeocerdo cuvier*) were significantly higher on wire leaders, while there was no significant difference in catch rates for bigeye thresher (*Alopias superciliosus*) and silky shark (Table 1). Catch rates for most target species did not differ significantly between leader types, with the exception of bigeye tuna which had significantly higher catch rates on monofilament leaders.

In an eastern south Pacific swordfish fishery, Vega & Licandeo (2009) conducted a fishing trial comparing the “American style” longline system of nylon monofilament mainline and leaders to the Spanish longline system of nylon multifilament mainline and wire leaders. The trial did not randomly distribute leader types but rather set one type on the first half of set and the other on the second half. The study found total catch and nominal catch rates of sharks were lower on monofilament leaders, and significantly different when compared to wire leaders (ANCOVA, $F_{1,71} = 3.90$; $p = 0.05$). The catch rates for the shortfin mako and unidentified whaler sharks (*Carcharhinus* spp.) were significantly higher on wire leaders (Table 1). While blue shark were found to have higher catch and CPUE on monofilament leaders, there was no statistical difference between the leader types. They found that catch rates of target species (bigeye tuna *Thunnus obesus*, swordfish *Xiphias gladius*, and albacore tuna *Thunnus alalunga*) were all significantly lower on wire leaders (Table 1).

In a pelagic longline fishery targeting swordfish and tunas (*Thunnus* spp.) in the southwest Atlantic Ocean, Afonso et al. (2012) examined both hook type and leader type effects, recording catches taken on 17 longline sets with random placement of even numbers of monofilament and wire leaders. They found that wire leaders had higher catch rates of blue sharks and sharks in total (Table 1). The catch rate for blue sharks (2-way ANOVA, $F_{1,64}$ p=0.034) and combined sharks (2-way ANOVA, $F_{1,64}$ p=0.031) were statistically different between the two leader types. They found that monofilament leader had higher catch rates of bigeye tuna and target species combined.

In the pelagic longline fishery in the southwest Indian Ocean targeting swordfish, Santos et al. (2017) conducted experimental trials that deployed equal numbers of wire and monofilament leaders alternating every section (per 84 hooks) along the longlines. They found that overall catch rates for sharks was 30% (95% CI 13-49%) higher on wire leaders, and at a species level, there was 31% (95% CI 14-52%) increase of blue shark CPUE on wire leaders (Table 1). They found that the catch rates of the target swordfish did not significantly differ between leader types.

In the US Pacific longline fishery, Scott et al. (2022) conducted paired gear trials over four fishing trips (deploying 15-20 sets per trip), in which wire and monofilament leader types were alternated every 10–30 segments of the longline to eliminate any influence of spatial variation on catch rates. They found a significantly higher (41%) catch rates of sharks (grouped) on wire leaders (CPUE = 1.36), compared to monofilament leaders (CPUE = 0.76, p = 0.004; Table 1). At an individual species level, blue shark and shortfin mako shark were the most commonly caught species and comprised 75.9% and 14.2% of the total shark catch, respectively (Table 1). Catch rates of blue shark and shortfin mako were significantly higher (35.3% and 64.5% respectively) on wire compared with monofilament gear types (Table 1). Catch rates of target bigeye tuna did not significantly differ between leader types.

This review notes that there are three additional research papers sometimes cited as examples of longline leader “trials” that have found either lower shark catch on wire leaders or no significant difference, these being the papers of Branstetter & Musick (1993), Berkeley et al. (1988) and Smukall et al. (2021). Following close examination of these research papers, it is very clear that these should not be considered as equivalent (to the above experimental trials) or even relevant research for informing IOTCs understanding of leader type effects on pelagic shark or target species catch rates. The reasons for this are as follows.

Branstetter & Musick (1993) conducted a longline sampling program very near the Atlantic coast of the USA (Chesapeake Bay). They recorded catches from 71 very short sets (150 hooks/set totalling only 11,200 hooks), each setting 100 steel leaders and then 50 monofilament leaders. The survey program sampled sharks across a range of depths (<10 m, 10-20m, 20-100m and >100m). Importantly, the authors noted that the fishing surveys were not designed to detect statistical differences between leader types but were a means to provide additional specimens for research purposes without increasing effort. Only 58 sets caught sharks and of these 31 sets were in coastal waters less than 20m deep, 19 in waters 20-100m deep and only 8 sets in waters >100m deep. Subsequently, the vast majority of the shark catch (95%) comprised coastal shark species of which most (77%, n = 288) was comprised on two coastal species (Atlantic sharpnose shark *Rhizoprionodon terraenovae* [31%, n = 197] and sandbar shark *Carcharhinus plumbeus* [56%, n = 360]). While the study found that the number of shortfin mako, blue shark, bignose shark *Carcharhinus altimus* and silky shark were higher on wire leaders compared to monofilament leaders (Table 1), the sample sizes are very low (a total of 20 sharks caught across 5 species). Individual catch rates were not presented due to the low number of individuals recorded. The study did note that the combined shark species CPUE that included predominantly coastal shark species was significantly lower on wire leaders (t-test, p> 0.05; Table 1). Overall, the study focused on very shallow waters and coastal shark sampling, had low sampling effort, very low pelagic shark sample sizes and lacked appropriate statistical design. The outcomes of this study therefore are not relevant to the consideration of leader type effects for pelagic sharks in the IOTC.

Berkeley et al. (1988) study was conducted off the Atlantic coast of Florida, USA. While the study conducted 111 short swordfish sets (90-120 hooks per set) overall, *only 13* of these sets included both steel and monofilament leaders, on a total of only 338 hooks and 1266 hooks respectively. The study reported that there were no significant differences (t-test, p>0.10) in combined shark catch rates between wire (mean CPUE = 0.47) and monofilament (mean CPUE = 0.54) leaders in the pelagic swordfish longline fishery. However, wire leaders only comprised of 21% of the longline sets and the CPUE was combined between inshore and offshore survey sites. The study also reported significantly higher target swordfish catch rates on monofilament leaders and it was for this reason that simultaneous trialling of steel leaders was discontinued very early in the trial (after 13 sets). Overall, the trial comprised very low sampling effort and had a very unbalanced design. While the full study (111 sets) recorded 13 species (bigeye thresher, bignose shark, silky shark, bull shark *Carcharhinus leucas*, oceanic whitetip shark, dusky shark *Carcharhinus obscurus*, sandbar shark *Carcharhinus plumbeus*, night shark *Carcharhinus signatus*, tiger shark, longfin mako *Isurus paucus*, blue shark, scalloped hammerhead shark *Sphyrna lewini*, and great hammerhead shark *Sphyrna mokarran*) it did not describe, for the 13 sets using both gears, what species were caught, nor the individual species catch numbers or rates for wire or monofilament leaders. Overall, the outcomes of this study should not be considered relevant to the consideration of leader type effects for pelagic sharks in the IOTC.

In the Bahamas, Smukall et al (2021) assessed the influence of gear strength and leader material on *coastal shark s*pecies during long-term shark abundance surveys (blacknose shark *Carcharhinus acronotus,* blacktip *Carcharhinus limbatus*, bull shark *Carcharhinus leucas*, tiger shark, nurse shark *Ginglymostoma cirratum*, lemon shark *Negaprion brevirostris*, Atlantic sharpnose and great hammerhead shark). The study conducted 28 longline sets with 4 combinations of hook size and leader material (light or heavy; see below 3.1.2 Key Considerations), with alternating monofilament and wire leaders. The leader construction were designed specifically to target shallow water (<5 m depth) coastal shark species (Hansell et al. 2018). The study reported a higher catch rate of coastal shark species on “light” monofilament leaders (compared to light wire leaders) and no difference in catch rates between the heavy monofilament and wire leaders. Overall, the study focused on very shallow water and coastal shark species and used different gear construction to commercial pelagic longline fisheries, and the outcomes of this study are of limited relevance to the consideration of leader effects for pelagic sharks in the IOTC.

Shark lines

The review did not find any research (based on experimental fishing trials) published that considered the influence of shark lines on shark catch rates and mortality.

Table 1 Summary of results from experimental fishing trials comparing the nominal catch per unit effort (CPUE) between wire and monofilament leaders for target tuna, billfish, and shark species. (Note that some non-shark bycatch species results were excluded to reduce the size of the tables).

				Nominal CPUE						
				n		Monofilament leader		Wire leader		p value
Location	**Species category**	**Common name**	**Scientific name**	**Mono filament**	**Wire**	**Circle hook ± SE or 95% CI**	**J hook ± SE or 95% CI**	**Circle hook ± SE or 95% CI**	**J hook ± SE or 95% CI**	
Eastern Australia, Southwest Pacific (Ward et al. 2008) [a]	Target	Yellowfin tuna	*Thunnus albacares*	838	848	–	22.24	–	22.66	0.16
		Bigeye tuna	*Thunnus obesus*	255	186	–	6.77	–	4.97	0.02*
		Tuna combined		1279	1208	–	33.94	–	32.28	0.95
		Broadbill Swordfish	*Xiphias gladius*	16	23	–	0.42	–	0.61	0.27
		Billfish combined		148	140	–	3.93	–	3.74	0.79
	Bycatch	Pelagic thresher shark	*Alopias pelagicus*	1	13	–	0.03	–	0.35	0.01*
		Bigeye thresher shark	*Alopias superciliosus*	6	5	–	0.16	–	0.13	0.91
		Whaler shark spp.	*Carcharhinus spp.*	6	27	–	0.16	–	0.72	0.00*
		Silky shark	*Carcharhinus falciformis*	12	20	–	0.32	–	0.53	0.18
		Oceanic whitetip shark	*Carcharhinus longimanus*	3	11	–	0.08	–	0.29	0.07*
		Australian blacktip shark	*Carcharhinus tilstoni*	1	0	–	0.03	–	0.00	–
		Tiger shark	*Galeocerdo cuvier*	14	24	–	0.37	–	0.64	0.07*
		Shortfin mako	*Isurus oxyrinhus*	0	3	–	0.00	–	0.08	–
		Hammerhead shark spp.	*Sphyrna spp.*	1	0	–	0.03	–	0.00	–
		Sharks combined		44	103	–	1.17	–	2.75	0.000*
Chile, Eastern South Pacific (Vega & Licandeo 2009)	Target	Broadbill swordfish	*Xiphias gladius*	498	249	–	15.98	–	6.09	0.000*
		Albacore tuna	*Thunnus alalunga*	21	3	–	0.67	–	0.07	0.000*
		Bigeye tuna	*Thunnus obesus*	37	7	–	1.19	–	0.17	0.000*
		Yellowfin tuna	*Thunnus albacares*	19	0	–	0.61	–	0.00	–
	Bycatch	Bigeye thresher shark	*Alopias superciliosus*	0	3	–	0.00	–	0.07	–
		Blue shark	*Prionace glauca*	54	91	–	1.73	–	2.22	0.162
		Whaler shark spp.	*Carcharhinus spp.*	3	16	–	0.10	–	0.39	0.022
		Pelagic stingray	*Pteroplatytrygon violacea*	3	0	–	0.10	–	0.00	–

CPUE is calculated by the number of individuals per 1000 hooks. **n** number of individuals caught per leader type; **± SE** standard error; **95% CI** 95% confidence intervals given as a range, ***** indicates significant statistical difference. **a** This study reported on other bycatch and/or byproduct species, however only target and shark species were included from this study. **b** Only presented the combined total catch and not between leader type. **c** Standard deviations presented

				Nominal CPUE						
				n		**Monofilament leader**		**Wire leader**		**p value**
Location	**Species category**	**Common name**	**Scientific name**	**Mono filament**	**Wire**	**Circle hook ± SE or 95% CI**	**J hook ± SE or 95% CI**	**Circle hook ± SE or 95% CI**	**J hook ± SE or 95% CI**	
		Porbeagle shark	*Lamna nasus*	1	0	–	0.03	–	0.00	–
		Shortfin mako shark	*Isurus oxyrinchus*	16	84	–	0.51	–	2.05	0.000*
		Cookiecutter shark	*Isistius brasiliensis*	1	0	–	0.03	–	0.00	–
Southwestern equatorial Atlantic (Afonso et al. 2012) [a, b]	Target	Broadbill Swordfish	*Xiphias gladius*	135		8.71 (± 9.19)	9.18 (± 7.45)	6.12 (± 8.01)	7.76 (± 5.74)	0.354
		Bigeye tuna	*Thunnus obesus*	104		7.06 (± 6.41)	8.47 (± 8.47)	4.71 (± 6.82)	4.24 (± 6.68)	0.042*
		Yellowfin tuna	*Thunnus albacares*	32		1.88 (± 2.87)	2.82 (± 3.09)	1.18 (± 1.88)	1.65 (± 2.85)	–
		Albacore tuna	*Thunnus alalunga*	13		0.94 (± 1.75)	1.41 (± 2.81)	0.47 (± 1.33)	0.24 (± 0.97)	–
		Blackfin tuna	*Thunnus atlanticus*	2		0.00 (± 0.00)	0.47 (± 1.94)	0.00 (± 0.00)	0.00 (± 0.00)	–
		Target combined		286		18.59 (± 10.86)	22.36 (± 13.05)	12.47 (± 9.15)	13.88 (± 8.50)	0.007*
	Bycatch	Blue shark	*Prionace glauca*	77		3.76 (± 5.38)	3.06 (± 4.59)	5.41 (± 4.23)	5.88 (± 5.12)	0.034*
		Pelagic stingray	*Pteroplatytrygon violacea*	40		0.24 (± 0.97)	0.47 (± 1.33)	1.18 (± 2.35)	0.71 (± 1.57)	0.345
		Silky shark	*Carcharhinus falciformis*	24		0.94 (± 2.66)	1.18 (± 3.40)	1.41 (± 4.23)	2.12 (± 6.02)	–
		Oceanic whitetip shark	*Carcharhinus longimanus*	11		0.00 (± 0.00)	0.24 (± 0.97)	0.24 (± 0.97)	0.24 (± 0.97)	–
		Crocodile shark	*Pseudocarcharias kamoharai*	11		0.47 (± 1.33)	0.24 (± 0.97)	0.00 (± 0.00)	0.24 (± 0.97)	–
		Thresher spp.	*Alopias spp.*	9		0.47 (± 1.33)	0.00 (± 0.00)	0.00 (± 0.00)	0.24 (± 0.97)	–
		Mako spp.	*Isurus spp.*	4		0.71 (± 1.57)	0.71 (± 2.11)	0.71 (± 2.11)	0.47 (± 1.94)	–
		Hammerhead shark spp.	*Sphyrna spp.*	3		0.00 (± 0.00)	0.71 (± 1.57)	1.41 (± 2.43)	0.00(± 0.00)	–
		Tiger shark	*Galeocerdo cuvier*	3		1.65 (± 2.85)	4.00 (± 5.58)	1.88 (± 3.50)	1.88 (± 3.77)	–
		Sharks combined		182		–	–	–	–	0.031*
Southwest Indian Ocean (Santos et al. 2017) [a]	Target	Swordfish	*Xiphias gladius*	519	499	–	12.8 (± 6.1)	–		0.28
	Byproduct	Albacore tuna	*Thunnus alalunga*	7	3	–	0.2 (± 0.8)	–		0.25
		Bigeye tuna	*Thunnus obesus*	6	14	–	0.2 (± 0.6)	–		0.67
		Yellowfin tuna	*Thunnus albacares*	11	8	–	0.3 (± 0.7)	–		0.29
	Bycatch	Blue shark	*Prionace glauca*	318	433	–	8.0 (± 6.3)	–		0.00*
		Bigeye thresher	*Alopias superciliosus*	5	1	–	0.2 (± 0.8)	–		–
		Manta sp.	*Manta sp.*	0	1	–	–			
		Oceanic whitetip shark	*Carcharhinus longimanus*	0	3	–	0.0 (± 0.2)	–		–
		Pelagic stingray	*Pteroplatytrygon violacea*				0.3 (± 0.9)			
		Porbeagle shark	*Lamna nasus*	0	2	–	–	–		–
		Crocodile shark	*Pseudocarcharias kamoharai*	0	1	–	–	–		–
		Shortfin mako	*Isurus oxyrinchus*	10	14	–	0.3 (± 0.7)	–		0.10

				Nominal CPUE						
				n		**Monofilament leader**		**Wire leader**		**p value**
Location	**Species category**	**Common name**	**Scientific name**	**Mono filament**	**Wire**	**Circle hook ± SE or 95% CI**	**J hook ± SE or 95% CI**	**Circle hook ± SE or 95% CI**	**J hook ± SE or 95% CI**	
		Hammerhead sp.	*Sphyrna sp.*	1	0		0.0 (±0.2)			
		Smooth hammerhead	*Sphyrna zygaena*	0	1	–	–	–		–
Hawaii, central North Pacific Ocean (Scott et al. 2022)	Target	Bigeye tuna	*Thunnus obesus*	463	462	4.772	–	4.752	–	0.7767
		Yellowfin tuna	*Thunnus albacares*	95	75	1.447	–	1.14	–	0.071
	Bycatch	Blue shark	*Prionace glauca*	73	113	0.976	–	1.501	–	0.0034*
		Shortfin mako	*Isurus oxyrinhus*	9	25	0.224	–	0.618	–	0.0086*
		Bigeye thresher shark	*Alopias superciliosus*	3	7	0.289	–	0.663	–	0.3266
		Pelagic stingray	*Pteroplatytrygon violacea*	4	6	0.313	–	0.503	–	–
Chesapeake Bay, Atlantic Ocean (Branstetter & Musick 1993)	Coastal	Sandbar shark	*Carcharhinus plumbeus*	163	195	–	–	–	–	–
		Atlantic sharpnose shark	*Rhizoprionodon terraenovae*	93	104	–	–	–	–	–
		Sand tiger	*Odontaspis taurus*	2	15	–	–	–	–	–
		Dusky shark	*Carcharhinus obscurus*	6	7	–	–	–	–	–
		Tiger shark	*Galeocerdo cuvier*	6	4	–	–	–	–	–
		Scalloped hammerhead	*Sphyrna lewini*	8	6	–	–	–	–	–
		Spinner shark	*Carcharhinus brevipinna*	1	3	–	–	–	–	–
		Blacktip shark	*Carcharhinus limbatus*	3	1	–	–	–	–	–
		Smooth dogfish	*Mustelus canis*	0	1	–	–	–	–	–
		Smooth hammerhead	*Sphyrna zygaena*	2	0	–	–	–	–	–
	Pelagic spp.	Shortfin mako	*Isurus oxyrinhus*	2	8	–	–	–	–	–
		Bignose shark	*Carcharhinus altimus*	1	5	–	–	–	–	–
		Silky shark	*Carcharhinus falciformis*	0	1	–	–	–	–	–
		Blue shark	*Prionace glauca*	0	2	–	–	–	–	–
		Bigeye thresher	*Alopias superciliosus*	1	0	–	–	–	–	–

CPUE is calculated by the number of individuals per 1000 hooks. **n** number of individuals caught per leader type; **± SE** standard error; **95% CI** 95% confidence intervals given as a range, * indicates significant statistical difference. **a** This study reported on other bycatch and/or byproduct species, however only target and shark species were included from this study. **b** Only presented the combined total catch and not between leader type. **c** Standard deviations presented

3.1.2 Key considerations

When assessing the results of the experimental trials described above its important to take account of three additional key considerations - being the effect of bite-offs (Afonso et al. 2012; Scott et al. 2022), nylon leader construction (monofilament vs multifilament) (Grant et al. 2020; Stone & Dixon 2001; Smukall et al. 2021), and hook type (circle vs j hook) (Afonso et al. 2011; Afonso et al. 2012; Reinhardt et al. 2018; Ward et al. 2009), by the species-specific catchability and species habitat preferences (Smukall et al. 2021; Ward et al. 2008). The influence of these factors is important to consider when comparing studies.

Bite-offs

There is significant evidence that differences in “at vessel” CPUE, specifically the higher CPUE on wire leaders, is attributable to the higher rate of bite-offs by pelagic sharks on monofilament leaders, and that initial catch rates (i.e. number of sharks taking baited hooks prior to bite off) does not differ significantly between leader types.

Ward et al. (2008) found considerable variation in bite off rates from monofilament leaders within longline operations. However, there were considerably higher bite off rates on monofilament leaders compared to wire leaders. Bite-offs may mask the “initial” catchability of monofilament leaders and a high bite-off rate indicates that as many animals escape from monofilament leaders as caught on monofilament leaders. In addition, Ward et al. (2008) attributed relative catchability of shark species caught on monofilament leaders to the species differential ability to bite off the line. For example, the heavily serrated teeth of tiger sharks are more likely to sever monofilament leaders than the smooth, needle like teeth of species such as the bigeye thresher. Species that tend to thrash violently when hooked, are more likely to break through a monofilament leader than those with relatively less energetic reaction to being hooked (Gilman et al. 2008; Ward et al. 2008).

Santos et al. (2017) found a significant difference in the bite off rates between wire and monofilament leaders ($p < 0.001$), with the latter having a higher rate of bites offs. Afonso et al. (2012) recorded 38 bite-offs, where all but one (97%) occurred on monofilament leaders. When the bite-off events were included in the CPUE as undetected sharks, there was no significant differences between the CPUE of all sharks combined between the two leader types ($p = 0.825$). Similar results were found by Scott et al. (2022) with a recorded total of 55 bite-offs with 4 of these bite-offs were on wire leaders and 51 (94%) occurred on monofilament leaders. When the authors assumed that the bite-offs were made by undetected sharks, there were no differences in the shark catch rates between the leader types ($p = 0.0963$).

These findings overall indicate that the often higher at vessel CPUE for sharks taken on wire leaders is likely due to escapement of sharks caught initially on monofilament leaders, prior to hauling to the vessel.

Nylon leader construction

While this paper is focussed on comparing catch rates of wire versus nylon monofilament leaders it should be noted that nylon leader construction (e.g. monofilament, multifilament, braided, tarred etc) and gear strength (i.e. line thickness) can also potentially impact the catch rates of shark bycatch.

A limited number of studies have investigated the effects of different nylon leader construction (e.g. monofilament vs. multifilament) on catch rates of sharks in commercial longline fisheries.

In an inshore bottom longline fishery on the east coast of Canada, Grant et al. (2020) found that the catch rates of Greenland sharks (*Somniosus microcephalus*) were significantly lower on the monofilament leaders compared to the braided multifilament leaders. The lower catch rates of Greenland sharks were thought to be result of the greater likelihood of bite-offs on the thinner monofilament leaders compared to the thicker multifilament leaders (Grant et al. 2020).

While Smukall et al. (2021) focussed on coastal (not pelagic) shark species, it is useful to note the outcomes pertaining to the two different nylon leader constructions. The study used double strand 2.3 mm or 3.5 mm nylon monofilament leaders. This was different to previous studies that focused on pelagic shark species such as Afonso et al (2012), Ward et al (2008), Santos et al. (2017), Stone & Dixon (2001) and Scott et al. (2022) that used single strand 2.0 mm monofilament, which was the standard gear in the respective commercial fisheries. Smukall et al (2021) attributed the similar coastal shark catch rates on the heavy duty gear, the higher CPUE and reduced number of bite-offs in the light gear to the increase difficulty for sharks to break or bite through the thicker and/or double strands of monofilament. The thickness of the nylon leaders reflects the strength of the gear and can impact the catch rates of shark species on longlines.

During experimental fishing trials in a Canadian pelagic longline fishery, Stone & Dixon (2001) compared catch rates on nylon monofilament and tarred nylon multifilament branchlines (gangions). While both branchline types used end monfilament leaders (with a line thickness of 2mm), it was noted that catch rates of blue sharks ($p = 0.00$) and pelagic stingrays (*Pteroplatytrygon violacea*) ($p = 0.001$) were still found to be significantly higher on the monofilament branchlines (Stone & Dixon, 2001) compared to the multifilament. This was considered to be due to the higher visibility of the tarred multifilament branchlines. Similarly, catch rates of the target species like swordfish were also higher on the monofilament branchlines. The authors concluded that some pelagic species may be able to detect and thus avoid the tarred multifilament leaders more easily due to their thicker diameter (5 mm vs 2 mm for monofilament) and darker colour (Stone & Dixon 2001).

The results of the studies discussed in this section highlight the importance of considering line strength and construction (including visibility) when comparing the catch rates of sharks on longlines.

Hook type

The hook type (circle or j-shaped) can impact the catch rates and post-release survival of shark bycatch (Afonso et al. 2011; Afonso et al. 2012; Coelho et al. 2012; Gilman et al. 2016b; Reinhardt et al. 2018; Ward et al. 2009). Circle hooks tend to hook sharks in the mouth or jaw, and the trace line tends to be less exposed to abrasion. Whereas j-shaped hooks are often embedded in the throat or gut (internal hooking) and the trace lines are more exposed to the abrasion against the teeth, resulting in higher rates of 'bite-off' (Ward et al. 2008).

When comparing the use of circle or j-shaped hooks on monofilament leaders only, circle hooks can increase the catch rates of sharks, and lower internal hooking rates (Table 1; Afonso et al. 2011; Afonso et al. 2012; Reinhardt et al. 2018). However, Afonso et al. (2012) found that when including the interaction between hook type and leaders, there was no effect on the CPUE of all species and groups analysed ($F (1, 64) = 0.006$, $p = 0.940$), except for blue sharks. There was significant differences in blue shark catch rate between leader types was found in j-shaped hook treatments only (Afonso et al. 2012). Regardless of hook type, catch rates of sharks were lower on monofilament leaders, compared to wire leaders.

Other factors
There are a range of other factors that may impact shark catch rates on pelagic longlines, including species habitat preferences, distribution, movement, environmental conditions (e.g. sea surface temperatures, wind velocity, oceanographic conditions, seasons) and other aspects of the fishing operations (e.g. spatial and temporal distribution of effort, bait type, fishing depth and soak time) (Bigelow et al. 1999; Branstetter & Musick 1993; Bromhead et al. 2012; Gilman et al. 2016b; Vega & Licandeo, 2009) that are not examined in this paper.

3.1.3 At-vessel condition and mortality

A key consideration in the potential impact of leader types on overall mortality of pelagic shark species is not just the differences in the number of sharks hauled to the vessel, but of those, the proportion that are alive or dead. Another consideration is post-release mortality, be that “post escape” mortality after bite offs or post-release (of live sharks) after hauling to the vessel and release by the crew.

A range of studies have investigated the catch-condition, at-vessel mortality, and post-release survival in commercial longlines for shark species (e.g. Coelho et al. 2012; Godin et al. 2012; Reinhardt et al.2018; Gilman et al. 2016b; Massey et al. 2022; Shea et al. 2023). However, only studies which considered the impact of leader material in relation to catch condition and at-vessel mortality are discussed here.

Scott et al. 2022 reported from their analysis that the use of wire leaders has the potential to increase the at-vessel mortality for sharks by up to 20%, compared to monofilament leaders. In their study, out of the 235 sharks caught, 178 sharks were brought to the vessel to record catch condition (i.e. also referred to as life status or health – e.g. alive healthy, sluggish, injured, dead etc). While there was a significantly greater number of sharks dead on wire leaders (n = 22 dead), compared with monofilament leaders (n = 4; p = 0.010) (Scott et al. 2022), he exact number of alive sharks per leader type or total sharks (at vessel) per leader type, was not clearly reported in the study. In addition, blue sharks were analysed separately, and the leader material did not have an effect on the catch condition (p = 0.251). These results were similar to other studies which found that blue sharks had the lowest relative mortality rate regardless of leader type, compared to other shark species (Afonso et al. 2012; Musyl & Gilman 2019).

Afonso et al. (2012) observed that wire leaders exhibited comparably higher mortality per unit effort (MPUE; dead individuals per 1000 hooks) for all sharks combined. Despite a significantly higher proportion (CMH $\chi 2 = 6.725$, df = 1, $P < 0.01$) of sharks caught on wire being alive (56%) compared to those caught on monofilament (34%), the overall mortality per unit effort (MPUE) was still higher on wire leaders, due to the significantly higher numbers (and CPUE) of shark recorded on wire leaders.

Santos et al. (2017) found hooking mortality increased for blue sharks (26%) and sharks group combined (27%) when wire leaders were used. However, the increase in mortality of both blue sharks and combined sharks were not statistically significant, based on the overlapping 95% confidence intervals (95% CI).

Gilman et al. (2016a) reported no significant difference (based on overlapping 95% CI) in the mean nominal haul-back survival rates (alive:total) from observer data for blue sharks (wire = 0.83, 95% CI = 051-1.16; monofilament = 0.84, 95% CI = 0.33-0.64), silky sharks (wire = na, 95% CI = na; monofilament = 0.71, 95% CI = -1.29-0.78), and pelagic stingrays (wire = 1.00, 95% CI = na; monofilament = 0.83, 95% CI = -1.16-0.88) between wire and monofilament leaders.

Wire leaders tend to indiscriminately retain all sharks that have ingested baited hooks (Afonso et al. 2012; Gilman et al. 2016a). The greater proportion of sharks that were observed dead upon haul-back on monofilament leaders may be due to the increased likelihood of escape, particularly for larger, stronger, and more vigorous individuals than smaller, weaker, and more seriously injured individuals (Afonso et al. 2012; Gilman et al. 2016a).

The review did not find any research that explicitly investigated the post-escape mortality of pelagic sharks. The available research indicates that reducing the fight time and the time spent on the longline can lower capture stress and mortality for pelagic sharks (e.g. Bowlby et al. 2021; Campana et al. 2009; Heberer et al. 2010; Massey et al. 2022; Zollett & Swimmer 2019). In addition, proper handling and quick release post-capture and haul to the vessel can improve a shark’s post-release survival rates (e.g. Campana et al. 2009; Carruthers et al. 2009; Diaz & Serafy 2005; Francis et al. 2023; Jordaan et al. 2020; Moyes et al. 2006; Sepulveda et al. 2015). While it cannot be assumed that all sharks survive post-escape after bite-offs from the line, it is likely that the post-escape mortality would be substantially lower than individuals who are caught on wire or monofilament that are handled, and released alive by crew (Ward et al., 2008; Gilman et al., 2013; Clarke et al. 2014).

Sharks with trailing gear have been found to have higher post-release mortality (Sepulveda et al. 2015). Scott et al. (2022) found in experimental trials that trailing monofilament gear did not break apart after 360 days, compared to wire leaders that began to break at the crimps after approximately 60 days. Any trailing gear (hooks, leaders and other gear that is foul hooked) should be removed before the shark is released and preferably prior to the shark being brought on aboard, to increase the post release survival (Francis et al. 2023; Jordaan et al. 2020; Scott et al. 2022; Sepulveda et al. 2015; Raoult et al. 2019).

3.2 Analysis of commercial fishing data

The review identified two studies that had analysed observer data from commercial longline fisheries and assessed the influence of leader material and/or presence of shark lines, on the catch rates of shark species. Both had limitations due to the smaller number of sets (in the overall data set) using either wire leaders and/or shark lines but are worth noting.

Gilman et al. (2016a) analysed observer data from the Palau longline fishery between 1999-2011 to assess changes in catch rates following a ban on shark retention and wire leaders in 2003. The main analysis used generalised additive mixed models (GAMMs) to assess factors impacting target and bycatch species catch rates (which did not include shark lines and leader material factors), and a secondary (non-model based) analysis undertook a simple comparison of catch rates of sharks for sets using (or not using) wire leaders and shark lines. The latter comparison indicated that; a) there was significantly higher (based on non-overlapping 95% CI) blue shark and lower pelagic stingray nominal catch rates on wire leaders compared to monofilament leaders (Table 2) and; b) blue shark CPUE was significantly higher in sets using shark lines (mean CPUE = 10.33, 95% CI = 8.31-12.36) than in sets not using shark lines (mean CPUE = 0.67, 95% CI =-0.04-1.39). However, the authors indicated the results should be interpreted very cautiously, noting the extremely small number of sets using wire leaders and shark lines when compared to the number of sets that did not use them. The authors did note however that in the period after the implementation of the shark retention and wire trace ban, there was a 57% reduction in nominal shark CPUE, a 48% reduction in the proportion of the total catch made up of sharks, 19% reduction in proportion of sharks that were alive on haul-back, and 98% reduction in the percentage of sharks retained. The available information on the total fishing mortality suggests that there was a large net decline in mortality rate following the ban.

Bromhead et al (2012) used Generalized additive model (GAM) to analyse observer data (pertaining to 1499 sets observed from 2005– 2009), from tuna longline vessels in the Republic of the Marshall Islands (RMI) and investigated factors influencing catch rates of sharks, including shark lines, as well as other environmental and fishing method factors. During the time series, wire leaders were used by nearly all observer vessels (~98% of sets) meaning the effects of wire leaders could not be estimated in the study. However, shark lines were used less frequently (27% of sets) throughout the fishery. The study found that species with surface layer (shallower) habitat preferences were caught in higher numbers when shark lines are used (silky shark, pelagic thresher shark and oceanic whitetip shark) or when the hooks are set shallow (pelagic thresher shark and oceanic whitetip shark) (Table 3). The study concluded that banning of wire leaders and shark lines would reduce the catch rates of sharks.

3.3 Predicting future changes in mortality

A number of studies have investigated the future impact on mortality for silky sharks and oceanic whitetip sharks if wire traces and shark lines were to be prohibited for commercial longline vessels within the Westen Central Pacific Fishing Commission (WCPFC) Area.

Harley et al (2015) undertook Monte Carlo simulation modelling to explore the impact of possible management measures (including the banning of wire leaders and shark lines) upon silky shark and oceanic whitetip shark bycatch on longlines in the WCPFC. The models were based on pelagic longline fisheries observer data from the Marshall Islands, Federated States of Micronesia, American Samoa, and Hawaii, and looked at the spatial fishing effort and the species abundance. Their results indicated that banning shark lines had the potential to reduce fishing mortality by 14.7% and 23.3% for silky sharks and oceanic whitetip sharks respectively. Banning wire leaders were unlikely to influence the initial interaction with the fishing gear, however this led to increase in the number of bite-offs that resulted in a reduction of 17.6% and 23.3% in mortality for silky sharks and oceanic whitetip sharks respectively. The study estimated that a combination of prohibiting both shark lines and wire traces was predicted to reduce mortality by 29.4% and 40% for silky sharks and oceanic whitetip sharks.

Table 2 Summary of the comparison of the nominal catch per unit effort (CPUE) between wire and monofilament leaders for commercial fishing data for the main target and shark bycatch species from Gilman et al. (2016).

				Nominal CPUE			
				n		**Monofilament leader**	**Wire leader**
Location	**Type**	**Common name**	**Shark species**	**Monofilament**	**Wire**	**95% CI**	**95% CI**
Palau, Southwest Pacific	Target	Bigeye tuna	*Thunnus obesus*	–	–	1.67 (1.36–1.98)	1.88 (-0.46–4.23)
		Yellowfin tuna	*Thunnus albacares*	–	–	3.65 (2.80–4.51)	1.81 (0.30–3.33)
	Bycatch	Blue shark	*Prionace glauca*	–	–	0.49 (0.33–0.64)	1.15 (0.72–1.59)
		Silky shark	*Carcharhinus falciformis*	–	–	1.34 (0.96–1.71)	0.00 (na)
		Pelagic stingray	*Pteroplatytrygon violacea*	–	–	1.21 (0.97–1.45)	0.24 (-0.23–0.70)

n number of individuals caught per leader type; **± SE** standard error; ***** indicates significant statistical difference. **CPUE** is calculated by the number of individuals per 1000 hooks.

Table 3 Summary of the observed catches and CPUE for the five most commonly caught shark species in Bromhead et al. 2012. The model statistics for influence of shark lines on catch rates from the generalized additive models (GAMs) are presented.

					Shark lines	
Location	**Common name**	**Shark species**	**n**	**CPUE**	**f**	**p**
Republic of the Marshall Islands	Blue shark	*Prionace glauca*	3452	1.0931	0.6	>0.05
	Silky Shark	*Carcharhinus falciformis*	3242	1.0266	4.6	<0.001*
	Bigeye thresher shark	*Alopias superciliosus*	1636	0.5181	-0.2	>0.05
	Pelagic thresher shark	*Alopias pelagicus*	1353	0.4284	3.88	<0.001*
	Oceanic whitetip shark	*Carcharhinus longimanus*	917	0.2904	10.7	<0.001*

n number of individuals observed in total; ***** indicates significant statistical difference; **CPUE** is calculated by the number of individuals per 1000 hooks.

Bigelow & Carvalho (2021) provided an update to the Harley et al (2015) models, by updating the gear types (hook type, leader material and shark lines) based on recently available observer data (2010-2018) and spatial distribution of fishing effort (2015-2019). The updated analysis found that banning shark lines had less of a potential to reduce fishing mortality for the two silky sharks (2.6%) and oceanic whitetip sharks (5.4%), compared to the original estimates by Harley et al. (2015). The authors attributed the decrease (in predicted potential of a shark line ban to reduce mortality) to the decline in use of shark lines in the fisheries since Harley et al (2015) analysis. The decline in shark line use likely resulted from WCPFC fleets opting to implement a ban on shark lines, associated with the WCPFCs 2014 revised shark measure. Banning wire leaders had an increased potential to reduce fishing mortality by 28.2% and 35.8% for silky sharks and oceanic whitetip sharks respectively. The higher estimates could be the result of improved characterisation of the gear use in the longline fisheries. Banning both shark lines and wire traces has the increased potential to reduce fishing mortality by 30.8% and 40.5% for silky sharks and oceanic whitetip sharks respectively.

3.4 Impact on target species

It is important to consider the target species catch rates when investigating the effects of wire and monofilament leaders in commercial longline fisheries.

A range of target species (tunas and swordfish) in commercial longline fisheries were found to have significantly lower CPUE on wire leaders (e.g. Afonso et al. 2012; Ward et al. 2008; Vega & Licandeo, 2009), or no significant difference in CPUE between wire and monofilament leaders (e.g. bigeye tuna, Santos et al. 2017; swordfish, Scott et al. 2021). It was thought that the wire leaders are more conspicuous in the water column than monofilament leaders and may result in some species avoiding wire leaders (Berkeley & Campos 1988; Ward et al. 2008). In addition, tuna have small conical teeth that are also thought to be less effective in severing monofilament leaders, likely attributing to the higher catch rates of tuna observed on monofilament leaders (Ward et al. 2008).

4 Discussion

Key review findings

This paper has provided a detailed review of the global scientific research and evidence pertaining to the influence of longline leader material (specifically wire leaders and monofilament leaders) and shark lines, upon the catch rates and mortality of pelagic shark species caught by longline fisheries targeting tuna and swordfish. It considered evidence from three types of research, being experimental designed fishing trials/surveys (e.g. Afonso et al. 2012; Santos et al. 2017; Scott et al. 2022; Ward et al. 2008; Vega & Licandeo, 2009), catch rates and analyses of data collected by observers on commercial fishing vessels (Gilman et al. 2016a; Bromhead et al. 2012), and predictive modelling of the outcomes of wire leader and shark line prohibitions (also utilising observer data) (Harley et al. 2015; Bigelow & Carvahlo 2021). The review highlights a number of consistent and relevant findings from the research, specifically:

1. All of the experimental fishing trials or surveys that were focussed on pelagic longline fisheries targeting tuna or swordfish (Afonso et al. 2012; Santos et al. 2017; Scott et al. 2022; Ward et al. 2008; Vega & Licandeo, 2009), determined that use of monofilament leaders result in significantly lower at-vessel catch rates of pelagic sharks (as a group), and significantly lower at vessel catch rates for some individual (but not all) pelagic shark species (most commonly shortfin mako and blue shark, but also pelagic thresher and oceanic whitetip), with the outcomes differing depending on species and trial and sampling numbers. Shark lines were not assessed in those trials. In none of these trials were *pelagic* shark species found to have higher at-vessel catch rates on monofilament when compared to wire leaders.
2. A number of these trials inferred from bite-off data that the difference in at-vessel CPUE was due to bite-offs on monofilament lines (Afonso et al. 2012; Scott et al. 2022; Ward et al. 2008), allowing sharks to escape after initial hooking, and that actual catch rates between leader types, at the point of bait being taken, were likely similar.
3. A number of the trials found that catch rates of at least one, and up to three, target tuna and billfish species were higher on monofilament leaders than wire leaders (e.g Afonso et al. 2012; Vega & Licandeo, 2009; Ward et al. 2008). None of the trials found that target species at-vessel catch rates were lower on monofilament leaders.
4. There is also strong evidence that prohibiting the use of shark lines can significantly reduce the mortality of some shark species (Bigelow & Carvahlo, 2021; Bromhead et al. 2012; Bromhead et al. 2013; Harley et al. 2015).
5. The review also looked at predictive modelling research conducted in the Pacific to assess the potential effectiveness of prohibitions on shark lines and wire leaders in reducing mortality of silky shark and oceanic whitetip (Bigelow & Carvahlo, 2021; Harley et al. 2015). That research determined that banning both shark lines and wire traces in the WCPFC Area had the potential to reduce fishing mortality by 30.8% and 40.5% for silky sharks and oceanic whitetip sharks respectively.

Implications of review findings for the IOTC management of sharks

Overall, the review found that there is consistent evidence across multiple research studies, conducted in multiple ocean locations around the world, to demonstrate that a prohibition on wire leaders (Afonso et al. 2012; Bigelow & Carvahlo, 2021; Bromhead et al. 2012; Bromhead et al. 2013; Harley et al. 2015; Santos et al. 2017; Scott et al. 2022; Ward et al. 2008; Vega & Licandeo, 2009) and shark lines (Bigelow & Carvahlo, 2021; Bromhead et al. 2012; Bromhead et al. 2013; Harley et al. 2015) would be highly likely to act to reduce mortality of pelagic sharks, without negative impacts on target tuna and swordfish catch rates.

However, the degree to which such measures, if adopted by the IOTC, would reduce future fishing mortality of pelagic shark species (as a group or individual species), relative to past fishing mortality, is dependent on a range of factors, including the degree to which wire leaders and shark lines have recently and/or are currently being used by longline fisheries in the IOTC.

Ideally, such information on the use of these gear types would be available through data collected by observers placed on longliners in the IOTC Area. However, while the collection and reporting of the use of shark lines by observers is mandatory under the IOTC Regional Observer Scheme minimum data standards, the collection of data on branchline (including leader) materials is not mandatory. It is unclear how much and how consistently such data are collected and reported by observers. A compilation and summary of available statistics (and data gaps) on the use of both gear types would help inform the WPEB, SC and Commission consideration of this issue. The Commission should also consider making collection of data on branchline materials mandatory for observers (see Recommendations, below).

Significant and consistent use of these gears by some fleets would imply that reductions (due to a prohibition of these gears) in mortality would be higher. However, even in scenarios where current/recent use of these gears was less frequent, a prohibition on their use can act to ensure that increases in fishing mortality due to use of these gears in future, would not occur (e.g. Bigelow & Carvahlo, 2021; Harley et al. 2015). In either scenario, a prohibition on the use of these gears will represent a strengthening of current IOTC shark conservation measures.

The likely effectiveness of such provisions in strengthening IOTC shark conservation measures is more apparent when considering the effectiveness of provisions in the existing resolutions. Despite the number of shark focussed IOTC resolutions (five) and the breadth of their content, taken together they are limited in the extent to which they require implementation of effective actions to directly reduce the level of fishing mortality on pelagic shark species. Currently such provisions are limited to prohibition of retention of thresher sharks (Family *Alopiidae*)(Resolution 12/09), oceanic whitetip sharks (Resolution 13/06) and whale sharks (Resolution 13/05) and provisions aimed at reducing finning of sharks (Resolution 17/05).

Retention bans are effective (in reducing species specific shark mortality) to the extent that they ensure survival of at least some shark (of those species) hauled to the vessel, but are highly dependent on the proportion of sharks alive and healthy at haul and their survivability post release, two factors known to vary among species (Afonso et al. 2012; Coelho et al. 2012; Godin et al. 2012; Reinhardt et al.2018; Gilman et al. 2016a,b; Jordaan et al. 2020; Massey et al. 2022; Scott et al. 2022; Sepulveda et al. 2015; Shea et al. 2023). The current retention bans are also limited to a small number of species and do not include some species (e.g. including silky shark, porbeagle *Lamna nasus* and shortfin mako) that the 2018 ERA (Murua et al. 2018) indicated were likely to have similar or higher vulnerability to longline fishing than those species already subject to retention bans.

The effectiveness of measures that prohibit the use of wire trace and shark lines is based on two factors: firstly, they act to reduce initial capture rates (shark line prohibition) and increase escapement post capture (wire leader prohibition), resulting in reduced overall mortality. Secondly, they are general provisions (not species specific) with the potential to reduce fishing mortality across a range of pelagic shark species (including those most vulnerable to longline). Based on the research evidence reviewed above, this type of measure would be, if implemented, consistent with:

- Current IOTC scientific advice (IOTC 2023c) on the need to reduce fishing mortality for shortfin mako.
- Scientific Committee (IOTC 2023b) advice to the Commission in relation to oceanic whitetip shark and silky shark, specifically that "*Mitigation measures should be taken to reduce at-vessel and post release mortality, including consideration of potential gear modifications in longline fleets targeting tuna and swordfish. Noting that a recent study (Bigelow et al. 2021) concluded in WCPFC that banning both shark lines and wire leaders has the potential to reduce fishing mortality by 40.5% for oceanic whitetip shark*" and "*30.8% for silky shark*".

It's worth noting that the three above species are also of global conservation concern according to the IUCN's Red List of Threatened Species. Of key IOTC shark bycatch species, IUCN classify two as Critically Endangered (oceanic whitetip shark; scalloped hammerhead), two as Endangered (shortfin mako; pelagic thresher) and two as Vulnerable (silky shark; bigeye thresher) (Rigby et al. 2019a, b, c, d, e; Rigby et al. 2021).

How have these research findings influenced national and regional shark conservation measures

The effectiveness of prohibitions on wire leaders and shark lines in reducing fishing mortality on pelagic shark species, as demonstrated by the significant level of research on this issue globally, has already been recognised in the national legislation of numerous countries around the world as well as by regional fisheries management organisations.

At the regional level, the WCPFC first implemented provisions requiring the prohibition of at least one of either wire trace and/or shark lines nearly a decade ago (WCPFC 2014), following the analyses provided in Bromhead et al. (2013) and Caneco et al. (2014), that identified the likely effectiveness of such provisions in reducing mortality of key shark species. The WCPFC then strengthened those provisions in Conservation and Management Measure for Sharks CMM 2022-04 (WCPFC 2022) to prohibit both wire leaders and shark lines in the area between 20N and 20S, following the more comprehensive and updated projections analyses of Harley et al. (2015) and Bigelow & Carvahlo (2021).

At the national level, Australia, Ecuador, New Caledonia, Papua New Guinea, South Africa, Republic of the Marshall Islands, Cook Islands, and Federation State of Micronesia have all prohibited the use of wire leaders in domestic longline fisheries (Lack & Meere 2009; Gilman et al. 2008), and in marine protected areas to reduce shark mortality (Ward-Paige et al. 2017). The widespread adoption of these measures globally has occurred despite initial concerns of some stakeholders over potential costs associated with higher loss of longline gear due to bite-offs on monofilament leaders. It is possible that such cost concerns have been offset by monofilament being considerably cheaper than wire and by potential increases in target species catch rates resulting in improved economic returns.

5 Recommendations

On the basis of this review, the authors suggest that the WPEB recommend to the IOTC Scientific Committee that the Scientific Committee should:

Note:

- While quantitative IOTC stock assessments for most pelagic shark species are not available due to a lack of appropriate data, IUCN assessments highlight the poor global state of a range of species caught in IOTC fisheries.
- A 2018 ERA (Murua et al 2018) highlighted those shark species with the highest vulnerability to longline, purse seine and gillnet in the IOTC. A number of these species (including silky shark, shortfin mako and porbeagle) were assessed to have similar or higher vulnerability to longline than those shark species already prohibited from being retained in IOTC fisheries (i.e. thresher sharks and oceanic whitetip).
- That there is clear and consistent evidence from scientific research (and in particular scientific fishing trials and surveys in pelagic longline fisheries) from around the world that nylon monofilament leaders result in significantly lower at-vessel catch rates of pelagic sharks by longline vessels targeting tuna and swordfish, than do wire leaders.
- That target tuna and billfish species catch rates were found in the same trials to not be significantly lower, and often significantly higher, on monofilament leaders when compared to wire leaders.
- That research undertaken in the WCPFC highlighted that very significant reductions in mortality of silky shark (30.8%) and oceanic whitetip shark (40.5%) could be achieved through the banning of wire trace and shark lines in that region, highlighting the potential for this type of measure to reduce longline shark mortality in the IOTC. This research led to the banning of these fishing gears in the main area of the WCPFC fishery.

Recommend to the Commission:

- That a prohibition on wire trace and shark line use by longline fisheries operating in the IOTC would be highly likely to result in a reduction in fishing mortality by longline on shark species, including those most vulnerable to that fishery, and reduce risks to pelagic shark populations in the IOTC area. Such a prohibition would be consistent with existing SC advice to the Commission, on the need to reduce fishing mortality for shortfin mako, and the need to implement mitigation measures for oceanic whitetip shark and silky shark to reduce at-vessel and post-release mortality.
- That the collection of branchline material data by observers be made mandatory under the Regional Observer Scheme minimum data requirements.

The review also recommends that the WPEB request the IOTC Secretariat to develop a summary paper, based on available observer data, that documents the fleet, spatial and temporal patterns in catch, catch rates, fate and condition (life status) of pelagic shark taken by the different IOTC fisheries, as well as high level statistics on the use of wire trace and shark lines. This will facilitate further discussion and development of scientific advice by the WPEB at its meeting in September 2024.

References

Afonso, AS, Hazin, FHV, Carvalho, F, Parcheco, JC, Hazin, H, Kerstetter, DW, Murie, D & Burgess, GH 2011, ‘Fishing gear modifications to reduce elasmobranch mortality in pelagic and bottom longline fisheries off Northeast Brazil’, *Fisheries Research*, vol. 108, pp. 336-343, DOI: 10.1016/j.fishres.2011.01.007 , accessed 8 January 2024.

—— , Santiago, R, Hazin, H & Hazin, FHV 2012, ‘Shark bycatch and mortality and hook bite-offs in pelagic longlines: Interactions between hook types and leader materials’, *Fisheries Research*, vol. 133, pp. 9-14, DOI: 10.1016/j.fishres.2012.07.001, accessed 8 January 2024.

Alverson, DL, Freeberg, MH, Pope, JG, & Murawski, SA 1994, ‘A global assessment of fisheries bycatch and discards’, FAO Technical Paper 339, Food and Agriculture Organisation, Rome.

Berkeley, SA & Campos, L 1988, ‘Relative abundance and fishery potential of pelagic sharks along Florida's east coast’, *Marine Fisheries* Review, vol. 50(1), pp. 9-16, accessed 22 March 2024.

Bigelow, KA, Boggs, CH & He, XI 1999, ‘Environmental effects on swordfish and blue shark catch rates in the US North Pacific longline fishery’, *Fisheries Oceanography*, vol. 8(3), pp. 178-198, DOI: 10.1046/j.1365-2419.1999.00105.x, accessed 22 March 2024.

—— & Carvalho F, ‘Review of potential mitigation measures to reduce fishing-related mortality on silky and oceanic whitetip sharks (Project 101)’, Western and Central Pacific Fisheries Commission, Kolona, Micronesia, pp. 1-15, DOI: 10.25923/10gt-as86, accessed 22 March 2024.

Bowlby, HD, Benoît, HP, Joyce, W, Sulikowski, J, Coelho, R, Domingo, A, Cortés, E, Hazin, F, Macias, D, Biais, G, Santos, C & Anderson, B 2021, ‘*Beyond Post-release Mortality: Inferences on Recovery Periods and Natural Mortality From Electronic Tagging Data for Discarded Lamnid Sharks*’, Frontiers in Marine Science, vol. 8, pp. 619190, DOI: 10.3389/fmars.2021.619190, accessed 1 April 2024.

Branstetter, S & Musick, JA 1993, ‘Comparisons of shark catch rates on longlines using rope/steel (Yankee) and monofilament gangions’, *Marine Fisheries Review*, vol. 55(3), pp. 4-9., accessed 8 January 2024.

Bromhead, D, Clarke, S, Hoyle, S, Muller, B, Sharples ,P & Harley S, 2012, ‘Identification of factors influencing shark catch and mortality in the Marshall Islands tuna longline fishery and management implications’, *Journal of Fish Biology*, vol. 80, pp. 1870–1894, DOI: 10.1111/j.1095-8649.2012.03238.x, accessed 22 March 2024.

——, Rice, J & Harley, SJ 2013, ‘Potential approaches to mitigate bycatch of oceanic whitetip and silky sharks from longline fisheries’, WCPFC-SC9-2013/EB-WP-02, Nineth Regular Session of the Scientific Committee of the Western and Central Pacific Fisheries Commission, Pohnpei, Federated States of Micronesia.

Campana, S., Joyce, W & Manning, MJ 2009, ‘Bycatch and discard mortality in commercially caught blue sharks *Prionace glauca* assessed using archival satellite pop-up tags’, Marine Ecology Progress Series, vol. 387, pp. 241–253, DOI: 0.3354/meps08109, accessed 1 April 2024.

Caneco, B, Donovan, C & Harley, S 2014, 'Analysis of WCPO Longline Observer Data to Determine Factors Impacting Catchability and Condition on Retrieval of Oceanic White-Tip, Silky, Blue, and Thresher Sharks', WCPFC-SC10-2014/EB-WP-01, Tenth Regular Session of the Scientific Committee of the Western and Central Pacific Fisheries Commission, Majuro, Republic of the Marshall Islands, pp.1-34, accessed 22 March 2024.

Clarke, S, Sato, M, Small, C, Sullivan, B, Inoue, Y & Ochi D, 2014, '*Bycatch in Longline Fisheries for Tuna and Tuna-like Species: A Global Review of Status and Mitigation Measures'*, FAO Fisheries and Aquaculture Technical Paper 588. Food and Agriculture Organization of the United Nations, Rome, pp. 1-199, accessed 22 March 2024.

Carruthers, EH, Schneider, DC & Neilson, JD 2009, 'Estimating the odds of survival and identifying mitigation opportunities for common by catch in pelagic longline fisheries, 'Biological Conservation vol. 142, pp. 2620–2630, DOI: 10.1016/j.biocon.2009.06.010, accessed 1 April 2024.

Coelho, R, Fernandez-Carvalho, J, Lino, PG & Santos, MN, 2012, 'An overview of the hooking mortality of elasmobranchs caught in a swordfish pelagic longline fishery in the Atlantic Ocean', *Aquatic Living Resources*, vol. 25(4), pp.311-319, DOI: 10.1051/alr/2012030, accessed 22 March, 2024.

Diaz, GA & Serafy, JE 2005, 'Longline-caught blue shark (*Prionace glauca*): factors affecting the numbers available for live release, *Fisheries Bulletin*, vol. 103, pp. 720–724, accessed 1 April 2024.

Dulvy, NK, Pacoureau, N, Rigby, CL, Pollom, RA, Jabado, RW, Ebert, DA, Finucci, B, Pollock, CM, Cheok, J, Derrick, DH, Herman, KB, Sherman, CS, Vanderwright, WJ, Lawson, LM, Walls, RHL, Carlson, JK, Charvet, P, Bineesh, KK, Fernando, D, Ralph, GM, Matsushiba, JH, Hilton-Taylor, C, Fordham, SV & Simpfendorfer, CA 2021, 'Overfishing drives over one-third of all sharks and rays toward a global extinction crisis', *Current Biology*, vol.31(21), pp. 4773-4787.e8, DOI: 10.1016/j.cub.2021.08.062, accessed 22 March 2024.

FAO 1999, 'International Plan of Action for the conservation and management of sharks (IPOA-sharks)', Food and Agricultural Organization, pp. 17-24, accessed 29 January 2024.

Francis, MP, Lyon, WS, Clarke, SC, Finucci, B, Hutchinson, MR, Campana, SE 2023, Musyl, MK, Schaefer, KM, Hoyle, SD, Peatman, T, Bernal, D, Bigelow, K, Carlson, J, Coelho, R, Heberer, C, Itano, D, Jones, E, Leroy, B, Liu, KM, Murua, H, Poission, F, Rogers, R, Sanchez, C, Semba, Y, Sippel, T & Smith N, 2023, 'Post-release survival of shortfin mako (Isurus oxyrinchus) and silky (Carcharhinus falciformis) sharks released from pelagic tuna longlines in the Pacific Ocean', *Aquatic Conservation: Marine and Freshwater Ecosystems*, vol. 33(4), pp. 366–378, DOI: 10.1002/aqc.3920, accessed 1 April 2024.

Gilman, E, Clarke, S, Brothers, N, Alfaro-Shigueto, J, Mandelman, J, Mangel, J, Petersen, S, Piovano, S, Thomson, N, Dalzell, P, Donoso, M, Goren, M & Werner T 2008, 'Shark interactions in pelagic longline fisheries', *Marine Policy*, vol. 32, pp. 1-18, DOI: 10.1016/j.marpol.2007.05.001, accessed 8 January 2024.

——, Suuronen, P, Hall, M & Kennelly, S 2013b, ‘Causes and methods to estimate cryptic sources of fishing mortality’, *Journal of Fish Biology*, vol. 83, pp. 766-803, DOI: 10.1111/jfb.12148, accessed 22 March 2024.

——, Chaloupka, M, Merrifield, M, Malsol, ND, & Cook, C 2016a ‘Standardised catch and survival rates, and effect of a ban on shark retention, Palau pelagic longline fishery’, *Aquatic Conservation: Marine and Freshwater Ecosystems,* vol. 26, pp. 1031-1062, DOI: 10.1002/aqc.2599, accessed 21 March 2024.

——, Chaloupka, M, Swimmer, Y & Piovano S, 2016b, ‘A cross-taxa assessment of pelagic longline by-catch mitigation measures: conflicts and mutual benefits to elasmobranchs’, *Fish and Fisheries*, vol. 17, pp. 748-784, DOI:10.1111/faf.12143, accessed 22 March 2024.

Godin, AC, Carlson, JK & Burgener, V 2012, ‘The effect of circle hooks on shark catchability and at-vessel mortality rates in longlines fisheries’. Bulletin of Marine Science, vol. 88(3), pp. 469-483, DOI: 10.5343/bms.2011.1054, accessed 22 March 2024.

Grant, SM, Munden, JG & Hedges, KJ 2020, ‘Effects of monofilament nylon versus braided multifilament nylon gangions on catch rates of Greenland shark (*Somniosus microcephalus*) in bottom set longlines’, *PeerJ*, vol. 8, pp. e10407, DOI: 10.7717/peerj.10407, accessed 22 March 2024.

Hansell, AC, Kessel, ST, Brewster, LR, Cadrin, SX, Gruber, SH, Skomal, GB & Guttridge, TL 2018, ‘Local indicators of abundance and demographics for the coastal shark assemblage of Bimini, Bahamas’, *Fisheries Research*, vol. 197, pp. 34-44, DOI: 10.1016/j.fishres.2017.09.016, accessed 22 March 2024.

Harley, S, Caneco, B, Donovan, C, Tremblay-Boyer, L & Brouwer, S, 2015, ‘Monte Carlo simulation modelling of possible measures to reduce impacts of longlining on oceanic whitetip and silky sharks’, Western and Central Pacific Fisheries Commission, Pohnpei, Federated States of Micronesia, pp. 1-30, accessed 22 March 2024.

Heberer, C, Albers, SA, Bernal, D, Kohin, S, DiFiore, B & Sepulveda, CA 2010, ‘Insights into catch-and-release survivorship and stress-induced blood biochemistry of common thresher sharks (*Alopias vulpinus*) captured in the southern California recreational fishery’, *Fisheries Research*, vol. 106, pp. 495–500, DOI: 10.1016/j.fishres.2010.09.024, accessed 1 April 2024.

IOTC 2023a, Report of the 27th Session of the Indian Ocean Tuna Commission, Indian Ocean Tuna Commission, Mauritius, 8-12 May, IOTC-2023-S27-R, pp. 43, accessed 1 April 2024.

IOTC 2023b, Report of the 26th Session of the IOTC Scientific Committee, Indian Ocean Tuna Commission, Mumbai, India and Online 4-8 December, IOTC-2023-SC26-R(E), pp. 207, accessed 1 April 2024.

IOTC 2023c, Report of the 19th Session of the IOTC Working Party on Ecosystems and Bycatch Assessment Meeting, Indian Ocean Tuna Commission, La Réunion France and Online 11 - 15 September, IOTC–2023–WPEB19–R[E]_rev, pp. 98, accessed 1 April 2024.

Jordaan, GL, Santos, J & Groeneveld, JC, 2020, ‘Shark discards in selective and mixed-species pelagic longline fisheries’, *PloS One*, vol. 15(8), pp. e0238595, DOI: 10.1371/journal.pone.0238595, accessed 22 March 2024.

Kennelly, SJ 2007, 'By-catch reduction in the world's fisheries', in JL Nielsen (eds), *Reviews: Methods and Technologies in Fish Biology and Fisheries*, vol. 7, Springer, Dordrecht, The Netherlands, pp. 289, accessed 29 January 2024.

Lack, M & Meere, F 2009, 'Regional Plan of Action for Sharks: Guidance for Pacific Island Countries and Territories on the Conservation and Management of Sharks'. Pacific Islands Forum Fisheries Agency, accessed 29 January 2024.

Massey, Y, Sabarros, PS & Bach, P 2022, '*Drivers of at-vessel mortality of the blue shark (Prionace glauca)* and oceanic whitetip shark (*Carcharhinus longimanus*) assessed from monitored pelagic longline experiments', *Canadian Journal of Fisheries and Aquatic Sciences*, vol. 79(9), pp. 1407-1419. DOI: 10.1139/cjfas-2021-0273, accessed 22 March 2024.

Moyes, CD, Fragoso, N, Brill, RW and Musyl, MK 2006, 'Predicting post-release survival in large pelagic fish', *Transactions of the American Fisheries Society*, vol. 135, pp. 1389–1397, DOI: 10.1577/T05-224.1, accessed 1 April 2024.

Murua, H, Santiago, J, Coelho, R, Zudaire, I, Neves, C, Rosa, D, Zudaire, I, Semba, Y, Geng, Z, Bach, P, Arrizabalaga, H, Bach, P, Baez, JC, Ramos, ML, Zhu, JF& Ruiz, J 2018, Updated ecological risk assessment (ERA) for shark species caught in fisheries managed by the Indian Ocean Tuna Commission (IOTC), IOTC-2018-SC21-14_Rev1, Indian Ocean Tuna Commission Scientific Committee meeting, Mahe, Seychelles, 3–7 December, accessed 12 March 2024.

Piovano, S & Gilman, E 2017, 'Elasmobranch captures in the Fijian pelagic longline fishery', *Aquatic Conservation: Marine and Freshwater Ecosystems*, vol. 27(2), pp. 381-393, DOI: 10.1002/aqc.2666, accessed 22 March 2024.

Reinhardt, JF, Weaver, J, Latham, PJ, Dell'Apa, A, Serafy, JE, Browder, JA, Christman, M, Foster, DG & Blankinship, DR 2018, 'Catch rate and at-vessel mortality of circle hooks versus J-hooks in pelagic longline fisheries: A global meta-analysis', *Fish and Fisheries*, *19*(3), pp.413-430, DOI: 10.1111/faf.12260, accessed 22 March 2024.

Rigby, CL, Barreto, R, Carlson, J, Fernando, D, Fordham, S, Francis, MP, Herman, K, Jabado, RW, Liu, KM, Marshall, A, Pacoureau, N, Romanov, E, Sherley, RB & Winker, H 2019a. *Carcharhinus longimanus*. *The IUCN Red List of Threatened Species*, pp. e.T39374A2911619, DOI: 10.2305/IUCN.UK.2019-3.RLTS.T39374A2911619.en, accessed 31 March 2024.

——, Dulvy, NK, Barreto, R, Carlson, J, Fernando, D, Fordham, S, Francis, MP, Herman, K, Jabado, RW, Liu, KM, Marshall, A, Pacoureau, N, Romanov, E, Sherley, RB & Winker, H 2019b, '*Sphyrna lewini*', *The IUCN Red List of Threatened Species*, pp. e.T39385A2918526, accessed 31 March 2024.

——, Barreto, R, Carlson, J, Fernando, D, Fordham, S, Francis, MP, Jabado, RW, Liu, KM, Marshall, A, Pacoureau, N, Romanov, E, Sherley, RB & Winker, H 2019c, '*Isurus oxyrinchus*', *The IUCN Red List of Threatened Species*, pp. e.T39341A2903170, DOI: 10.2305/IUCN.UK.2019-1.RLTS.T39341A2903170.en, accessed 31 March 2024.

——, Barreto, R, Carlson, J, Fernando, D, Fordham, S, Francis, MP, Herman, K, Jabado, RW, Liu, KM, Marshall, A, Pacoureau, N, Romanov, E, Sherley, RB & Winker, H 2019d, '*Alopias pelagicus*', *The IUCN Red List of Threatened Species*, pp. e.T161597A68607857, DOI: 10.2305/IUCN.UK.2019-3.RLTS.T161597A68607857.en, accessed 31 March 2024.

——, Barreto, R, Carlson, J, Fernando, D, Fordham, S, Francis, MP, Herman, K, Jabado, RW, Liu, KM, Marshall, A, Pacoureau, N, Romanov, E, Sherley, RB & Winker, H 2019e, '*Alopias superciliosus*', *The IUCN Red List of Threatened Species*, pp. e.T161696A894216, DOI: 10.2305/IUCN.UK.2019-3.RLTS.T161696A894216.en, accessed 31 March 2024.

——, Sherman, CS, Chin, A & Simpfendorfer, C 2021, '*Carcharhinus falciformis* (amended version of 2017 assessment)', *The IUCN Red List of Threatened Species*, pp. e.T39370A205782570, DOI: 10.2305/IUCN.UK.2021-3.RLTS.T39370A205782570.en, accessed 31 March 2024.

Raoult, V, Williamson, J., Smith, TM & Gaston, TF 2019, 'Effects of on-deck holding conditions and air exposure on post-release behaviours of sharks revealed by a remote operated vehicle', *Journal of Experimental Marine Biology and Ecology,* vol. 511, pp.10-18, DOI: 10.1016/j.jembe.2018.11.003, accessed 1 April 2024.

Santos, M, Lino, P & Coelho, R 2017, 'Effects of leader material on catches of shallow pelagic longline fisheries in the southwest Indian Ocean', *Fishery Bulletin*, vol. 115, pp. 219-232, DOI: 10.7755/FB115.2.9, accessed 24 March 2024.

Scott, M, Cardona, E, Scidmore-Rossing, K, Royer, M, Stahl, J & Hutchinson, M 2022, 'What's the catch? Examining optimal longline fishing gear configurations to minimize negative impacts on non-target species', *Marine Policy*, vol. 143, pp. 105186, DOI: 10.1016/j.marpol.2022.105186, accessed 8 January 2024.

Sepulveda, CA, Heberer, C, Aalbers, SA, Spear, N, Kinney, M, Bernal, D & Kohin, S, 2015, 'Post-release survivorship studies on common thresher sharks (*Alopias vulpinus*) captured in the southern California recreational fishery', *Fisheries Research*, vol. 161, pp. 102-108, DOI: 10.1016/j.fishres.2014.06.014, accessed 22 March 2024.

Shea, BD, Gallagher, AJ, Bomgardner, LK & Ferretti, F 2023, 'Quantifying longline bycatch mortality for pelagic sharks in western Pacific shark sanctuaries', *Science Advances*, vol. 9(33), DOI: 10.1126/sciadv.adg3527, accessed 29 January 2024.

Smukall, M, Guttridge, T, Dhellemmes, F, Seitz, AC, & Gruber, SH 2021, 'Effects of leader type and gear strength on catches of coastal sharks in a longline survey around Bimini, The Bahamas', *Fisheries Research*, vol. 240, pp. 105989, DOI: 10.1016/j.fishres.2021.105989, accessed 8 January 2024.

Stone, HH & Dixon, LK 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', *Fishery Bulletin-National Oceanic And Atmospheric Administration*, vol. 99, pp. 210–216, accessed 29 January 2024.

Swimmer, Y, Zollett, E & Gutierrez, A 2020, 'Bycatch mitigation of protected and threatened species in tuna purse seine and longline fisheries'. *Endangered Species Research*, vol 43, pp. 517–542, DOI: 10.3354/esr01069, accessed 29 January 2024.

Ward-Paige, CA 2017, 'A global overview of shark sanctuary regulations and their impact on shark fisheries', *Marine Policy*, vol. 82, pp. 87-97, DOI: 10.1016/j.marpol.2017.05.004, accessed 8 January 2024.

Ward, P, Lawrence, E, Darbyshire, R & Hindmarsh, S 2008, 'Large-scale experiment shows that nylon leaders reduce shark bycatch and benefit pelagic longline fishers', *Fisheries Research,* vol. 90 (1-3), pp. 100 – 108, DOI: 10.1016/j.fishres.2007.09.034, accessed 8 January 2024.

Watson, JW, Epperly, SP, Shah, AK & Foster, DG 2005, 'Fishing methods to reduce sea turtle mortality associated with pelagic longlines', *Canadian Journal of Fisheries and Aquatic Sciences*, vol. 62, pp. 965–981, DOI: 10.1139/f05-004, accessed 29 January 2024.

WCPFC 2014, Conservation and Management Measure for sharks CMM 2014-05, Eleventh Regular Session of the Western and Central Pacific Fisheries Commission, Apia, Samoa, 1-5 December, pp. 2, accessed 1 April 2024.

WCPFC 2022, Conservation and Management Measure for Sharks CMM 2022-04, Nineteenth Regular Session of the Western and Central Pacific Fisheries Commission, Da Nang, Vietnam, 28 November – 8 December, pp. 8, accessed 1 April 2024.

Vega, R & Licandeo, R, 2009, 'The effect of American and Spanish longline systems on target and non-target species in the eastern South Pacific swordfish fishery', *Fisheries Research,* vol. 98(1-3), pp. 22-32, DOI: 10.1016/j.fishres.2009.03.010, accessed 22 March 2024.