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New technologies to improve bycatch mitigation in industrial tuna fisheries

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Abstract

For many years, tremendous effort has been dedicated to developing new industrial tuna fisheries, while their adverse impacts on threatened marine species have received relatively little attention. In tuna fisheries, bycatch is the major anthropogenic threat to marine megafauna in general, particularly sharks. Research on the development of gear technology for bycatch reduction and potential mitigation measures helped tuna Regional Fisheries Management Organizations adopt bycatch reduction management measures. After reviewing past research on the development of mitigation measures for pelagic longline and tropical purse seine fisheries based on pelagic species' behaviours, we describe promising new approaches integrating recent technological breakthroughs. New innovations include autonomous underwater vehicles carrying cameras along with miniaturized sensors, aerial drones, computer simulation of fishing gear geometry, environmental DNA assays, computer visualizations and deep learning. The successful application of such tools and methods promises to improve our understanding of factors that influence capture, escape and stress of caught species. Moreover, results emerging from recent ethological research explaining the power of social connection and learning in the "fish world" such as social learning from congeners, habituation to deterrents, and how past fishery interactions affect responses to fishing gear should be taken into account when developing technical mitigation measures.

KEYWORDS
autonomous underwater vehicle (AUV), behaviour, capture process, deep learning, eDNA, ethology

1 | INTRODUCTION

Industrial tuna fishing was initiated in the 1950s by the Japanese distant water longline fleet (Suda & Schaefer, 1965) after an exploratory phase of offshore longline fishing to locate productive grounds (Shapiro, 1950). In the 1960s, Japanese longliners were equipped to deep freeze catches to −55°C and this new technology allowed high-quality tuna and billfish exploitation from distant fishing grounds. Taiwan and the Republic of Korea started long-distance longline fishing in the late 1960s primarily targeting tunas for canning and by the 1970s were the major competitors to Japanese longlining for albacore (*Thunnus alalunga*, Scombridae; Gillet, 2007). For all these vessels, because the value of sharks was relatively small when operating at such long distances from port, it was not profitable to retain them as the hold space was more valuable for the tunas and billfishes. Therefore, pelagic sharks were generally discarded and not recorded (Okamoto & Bayliff, 2003; Suda & Schaefer, 1965). Eventually, the demand for shark fins emerged in the late 80s and various sharks species were finned at sea, but the carcasses were usually discarded at sea and not reported (Clarke, 2008) and shark fin exports became a valuable source of revenue for many countries (Dent & Clarke, 2015). To partially address these concerns, effective logbook systems and observer programmes have been gradually implemented in major Asian long-distance commercial longline fleets. Thus, the activity and the catches of the major longline fleets have been partly documented from the mid-1990s onwards (Huang, 1995; Matsumoto & Miyabe, 1998; Moon et al., 2007). During the expansion of these fisheries, however, most of the information on incidental catches has been lost, and therefore, the lack of historical catch statistics has hampered shark stock assessments worldwide (Clarke, 2008).

Most offshore tuna were caught by longline vessels and bait boats until technical evolution in gear technology (e.g. invention of the power-block, development of nylon net webbing and progress of refrigeration technology using ammonia) led to the feasibility of using purse seine gear in the early 1960s for capturing tuna far from their bases during extended periods of time (Gillet, 2007; McNeely, 1961). The number of tropical purse seine vessels operating in the Pacific Islands increased rapidly during the early 1980s (Gillet, 2007).

Capture of non-targeted species was an acknowledged component of fishery management for many years, but it was not until the early 1990s that some scientists started addressing this issue in industrial fisheries (Alverson, 1992; Alverson et al., 1994; Murawski, 1991). A global review of the magnitude of the issue by gear and regions was conducted, and the operational definitions used to identify bycatch or discards were initiated (Alverson et al., 1994). Bycatch was defined by Hall (1996) as "the portion of the capture that is discarded at sea dead (or injured to an extent that death is the most likely outcome) because it has little or no economic value or because its retention is prohibited by law." Bycatch in tuna fisheries is the major anthropogenic threat facing endangered, threatened and protected (ETP) species (Swimmer et al., 2020; Thorne et al., 2019; Zhou et al., 2019). The discard ratios by weight or by numbers were estimated for various gears and regions by Alverson et al. (1994). Global tuna fisheries are estimated to annually discard 265,279 t (95% CI: 52,283–478,275 t), which is about 5% of the weight of the total catch. Purse seine and large pelagic longline fisheries contribute about 36% and 64% of global discards, respectively (Gilman et al., 2017).

In parallel to the development of tuna fishing, fisheries scientists tried to improve the understanding of the distribution and behaviour of target fishes to improve economic efficiency by reducing the time and fuel expended while seeking optimal fishing grounds. Researchers were embracing fisheries oceanography using catch statistics linked to remote sensing and satellite imagery to better understand the ecology of tuna and tuna-like species, and this information was transmitted to fishers via radio facsimile charts containing oceanographic and weather information to support their fishing campaigns (Laurs, 1971, 1977; Tomczak, 1977). Gradually, satellite imagery helped fishers locate ocean areas and habitats suitable for fish aggregation (e.g. frontal areas, cold core eddies and gyres; Laurs & Brucks, 1985; Laurs & Fiedler, 1985). Moreover, the natural tendency for pelagic fishes to concentrate under floating objects (FOBs) became a source of interest

and enabled the development of new fisheries. Fish aggregating devices (FADs) were traditionally used by Southeast Asian coastal fisheries, particularly in the Philippines (bamboo rafts named "payaos";

Armstrong & Oliver, 1996; De Jesus, 1982; Mitsunaga et al., 2012; Shomura & Matsumoto, 1982), in Japan and Indonesia (Chagoma, 1960; Soemarto, 1960). FADs were used by Japanese commercial fishing operations in the central and western Pacific Ocean in the mid-1970s (Armstrong & Oliver, 1996). FADs indirectly contributed to the massive development of industrial offshore fisheries worldwide (Hall & Roman, 2013). The optimization and instrumentation of drifting fish aggregating devices (DFADs), tracked via satellites, resulted in successful tropical tuna purse seine fisheries. Remote sensing tools and sophisticated DFADs became widely used to increase yields at a time when the resource seemed inexhaustible and increasing catches prevailed (Butler et al., 1988; Klemas, 2013; Torres-Irineo et al., 2014; Wang et al., 2014). Modern FAD designs were also linked to adverse impacts on non-targeted species. As tuna landings increased, the removal of sharks from the ecosystem and the incidental mortality of other unwanted species and under-sized target species increased. For tropical purse seiners, the shark bycatch to tuna catch ratio is low, for example, 0.10 in the Indian Ocean for European fleets (Amandè et al., 2010), but is substantial when considering the global magnitude of the catch by these fleets. The percentage of the catch comprised of sharks is on average much higher for pelagic longliners relative to tuna purse seiners and is highly variable by fishery, ranging between 1% and 50% of the total number of the catch (Gilman et al., 2008).

For many years, tremendous effort has been dedicated to the development of new industrial fisheries while their adverse impacts on threatened marine fishes received relatively little attention (Roberson et al., 2020). Legal instruments establishing international responsibility to conserve associated and dependent species are relatively recent, first becoming an obligation under the 1982 Law of the Sea Convention, and elaborated further in subsequent instruments and guidance from multilateral organizations such as the United Nations (CBD, 2010; FAO, 1995, 1999a, 1999b, 2010, 2011; United Nations, 1982, 1995). These new instruments and international guidance broadened the mandate of pre-existing Regional Fisheries Management Organizations (RFMO). There has been increasing recognition of the need for RFMOs to improve their governance of fisheries and conservation and management of fishery resources, including for older RFMOs by expanding their mandates from a target species focus to meet broadened expectations, including to monitor and manage vulnerable bycatch (Gilman et al., 2014). In 1997, the Inter-American Tropical Tuna Commission established the first working group to address problematic bycatch in the tuna purse seine fishery of the Eastern Pacific Ocean. One of the terms of reference for this group was to develop gear technology for bycatch reduction. Other tuna RFMOs (t-RFMOs) have gradually included bycatch issues in their mandate and established working groups on bycatch and ecosystems. For instance, the first Indian Ocean Tuna Commission (IOTC) Working Party on Ecosystems and Bycatch took place in 2005. Research on the development of gear technology for bycatch reduction and potential mitigation measures influenced t-RFMOs' adoption of conservation and management measures on bycatch.

Nonetheless, the challenges, promulgation and adoption of mitigation measures represent only the first step to critically evaluate implementation and effectiveness of each mitigation measure. For it to be economically viable as well as meet conservation objectives, the mitigation measures should eliminate or reduce shark fishing mortalities, maintain target species catch rates and not increase the catch risk of other vulnerable bycatch species.

In the case of tropical purse seine fisheries, recent innovations in the development of technical bycatch mitigation measures were conceptualized, designed and disseminated from large-scale international research projects (e.g. ABNJ Tuna Project (http://www.fao.org/in-action/commonoceans/en/; International Seafood Sustainability Foundation; https://iss-foundation.org/). The development of technical mitigation measures over the last two decades has also focused on longline gears, which have relatively high bycatch levels (Dent & Clarke, 2015; Roda et al., 2019). While substantial progress was made in various tuna fisheries in reducing bycatch and mortality of sea turtles (e.g. finfish instead of squid for bait; Watson et al., 2005), seabirds (e.g. night setting; Brothers et al., 1999) and marine mammals (e.g. Medina panel; Barham et al., 1977), there has been relatively limited development of technical approaches to reduce shark bycatch and catch of under-sized or juveniles of target species in longline fisheries.

The number of mitigation measures to reduce the fishing mortality of sharks that involve gear modifications is limited and not always transferable from one region to another without adequate trials on commercial vessels (Poisson et al., 2016; Swimmer et al., 2020). Finally, in some cases, methods to mitigate certain bycatch species could result in adverse cross-taxa conflicts, where, for example, the use of circle-shaped hooks to mitigate marine turtle bycatch exacerbates catch rates of pelagic sharks (Gilman et al., 2019).

Despite the urgency in investigating and implementing mitigation measures in fisheries, there are still a number of burgeoning questions inherent in the process: (1) Do we know enough about the capture process? (2) How can approaches for the assessment of the efficacy of mitigation measures in practice be improved? (3) Why are mitigation measures not always transferable? (4) What should we study to innovate effective mitigation measures? And, (5) which tools should we develop in the future?

This study presents a history of the development of techniques and research facilities for studying the behaviour of tunas and other marine megafauna and reviews research on the development of mitigation measures for pelagic longline and tropical purse seine fisheries. The study also presents new perspectives for integrating recent technological breakthroughs based on investigations on bycatch behaviours, especially related to sharks and fishing gear dynamics. Lastly, this study highlights new discoveries on fish sentience and the implications of these capabilities.

2 | FISHING GEARS

2.1 | Pelagic longline

A pelagic longline is a passive fishing gear consisting of a mainline stretched horizontally, immersed to a desired depth by using floats regularly spaced and with adapted snoods (also called gangions and branchlines; Beverly et al., 2003). Pelagic longline gear and labour conditions have evolved thanks to the improvements in materials used for fishing gear components (e.g. nylon mainline, branchlines and floatlines, floats and hooks) and vessel equipment such as hydraulic line haulers, setters and reels. This allowed for the development of various strategies to increase the selectivity for many target species (Ward & Hindmarsh, 2007; Watson & Kerstetter, 2006). Baited hooks are attached at regular intervals on the mainline to achieve desired depths. The fishing operation can be divided into four stages: setting, sinking, soaking and retrieval. The fishing gear and baited hooks are presented in a way that is attractive to fish. Myriad physical and chemical factors can influence the degree of species-specific attraction towards pelagic longline gear, including (1) environmental factors such as temperature, current speed and direction, water clarity, brightness, time of day and lunar phase; (2) operational factors related to the gear design and fishing strategy, bait (type and size), mainline (monofilament or multifilament), hook type and model, snood and snood attachment, sag, the distance between two successive hooks ("hook-spacing"), depth of line, number of fishing vessels in the area and associated sounds and harmonics; (3) intrinsic factors such as satiety of individuals, sexual maturation, body size, food deprivation; (4) interactions with other surrounding fauna: presence of other prey and/or predators and dominant animals within the same guild; and (5) factors such as hormonal/chemical signals and odour plumes (Bjordal & Lokkeborg, 1996; Jordan et al., 2013; Løkkeborg & Pina, 1997; Monnahan & Stewart, 2018; Mourier et al., 2017; Myrberg et al., 1978).

2.2 | Tropical purse seine

A tropical purse seine is an active fishing gear that obstructs the path of the fish and encloses a free swimming school, or encircles tuna schools that aggregate either under a FOB (natural or man-made) or large marine species (whales and whale sharks or dolphins shoals; Escalle et al., 2019; Hall & Roman, 2013). Sea conditions and fishing operations make gear movements complex, and external stimuli provided by the dynamic movement of fishing gear during operation can drastically change fish behaviour over fine spatiotemporal scales. FAD technology is often used in conjunction with purse seines and has evolved rapidly worldwide, and their characteristics and efficiency vary according to different locations (Fonteneau et al., 2000). The operational procedure consists of six routine steps: setting, pursing, net hauling, preparation of the bunt, brailing, sorting and preparing the gear (Ben-Yami, 1994; Poisson et al., 2014).

3 | BEHAVIOURAL OBSERVATIONS AND DEVELOPMENT OF MITIGATION MEASURES

It is inspirational to study and appreciate how the first naturalists, from Aristotle (4th BCE) and Pliny the Elder (Ith A.C.), who described seasonal migration of bluefin tuna (*Thunnus thynnus*, Scombridae) in the Mediterranean Sea in their writings "History of Animals" and the encyclopaedia Naturalis Historia ("Natural History"), respectively, to Guillaume Rondelet (16th century), Carl Linnæus (18th century) and Pierre-Paul Grassé (19th century) who learned about species biology, ecology and behaviours by carefully making direct observations and cross-referencing information. This critical observational and comparative approach was able to penetrate the intimate secrets of many living organisms. The observation of marine animals, however, has always been challenging, with much of the knowledge from surface observations and concomitant catch sampling linked to environmental conditions. Despite the limitations and lack of instruments, these scientists were able to documented fundamental life-history traits and biology of marine animals.

Modern studies on fish initially concentrated on the physiology, biology and behaviour of commercial species and also dealt directly with the reactions of tunas to assorted stimuli in both the laboratory and the field. For the first time, in the early 1950s, experiments on reactions to chemical, light and sound were conducted on tunas maintained in captivity. Studies reported that yellowfin tuna (*Thunnus albacares*, Scombridae) were attracted by particular protein-infused attractants rather than by saturated fats (Van Weel, 1952) and by moderate intensity of white light but were repelled when flashing light (Hsiao, 1952). The research discovered that sudden movements of yellowfin tuna's tails can produce low-frequency sounds which could have a role in school formation (Miyake, 1952).

Tank studies became possible thanks to the development of more sophisticated instruments and facilities to observe tunas' underwater behavioural patterns. Significant knowledge on the behaviour of tunas was gained after the 1950s (e.g. feeding, schooling, swimming, reaction to stimuli, behaviour in relation to environmental features and associations with other organisms and objects) by observations from the decks of tuna pole-and-line fishing vessels (Nakamura, 1972). The use of a caisson immersed below the surface or from a stern chamber permitted scientists to observe the behaviour of tuna under varying fishing conditions (Strasburg & Yuen, 1960). Catch rates, rates of attack on bait and numbers of tunas attracted to the vessel during experimental fishing were collected. Schooling behaviour and swimming speeds were analysed by movie cameras (Nakamura, 1972). A raft with underwater observational facilities was also built to conduct observations of animals which visited and aggregated under and around structures (Gooding, 1965). These first attempts at bait stations highlighted some limitations such as observations were relatively short, impossible to make at night and at depths exceeding 25 m. The use of submersible vehicles and acoustic devices was considered and tested to overcome these limitations (Strasburg, 1965). This research gave the scientific community the first understanding of the capture process in detail and helped to open up new lines of research to prevent or reduce unwanted catch.

Direct visual observation on drifting FADs and when encircled by purse seine gear and acoustic tagging studies on FADs provided new insights to behavioural patterns of non-target and unwanted species. Nevertheless, additional research is needed for the development of options to selectively release or sort animals from the net before they sustain lethal injuries (Forget et al., 2015; Muir et al., 2012). Statistical analyses demonstrated that fishers could avoid unwanted species by modifying the depth of the material hanging from FADs and the fishing depth of the purse seine gear but also by moving to other fishing areas (Lennert-Cody et al., 2008).

By reviewing the literature on the development of mitigation measures, it appears that effective methods or promising concepts to avoid capture of unwanted species and methods to reduce bycatch mortality arose from four main types of approach: (1) shark biology and sensory physiology, (2) aggregating behaviour of various species under natural or man-made FADs, (3) fishing gear behaviour and marine animals interactions during the fishing process and (4) habitat use.

3.1 | Shark biology and sensory physiology

3.1.1 | Chemical deterrents and attractants

An understanding of the sensory cues that attract sharks could help guide efforts to adapt gear and bait to make them less attractive, repellent or non-detectable. Chemical signals have been reported to be major sensory modalities at different various stages of their life cycle (Johnsen, 1986; Rigg et al., 2009). As sharks are considered a threat to humans, there has been a particular interest to study their biology and sensory physiology since the 1950s to discover efficacious shark repellents (Gilbert & Springer, 1963; Springer, 1955; Tuve, 1963) but none of the chemical substances tested were found to produce a quick and effective repellent response in the field (Sisneros & Nelson, 2001). After 70 years of research on shark repellents, no effective solution to reduce shark bycatch and depredation in commercial fisheries has been developed (Hart & Collin, 2015).

As a possible mitigation method, the deployment of "bait stations" using natural "chemical attractants" was suggested as a way to attract sharks away from purse seines (Kondel & Rusin, 2007; Scott, 2007). This technique was tested with limited success (Restrepo et al., 2018). Meanwhile, Hall and Roman (2013) estimated that 24% of FADs in the eastern Pacific included a bait container hung under the FAD.

3.1.2 | Magnetic, E+ metals, electrical deterrents

The idea to swamp sharks' electrical field detection system in the perception of their environment and location of prey has been tried (Jordan et al., 2013; Kalmijn, 1974) to reduce interactions with hooks and other fishing gear types. Unfortunately, field tests of magnets, lanthanide metals and battery-powered electric devices have failed at significantly reducing shark catches (Godin et al., 2013; Hazin et al., 2005; Rigg et al., 2009) likely because the range and magnitude of the devices and charge is too small.

3.1.3 | Auditory deterrents and attractors

Investigation into the ethology of sharks and observations of reactions to various wavelengths (Gruber & Myrberg, 2015; Myrberg, 2001; Myrberg et al., 1972; Nelson & Gruber, 1963) led to the development of "auditory deterrents and attractors." Diffusion of high intensity sounds at close range can trigger quick withdrawal in both silky (*Carcharinus falciformis*, Carcharhinidae) and oceanic whitetip (*Carcharinus. Longimanus*, Carcharhinidae) sharks (Myrberg et al., 1978). Studies of acoustic attraction in pelagic shark species support the general conclusion that sharks, such as pelagic teleosts, are low-frequency specialists (Myrberg, 2001). Silky and oceanic whitetip sharks are attracted to low-frequency sound within the range of 25–1000 Hz, with attractiveness increasing as sound frequency decreases (Myrberg et al., 1972, 1978). Sharks can orient their course towards a low-frequency signal from distances of 125 to over 400 m away (Myrberg et al., 1969). Devices producing attractant sound with a transducer have been manufactured (http://www.makomagnet.com) for the big game sports fishing market and other fishing gears (Scott, 2007). It has been tried in FAD trials with little success (Restrepo et al., 2018).

3.1.4 | Light attractors combined with sounds

Preliminary tests of strobe light combined with sound showed that white sharks (*Carcharodon carcharias*, Lamnidae) spent significantly less time in proximity to the bait. This approach can effectively mitigate shark–human interactions (Ryan et al., 2017). It also holds promise to reduce shark interactions with fishing gear and warrants further investigation.

3.2 | Investigations and observations on the aggregating behaviour of species under natural and man-made FOBs

Purse instrument FADs with echo sounders for various reasons, but mainly to obtain an index of biomass, indicating whether the FAD has a large enough aggregation to warrant travelling to the FAD to make a set. This information is not the sole determining factor for fishers to set on the FAD but complements other sources of information. Targeting bigger schools can reduce ecosystem impacts of fisheries (Dagorn et al., 2012). DFADs are an integral part of todays' fishing strategies in tropical tuna purse seiners. These DFADS attract and aggregate multiple pelagic species that can potentially be caught during fishing operations (Hallier & Gaertner, 2008). For instance, the average continuous residence times at FADs have been estimated at 6 days for silky sharks (Tolotti et al., 2020). New DFAD designs could drastically reduce their capture from entanglement in the DFAD appendage (Filmalter et al., 2013; Schaefer et al., 2021). The most promising mitigation measures are the use of "non-entangling" designs of DFADs which drastically reduce sea turtle and shark entanglement (Moreno et al., 2018), and their deployment, in limited numbers, is proposed in the section, "FAD design and Management" (Gilman et al., 2018). Anchored FADs are also used by tuna purse seine fisheries, and a majority of the catch by tuna pole-and-line fisheries also comes from fishing on anchored and DFADs (Adam et al., 2019; Defaux et al., 2018; ISSF, 2020; ISSF & IPNLF, 2019; Sibisopere, 2000; Thai-Union, 2017; Widodo et al., 2016). Underwater observations of pelagic fish swimming behaviours in purse seines during net hauling and pursing phases by divers highlighted the clear segregation between tuna and non-target species in the Western Pacific. For example, under certain conditions (e.g. deep thermocline, low current), silky sharks tend to swim in schools close to a particular location of the net called "the pocket" and researchers investigated the feasibility of using an escape panel installed on the net (Itano et al., 2012). However, when trialled, only two sharks moved momentarily out of the net through the escape panel, only to quickly return to inside the net where the group of other sharks were.

3.3 | Investigation on longline fishing gear behaviour and marine animals' interactions during the fishing process

Concerning investigations into the interactions of pelagic fish and fishing gear, notable experiments have been implemented with the collection of data obtained with sophisticated electronic tools and instruments. This research provided information which allowed the direct observation of pelagic fish behaviours and to propose technical mitigation measures. Thus, during pelagic longline operation, the use of "hook timers" coupled with "Time Depth Recorders" helped to clarify the impact of capture time, soak time and depth distribution of fishing gear on catch yield and haulback survival rates (Boggs, 1992; Erickson et al.,2000; Peterson et al., 2017; Poisson et al., 2010). The definition of preferred vertical habitat, for pelagic species, can be confirmed by pop-up satellite archival tags (PSATs) and other electronic tags (e.g. Musyl et al., 2011). This research provided justification to three technical mitigation measures (1). "Deep setting" which consists of setting the line beneath the mixed-layer to reduce vertical overlap between the fishing gear and epipelagic sharks (Beverly et al., 2009; Musyl & Gilman, 2018; Musyl et al., 2009), (2). "Reduced soak times" and (3). "Retention bans" which could increase the survivorship of unwanted species (Dapp et al., 2016; Marshall et al., 2015).

3.4 | Identification of habitat

The identification of shark spatially static "hot spots" (e.g. submerged features, seamounts and banks) afforded by satellite tagging led to restriction of fishing in these areas ("Time-area closure"; Calich et al., 2018; Chapman et al., 2015; Lucifora et al., 2011). Moreover, combining information from satellite telemetry from several ETP species, with fisheries observer and environmental data, the ability to model and predict "dynamic closures" that are spatially mobile and temporally variable became realistic (Hazen et al., 2018).

4 | WHAT IS MISSING IN OUR UNDERSTANDING OF FISH CAPTURE AND ESCAPE PROCESSES?

The capture process is the final result of fishes' responses to multiple and various stimuli. Fish react to odour plumes released by the baited hooks of longline gear dispersed in the environment but also to bait shape, size, texture, colour/light reflection and movements which are thought to trigger (or not) the attack decision (Bjordal & Lokkeborg, 1996). Sharks approach their prey on the surface, in midwater, or on the bottom, and they display a number of specializations for feeding (grasping, sucking, crushing, gouging, cutting and filtering systems; Jordan et al., 2013; Moss, 1977). The final attack decision and behaviour to take baited hooks could be dictated by other factors which could be detected visually and acoustically as soon as the gear is set (e.g. occurrence of various types of prey species, ambient noise, propellers, boat harmonics, marine mammal signals, physico-chemical characteristics) which could affect catch rates. Social interactions between conspecifics could alter responses towards baited hooks (Robbins et al., 2011). Patterns of four carcharhinid shark movements and approach to food items, including biting and eating, were filmed in detail in the laboratory (Frazzetta & Prange, 1987). For pelagic sharks, the understanding of predatory behaviour and foraging patterns of tiger sharks (*Galeocerdo cuvier*, *Carcharhinidae*) was improved due to advanced telemetry studies using cameras ("Critter Cams") affixed to their bodies (Heithaus et al., 2002). However, most of the information and observations on fish behaviour towards bait in the wild come from demersal fisheries (He, 1996; Lokkeborg & Bjordal, 1992; Løkkeborg et al., 2014; Vabo et al., 2004).

Various factors are known to modify sharks' catchability. Hook shape can significantly affect the catch risk of most pelagic shark species. There is higher shark catch risk on circle as compared to J-shaped hooks, presenting a conflict with marine turtles (Gilman et al., 2016; Reinhardt et al., 2017).

The effect of hook shape on shark catch risk may be due, in part, to the way sharks approach and capture their prey. Sharks bite their prey (and baited hooks) repeatedly before swallowing, unlike teleosts who suck in and swallow their prey. While being repeatedly bitten by sharks, due to their shape, circle hooks roll and slide more so than J-shaped hooks, perhaps creating a higher probability that circle hooks will become oriented so that it lodges. Factors such as "hook-spacing" and "bait loss" have been investigated in demersal longlines (Monnahan & Stewart, 2018; Skud, 1978) where catch rates can be affected by the "hook-spacing" and thereby impact catching efficiency in Pacific halibut fisheries (Bjordal & Lokkeborg, 1996). Moreover, it was reported that bait loss was correlated with soak time and loss was lower for firm-bodied bait, such as squid (Shomura, 1955; Ward & Myers, 2007). Estimates of hooking ratios showed that approximately 200 baits are spent to catch one tuna (Januma et al., 2003). Capture on vertical longlines was approached by estimating bait retention and by the number of fish/hook contacts (Matsuoka et al., 1992). The prior study suggested that gear interactions could induce cryptic mortality. In addition, depredation of bait by "bait stealers" (small fish, pelagic fish, invertebrates) and sea conditions is likely to affect bait retention during soaking and hauling phases (Shomura, 1955) and other authors have demonstrated that bait loss rates varied among bait species (Kumar et al., 2016). Events including bait loss, twisted or broken hooks and depredation of bait or captured fish have been documented (Gilman et al., 2006; Kumar et al., 2016; Mitchell et al., 2018). These events can also bias experiments aimed at demonstrating the effectiveness of a technical mitigation measures. For example, during a study assessing the effect of bait type, unobserved cetacean depredation on one bait type can bias observed bait-specific catch rates. Therefore, more research effort is needed in pelagic longline fisheries to determine the influence and priority of proximate factors affecting baited hooks.

The efficiency of a measure is evaluated based on data collected by scientists. However, various interactions with fishing gear types other than captures are generally not observed and remain cryptic. Moreover, no study has tested the responses of sharks and other prey using the same experimental procedures. In other words, results of the experiments were never fully duplicated or extended to other species. This could be the reason why the transfer of a successful mitigation measure from one region to another did not always occur. Understanding species' behaviours especially during capture is essential for formulating further bycatch reduction approaches and to assess the effectiveness of mitigation measures.

5 | NEW TOOLS TO INVESTIGATE BYCATCH BEHAVIOUR AND FISHING GEAR DYNAMICS

Aerial drones have provided new opportunities for biologists, including the ability to identify biodiversity and environmental patterns in hard-to-reach areas, counting animals in populations and studying the behaviour of individuals in their environment; ensuring that they are not disturbed (Anderson & Gaston, 2013; Rümmler et al., 2016; Vas et al., 2015). This technology has been used to monitor white shark movements and behaviours near surf zones, where shark attacks have occurred (Colefax et al., 2020; Gorkin et al., 2020). Aerial drones have been used to elucidate shark behaviours, movements, social interactions and predation across multiple species (Butcher et al., 2021). Aerial drones can increase fish detection and resolution contributing to fishing efficiency of tuna fishing and the IOTC prohibited their use (Resolution 16/08 On the prohibition of the use of aircrafts and unmanned aerial vehicles [UAVs] as fishing aids).

In the marine environment, underwater remotely operated vehicles (ROVs) have generally been used to access areas that would otherwise be inaccessible to divers (Ambrose et al., 2005; Jones, 2009; Trenkel et al., 2004) to observe marine turtles (Dodge et al., 2018; Smolowitz et al., 2015) or the condition of elasmobranchs incidentally captured and released back into the water (Raoult et al., 2019). However, ROVs used in fisheries research and ecology have been limited due to high capital and operating costs, and the need for specialized vessels for deployment and recovery operations. More recently, miniature ROV technology has significantly reduced the cost and has the potential to revolutionize marine research in a manner similar to the development of UAVs (Anderson & Gaston, 2013). An autonomous underwater vehicle (AUV) was used to photograph the seafloor and to evaluate its use for determining scallop density and size (Trembanis et al., 2016). ROVs provide the ability to visually track animals in environments where diving conditions for humans are implausible and where the animal's swimming ability is greater than that of the diver. For example, this approach has been used to track loggerhead turtles (Smolowitz et al., 2015) to continuously document their real-time behaviour for several hours (Patel et al., 2016). New generations of ROVs are continuously being miniaturized and are now considered an appropriate tool to observe the short-term behavioural effects of catch and release of sharks (Baronio, 2012). Preliminary investigations and observations are needed to understand and clarify how the noise, electrical fields and light produced by the AUVs could alter the natural behaviours of sharks. As has been documented in livestock behavioural surveys (Saitoh & Kobayashi, 2021), similar studies in the marine environment are necessary to verify the appropriate animal–drone distance for behavioural observations in the wild. The underwater drone, like its aerial counterpart, will continue to be optimized, and the technology will be validated as a requisite tool for researchers studying the marine environment; much like the proliferation of PSATs in marine research. This technology makes it possible to pose different hypotheses and to innovate research concepts to inform management on a hitherto unimagined level. An underwater drone capable of carrying cameras and other miniaturized sensors (e.g. Conductivity Temperature Depth probe to measure dissolved oxygen and mixed-layer depth) is an innovative tool that can be integrated into expanding new research areas. This technology and accompanying wealth of data should be merged with data from various fields to study the physical and environmental parameters of the water column, how marine species interact with fishing gear and to determine the fate of captured organisms.

Pelagic fishing gear types are generally large, and many factors can affect the underwater shape of the gear during actual operations. To understand the behaviour of fish during capture, it is necessary to correctly acquire and chronicle fishing gear movements and the underwater shape and dynamics during fishing affected by ambient conditions (e.g. current, wind, catch). Numerical simulation can estimate the geometry and dynamics of various large fishing gear types by solving the equations of motion and studying the design and operational characteristics in a virtual space. Although researchers have used computer simulations to estimate the dynamics of fishing gear in water, most of the discussions were focused on the accuracy of the results and applicability of the models for longlines (Rice et al., 2007; Yoshihara, 1951) and purse seines (Lee et al., 2005; Priour, 1999; Takagi et al., 2002).

6 | FOCUS ON THE POTENTIAL MISSIONS FOR MINI-AUVs

Below we present some innovative research directions for potential applications of new mitigation measures in pelagic longlines and tropical purse seine fisheries to reduce catch and mortality of sharks and other taxa. Table 1 summarizes the information for each approach proposed mitigation measure.

6.1 | Longline and mini-AUVs: Platforms of observation

Instrumented pelagic longline gear could be used to investigate specific animal behaviours, to evaluate a suite of prognostic environmental and operational factors determining the effectiveness of candidate mitigation measures. Furthermore, it requires designing a comprehensive system of "monitored" fishing gear to assess gear dynamics during fishing and the effectiveness of candidate mitigation measures during specific experiments (e.g. hook tests of a different shape or size, bait test and repellents).

Thus, an array of miniaturized cameras suspended vertically on hook snoods and horizontally placed along the mainline would provide 270° views of the gear (Figure 1). This comprehensive monitoring would provide a wealth of critical information to: (1) record the occurrence of species in close vicinity of the gear, (2) quantify the operational range of gear/bait attraction on the behaviour of different species, (3) document the interactions between animals from the same species (social behaviour) or different species (prey–predator), (4) understand the process of capture avoidance, (5) quantify the number of sharks that bite through the gear and free themselves; cetaceans that unbend hooks and free themselves (i.e. pre-catch escapement), (6) document predation of the bait or captured fish by other animals (i.e. depredation) and (7) investigate the behaviour of the gear when deployed (e.g. hook sinking, vertical movement of the gear components) along with the movement of the bait on the hook linked to the stiffness of the line and the current. Furthermore, by instrumenting the fishing gear with various sensors (depth, light, d.o. and hydrophone), it would be possible to obtain evidence of the underlying factors that influence specific behaviours. All of the observations collected could then help to identify the selectivity of the mitigation measure tested and describe the specific behaviours to avoid and/or reduce mortality outcomes.

Ethograms could be constructed for each species in order to identify major factors that significantly influence interactions (i.e. time to strike the bait, number of prior encounters (bumps and bites) and other patterns in the capture or escape process (e.g. fighting duration, type of movements or escape pattern, elapsed time before death, interaction-induced injuries). The success of the capture event relies in a second phase of the efficiency of the hook to retain the fish and the capacity of the fish to cut the gear at various levels: hook, line and snood. These events have never been satisfactorily quantified because of a lack of adapted tools. The ratio of attack/capture versus interactions with hooks (e.g. touch, escape) could be a good index to assess the efficiency of modified and experimental longline gear.

In situ monitoring would also be very useful to document "pre-catch" escapement rates, depredation rates and catch that fall off the gear due to mechanical action. Direct recording and examination of individual behaviours at different spatial scales from the periphery of passive fishing gear (less than 500 m) to the proximate vicinity close to the hook could offer new approaches to studying the selectivity of fishing gears. The observational range with cameras is from few metres as the visibility in water is limited.

The behaviour of the gear could be studied (i.e. sinking and sag of the branch line with regards to bait type (alive, frozen, fresh) and size/weight), along with the movements and harmonics of the mainline or branch line with the current. Similarly, an ethogram could be developed. Simultaneously, the occurrence and density of other planktonic organisms could be recorded.

To simplify laborious visualization of the underwater videos, automatic computer-based fish detection is needed. The species classification for all the captured images validated by experts will constitute a crucial reference data set for machine learning process development. A large amount of verified data will be required to supply machine learning algorithms. Multiple sources of information in various formats (i.e. image, audio and text files) on gear and marine animal's behaviours and environmental parameters will constitute important data sets to be explored to assess the characteristics of the capture process. All of this information could be compiled in a common database and searched for patterns with machine learning algorithms.

An autonomous underwater drone equipped with high-definition cameras could be used to study the response of fish to baited hooks or any gear parameters and/or dynamics affecting the catch efficiency or selectivity at distances of several hundred metres. The autonomous drone is equipped with scalable artificial intelligence that has unique qualities with GPS, located by a compact autonomous surface vehicle, and internal navigation tools so that it is able to be in self-pilot mode by following a pre-recorded route near the fishing gear in order to detect the presence of pelagic species (Figure 1). In other words, by a process similar to dynamic positioning, the highly accurate navigation system (i.e. typically few metres drift over 1 km of trackline of the mini-AUV) would allow for the repeatability of survey tracts lines. The AUV is an effective tool for the collection of complementary images as part of the investigation of monitoring longlines. The ability to quickly deploy and retrieve the mini-AUV from a vessel allows for the rapid downloading of photographic and acoustic data.

In order to build a reliable monitoring system, experiments in the field are necessary to validate system components, data retrieval and downloading and to make improvements. This fishery independent system strives to quantify types and frequencies of interactions in

TABLE 1 Innovative research directions for potential application of new mitigation measures in pelagic longline and tropical purse seine and gill net fisheries to reduce catch and mortality of sharks and other taxa

Innovative direction	Devices/methodologies	Investigation	Derived information	Outputs/implications
Instrumented pelagic longline	Miniaturized cameras suspended vertically on hook snoods and cameras horizontally placed (270° views of the gear) Hydrological parameters sensors (measure typical such as water temperature, salinity and pressure dissolved oxygen and Chlorophyll-*a* concentrations) turbidity) hydrophone	In order to • record the occurrence of all the species in the close vicinity of the gear • quantify the operational range of gear/ bait attraction on the behaviour of different species; • document the interactions between animals from the same species (social behaviour) or different species (prey–predator) • understand the process of capture avoidance, • quantify the number of sharks that bite through the gear and free themselves (i.e. pre-catch escapement), • document predation of the bait or captured fish by marine creatures investigate the behaviour of the gear when deployed (e.g. hook sinking, vertical movement of the gear components) along with the movement of the bait on the hook linked to the stiffness of the line and the current • record the occurrence and density of planktonic organisms obtain evidence of the underlying factors that influence behaviours	Development of ethograms for each species in order to Identify • major factors that significantly influence interactions (i.e. time to strike the bait, number of prior encounters (bumps and bites)) • Other patterns in the capture or escape process (e.g. fighting duration, type of movements or escape pattern, elapsed time before death, interaction-induced injuries) Study of the behaviour of the gear, that is sinking and sag of the branch line with regard to bait type (alive, frozen, fresh) and size/weight), along with the movements and harmonics of the mainline or branch line with the current Identification of environmental indices based on in situ observations and measurements	Assessment of the effectiveness of candidate MMs during specific experiments (e.g. hook tests of a different shape or size and bait test) Computer vision applications, deep learning, big data: Collection of large amount of labelled data, Multiple sources of information in various formats (i.e. image and audio and text files) on gear and marine creature's behaviours, environmental parameters to supply machine learning algorithms
Autonomous underwater Around longline gear Around FADs	High-definition cameras Miniaturized sonar off-the-shelf probes	Response of fish to baited hooks or any gear parameters and/or dynamics at distances of several hundred metres Collection of complimentary data to fulfil many missions documenting many aspects of free swimming creatures' behaviour and their environment inspection of deployed DFADs and to observe at different spatial and temporal scales the occurrence, density and location of pelagic organisms	Study of catch efficiency or selectivity understanding of capture or (escape process) and enumeration and identification of marine creatures in the vicinity of gear Monitoring the free swimming schools of pelagic species during purse seining operation	AUVs used as a platform that allows simultaneous surveys from both optical and acoustical images around fishing gear Continual visual observations and recording of environmental conditions to supply machine learning algorithms
Environmental DNA (eDNA)	Water samplings collection close to fishing gear	Occurrence of species in the vicinity of the fishing gear during deployment	assays to compare with the observed CPUE and species identifications	Assessment of the effectiveness of candidate MMs during specific experiments

(Continues)

TABLE 1 (Continued)

Innovative direction	Devices/methodologies	Investigation	Derived information	Outputs/implications
Computer simulation and analysis of fishing gear geometry and dynamics	Multi-disciplinary and comparative approach, combining biological, behavioural, and technological studies	understand the shape and deformation of purse seine and gill nets over time and under certain sea conditions in order to predict whether the target fish can be caught and avoid associated bycatch	The underwater dynamics of fishing gear help to understand the behaviour of individuals towards fishing gear It is possible to estimate the three-dimensional trajectory of an individual's behaviour with respect to fishing gear	New insights on purse seine and gill net capture processes and perspectives for the development of technical MMs

real time that can be compared to visual observations. AUVs could be used as a platform that allows simultaneous surveys from both optical and acoustical images around fishing gear that will require a stereo camera system. Continual visual observations and recording of environmental conditions will allow for a better understanding of capture or (escape process) and enumeration and identification of marine animals in the vicinity of gear.

In addition to collection of images, advancements in AUV technology incorporating off-the-shelf probes and the increase of the ability for payloads to collect complimentary data will provide the potential to fulfil many missions to document many aspects of free swimming animals' behaviour and their environment. The manufacturers have developed platforms allowing for the storage and the visualization of all the data recorded (videos, pictures, acoustic and hydrological parameters). These data are obtained by various sensors to provide for a time synchronized analysis.

In parallel, dedicated software to detect the appearance of an organism on video recorded by miniature cameras placed above the baited hooks is currently in the testing phase. This software streamlines and saves considerable time interrogating the data. During preliminary tests, interactions of several species were recorded (Figure 2).

6.2 | Visual inspection of DFADs and in the purse seine

The mini-AUV could be used to approach and inspect deployed DFADs and to observe at different spatial and temporal scales the occurrence, density and location of pelagic organisms and to monitor the free swimming schools of pelagic species during purse seining operations. Visual inspection could be done using its embedded camera but multiple cameras can be added to record the whole environment. Sonar could be used to assist the drone to track tunas (large swim bladder) to analyse their movements near the DFAD (Figure 3).

6.3 | Environmental DNA samplings

The deployment of AUVs in parallel to the longline gear could be used to collect water samples for environmental DNA assays to compare with the observed CPUE and species identifications. This method has also applications in conservation applications and a large array of ecological goals (Le Port et al., 2018).

6.4 | Horizontal and vertical measurements along the line with YSI probe and/or Turner Design Fluorometer

The autonomous underwater drone can be equipped with the standard embedded YSI probe (https://www.ysi.com/) in order to measure typical hydrological parameters such as water temperature, salinity and pressure as well as dissolved oxygen concentration, to better

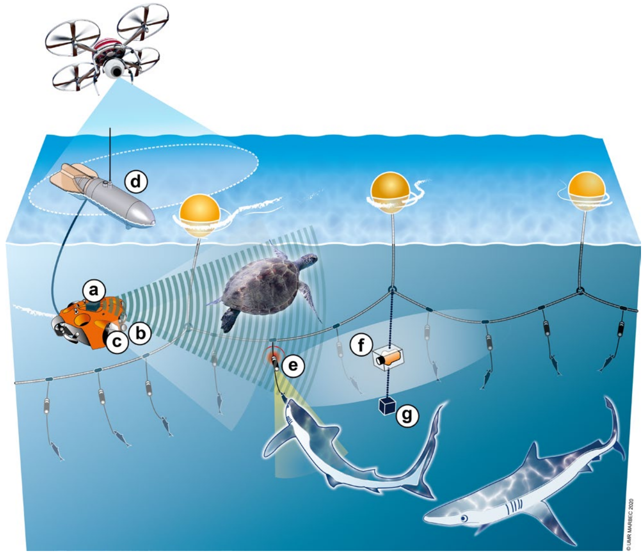


FIGURE 1 An instrumented longline equipped with sensors and cameras and a mini autonomous underwater vehicles patrolling around the fishing gear (a: miniaturized sonar; b: lights; c: internal camera; d: positioning buoy, e: miniaturized camera, f: 270° view camera, g: acoustic attractant)

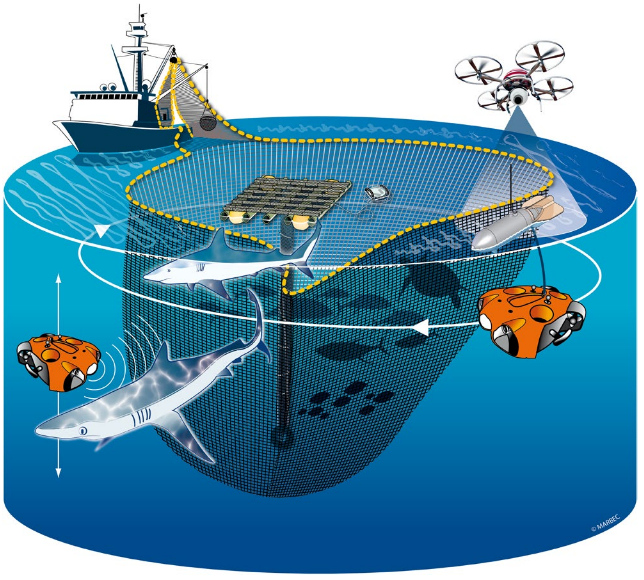
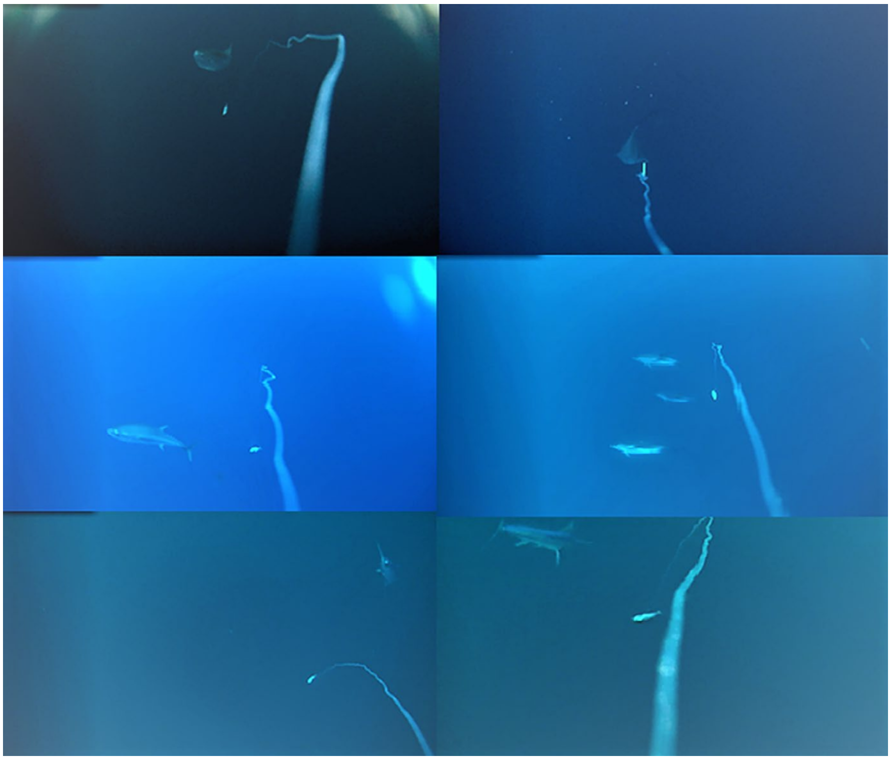


FIGURE 3 Behaviours' inspection of target and non-target species, by a mini autonomous underwater vehicle, on DFADs and when encircled by the purse seine gear

FIGURE 2 Images captured of various individuals around branchlines of a deployed surface longline: sunfish (*Mola mola*, Molidae), Pelagic stingray (*Pteroplatytrygon violacea*, Dasyatidae), Atlantic bluefin tuna (*Thunnus thynnus*, Scombridae), Common dolphin (*Delphinus delphis*, Delphinidae), Swordfish (*Xiphias gladius*, Xiphiidae)



characterize environmental variability over space and time. In addition, the robotic unit could be optimized via its Serial Hub with a Turner Design Fluorometer to provide real-time the total Chlorophyll-*a* concentrations. To complete the physical environmental characterization, vertical profiles at fixed points can also be executed by the robot in order to give a precise vertical record of the stratification parameters: thermocline depth and water density post-calculated for each layer.

6.5 | Post-release mortality

In order to validate good practices by fisheries during handling and release practices, post-release behaviour and time spent hooked and struggling could be monitored by the same autonomous underwater drone system assigned to follow a released telemetered animal (Raoult et al., 2019) to document this critical period within the current limits of the drone's performances in terms of battery speed and depth. The first 24–48 hr after release is an important recovery period for species that are offloading excess CO_2 and lactic acid (metabolic and respiratory acidosis) and thus are vulnerable to predation (Musyl et al., 2015). To improve our knowledge of pelagic fish behaviour, morbidity and mortality, equipping the drone with a dissolved oxygen sensor and calculating the mixed-layer depth would be important prognostic parameters to quantify whether discarded sharks ultimately die after release. Musyl and Gilman (2018) hypothesized that sharks captured on shallow hooks trapped in warm water on commercial longlines in Palau probably suffered higher mortality outcomes because sharks could not cool themselves or repay oxygen debts by diving past the shallow mixed-layer. The drone could also mimic the diving behaviour (W-shaped) of pelagic fish to ascertain energetic costs and how this might affect morbidity. Recent research has shown that fishing also has the capacity to exert sub-lethal effects at the population level (e.g. spawning, migration, reproduction) which, due to logistical challenges, is rarely measured in large pelagic species (Guida, 2016; Wosnick et al., 2019).

7 | COMPUTER SIMULATION AND ANALYSIS OF FISHING GEAR GEOMETRY AND DYNAMICS

The recent development of numerical simulations of the three-dimensional dynamics of fishing nets (Takagi et al., 2002) has brought new insights on purse seine capture processes and perspectives for the development of technical mitigation measures. The technique proposed here contributes to a multi-disciplinary and comparative approach, combining biological, behavioural and technological studies (Takagi et al., 2007). It enables the understanding of the shape and deformation of various fishing gears such as purse seine and gill nets. The analysis also makes it possible to estimate each mesh shape and how it changes over time. Hence, it is easy to estimate whether target fish can be caught. Thus, the capture process is better quantified than in traditional methods such as underwater video.

Figure 4 shows purse seine and bottom gill nets during operations under certain sea conditions. Estimating the whole shape of fishing gear using the technique helps in understanding how shape affects fish shoaling and thigmotactic behaviour. The fine-scale deformation of net meshes obtained from the simulation enables the evaluation of its impact on selectivity and the attractive or repulsive behaviour of target species. The significance of an individuals' behaviour can be revealed through the information and communications technology solution.

Integration of purse seiner sonar data collected in thousands of sets could help gain information on tuna behaviour in the net in different fishing conditions and school sizes. Therefore, it is necessary to establish a technology that captures the behaviour of individuals in detail during fishing. It is possible to estimate the three-dimensional trajectory of an individual's behaviour with respect to fishing gear. Figure 5 shows the estimated three-dimensional behaviour of yellowfin tuna during a purse seine operation using dead-reckoning and ultrasonic equipment. Dead-reckoning enables us to draw detailed three-dimensional paths using time series data of the direction, speed and depth of the individual affixed with a measuring device. In order to eliminate the accumulation of errors, the data assimilation method was used, and higher accuracy of three-dimensional positional information could be achieved (Shimizudani, 2019).

8 | NEW PARADIGMS FOR FUTURE RESEARCH

8.1 | Shark social learning and other abilities

Researchers used knowledge of sharks' sensory capabilities to develop elasmobranch bycatch reduction methods (Jordan et al., 2013). Studies exploring social learning, however, about sharks' ability to learn from congeners are limited, and the ethology of sharks remains enigmatic (Nelson, 1977). Experimental studies on shark behaviours have been conducted for a limited number of species (Guttridge et al., 2009). There is evidence from field and laboratory experiments that social learning among fish has been underestimated. For example, it has been demonstrated that their ability to learn from congeners may allow them to adapt (a) anti-predator behaviour; (b) migration and orientation; (c) foraging; (d) mate choice; and (e) rival quality assessment ("eavesdropping"; Brown & Laland, 2003). Like teleost fishes, sharks appear to have the same ability (Guttridge et al., 2009). The knowledge of the learning behaviour of elasmobranchs should be explored as it could have direct implications for the development of catch reduction methods. The demonstration of the role of learning in fishing activity has been recently

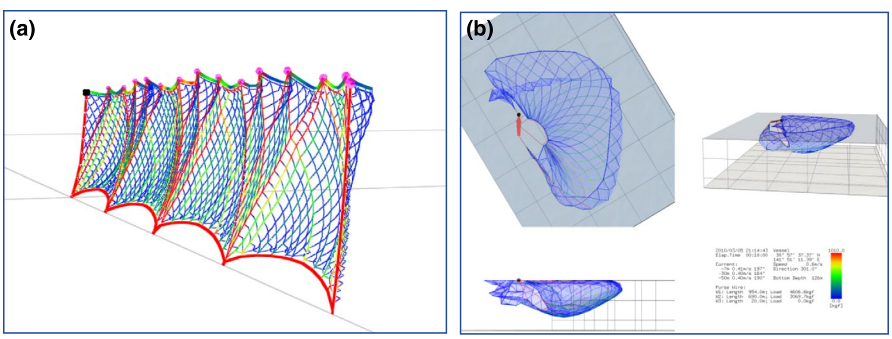


FIGURE 4 Examples of computer simulation results of a bottom gillnet with a 10 cms^{-1} steady current speed (a) and purse seine fishing net geometry 18 min after casting (b)

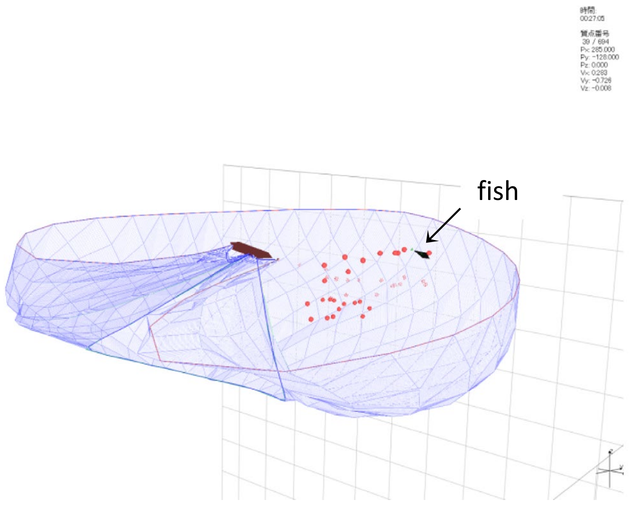


FIGURE 5 The fish position and trajectory (marked in red) for 18 min during pursing (using a purse seine net) obtained by computer simulation. The trajectory was estimated by the data assimilation method combining dead-reckoning and the ultrasonic positioning

highlighted (Mourier et al., 2017). The authors showed that sharks may learn from previous non-lethal interactions with fishing gear which could create and reinforce future gear avoidance behaviours. This potential ability could partly explain the occurrence of hooks retrieved with no or half-eaten bait (Matsuoka et al., 1992; Ward & Myers, 2007). Conversely, sharks receive a positive reinforcement by depredating bait from hooks, which could explain why sharks are often caught with retained hooks in the jaw (Ward et al., 2008). Similarly, it was demonstrated that sharks learned to avoid capture in gillnets during a long-term population census (Manire & Gruber, 1993). The sounds produced by the fishing vessels engines could also attract sharks (Guttridge et al., 2009) which can identify longline gear as a source a food almost like marine mammals (Rosa & Secchi, 2007). Knowledge of these mechanisms in elasmobranchs is lacking and should be investigated. Sharks ethology research at fine spatial scales was studied primarily by combined telemetry/direct observation by divers (Nelson, 1977), but recent technological advances provide for a better understanding. Thus, behaviours of sharks and other animals could be recorded by attached cameras "crittercams" which provide relevant information on feeding behaviour and social interactions (Marshall, 1998; Marshall et al., 2007). A combination of instrumented longlines, mini-AUVs and associated with aerial drones would also suit this purpose. It has been shown on several species that fish can undertake long migrations and return to the same spot during reproduction (philopatry or "site fidelity"; Hueter et al., 2005; Tillett et al., 2012). Recent studies have demonstrated that fishes have complex behaviours that enable them to use tools and communicate by various forms. They all have distinctive personality traits and they individually recognize their congeners, with whom they communicate (Balcombe, 2016). There is no reason to doubt that sharks could also show similar abilities (Jacoby et al., 2014).

9 | CONCLUSION

Bycatch in tuna fisheries is the main anthropogenic threat facing sharks and other ETP species. A mitigation measures' success depends upon its effectiveness and industry acceptance. Direct fishing mortality of pelagic marine fisheries is the main driver of reductions in the size and abundance of pelagic apex predators, including the bycatch mortality of sharks (Pacoureau et al., 2021). Of 1004 assessed elasmobranch species, 18% were categorized as Critically Endangered, Endangered and Vulnerable under the IUCN Red List, with the main threat being fishing mortality from incidental catch. This is a conservative estimate, however, as over 46% were categorized as data deficient (Dulvy et al., 2014). The transfer of technical mitigation measures from one region to another has not always been effective and can result in unintended cross-taxa conflicts (Gilman et al., 2019). The various potential interactions of sharks with fishing gear and capture or escape processes remain enigmatic and require additional investigations. Complementary investigations are needed to understand the attraction and capture processes in order to assess technical mitigation measures that are implemented and in situ observational methods are needed.

The proposed technological innovations could help scientists explore the mechanisms of interactions of animals interacting with fishing gears, and the causes of differing responses among individuals and species, allowing for an understanding of potential adverse effects of the fishing gear on unwanted individuals and how these interactions could be reduced. In the light of the results, simplified technological transfers to fishers could be envisaged giving them the ability to monitor their fishing operations and to make adjustments to maximize catch and avoid or reduce mortality of bycatch. AUVs in the vicinity of deployed gear can be used for studying distribution and abundance patterns of organisms, behaviours while hooked and injury/stress, survival outcomes, feeding and movements, species identification and predator/prey interactions.

In the past, fishing gear simulations have been used by industry to make more efficient nets and longlines but in combination with a suite of data on fish and shark movements, could also provide valuable and actionable insights from a management perspective. The successful application of such tools and methods will provide conservation benefits in understanding factors influencing capture, escape and stress of hooked species. Standardized fishing methods are needed for future studies aiming at investigating comparative fishing trials to reduce experimental bias and improve data collection. Studies indicate that well managed and sustainable fisheries require good data (Sibert et al., 2006). Finally, much like the tenets embraced in fish farming and aquaculture, the designation of mitigation as it applies to capture fisheries should be centred on animal welfare concerns. It is time to recognize this important animal welfare problem in fisheries. There is growing evidence that fishes, including sharks, have sentience and that they can feel pain. Moreover, results emerging from recent ethological research explaining the power of social connection in the "fish world" should be taken into account during development phases of mitigation measures.

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DATA AVAILABILITY STATEMENT

No data have been made available for this manuscript, since no data have been used or analysed in its preparation.

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REFERENCES

Adam, M. S., Jauhary, A. R., Azheem, M., & Jaufar, A. (2019). Use of Anchored FADs in the Maldives – Notes for a case study for assessing ALDFG. IOTC-2019-WPTT21-58.

Alverson, D. L. (1992). *An industry perspective on addressing the bycatch problem*. Paper presented at the Proceedings of the National Industry Bycatch Workshop.

Alverson, D. L., Freeberg, M. H., Murawski, S. A., & Pope, J. G. A. (1994). A global assessment of fisheries bycatch and discards. FAO fisheries technical paper 339, 233 pp.

Amandè, M. J., Ariz, J., Chassot, E., de Molina, A. D., Gaertner, D., Murua, H., Pianet, R., Ruiz, J., & Chavance, P. (2010). Bycatch of the European purse seine tuna fishery in the Atlantic Ocean for the 2003–2007 period. *Aquatic Living Resources*, *23*(4), 353–362. https://doi.org/10.1051/Alr/2011003

Ambrose, W. G., Quillfeldt, C. V., Clough, L. M., Tilney, P. V. R., & Tucker, T. (2005). The sub-ice algal community in the Chukchi sea: Large- and small-scale patterns of abundance based on images from a remotely operated vehicle. *Polar Biology*, *28*(10), 784–795. https://doi.org/10.1007/s00300-005-0002-8

Anderson, K., & Gaston, K. J. (2013). Lightweight unmanned aerial vehicles will revolutionize spatial ecology. *Frontiers in Ecology and the Environment*, *11*(3), 138–146. https://doi.org/10.1890/120150

Armstrong, W. A., & Oliver, C. W. (1996). Recent use of fish aggregating devices in the eastern tropical Pacific Tuna purse-seine fishery: 1990-1994 (Revised March 1996).

Balcombe, J. (2016). *What a fish knows: The inner lives of our underwater cousins*. Scientific American/Farrar, Straus and Giroux.

Barham, E. G., Taguchi, W. K., & Reilly, S. B. (1977). Porpoise rescue methods in yellowfin purse seine fishery and importance of medina panel mesh size. *Marine Fisheries Review*, *39*(5), 1–10.

Baronio, M. (2012). *The use of a micro remotely operated vehicle as a tool for studies of shark behaviour and diver impact*. PhD thesis. Southern Cross University, Lismore, NSW.

Ben-Yami, M. (1994). *Purse seining manual*. Fishing News Books, 406 pp.

Beverly, S., Chapman, L., & Sokimi, W. (2003). Horizontal longline fishing methods and techniques: A manual for fishermen: Secretariat of the Pacific Community Nouméa, New Caledonia.

Beverly, S., Curran, D., Musyl, M., & Molony, B. (2009). Effects of eliminating shallow hooks from tuna longline sets on target and non-target species in the Hawaii-based pelagic tuna fishery. *Fisheries Research*, *96*(2), 281–288. https://doi.org/10.1016/j.fishres.2008.12.010

Bjordal, A., & Lokkeborg, S. (1996). *Longlining*. Fishing News Books.

Boggs, C. H. (1992). Depth, capture time and hooked longevity of longline-caught pelagic fish—Timing bites of fish with chips. *Fishery Bulletin*, *90*(4), 642–658.

Brothers, N. P., Cooper, J., & Løkkeborg, S. (1999). The incidental catch of seabirds in longline fisheries: Worldwide review and technical guidelines for mitigation. FAO Fisheries Circular No. 937., 107 p.

Brown, C., & Laland, K. N. (2003). Social learning in fishes: A review. *Fish and Fisheries*, *4*(3), 280–288. https://doi.org/10.1046/j.1467-2979.2003.00122.x

Butcher, P., Colefax, A., Gorkin, R., Kajiura, S., López, N., Mourier, J., Purcell, C., Skomal, G., Tucker, J., Walsh, A., Williamson, J., & Raoult, V. (2021). The drone revolution of shark science: A review. *Drones*, *5*(1), 8.

Butler, M. J. A., Mouchot, M. C., & Barale, V. (1988). The application of remote sensing technology to marine fisheries: An introductory manual toon extra info. FAO Fisheries technical paper (295). ISBN 9251026947.

Calich, H., Estevanez, M., & Hammerschlag, N. (2018). Overlap between highly suitable habitats and longline gear management areas reveals vulnerable and protected regions for highly migratory sharks. *Marine Ecology Progress Series*, *602*, 183–195. https://doi.org/10.3354/meps12671

CBD. (2010). *Strategic plan for biodiversity 2011–2020 and the Aichi biodiversity targets. COP 10 annex to decision X/2*. Convention on Biological Diversity Secretariat.

Chagoma, S. (1960). Fishing for dolphin in the western part of the Japan Sea-V. Species of fish attracted to bamboo rafts. (In Jan., Angel. summ.) *Bulletin of the Japanese Society of Scientific Fisheries*, *26*, 379–382. (eng. transl. by W.G. Van Capen, 1962, 4 p.; Southwest Fisheries Science Center, Honolulu, HI 96812).

Chapman, D. D., Feldheim, K. A., Papastamatiou, Y. P., & Hueter, R. E. (2015). There and back again: A review of residency and return migrations in sharks, with implications for population structure and management. *Annual Review of Marine Science*, *7*(1), 547–570. https://doi.org/10.1146/annurev-marine-010814-015730

Clarke, S. (2008). Use of shark fin trade data to estimate historic total shark removals in the Atlantic Ocean. *Aquatic Living Resources*, *21*(4), 373–381. https://doi.org/10.1051/Alr:2008060

Colefax, A. P., Kelaher, B. P., Pagendam, D. E., & Butcher, P. A. (2020). Assessing white shark (*Carcharodon carcharias*) behavior along coastal beaches for conservation-focused shark mitigation. *Frontiers in Marine Science*, *7*(268). https://doi.org/10.3389/fmars.2020.00268

Dagorn, L., Filmalter, J. D., Forget, F., Amandè, M. J., Hall, M. A., Williams, P., Murua, H., Ariz, J., Chavance, P., & Bez, N. (2012). Targeting bigger schools can reduce ecosystem impacts of fisheries. *Canadian Journal of Fisheries and Aquatic Sciences*, *69*(9), 1463–1467. https://doi.org/10.1139/F2012-089

Dapp, D. R., Huveneers, C., Walker, T. I., Drew, M., & Reina, R. D. (2016). Moving from measuring to predicting bycatch mortality: Predicting the capture condition of a longline-caught pelagic shark. *Frontiers in Marine Science*, *2*(126). https://doi.org/10.3389/fmars.2015.00126

De Jesus, A. S. (1982). Tuna fishing gear of the Philippines, IPTP/82/WP/2, 47 pp.

Defaux, V., Gascoigne, J., & Huntington, T. (2018). *MSC pre-assessment of a Ghana based pole and line tuna fishery*. Prepared for Thai Union. Poseidon Aquatic Resource Management Ltd.

Dent, F., & Clarke, S. (2015). *State of the global market for shark products*. FAO, 187 pp.

Dodge, K. L., Kukulya, A. L., Burke, E., & Baumgartner, M. F. (2018). TurtleCam: A "smart" autonomous underwater vehicle for investigating behaviors and habitats of sea turtles. *Frontiers in Marine Science*, *5*(90). https://doi.org/10.3389/fmars.2018.00090

Dulvy, N. K., Fowler, S. L., Musick, J. A., Cavanagh, R. D., Kyne, P. M., Harrison, L. R., Carlson, J. K., Davidson, L. N. K., Fordham, S. V., Francis, M. P., Pollock, C. M., Simpfendorfer, C. A., Burgess, G. H., Carpenter, K. E., Compagno, L. J. V., Ebert, D. A., Gibson, C., Heupel, M. R., Livingstone, S. R., … White, W. T. (2014). Extinction risk and conservation of the world's sharks and rays. *eLife*, *3*. https://doi.org/10.7554/eLife.00590

Erickson, D., Goldhor, S., & Giurca, R. (2000). *Efficiency and species selectivity of fabricated baits used in Alaska demersal longline fisheries*. ICES CM.

Escalle, L., Gaertner, D., Chavance, P., Murua, H., Simier, M., Pascual-Alayón, P. J., Ménard, F., Ruiz, J., Abascal, F., & Mérigot, B. (2019). Catch and bycatch captured by tropical tuna purse-seine fishery in whale and whale shark associated sets: Comparison with free school and FAD sets. *Biodiversity and Conservation*, *28*(2), 467–499. https://doi.org/10.1007/s10531-018-1672-1

FAO. (1995). *Code of conduct for responsible fisheries*. FAO, 4 pp.

FAO. (1999a). *International Plan of Action for reducing incidental catch of seabirds in longline fisheries. International Plan of Action for the conservation and Management of sharks. International Plan of Action for the management of fishing capacity*. FAO.

FAO. (1999b). *International Plan of Action for the conservation and management of sharks*. Food and Agriculture Organization of the United Nations.

FAO. (2010). *Guidelines to reduce sea turtle mortality in fishing operations*. FAO technical guidelines for responsible fisheries. Prepared by Gilman, E., Bianchi, G. ISBN 978-92-106226-5. FAO.

FAO. (2011). *International guidelines on bycatch management and reduction of discards*. Food and Agriculture Organization of the United Nations.

Filmalter, J. D., Capello, M., Deneubourg, J.-L., Cowley, P. D., & Dagorn, L. (2013). Looking behind the curtain: Quantifying massive shark mortality in fish aggregating devices. *Frontiers in Ecology and the Environment*, *11*(6), 291–296. https://doi.org/10.1890/130045

Fonteneau, A., Pallares, P., & Pianet, R. (2000). *A worldwide review of purse seine fisheries on FADs*. Paper presented at the Pêche thonière et dispositifs de concentration de poissons, Caribbean-Martinique, 15–19 Oct 1999.

Forget, F. G., Capello, M., Filmalter, J. D., Govinden, R., Soria, M., Cowley, P. D., & Dagorn, L. (2015). Behaviour and vulnerability of target and non-target species at drifting fish aggregating devices (FADs) in the tropical tuna purse seine fishery determined by acoustic telemetry. *Canadian Journal of Fisheries and Aquatic Sciences*, *72*(9), 1398–1405. https://doi.org/10.1139/cjfas-2014-0458

Frazzetta, T., & Prange, C. (1987). Movements of cephalic components during feeding in some requiem sharks (Carcharhiniformes: Carcharhinidae). *Copeia*, 979–993. https://doi.org/10.2307/1445562

Gilbert, P. W., & Springer, S. (1963). *Testing shark repellents. Sharks and survival* (pp. 477–494). Boston: DC Heath and Company.

Gillet, R. (2007). *A short history of industrial fishing in the Pacific Islands*. RAP Publication (FAO).

Gilman, E., Bigler, B., Muller, B., Moreno, G., Largacha, E. D., Hall, M., Poisson, F., Toole, J., He, P. & Chiang, W.-C. (2018). Stakeholder views on methods to identify ownership and track the position of drifting fish aggregating devices used by tuna purse seine fisheries with reference to FAO's draft guidelines on the marking of fishing gear (FAO fisheries circular 1163).

Gilman, E., Brothers, N., McPherson, G., & Dalzell, P. (2006). Review of cetacean interactions with longline gear. *Journal of Cetacean Research and Management*, *8*, 215–223.

Gilman, E., Chaloupka, M., Dagorn, L., Hall, M., Hobday, A., Musyl, M., Pitcher, T., Poisson, F., Restrepo, V., & Suuronen, P. (2019). Robbing Peter to pay Paul: Replacing unintended cross-taxa conflicts with intentional tradeoffs by moving from piecemeal to integrated fisheries bycatch management. *Reviews in Fish Biology and Fisheries*, *29*(1), 93–123. https://doi.org/10.1007/s11160-019-09547-1

Gilman, E., Chaloupka, M., Swimmer, Y., & Piovano, S. (2016). A cross-taxa assessment of pelagic longline by-catch mitigation measures: Conflicts and mutual benefits to elasmobranchs. *Fish and Fisheries*, *17*(3), 748–784. https://doi.org/10.1111/faf.12143

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*, *32*(1), 1–19. https://doi.org/10.1016/j.marpol.2007.05.001

Gilman, E., Passfield, K., & Nakamura, K. (2014). Performance of regional fisheries management organizations: Ecosystem-based governance of bycatch and discards. *Fish and Fisheries*, *15*(2), 327–351. https://doi.org/10.1111/faf.12021

Gilman, E., Suuronen, P., & Chaloupka, M. (2017). Discards in global tuna fisheries. *Marine Ecology Progress Series*, *582*, 231–252. https://doi.org/10.3354/meps12340

Godin, A. C., Wimmer, T., Wang, J. H., & Worm, B. (2013). No effect from rare-earth metal deterrent on shark bycatch in a commercial pelagic longline trial. *Fisheries Research*, *143*, 131–135. https://doi.org/10.1016/j.fishres.2013.01.020

Gooding, R. M. (1965). *A raft for direct subsurface observation at sea*. US Department of the Interior, Fish and Wildlife Service, Bureau of Commercial Fisheries.

Gorkin, R., Adams, K., Berryman, M. J., Aubin, S., Li, W., Davis, A. R., & Barthelemy, J. (2020). Sharkeye: Real-time autonomous personal shark alerting via aerial surveillance. *Drones*, *4*(2), 18. https://doi.org/10.3390/drones4020018

Gruber, S. H., & Myrberg, A. A. Jr (2015). Approaches to the study of the behavior of sharks. *American Zoologist*, *17*(2), 471–486. https://doi.org/10.1093/icb/17.2.471

Guida, L. (2016). *The effects of fishing on Chondrichthyans*. Dissertation, Monash University.

Guttridge, T. L., Myrberg, A. A., Porcher, I. F., Sims, D. W., & Krause, J. (2009). The role of learning in shark behaviour. *Fish and Fisheries*, *10*(4), 450–469. https://doi.org/10.1111/j.1467-2979.2009.00339.x

Hall, M. A. (1996). On bycatches. *Reviews in Fish Biology and Fisheries*, *6*(3), 319–352. https://doi.org/10.1007/bf00122585

Hall, M., & Roman, M. (2013). *Bycatch and non-tuna catch in the tropical tuna purse seine fisheries of the world*. FAO. Fisheries and Aquaculture technical paper no. 568, 249 pp.

Hallier, J., & Gaertner, D. (2008). Drifting fish aggregation devices could act as an ecological trap for tropical tuna species. *Marine Ecology Progress Series*, *353*, 255–264. https://doi.org/10.3354/meps07180

Hart, N. S., & Collin, S. P. (2015). Sharks senses and shark repellents. *Integrative Zoology*, *10*(1), 38–64. https://doi.org/10.1111/1749-4877.12095

Hazen, E. L., Scales, K. L., Maxwell, S. M., Briscoe, D. K., Welch, H., Bograd, S. J., Bailey, H., Benson, S. R., Eguchi, T., Dewar, H., Kohin, S., Costa, D. P., Crowder, L. B., & Lewison, R. L. (2018). A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Science Advances*, *4*(5), eaar3001. https://doi.org/10.1126/sciadv.aar3001

Hazin, H. G., Hazin, F. H. V., Travassos, P., & Erzini, K. (2005). Effect of light-sticks and electralunie attractors on surface-longline catches of swordfish (*Xiphias gladius*, Linnaeus, 1959) in the southwest equatorial Atlantic. *Fisheries Research*, *72*(2–3), 271–277. https://doi.org/10.1016/j.fishres.2004.10.003

He, P. (1996). Bait loss from bottom-set longlines as determined by underwater observations and comparative fishing trials. *Fisheries Research*, *27*(1–3), 29–36. https://doi.org/10.1016/0165-7836(96)00477-8

Heithaus, M., Dill, L., Marshall, G., & Buhleier, B. (2002). Habitat use and foraging behavior of tiger sharks (*Galeocerdo cuvier*) in a seagrass ecosystem. *Marine Biology*, *140*(2), 237–248. https://doi.org/10.1007/s00227-001-0711-7

Hsiao, S. (1952). Part III: Observations on the reaction of tuna to artificial light. Reaction of tuna and other fish to stimuli—1951 (pp. 36–58).

Huang, H.-Y. (1995). National report on Taiwanese longline fisheries in the Indian Ocean in 1994. FAO IPTP Collective Volume, *9*, 47–48.

Hueter, R., Heupel, M., Heist, E., & Keeney, D. (2005). Evidence of philopatry in sharks and implications for the management of shark fisheries. *Journal of Northwest Atlantic Fishery Science*, *35*, 239–247. https://doi.org/10.2960/J.v35.m493

ISSF. (2020). *Pole and line fishing*. International Seafood Sustainability Foundation. https://iss-foundation.org/about-tuna/fishing-methods/pole-line/

ISSF, & IPNLF. (2019). *Skippers' guidebook to pole-and-line fishing best practices*. International Seafood Sustainability Foundation, and International Pole and Line Foundation.

Itano, D., Muir, J., Hutchinson, M., & Leroy, B. (2012). Development and testing of a release panel for sharks and non-target finfish in purse seine gear. WCPFC-SC-2012/EB-WP-14.

Jacoby, D. M., Fear, L. N., Sims, D. W., & Croft, D. P. (2014). Shark personalities? Repeatability of social network traits in a widely distributed predatory fish. *Behavioral Ecology and Sociobiology*, *68*(12), 1995–2003. https://doi.org/10.1007/s00265-014-1805-9

Januma, S., Miyajima, K., & Abe, T. (2003). Development and comparative test of squid liver artificial bait for tuna longline. *Fisheries Science*, *69*(2), 288–292. https://doi.org/10.1046/j.1444-2906.2003.00619.x

Johnsen, P. B. (1986). Chemosensory orientation mechanisms of fish. In D. Duvall, D. Müller-Schwarze, & R. M. Silverstein (Eds.), *Chemical signals in vertebrates 4: Ecology, evolution, and comparative biology* (pp. 135–148). Springer US.

Jones, D. O. B. (2009). Using existing industrial remotely operated vehicles for deep-sea science. *Zoologica Scripta*, *38*(SUPPL. 1), 41–47. https://doi.org/10.1111/j.1463-6409.2007.00315.x

Jordan, L. K., Mandelman, J. W., McComb, D. M., Fordham, S. V., Carlson, J. K., & Werner, T. B. (2013). Linking sensory biology and fisheries bycatch reduction in elasmobranch fishes: A review with new directions for research. *Conservation Physiology*, *1*(1). https://doi.org/10.1093/conphys/cot002

Kalmijn, A. J. (1974). The detection of electric fields from inanimate and animate sources other than electric organs. In: A. Fessard (Ed.), *Electroreceptors and other specialized receptors in lower vertrebrates. Handbook of sensory physiology* (Vol. *3/3*). Springer.

Klemas, V. (2013). Fisheries applications of remote sensing: An overview. *Fisheries Research*, *148*, 124–136. https://doi.org/10.1016/j.fishres.2012.02.027

Kondel, J., & Rusin, J. (2007). Report on the second workshop on bycatch reduction in the ETP purse seiner fishery. October 3–4, 2006. Best Western – Inn by the Sea, La Jolla, CA.

Kumar, K. A., Pravin, P., & Meenakumari, B. (2016). Bait, bait loss, and depredation in pelagic longline fisheries—A review. *Reviews in Fisheries Science & Aquaculture*, *24*(4), 295–304. https://doi.org/10.1080/23308249.2016.1162134

Laurs, R. (1971). Fishery-advisory information available to tropical Pacific tuna fleet via radio facsimile broadcast. *Commercial Fish Revenue*, *33*, 40–42.

Laurs, R. M. (1977). Small scale movements of albacore *Thunnus alalunga*, in relation to ocean features as indicated by ultrasonic tracking and oceanic sampling. *Fishery Bulletin*, *75*, 347–355.

Laurs, R. M., & Brucks, J. T. (1985). Living marine resources applications. In *Advances in geophysics* (Vol. *27*, pp. 419–452). Elsevier.

Laurs, R., & Fiedler, P. (1985). *Application of satellite remote sensing to US fisheries*. Paper presented at the OCEANS'85-Ocean Engineering and the Environment.

Lee, C.-W., Lee, J.-H., Cha, B.-J., Kim, H.-Y., & Lee, J.-H. (2005). Physical modeling for underwater flexible systems dynamic simulation. *Ocean Engineering*, *32*, 331–347.

Le Port, A., Bakker, J., Cooper, M. K., Huerlimann, R., & Mariani, S. (2018). *Environmental DNA (eDNA): A valuable tool for ecological inference and management of sharks and their relatives* (pp. 255–283). CRC Press.

Lennert-Cody, C. E., Roberts, J. J., & Stephenson, R. J. (2008). Effects of gear characteristics on the presence of bigeye tuna (*Thunnus obesus*) in the catches of the purse-seine fishery of the eastern Pacific Ocean. *Ices Journal of Marine Science*, *65*(6), 970–978. https://doi.org/10.1093/icesjms/fsn075

Løkkeborg S., & Bjordal A. 1992. Species and size selectivity in longline fishing: a review. *Fisheries Research*, *13*, 311–322.

Løkkeborg, S., & Pina, T. (1997). Effects of setting time, setting direction and soak time on longline catch rates. *Fisheries Research*, *32*(3), 213–222. https://doi.org/10.1016/S0165-7836(97)00070-2

Løkkeborg, S., Siikavuopio S. I., Humborstad O-B, Utne-Palm A. C., Ferter K. 2014. Towards more efficient longline fisheries: fish feeding behaviour, bait characteristics and development of alternative baits. *Reviews in Fish Biology and Fisheries*, *24*, 985–1003.

Lucifora, L. O., García, V. B., & Worm, B. (2011). Global diversity hotspots and conservation priorities for sharks. *PLoS One*, *6*(5), e19356. https://doi.org/10.1371/journal.pone.0019356

Manire, C. A., & Gruber, S. H. (1993). A preliminary estimate of natural mortality of age-0 lemon sharks, *Negaprion brevirostris*. NOAA technical report NMFS, *115*, 65–71.

Marshall, G. J. (1998). Crittercam: An animal-borne imaging and data logging system. Marine Technology Society. *Marine Technology Society Journal*, *32*(1), 11.

Marshall, G., Bakhtiari, M., Shepard, M., Tweedy III, J., Rasch, D., Abernathy, K., Joliff, B., Carrier, J. C., & Heithaus, M. R. (2007). An advanced solid-state animal-borne video and environmental data-logging device ("Crittercam") for marine research. *Marine Technology Society Journal*, *41*(2), 31–38. https://doi.org/10.4031/002533207787442240

Marshall, H., Skomal, G., Ross, P. G., & Bernal, D. (2015). At-vessel and post-release mortality of the dusky (*Carcharhinus obscurus*) and sandbar (*C. plumbeus*) sharks after longline capture. *Fisheries Research*, *172*, 373–384. https://doi.org/10.1016/j.fishres.2015.07.011

Matsumoto, T., & Miyabe, N. (1998). *SCRS/97/56 (Rev.) Report of 1997 observer program for Japanese tuna longline fishery in the Atlantic Ocean* (Vol. *48*, pp. 263–276). Collective Volume of Scientific papers. International Commission for the Conservation of Atlantic Tunas.

Matsuoka, T., Kasu, J., & Nagaleta, H. (1992). Capture process in vertical longline fishing. *Nippon Suisan Gakkaishi*, *58*(2), 213–222. https://doi.org/10.2331/suisan.58.213

McNeely, R. L. (1961). The purse seine revolution in tuna fishing. *Pacific Fisherman*, *59*(7), 27–58.

Mitchell, J., McLean, D., Collin, S., & Langlois, T. (2018). Shark depredation in commercial and recreational fisheries. *Reviews in Fish Biology and Fisheries*, *28*(4), 715–748. https://doi.org/10.1007/s11160-018-9528-z

Mitsunaga, Y., Endo, C., Anraku, K., Selorio, C. M., & Babaran, R. P. (2012). Association of early juvenile yellowfin tuna *Thunnus albacares* with a network of payaos in the Philippines. *Fisheries Science*, *78*(1), 15–22. https://doi.org/10.1007/s12562-011-0431-y

Miyake, I. (1952). *Reaction of tunas and other fishes to stimuli, Part VI: Observations on sound production and response in tuna* (pp. 59–68). U.S. Fish Wildlife Service. Spec. Sci. Rep., Fish. No. 91.

Monnahan, C. C., & Stewart, I. J. (2018). The effect of hook spacing on longline catch rates: Implications for catch rate standardization.

Fisheries Research, *198*, 150–158. https://doi.org/10.1016/j.fishres.2017.10.004

Moon, D.-Y., Hwang, S.-J., An, D.-H., & Kim, S.-S. (2007). Bycatch of sharks in Korean tuna longline fishery. [Bycatch of sharks in Korean tuna longline fishery]. *Bulletin of the Korean Society of Fisheries Technology*, *43*(4), 329–338. https://doi.org/10.3796/KSFT.2007.43.4.329

Moreno, G., Murua, J., & Restrepo, V. (2018). The use of non-entangling FADs to reduce ghost fishing. FADMO-IWG3-IP-11.

Moss, S. (1977). Feeding mechanisms in sharks. *American Zoologist*, *17*(2), 355–364. https://doi.org/10.1093/icb/17.2.355

Mourier, J., Brown, C., & Planes, S. (2017). Learning and robustness to catch-and-release fishing in a shark social network. *Biology Letters*, *13*(3), 20160824. https://doi.org/10.1098/rsbl.2016.0824

Muir, J., Itano, D., Hutchinson, M., Leroy, B., & Holland, K. (2012). Behavior of target and non-target species on drifting FADs and when encircled by purse seine gear. *Western and Central Pacific Fisheries Commission*, *8*, 1–8.

Murawski, S. A. (1991). Can we manage our multispecies fisheries? *Fisheries*, *16*, 5–13. https://doi.org/10.1577/1548-8446(1991)016<0005:CWMOMF>2.0.CO;2

Musyl, M. K., & Gilman, E. L. (2018). Post-release fishing mortality of blue (*Prionace glauca*) and silky shark (*Carcharhinus falciformes*) from a Palauan-based commercial longline fishery. *Reviews in Fish Biology and Fisheries*, *28*(3), 567–586. https://doi.org/10.1007/s11160-018-9517-2

Musyl, M. K., Moyes, C. D., Brill, R. W., & Fragoso, N. M. (2009). Factors influencing mortality estimates in post-release survival studies. *Marine Ecology Progress Series*, *396*, 157–159. https://doi.org/10.3354/Meps08432

Musyl, M. K., Domeier, M. L., Nasby-Lucas, N., Brill, R. W., McNaughton, L. M., Swimmer, J. Y., Lutcavage, M. S., Wilson, S. G., Galuardi, B., & Liddle, J. B. (2011). Performance of pop-up satellite archival tags. *Marine Ecology Progress Series*, *433*, 1–U58. https://doi.org/10.3354/Meps09202

Musyl, M. K., Moyes, C. D., Brill, R. W., Mourato, B. L., West, A., McNaughton, L. M., Chiang, W.-C., & Sun, C.-L. (2015). Postrelease mortality in istiophorid billfish. *Canadian Journal of Fisheries and Aquatic Sciences*, *72*(4), 538–556. https://doi.org/10.1139/cjfas-2014-0323

Myrberg, A. A., Banner, A., & Richard, J. D. (1969). Shark attraction using a video-acoustic system. *Marine Biology*, *2*, 264–276.

Myrberg Jr., A. A., Gordon, C. R., & Klimley, A. P. (1978). Rapid withdrawal from a sound source by open-ocean sharks. *The Journal of the Acoustical Society of America*, *64*(5), 1289–1297. https://doi.org/10.1121/1.382114

Myrberg, A. A. Jr, Ha, S. J., Walewski, S., & Banbury, J. C. (1972). Effectiveness of acoustic signals in attracting epipelagic sharks to an underwater sound source. *Bulletin of Marine Science*, *22*(4), 926–949.

Myrberg, A. A. (2001). The acoustical biology of elasmobranchs. *Environmental Biology of Fishes*, *60*, 31–45. https://doi.org/10.1023/A:1007647021634

Nakamura, E. L. (1972). Development and uses of facilities for studying tuna behavior. In H. E. Winn & B. L. Olla (Eds.), *Behavior of marine animals*. Springer.

Nelson, D. R. (1977). On the field study of shark behavior. *American Zoologist*, *17*(2), 501–507. https://doi.org/10.1093/icb/17.2.501

Nelson, D. R., & Gruber, S. H. (1963). Sharks: Attraction by low-frequency sounds. *Science*, *142*, 975–977. https://doi.org/10.1126/science.142.3594.975

Okamoto, H., & Bayliff, W. H. (2003). A review of the Japanese longline fishery for tunas and billfishes in the eastern Pacific Ocean, 1993–1997. *Inter-American Tropical Tuna Commission Bulletin*, *22*(4), 221–431.

Pacoureau, N., Rigby, C. L., Kyne, P. M., Sherley, R. B., Winker, H., Carlson, J. K., Fordham, S. V., Barreto, R., Fernando, D., Francis, M. P., Jabado, R. W., Herman, K. B., Liu, K.-M., Marshall, A. D., Pollom, R. A., Romanov, E. V., Simpfendorfer, C. A., Yin, J. S., Kindsvater, H. K., & Dulvy, N. K. (2021). Half a century of global decline in oceanic sharks and rays. *Nature*, *589*(7843), 567–571. https://doi.org/10.1038/s41586-020-03173-9

Patel, S. H., Dodge, K. L., Haas, H. L., & Smolowitz, R. J. (2016). Videography reveals in-water behavior of loggerhead turtles (*Caretta caretta*) at a foraging ground. *Frontiers in Marine Science*, *3*(254). https://doi.org/10.3389/fmars.2016.00254

Peterson, C. D., Gartland, J., & Latour, R. J. (2017). Novel use of hook timers to quantify changing catchability over soak time in longline surveys. *Fisheries Research*, *194*, 99–111. https://doi.org/10.1016/j.fishres.2017.05.010

Poisson, F., Crespo, F. A., Ellis, J. R., Chavance, P., Bach, P., Santos, M. N., Séret, B., Korta, M., Coelho, R., Ariz, J., & Murua, H. (2016). Technical mitigation measures for sharks and rays in fisheries for tuna and tuna-like species: Turning possibility into reality. *Aquatic Living Resources*, *29*(4), 402. https://doi.org/10.1051/alr/2016030

Poisson, F., Gaertner, J. C., Taquet, M., Durbec, J. P., & Bigelow, K. (2010). Effects of lunar cycle and fishing operations on longline-caught pelagic fish: Fishing performance, capture time, and survival of fish. *Fishery Bulletin*, *108*(3), 268–281.

Poisson, F., Seret, B., Vernet, A. L., Goujon, M., & Dagorn, L. (2014). Collaborative research: Development of a manual on elasmobranch handling and release best practices in tropical tuna purse-seine fisheries. *Marine Policy*, *44*, 312–320. https://doi.org/10.1016/j.marpol.2013.09.025

Priour D. 1999. Calculation of net shapes by the finite element method with triangular elements. *Communications in Numerical Methods in Engineering*, *15*, 755–763.

Raoult, V., Williamson, J. E., Smith, T. M., & Gaston, T. F. (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*, *511*, 10–19. https://doi.org/10.1016/j.jembe.2018.11.003

Reinhardt, J. F., Weaver, J., Latham, P. J., Dell'Apa, A., Serafy, J. E., Browder, J. A., Christman, M., Foster, D. G., & Blankinship, D. R. (2017). Catch rate and at-vessel mortality of circle hooks versus J-hooks in pelagic longline fisheries: A global meta-analysis. *Fish and Fisheries*. https://doi.org/10.1111/faf.12260

Restrepo, V., Dagorn, L., Moreno, G., Forget, F., Schaefer, K., Sancristobal, I., Muir, J., Itano, D., & Hutchinson, M. (2018). Compendium of ISSF At-Sea Bycatch Mitigation Research Activities as of September 2018. ISSF Technical Report 2018–20. International Seafood Sustainability Foundation, Washington D.C., USA.

Rice, P. H., Goodyear, C. P., Prince, E. D., Snodgrass, D., & Serafy, J. E. (2007). Use of catenary geometry to estimate hook depth during near-surface pelagic longline fishing: Theory versus practice. *North American Journal of Fisheries Management*, *27*(4), 1148–1161. https://doi.org/10.1577/m06-114.1

Rigg, D. P., Peverell, S. C., Hearndon, M., & Seymour, J. E. (2009). Do elasmobranch reactions to magnetic fields in water show promise for bycatch mitigation? *Marine and Freshwater Research*, *60*(9), 942–948. https://doi.org/10.1071/Mf08180

Robbins, W. D., Peddemors, V. M., & Kennelly, S. J. (2011). Assessment of permanent magnets and electropositive metals to reduce the line-based capture of Galapagos sharks, *Carcharhinus galapagensis*. *Fisheries Research*, *109*(1), 100–106. https://doi.org/10.1016/j.fishres.2011.01.023

Roberson, L. A., Watson, R. A., & Klein, C. J. (2020). Over 90 endangered fish and invertebrates are caught in industrial fisheries. *Nature Communications*, *11*(1), 1–8. https://doi.org/10.1038/s41467-020-18505-6

Roda, M. A. P., Gilman, E., Huntington, T., Kennelly, S. J., Suuronen, P., Chaloupka, M., & Medley, P. A. (2019). *A third assessment of global* *marine fisheries discards*. Food and Agriculture Organization of the United Nations.

Rosa, D. L., & Secchi, E. R. (2007). Killer whale (*Orcinus orca*) interactions with the tuna and swordfish longline fishery off southern and south-eastern Brazil: A comparison with shark interactions. *Journal of the Marine Biological Association of the United Kingdom*, *87*(1), 135–140. https://doi.org/10.1017/s0025315407054306

Rümmler, M.-C., Mustafa, O., Maercker, J., Peter, H.-U., & Esefeld, J. (2016). Measuring the influence of unmanned aerial vehicles on Adélie penguins. *Polar Biology*, *39*(7), 1329–1334. https://doi.org/10.1007/s00300-015-1838-1

Ryan, L. A., Chapuis, L., Hemmi, J. M., Collin, S. P., McCauley, R. D., Yopak, K. E., Gennari, E., Huveneers, C., Kempster, R. M., Kerr, C. C., Schmidt, C., Egeberg, C. A., & Hart, N. S. (2017). Effects of auditory and visual stimuli on shark feeding behaviour: The disco effect. *Marine Biology*, *165*(1), 11. https://doi.org/10.1007/s00227-017-3256-0

Saitoh, T., & Kobayashi, M. (2021). Appropriate drone flight altitude for horse behavioral observation. *Drones*, *5*(3), 71. https://doi.org/10.3390/drones5030071

Schaefer, K. M., Fuller, D. W., & Chaloupka, M. (2021). Performance evaluation of a shallow prototype versus a standard depth traditional design drifting fish-aggregating device in the equatorial eastern Pacific tuna purse-seine fishery. *Fisheries Research*, *233*, 105763. https://doi.org/10.1016/j.fishres.2020.105763

Scott, M. D. (2007). *IATTC research on reducing shark bycatch in the tuna purse seine fishery in the eastern tropical Pacific Ocean*. WCPFC-SC3-EB SWG/IP-3. Third Regular Session of the Scientific Committee13–24 August 2007, Honolulu, USA.

Shimizudani, Y. (2019). *Estimating behavioral trajectory of individuals in a purse seine fishery and the influence of the fishing process on their behavior*. Master's thesis, Hakodate, Hokkaido University.

Shapiro, S. (1950). The Japanese long-linefishery for tunas. *Commercial Fisheries Review*, *12*(4), 1–26.

Shomura, R. S. (1955). *A comparative study of longline baits* (Vol. *151*). US Department of the Interior, Fish and Wildlife Service.

Shomura, R. S., & Matsumoto, W. M. (1982). *Structured flotsam as fish aggregating devices*. NOAATM-NMFS-SWFSC-22. Southwest Fisheries Science Center.

Sibert, J., Hampton, J., Kleiber, P., & Maunder, M. (2006). Biomass, size, and trophic status of top predators in the Pacific Ocean. *Science*, *314*(5806), 1773–1776. https://doi.org/10.1126/science.1135347

Sibisopere, M. (2000). *The significant contribution of FADs to Solomon Taiyo Limited's fishing operations*. Paper presented at the Pêche thonière et dispositifs de concentration de poissons, Caribbean-Martinique, 15–19 Oct 1999.

Sisneros, J. A., & Nelson, D. R. (2001). Surfactants as chemical shark repellents: Past, present, and future. *Environmental Biology of Fishes*, *60*, 117–129.

Skud, B. E. (1978). *Factors affecting longline catch and effort: III. Bait loss and competition*. International Pacific Halibut Commission. Scientific report no. 64.

Smolowitz, R. J., Patel, S. H., Haas, H. L., & Miller, S. A. (2015). Using a remotely operated vehicle (ROV) to observe loggerhead sea turtle (*Caretta caretta*) behavior on foraging grounds off the mid-Atlantic United States. *Journal of Experimental Marine Biology and Ecology*, *471*, 84–91. https://doi.org/10.1016/j.jembe.2015.05.016

Soemarto. (1960). Fish behaviour with special reference to pelagic shoaling species: Lajang (DecaDterus spp.). Proc. Indo-Pac. Fish. Counc., 8 Sess. Sect. 3, 89–93.

Springer, S. (1955). Laboratory experiments with shark repellents.

Strasburg, D. (1965). *A submarine for research in fisheries and oceanography*. Paper presented at the Trans. Joint Conf. Exhibit. MTS/ASLO.

Strasburg, D., & Yuen, H. (1960). Preliminary results of underwater observations of tuna schools and practical applications of these results. Proceedings of the Indo-Pacific Fisheries Council, 8th Session, Section, 3, 84–89.

Suda, A., & Schaefer, M. B. (1965). General review of the Japanese tuna long-line fishery in the eastern tropical Pacific Ocean 1956–1962. *Inter-American Tropical Tuna Commission Bulletin*, *9*(6), 305–462.

Swimmer, Y., Zollett, E. A., & Gutierrez, A. (2020). Bycatch mitigation of protected and threatened species in tuna purse seine and longline fisheries. *Endangered Species Research*, *43*, 517–542. https://doi.org/10.3354/esr01069

Takagi, T., Shimizu, T., & Korte, H. (2007). Evaluating the impact of gillnet ghost fishing using a computational analysis of the geometry of fishing gear. *ICES Journal of Marine Science*, *64*(8), 1517–1524. https://doi.org/10.1093/icesjms/fsm097

Takagi, T., Suzuki, K., & Hiraishi, T. (2002). Development of the numerical simulation method of dynamic fishing net shape. *Nippon Suisan Gakkaishi*, *68*(3), 320–326. https://doi.org/10.2331/suisan.68.320

Thai-Union. (2017). *Marine Stewardship Council pre-assessment of the pole and line fishery in Senegal*. Thai Union Europe. Prepared by Poseidon Aquatic Resource Management Ltd, Hampshire, UK.

Thorne, L. H., Baird, R. W., Webster, D. L., Stepanuk, J. E., & Read, A. J. (2019). Predicting fisheries bycatch: A case study and field test for pilot whales in a pelagic longline fishery. *Diversity and Distributions*, *25*(6), 909–923. https://doi.org/10.1111/ddi.12912

Tillett, B., Meekan, M., Field, I., Thorburn, D., & Ovenden, J. (2012). Evidence for reproductive philopatry in the bull shark Carcharhinus leucas. *Journal of Fish Biology*, *80*(6), 2140–2158. https://doi.org/10.1111/j.1095-8649.2012.03228.x

Tolotti, M. T., Forget, F., Capello, M., Filmalter, J. D., Hutchinson, M., Itano, D., Holland, K., & Dagorn, L. (2020). Association dynamics of tuna and purse seine bycatch species with drifting fish aggregating devices (FADs) in the tropical eastern Atlantic Ocean. *Fisheries Research*, *226*, 105521. https://doi.org/10.1016/j.fishres.2020.105521

Tomczak, G. (1977). Environmental analyses in marine fisheries research. Fisheries environmental services. FAO Fisheries Technical Papers (FAO). No. 170.

Torres-Irineo, E., Gaertner, D., Chassot, E., & Dreyfus-León, M. (2014). Changes in fishing power and fishing strategies driven by new technologies: The case of tropical tuna purse seiners in the eastern Atlantic Ocean. *Fisheries Research*, *155*, 10–19. https://doi.org/10.1016/j.fishres.2014.02.017

Trembanis, A. C., Walker, J. H., & Miller, D. C. (2016). Assessing the use of a camera system within an autonomous underwater vehicle for monitoring the distribution and density of sea scallops (*Placopecten magellanicus*) in the Mid-Atlantic Bight.

Trenkel, V. M., Francis, R. I. C. C., Lorance, P., Mahévas, S., Rochet, M.-J., & Tracey, D. M. (2004). Availability of deep-water fish to trawling and visual observation from a remotely operated vehicle (ROV). *Marine Ecology Progress Series*, *284*, 293–303. https://doi.org/10.3354/meps284293

Tuve, R. L. (1963). Development of the US Navy 'Shark Chaser' chemical shark repellent. In *Sharks and survival* (pp. 455–464). DC Heath and Company.

United Nations. (1982). *United Nations Convention on the Law of the Sea of 10 December 1982 relating to the conservation and management of straddling fish stocks and highly migratory fish stocks*. United Nations.

United Nations. (1995). *Agreement for the implementation of the provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks*. UN General Assembly, Doc. A/CONF.164/37, 8 September 1995. United Nations.

Vabo, R., Huse, G., Ferno, A., Jorgensen, T., Lokkeborg, S., & Skaret, G. (2004). Simulating search behaviour of fish towards bait. *ICES Journal of Marine Science*, *61*(7), 1224–1232.

Van Weel, P. (1952). *Reaction of tunas and other fishes to stimuli, Part II: Observations on the chemoreception of tuna*. US Fish Wildlife Service. Spec. Sci. Rep. Fish (Vol. *91*, pp. 8–35).

Vas, E., Lescroël, A., Duriez, O., Boguszewski, G., & Grémillet, D. (2015). Approaching birds with drones: First experiments and ethical guidelines. *Biology Letters*, *11*(2), 20140754. https://doi.org/10.1098/rsbl.2014.0754
Wang, X., Chen, Y., Truesdell, S., Xu, L., Cao, J., & Guan, W. (2014). The large-scale deployment of fish aggregation devices alters environmentally-based migratory behavior of skipjack tuna in the western Pacific Ocean. *PLoS One*, *9*(5), e98226. https://doi.org/10.1371/journal.pone.0098226
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. *Reviews in Fish Biology and Fisheries*, *17*(4), 501–516. https://doi.org/10.1007/s11160-007-9051-0
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*, *90*(1–3), 100–108. https://doi.org/10.1016/j.fishres.2007.09.034
Ward, P., & Myers, R. A. (2007). Bait loss and its potential effects on fishing power in pelagic longline fisheries. *Fisheries Research*, *86*(1), 69–76. https://doi.org/10.1016/j.fishres.2007.05.002
Watson, J. W., Epperly, S. P., Shah, A. K., & Foster, D. G. (2005). Fishing methods to reduce sea turtle mortality associated with pelagic longlines. *Canadian Journal of Fisheries and Aquatic Sciences*, *62*(5), 965–981. https://doi.org/10.1139/f05-004
Watson, J. W., & Kerstetter, D. W. (2006). Pelagic longline fishing gear: A brief history and review of research efforts to improve selectivity. *Marine Technology Society Journal*, *40*(3), 6–11. https://doi.org/10.4031/002533206787353259
Widodo, A. A., Wudianto, W., & Satria, F. (2016). Current status of the pole-and-line fishery in eastern part of Indonesia. *Indonesian Fisheries Research Journal*, *22*(1), 43–52. https://doi.org/10.15578/ifrj.22.1.2016.43-52
Wosnick, N., Awruch, C. A., Adams, K. R., Gutierre, S. M. M., Bornatowski, H., Prado, A. C., & Freire, C. A. (2019). Impacts of fisheries on elasmobranch reproduction: High rates of abortion and subsequent maternal mortality in the shortnose guitarfish. *Animal Conservation*, *22*(2), 198–206. https://doi.org/10.1111/acv.12458
Yoshihara, T. (1951). Distribution of fisheries caught by the long line-II, Vertical distribution. *Nippon Suisan Gakkaishi*, *16*, 370–374.
Zhou, C., Jiao, Y., & Browder, J. (2019). Seabird bycatch vulnerability to pelagic longline fisheries: Ecological traits matter. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *29*(8), 1324–1335. https://doi.org/10.1002/aqc.3066

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