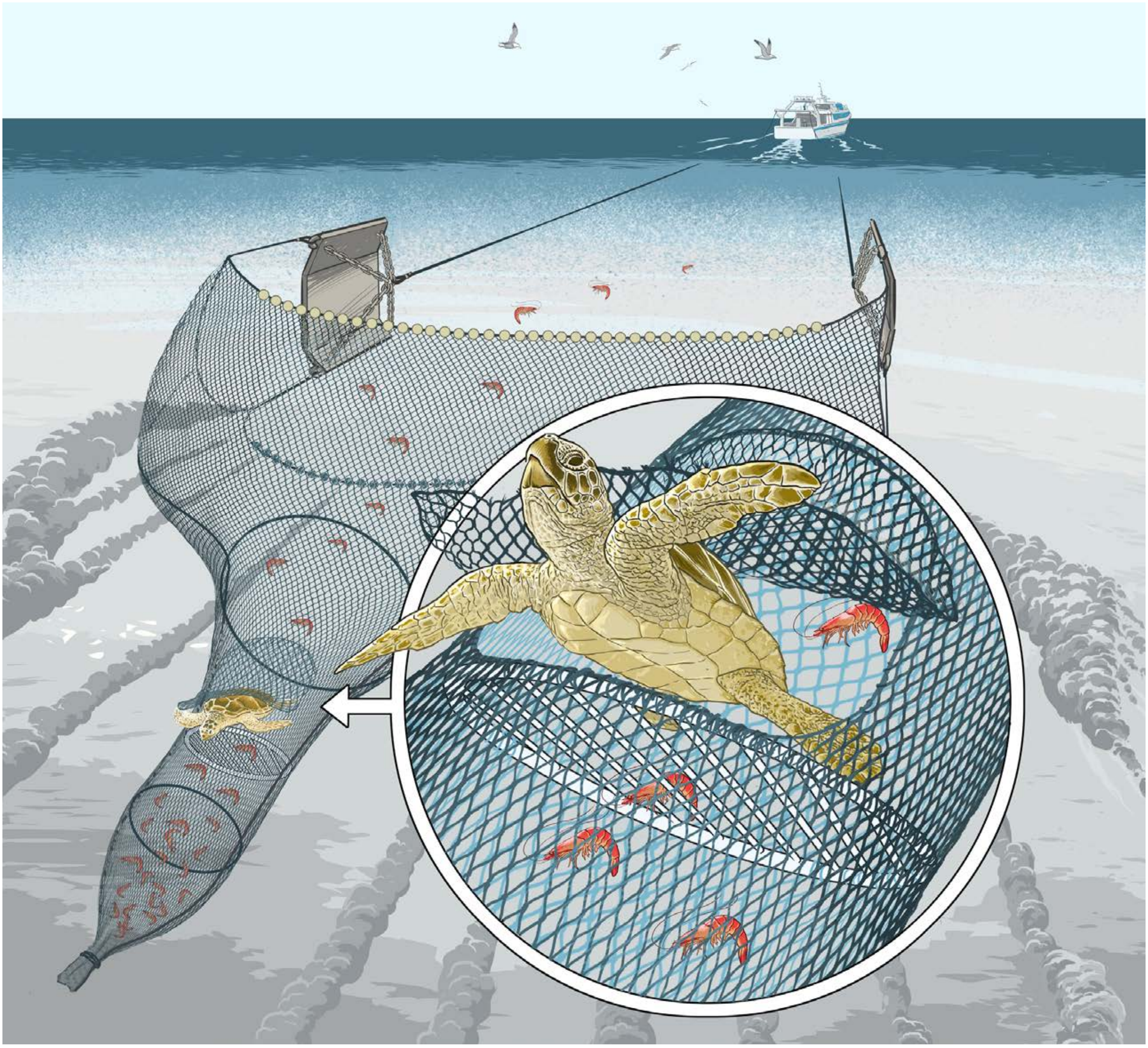
Food and Agriculture Organization of the United Nations

General Fisheries Commission for the Mediterranean
Commission générale des pêches pour la Méditerranée

STUDIES AND REVIEWS 100

ISSN 1020-9549

OVERVIEW OF MITIGATION MEASURES TO REDUCE THE INCIDENTAL CATCH OF VULNERABLE SPECIES IN FISHERIES



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GENERAL FISHERIES COMMISSION FOR THE MEDITERRANEAN

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OVERVIEW OF MITIGATION MEASURES TO REDUCE THE INCIDENTAL CATCH OF VULNERABLE SPECIES IN FISHERIES

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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2021

Required citation:
Sacchi, J. 2021. *Overview of mitigation measures to reduce the incidental catch of vulnerable species in fisheries.* Studies and Reviews No. 100 (General Fisheries Commission for the Mediterranean). Rome, FAO. https://doi.org/10.4060/cb5049en

ISBN 978-92-5-134539-9

Preparation of this document

This technical document was prepared within the framework of the project on "Mitigating the negative interactions between threatened marine species and fishing activities", coordinated by the Secretariats of the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic area (ACCOBAMS) and of the General Fisheries Commission for the Mediterranean (GFCM) in 2015–2018. The Regional Activity Centre for Specially Protected Areas (RAC/SPA) of the United Nations Environment Programme/ Mediterranean Action Plan (UN Environment/MAP) also collaborated on the project.

Supported by the MAVA Foundation, this project focused on the conservation of endangered marine species, such as marine mammals, sea turtles, sharks and seabirds, in order to promote responsible fishing practices in the Mediterranean, in line with the relevant provisions adopted at the regional level within the framework of ACCOBAMS, GFCM and UNEP/MAP.

Practical fieldwork for this project included the implementation of pilot activities in Algeria, France, Morocco, Spain and Tunisia in order to assess and mitigate the negative interactions between endangered species and fisheries. The methodology implemented was similar for each pilot action: the national coordinators engaged in a participatory approach with fishers, and after a preliminary phase dedicated to data collection and the identification of the main issues, fishing mitigation measures were tested, when possible, so as to limit the incidental catch of endangered species, as well as depredation. In order to build on existing experiments and lessons learned, the project included the preparation of a review of fishing mitigation measures and techniques tested worldwide to mitigate bycatch and depredation, which is presented in this document.

This report gathers recent literature, international reports and guidelines addressing bycatch and depredation issues in different parts of the world. International experts and scientists worldwide were consulted so as to gather up-to-date information on experiences regarding bycatch/depredation mitigation, including the results of experiments carried out to test (or to develop) equipment and devices aimed at decreasing the interactions between vulnerable marine species and fisheries. Fruitful exchanges were held with scientists from the National Oceanic and Atmospheric Administration (NOAA) in the United States of America, the University of Saint Andrews in the United Kingdom, the University of Minho in Portugal, the Institut français de recherche pour l'exploitation de la mer (Ifremer) in France and the Inter-American Tropical Tuna Commission (IATTC).

Mitigation measures are grouped according to the main categories of fishing gear – gillnets and trammel nets, longlines and lines, trawls, purse seines, traps and pots – and further subdivided according to the four main groups of vulnerable species – marine mammals, seabirds, sharks and rays, and sea turtles. The bibliography at the end of this report includes all sources cited in the text, as well as separate additional material used for the writing of the publication, but not directly cited. Finally, a glossary at the end of this publication provides explanations and definitions of the technical terms used throughout the document.

Abstract

Interactions between fisheries and marine vulnerable species, in particular marine mammals, seabirds, sharks and rays, and sea turtles, represent a global conservation issue, and mitigating the impacts of these interactions is an important step to ensure the sustainability of fisheries.

This literature review presents information on mitigation measures and techniques that have been developed and tested worldwide in order to address both the incidental catch of highly mobile species (marine mammals, seabirds, sharks and rays, and sea turtles) and depredation caused by dolphins. It is based on more than 300 documents, including peer-reviewed publications, reports from international organizations and papers available on the Internet. Most of the mitigation techniques illustrated are still under development and very few have been adopted through legislation.

Mitigation measures are presented according to the main groups of fishing gear – gillnets and trammel nets, longlines and lines, trawls, purse seines, traps and pots – and subdivided according to the four main groups of vulnerable species: marine mammals, seabirds, sharks and rays, and sea turtles. Preventive and curative approaches covering both technical measures (gear modifications, strategies, as well as acoustic, visual, magnetic and chemosensory deterrents) and management measures are described.

Contents

Tables and figures

Abbreviations and acronyms

ACAP	Agreement on the Conservation of Albatrosses and Petrels
ACCOBAMS	Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic area
ADD	acoustic deterrent device
AHD	acoustic harassment device
BRD	bycatch reduction device
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
DDD	dolphin deterrent device
EBAB	ecological-based artificial bait
ISSF	International Seafood Sustainability Foundation
FAD	fish aggregating device
FAO	Food and Agriculture Organization of the United Nations
GFCM	General Fisheries Commission for the Mediterranean
IATTC	Inter-American Tropical Tuna Commission
ICCAT	International Commission for the Conservation of Atlantic Tunas
IDDRA	Institut du développement durable et des ressources aquatiques
Ifremer	Institut français de recherche pour l'exploitation de la mer
IOTC	Indian Ocean Tuna Commission
LED	light-emitting diode
NOAA	National Oceanic and Atmospheric Administration
RAC/SPA	Regional Activity Centre for Specially Protected Areas
RFMO	regional fisheries management organization
TED	turtle excluder device
UN Environment/MAP	United Nations Environment Programme/Mediterranean Action Plan
UV	ultraviolet
WCPFC	Western and Central Pacific Fisheries Commission
WWF	World Wildlife Fund

Acknowledgements

The author would like to thank the Secretariats of the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic area (ACCOBAMS) and of the General Fisheries Commission for the Mediterranean (GFCM), through their Executive Secretaries, Florence Descroix-Comanducci and Abdellah Srour, as well as the Regional Activity Centre for Specially Protected Areas (RAC/SPA) for making it possible to publish this review. In particular, Célia Le Ravallec (ACCOBAMS Project Officer), Margherita Sessa (GFCM Fishery Officer), Aurora Nastasi (GFCM Fisheries and Environment Specialist) and Paolo Carpentieri (Fishery Resources Monitoring Specialist) are gratefully acknowledged for the substantial inputs provided in the compilation and preparation of this publication.

John H. Wang, PhD, Research Ecologist at the National Oceanic and Atmospheric Administration (NOAA) Pacific Islands Fisheries Science Center acted as a peer-reviewer and is warmly thanked for providing in-depth analysis and substantial comments on the technical contents.

This review was originally drafted in French and translated into English thanks to the collaboration of Steve Cunningham, Economist at the Institut du développement durable et des ressources aquatiques (IDDRA). Alex Chepstow-Lusty is gratefully acknowledged for his thorough technical editing and valuable comments. The editing, graphic layout and publishing were coordinated by Dominique Bourdenet (GFCM Scientific Editor) with the support of Matthew Kleiner (GFCM Editing and Publication Intern) and Ysé Bendjeddou (GFCM Publication and Documentation Specialist). The publication also benefitted from the creative skills of Alberto Gennari, who designed the cover artwork and the internal illustrations, and José Luis Castilla Civit, who carried out graphic design and layout.

Finally, special thanks are due to the MAVA Foundation, which supports regional efforts to facilitate sustainable fishing practices and the conservation of marine vulnerable species.

1. Introduction

Marine megafauna, which are highly migratory for the most part and travel widely across the oceans, are susceptible to many forms of human pressure. Among these stresses, bycatch fishing has increased exponentially in recent years and is considered a serious threat to these highly vulnerable species, especially in certain regions. Minimizing bycatch is therefore a key component of sustainable fisheries management in order to maintain marine biodiversity and consequently reduce negative effects on marine resources (see Hall, 1996; Hall, Alverson and Metuzals, 2000).

The aim of this document is to present various experimental approaches and strategies for reducing the bycatch of vulnerable species that can hopefully serve as examples for fisheries facing the same problems. This review of the different mitigation measures draws on an analysis of the available literature, comprising scientific journal articles together with reports from international organizations and documents available on the Internet.

The following review is guided by the principle that instead of the vulnerable species themselves, fishing activities should be the targets of the technical or management measures required to reduce the impacts of unwanted interactions between these species and fisheries. From the definition of fishing gear categories (Nédélec and Prado, 1990; FAO, 2013), two broad categories can be identified: mobile fishing gear (e.g. trawls and purse seines, etc.) on the one hand and static fishing gear (e.g. gillnets and other entangling nets, longlines and lines, trap nets and pots, etc.) on the other. The various solutions found in the relevant literature are examined for each of the main groups of vulnerable species (marine mammals, seabirds, sharks and sea turtles).

2. Trawls

2.1 Marine mammals

Marine mammals are reported to be caught more often by pelagic or midwater trawls (for example, Fertl and Leatherwood, 1997; Hamilton and Baker, 2019; Fortuna *et al.*, 2010) than by demersal trawls, which have a greater effect on seals, though they may occasionally be responsible for catching dolphins as observed in some fisheries in the United States of America (Jannot *et al.*, 2011; Waring *et al.*, 2016) or in Australian waters (Allen *et al.*, 2014).

Several studies, mainly in the United States of America and in Europe, have attempted to resolve the issue of marine mammal mortality in trawl fisheries. They have focused especially on small dolphin bycatch, of, for example, the harbour porpoise (*Phocoena phocoena*), the short-beaked common dolphin (*Delphinus delphis*) and the common bottlenose dolphin (*Tursiops truncatus*). Some of the various solutions examined below seek to avoid bycatch through dissuasion, using either physical barriers or acoustic deterrents. Other techniques aim to reduce the risk of drowning and employ exclusion devices enabling large specimens to escape.

2.1.1 Exclusion barriers

While the results of trials in which vertical ropes were employed before trawl extension (de Haan *et al.*, 1998) have not convincingly shown that there are benefits to their use, square-mesh barriers placed further forward (the NECESSITY project; ICES, 2021), at the level of the junction with the large mesh, could perform better. However, this solution did not prevent the enmeshment of dolphins in the barrier or their entanglement in the large meshes at the front part of the trawl (i.e the trawl body).

2.1.2 Bycatch reduction devices

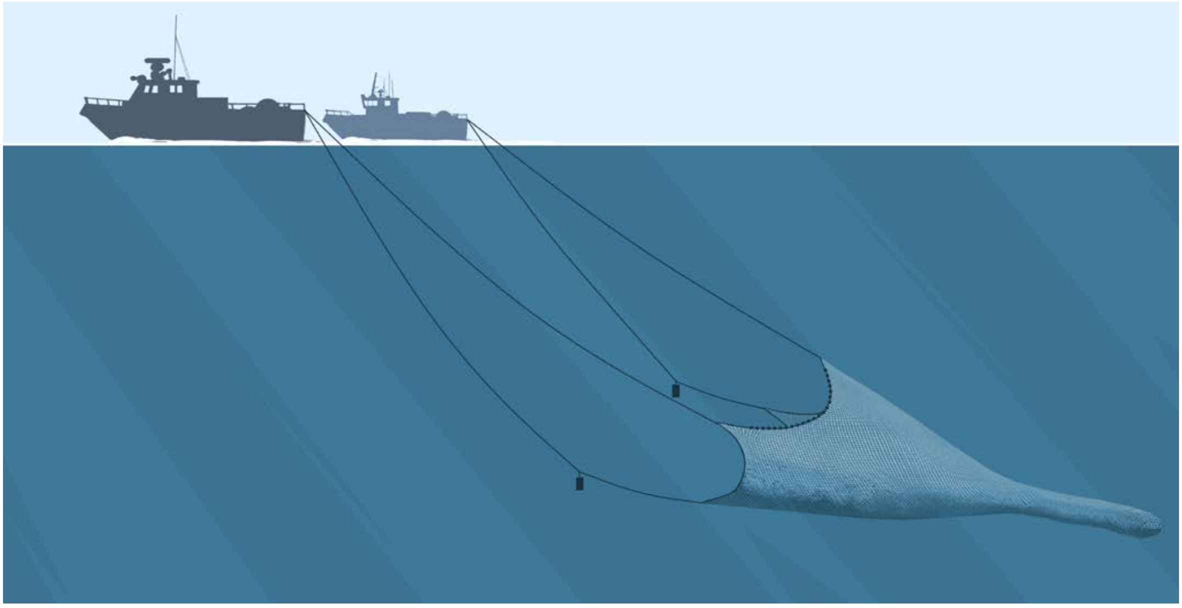
According to the definition of the Food and Agriculture Organization of the United Nations (FAO), bycatch reduction devices (BRDs) are devices inserted in a fishing gear, usually a trawl, to allow for the live escape of unwanted species (including jellyfish), individuals (juveniles) or endangered species (such as seals, sea turtles and dolphins). Various types can be used depending on the type of bycatch that the fishers wish to exclude (FAO, 2004; 2021a).

Bycatch reduction devices used to prevent marine mammals and other large vertebrates from being caught consist primarily of an inclined grid placed in front of the codend in order to deflect the animals towards an escape opening at either the top or bottom (FAO, 2021a; Northridge *et al.*, 2011).

Since the end of the 1990s, BRDs have been used in several pelagic trawl fisheries (for example, in the French and British pelagic pair trawl (Figure 1) fisheries for seabass (*Dicentrarchus labrax*), with mixed success in reducing the bycatch of small cetaceans (dolphins) and seals (Lyle and Willcox, 2008; Northridge, 2003; Larnaud *et al.*, 2006; Northridge *et al.*, 2011; Baker *et al.*, 2014).

In the Mauritanian exclusive economic zone, Zeeberg, Corten and de Graaf (2006) indicated that, in May or in summer, 50 to 70 freezer pelagic trawlers fishing sardinella (*Sardinella aurita*) can incidentally capture pods of 10 to 20 long-finned pilot whales (*Globicephala melas*) or groups of 5 to 30 dolphins, mostly the short-beaked common dolphin. From their own observations, the authors estimated an annual removal of between 70 and 720 dolphins by the complete trawler fleet. In an

FIGURE 1
Midwater pair-trawl



Redrawn from FAO, 2021a.

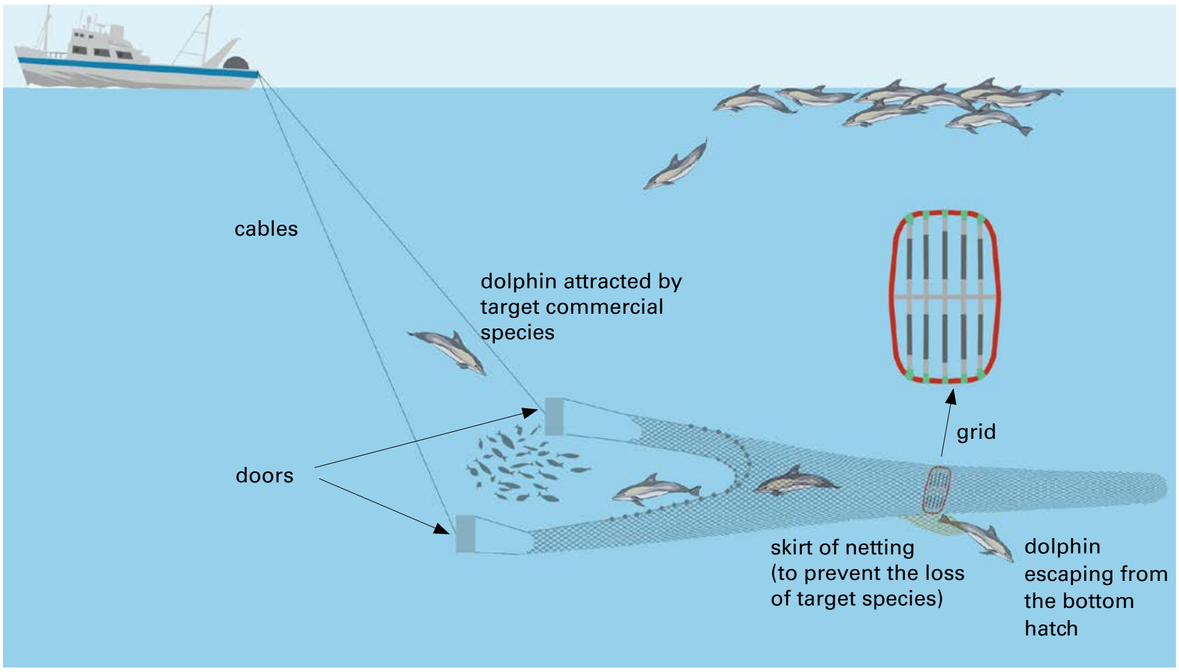
effort to reduce the bycatch of cetaceans, as well as of other vulnerable species (sharks, rays and sea turtles), a megafaunal excluder device known as the large animal reduction device, made of a filter grid connected to an escape tunnel, was positioned before the last part of the trawl net (the codend). While rays, sharks and sea turtles nearly all escaped through this BRD, none of the eight short-beaked common dolphins caught managed to pass through the escape opening (de Haan and Zeeberg, 2005; Zeeberg, Corten and de Graaf, 2006).

In contrast, a significant reduction in bycatch rates of bottlenose dolphins has been achieved in the Pilbara trawl fishery, a bottom trawl fishery operating off the coast of Western Australia (Stephenson, Wells and King, 2008). This fishery targets a variety of fish species, including emperors (for example, *Lethrinus punctulatus*) and snappers (*Lutjanus* spp.) Nevertheless, the Pilbara trawl fishery is responsible for the bycatch of numerous shark and ray species and of protected species of sea turtles, sawfish (Pristidae) and sea snakes, as well as of bottlenose dolphins, which deliberately enter the trawl nets to depredate captured fish (Stephenson and Chidlow, 2003). According to Stephenson and Wells (2006), the Pilbara trawl fishery captures approximately 70 dolphins per year, which are nearly always killed. However, the use of a semi-flexible exclusion grid (Figure 2) has been shown to reduce the capture of bottlenose dolphins by about half (Stephenson, Wells and King, 2008).

Despite these advances, no further reduction in dolphin bycatch has been observed since these BRDs were introduced to this fishery, meaning further technical improvements are needed, such as modified BRDs (Figure 3) with top-opening escape hatches (Northridge, Vernicos and Raitsos-Exarchopolous, 2003; Allen *et al.*, 2014).

On the other hand, underwater observations made with cameras during experiments on BRDs in the Pilbara trawl fishery (MacKay, 2011) have shown that bottlenose dolphins deliberately entering the trawl cannot easily cope with trawling at high speeds. Even with the exclusion grid in place, the dolphins prefer to seek the known exit at the entrance of the trawl and thus risk being trapped. This behavior can lead to mortality, especially when hauling in the trawl net (Wakefield *et al.*, 2017).

FIGURE 2
Escape device used in the Pilbara trawl fishery



Adapted from Stephenson, Wells and King, 2008 and Allen *et al.*, 2014.

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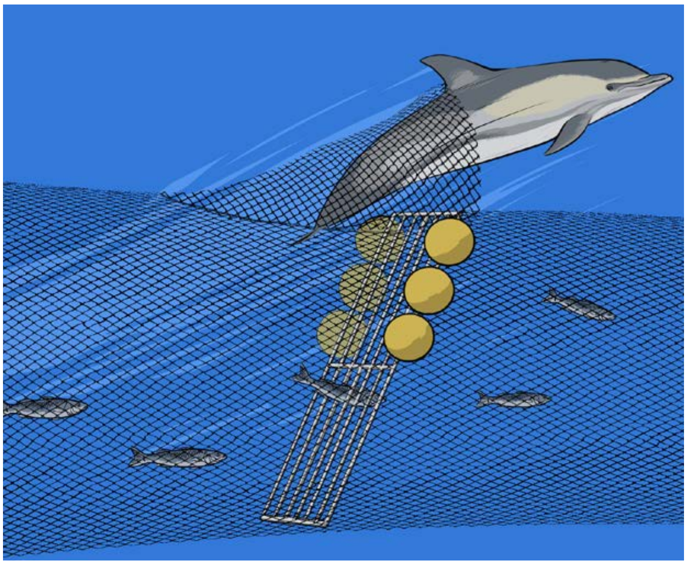
Although escape devices, such as BRDs, can be beneficial in reducing the bycatch of small cetaceans by trawls with minimal effects on the target catch, further studies are needed to indicate if these devices are fully effective in reducing the mortality of escaped animals (FAO, 2018).

FIGURE 3
Top opening escape for small cetaceans



Adapted from Northridge, 2003.

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2.1.3 Acoustic deterrents

The emission of acoustic signals between 99 and 117 dB at frequencies ranging from 7.5 to 140 kHz is sufficient to keep the harbour porpoise away from the trawls (Kastelein, de Haan and Verboom, 2007; de Haan *et al.*, 1998;). However, acoustic deterrents are of limited use given the habituation capacity of cetaceans (Zollett and Rosenberg, 2005). Over a variable period, the mammals come to recognize the emitted sound as a signal for available food (the dinner-bell effect). The downside of employing increasingly stronger emissions, such as those used in certain devices to prevent seals from approaching fish farms (for example, the acoustic harassment device emits noise at more than 190 dB), is the serious auditory damage likely done to cetaceans (Olesiuk *et al.*, 2002).

2.1.4 Alternative methods

Cetacean–fishery interactions can be minimized by gear modifications, time or area closures or adapting fishing practices. Fernández-Contreras *et al.* (2010) found that if pelagic trawlers only operated in water deeper than 250 m, the bycatch of common dolphins could be significantly reduced and almost entirely avoided if fishing was restricted to waters over 300 m deep. Several studies have found that most bycatch in trawls occurs during nocturnal trawling (for example, Morizur *et al.*, 1999; López *et al.*, 2003; Fernández-Contreras *et al.*, 2010). Therefore, limiting trawling to only daylight hours, or hauling in the gear more slowly at night, as well as not setting gear when cetaceans are present, would reduce cetacean bycatch (Read, Drinker and Northridge, 2006; Read and Dollman, 2017).

2.2 Seabirds

In trawl fisheries, seabirds can become entangled in the net and sometimes strangled in the cables pulling the trawl or the acoustic net-sounder monitor cable (Bartle, 1991; Weimerskirch, Capdeville and Duhamel, 2000). Large-winged birds such as albatrosses are the most vulnerable (Small and Taylor, 2006). Only visual deterrents have been proposed as of the publication of this review as seabird deterrents.

2.2.1 Streamer lines

During the austral spring, when albatross density and incidental mortality are high in the waters around the Falkland Islands, Sullivan *et al.* (2006) conducted trials onboard a stern trawler in 2003 to compare the efficacy of three streamer line devices (warp scarer, Brady baffler and Tori lines).

The warp scarer consists of a series of rings, joined by a length of square netting and a rope with reflective tape hanging from each ring. The Brady baffler is a pair of towers, one fitted to each side of the stern gantry, accompanied by two steel arms, one aft of the stern and one outboard, with ropes and plastic.

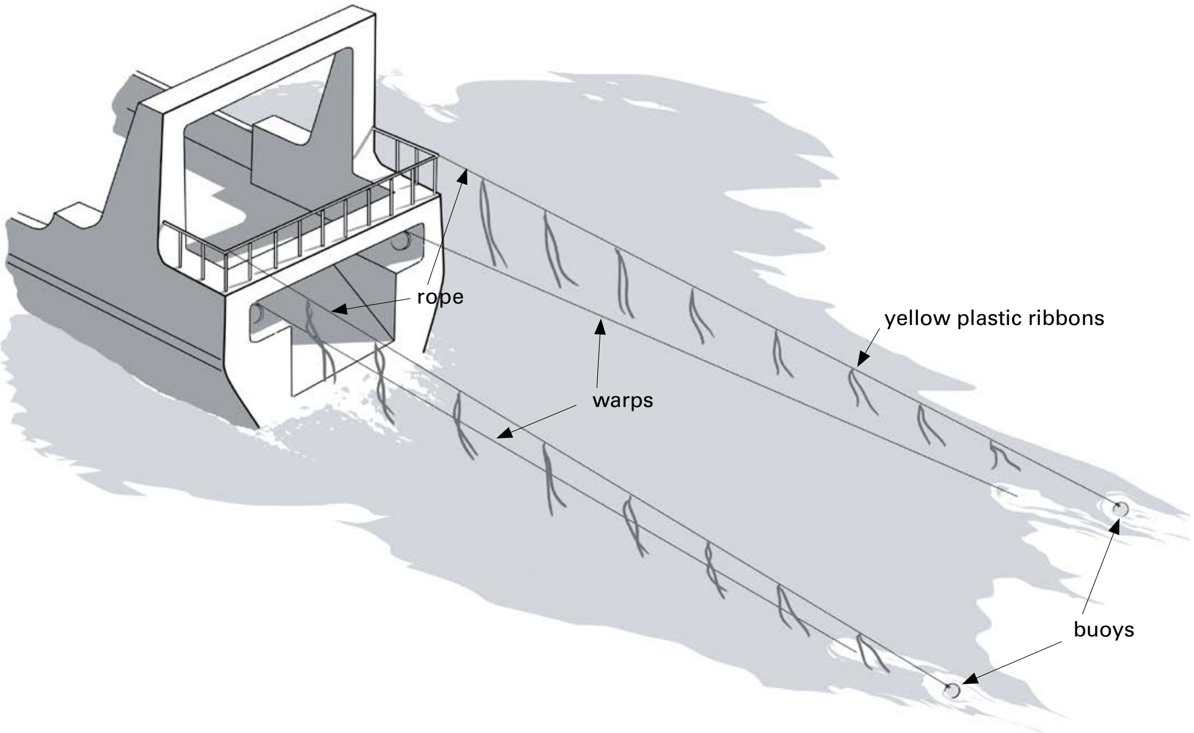
Tori lines used for longlines were adapted for trawls with one line attached to one side of the vessel's stern and the other attached above the trawl deck.

Results showed that the Tori lines are slightly more efficient than the two other systems in terms of reducing seabird contacts, with additional advantages including lower costs, smaller space requirements and easier set-up.

Testing different repellent devices on two trawls targeting walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea, Melvin *et al.* (2011) came to the same conclusion that seabird warp strikes can be reduced with properly deployed streamer lines and by limiting the aerial prominence of wires (particularly the sonar wire cable).

Because their effectiveness was limited in cases of rough seas (Bull, 2009), Snell, Brickle and Wolfaardt (2012) have refined the oiginal design for reducing mortality of albatrosses and petrels by collision with warp cables on stern trawlers in the Falkland Islands. The modification consists of shortening the length of the Tori lines, allowing the devices to ride over the waves with the float buoy (used as a towed device) without any risk of breakage and to be deviated less from the warps in rough seas and crosswinds (Figure 4). The new Tori lines (TL-2008) were found by the crew to be easy and fast and safe for retrieval thanks to the addition of a lazy line attached to the streamer and the vessel. Consequently, since 2009, the TL-2008 have been prescribed as a mandatory requirement for all trawl vessels in the Falkland Islands.

FIGURE 4
Tori lines for trawls



Each line consists of 50 m of rope with a buoy attached to the end for tension; six streamers made of yellow plastic ribbons are attached at 5 m intervals along the stream line and above the warps.

Redrawn from Sullivan *et al.*, 2006 and Bull, 2009.

2.2.2 Laser beams

The use of lasers as a deterrent for birds has been considered but research on their effectiveness and consequences for avian visual systems remain limited (Blackwell, Bernhardt and Dolbeer, 2002; Glahn *et al.*, 2001). Since 2013, Mustad Autoline, in partnership with SaveWave, has developed and marketed the SeaBird Saver, a laser-based tool for preventing seabird interactions with longline fishing gear. The SeaBird Saver was awarded the 2014 World Wildlife Fund Smart Gear Competition Tuna Bycatch Reduction prize and second place in the Nor-Fishing Foundation competition for innovation.

Preliminary tests have shown that the SeaBird Saver is capable of dispersing an assemblage of seabirds largely dominated by gulls (*Larus* spp.) far from the stern of the ship at both dawn and dusk, and in cloudy, rainy or misty conditions (Schrijver, 2014). However, these results have not been confirmed since then. During field trials with this device on a trawler in 2015, only one of the 14 observations showed a dramatic avoidance response by gulls to the laser beam. In addition, this response was recorded mainly at night, suggesting that the effects of the laser may be limited to low-light conditions and perhaps also species-specific (Melvin *et al.*, 2016).

2.3 Sharks and rays

Towed by one or two boats as they are pulled along the seafloor or in midwaters, trawls are responsible for significant bycatch and mortality of various species of sharks. Trawlers targeting small pelagic species with their large vertical-opening trawl nets can occasionally catch pelagic sharks, such as blue sharks (*Prionace glauca*), common threshers (*Alopias vulpinus*) and shortfin mako sharks (*Isurus oxyrinchus*). Although not usually targeted by bottom trawlers, sharks can form a significant part of their catch as well. Bottom trawlers mainly targeting deep-water shrimps and Norway lobster (*Nephrops norvegicus*), usually discard large quantities of small shark species, such as small-spotted catshark (*Scyliorhinus canicula*), smooth hound sharks (*Mustelus* spp.), blackmouth catshark (*Galeus melastomus*), and velvet belly lanternshark (*Etmopterus spinax*) among others.

2.3.1 Fishing gear improvements

Tickler chains

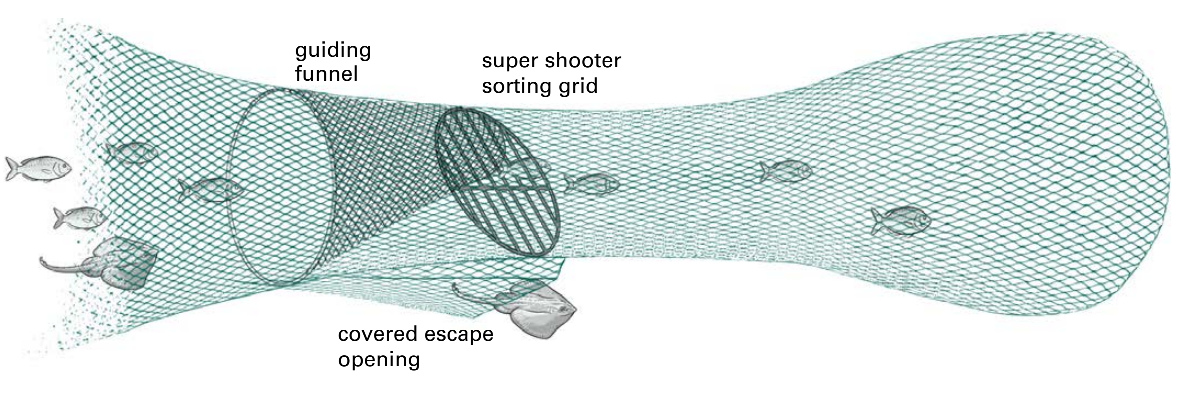
In the mixed-species bottom-trawl fisheries of the North Atlantic, catches can be increased by fitting a length of chain known as a tickler in front of the trawl's ground gear; Kynoch, Fryer and Neat (2015) have demonstrated that the catch rate of skates and sharks can be significantly lowered by removing the tickler.

Bycatch reduction devices

Adapting the BRDs used for sea turtles would be an effective means of reducing shark mortality rates by allowing them escape routes during trawling. Successfully tested in Australian fisheries, these escape systems placed before the trawl codend (Figure 5) consist of a rigid sorting grid that forces sharks and rays downward to a covered escape opening and a guiding funnel, which helps the target species pass through the grid (Brewer *et al.*, 1998). Some of these systems, such as the NAFTED or the Super shooter, work as well for sharks and rays as for sea turtles.

In 2001, Brewer *et al.* (2006) assessed the effect of turtle excluder devices (TEDs) using pair trawl comparisons in Australia's northern prawn fishery. The results showed a reduction of shark bycatch by 17.7 percent, including of species like the whitecheek shark (*Carcharhinus dussumieri*) and the Australian blacktip shark (*Carcharhinus tilstoni*), and by 36.3 percent for ray species, such as the white-spotted guitarfish (*Rhynchobatus australiae*), the Australian butterfly ray (*Gymnura australis*) and the black-spotted whipray (*Himantura toshi*), in comparison with control nets without TEDs. According to the authors, the introduction of TEDs in 2000 in this fishery, in combination with the retention ban on elasmobranch products in 2001, which aimed to eliminate the practice of shark finning, has reduced the capture of large sharks by 86 percent and of rays by 94 percent, as well as the capture of the most commonly caught sawfish, the narrow sawfish (*Anoxypristis cuspidata*), by 73.3 percent, but has not significantly reduced the catch of smaller sharks and rays.

FIGURE 5
Selective device enabling benthic species (including rays and sharks) to escape



Redrawn from Brewer *et al.*, 1998.

Brčić *et al*. (2015) showed that, with appropriate adaptations, these BRDs may represent a reasonable compromise between easier escape for sharks, such as the blackmouth catshark, and the economic losses due to the reduced catch of target species, like the Norway lobster and the greater forkbeard (*Phycis blennoides*).

Tested in the trawl fishery targeting the Atlantic seabob (*Xiphopenaeus kroyeri*), a commercially important prawn found off the coasts of Suriname, the combination of a square-mesh panel and a TED of the Super shooter type may increase considerably the chances of escape for large rays, as in by 77 percent for the sharpsnout stingray (*Dasyatis geijskesi*), while the reduction in bycatch of smaller species, such as the smalleyed round stingray (*Urotrygon microphthalmum*), is lower due to their morphology enabling them to pass through the grid towards the trawl codend. The escape rate of various medium-sized species, which are the most abundant, such as the longnose stingray (*Dasyatis guttata*) and the smooth butterfly ray (*Gymnura micrura*), depends mainly on their size (Willems *et al*., 2016).

In the study by Wakefield *et al*. (2017) which compared the escape behaviour of different megafaunal species, 1 320 hours of observation showed that most of the specimens which had escaped were demersal sharks (80 percent), rays (66.3 percent) and hammerhead sharks (57.1 percent). While all types of BRDs suit most demersal chondrichthyans, BRDs placed on the upper part of the trawl are 20 to 30 percent more effective for benthopelagic species, i.e. those species living and feeding near the bottom, as well as in midwaters or near the surface.

2.3.2 Setting improvements

Except for restrictions on access to spawning and nursery areas, there are no preventive measures that would enable shark capture by trawls to be avoided.

2.4 Sea turtles

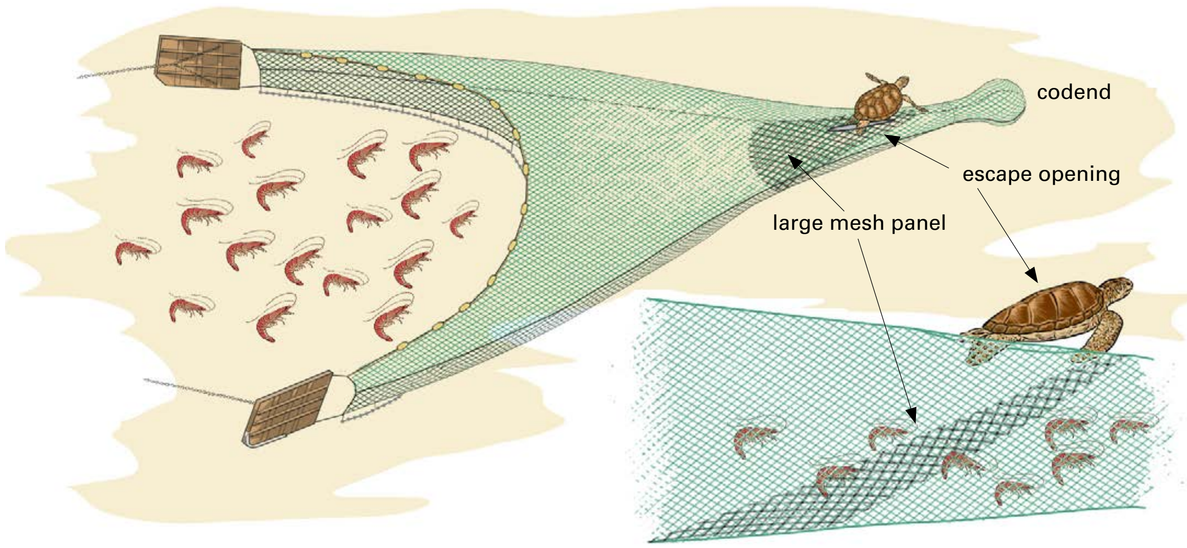
All types of trawling activities can result in sea turtle bycatch; bottom trawls working particularly in coastal waters, in the wintering and breeding areas of sea turtles, have the greatest impact on these species (Cardona *et al.*, 2009; Casale *et al.*, 2010; Lewison *et al.*, 2013; Levy *et al.*, 2015). But sea turtles can also be captured by midwater trawlers when the animals transit from the bottom, where they rest and forage, to the surface, where they breathe (NOAA, 2019a). Midwater freezer trawlers targeting sardinella off northwest Africa capture up to 50 sea turtles annually, including leatherback (*Dermochelys coriacea*), loggerhead (*Caretta caretta*) and hawksbill (*Eretmochelys imbricata*) turtles (Zeeberg, Corten and de Graaf, 2006). Elsewhere, in the northern and central Adriatic Sea, the Italian midwater pair trawl fishery is responsible for the bycatch of loggerhead turtles (Lucchetti *et al.*, 2016; Pulcinella *et al.*, 2019).

2.4.1 Fishing gear improvements

Turtle excluder devices

Turtle excluder devices are BRDs specially designed to allow for the redirection of sea turtles incidentally caught by a trawl towards an escape opening located on the upper or lower part of the trawl body. Turtle excluder devices may include either a soft turtle excluder device (of the Morrison type) (Figure 6) or a hard device (of the Super shooter type), preferred when there is an important risk of bycatch and debris clogging. The effectiveness of their operation is based on compliance with widely proven technical specifications which are well-described in the relevant literature (Eayrs, 2007, 2012; Mitchell *et al.*, 1995).

FIGURE 6
Morrison turtle excluder device



The Morrison TED is an example of a soft TED: large meshes panel set in front of the codend allow shrimp to pass through the meshes to the codend and deflect sea turtles or other large unwanted animals (e.g. rays and sharks) towards an escape opening.

Redrawn from Eayrs, 2007.

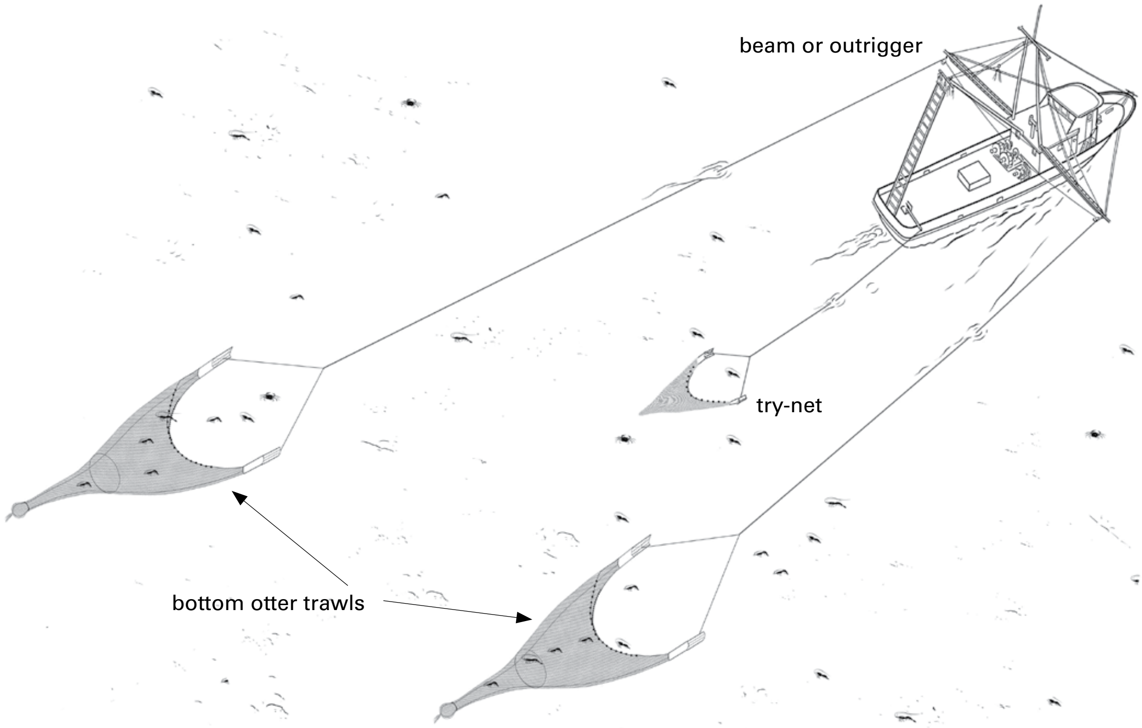
In many countries, as in North and Central America, and in the Arabian Sea, the Gulf of Guinea, and off northern Australia, most trawl fisheries targeting shrimps on the tropical continental shelves have adopted the double-rigged Florida-type otter trawl (Figure 7).

Tropical shrimp trawl fisheries have a serious impact on sea turtles as several thousand turtles can be caught and drowned each year (Eayrs, 2007; Gillett, 2008). This critical problem led the United States of America to prohibit the import of shrimps caught in fisheries without sea turtle conservation measures in 1989 and to the enforcement on 2 May 2001 of the Inter-American Convention for the Protection and Conservation of Sea Turtles. The most notable and significant protection measure has been the requirement of the use of TEDs in shrimp trawl fisheries (NOAA, 2019a). The trade embargo and the certification process that followed these decisions have consequently hastened the adoption of TEDs in countries in Southeast Asia, South America and Africa wishing to export their prawn products to the United States of America (Shiode and Tokai, 2004).

The enforcement of these measures has demonstrated their efficacy in substantially reducing the capture of sea turtles by shrimp trawlers in, for example, the Gulf of Mexico shrimp trawl fishery, where captures went down by approximately 60 percent (Finkbeiner *et al.*, 2011), or Australia's northern prawn fishery, which saw a decrease of 99 percent (Brewer *et al.*, 2006) or Gabon, where no turtles were caught by trawlers with TEDs during the 34 fishing days of an onboard observer programme (Casale *et al.*, 2017).

Furthermore, most of the studies show that TEDs may be an effective way to enable unwanted species or small specimens of commercial species to escape, while eliminating large objects such as plastic materials, pieces of wood and stones (Atabey and Taskavak, 2001; Lucchetti and Sala, 2010; Bitón Porsmoguer, Merchán Fornelino and Tomás, 2011; Sala, Luchetti and Affronte, 2011; Brewer *et al.*, 1998; Lucchetti *et al.*, 2008; Fortuna *et al.*, 2010).

FIGURE 7
Florida-type outrigger trawler



Florida-type outrigger trawlers are the most widely used type of fishing vessel in shrimp trawling.

Adapted from FAO, 2021b.

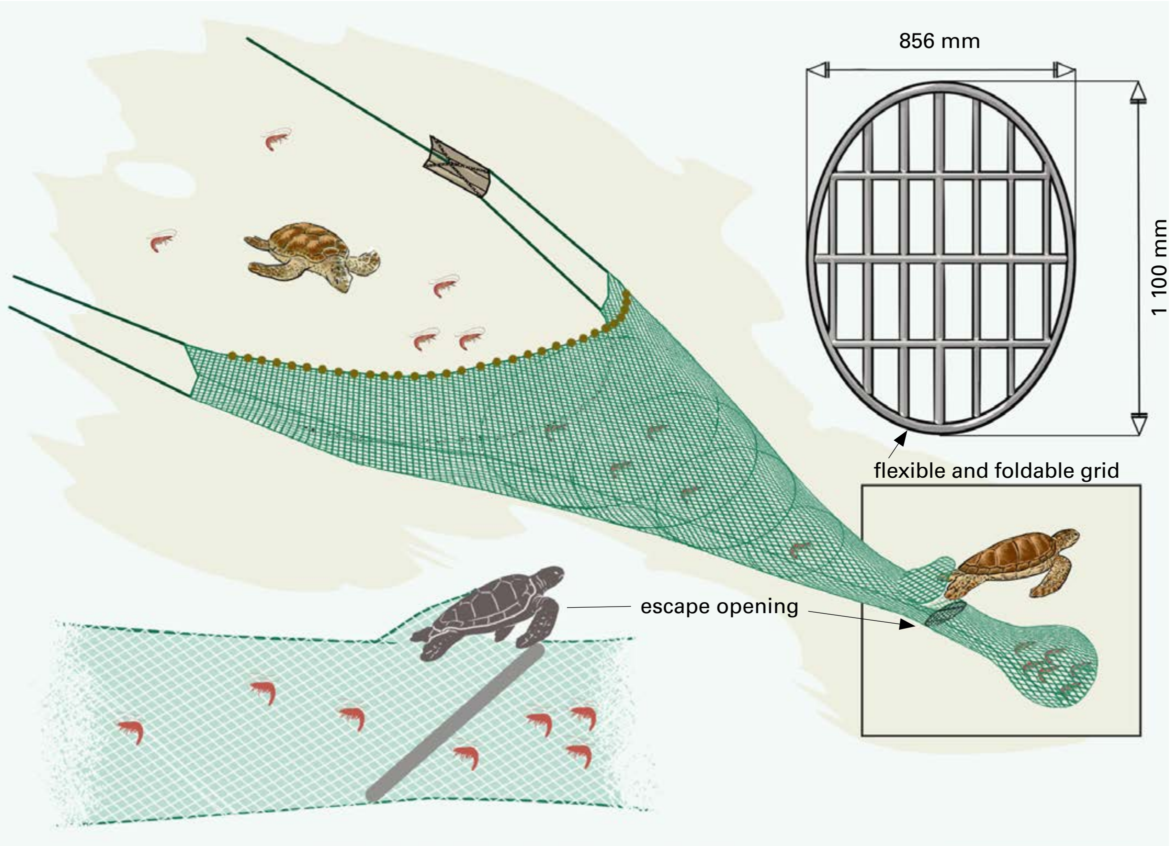
Considering the reluctance of fishers to change the gear that they traditionally use, the implementation of TEDs and BRDs remains a difficult task if the devices are shown to cause significant reductions in commercial catch or are too cumbersome or difficult to handle on small-sized vessels, such as those of small-scale coastal trawl fisheries. Taking this situation into account, Gahm (2019) tested and compared several grids for small shrimp trawlers working in the southeastern United States of America in order to mitigate sea turtle bycatch; the results showed that TEDs can function properly in small trawl types, although a reduction in both bycatch and desired shrimp is observed depending on the type of trawl employed. On the other hand, Boopendranath *et al.* (2010) have also proposed a range of soft BRDs, which are more appropriate than hard BRDs for artisanal Indian trawlers and are made with minimum use of rigid parts, thereby granting the advantages of easy handling, light weight and simple construction.

In the northern Adriatic Sea, an area of high concentration of loggerhead turtles, a flexible and foldable TED made of high-density polymer was tested on commercial bottom trawlers in order to assess its effectiveness in decreasing bycatch (Figure 8). The trials carried out in the framework of the TartaLife[1] project have given promising results in terms of reducing sea turtle, shark and ray bycatch, while decreasing the amount of large debris caught and not significantly affecting commercial catch. The flexible TED has the advantage of keeping a stiff configuration during trawling, and riding on the net drum as the net is recovered (Luchetti *et al.*, 2016, 2019; Vasapollo *et al.*, 2019).

In French Guyana, the shrimp trawl fishery primarily targets two species, the red-spotted shrimp (*Farfantepenaeus brasiliensis*) and the southern brown shrimp (*Farfantepenaeus subtilis*), which represent only 10 to 30 percent of the total catch. This fishery's catch is mainly composed of unwanted

1. Tartalife: Reduction of sea turtle mortality in professional fishing (LIFE12 NAT/IT/000937).

FIGURE 8
FLEXI GRID used in the northern Adriatic Sea



Redrawn from Vasapollo *et al.*, 2019.

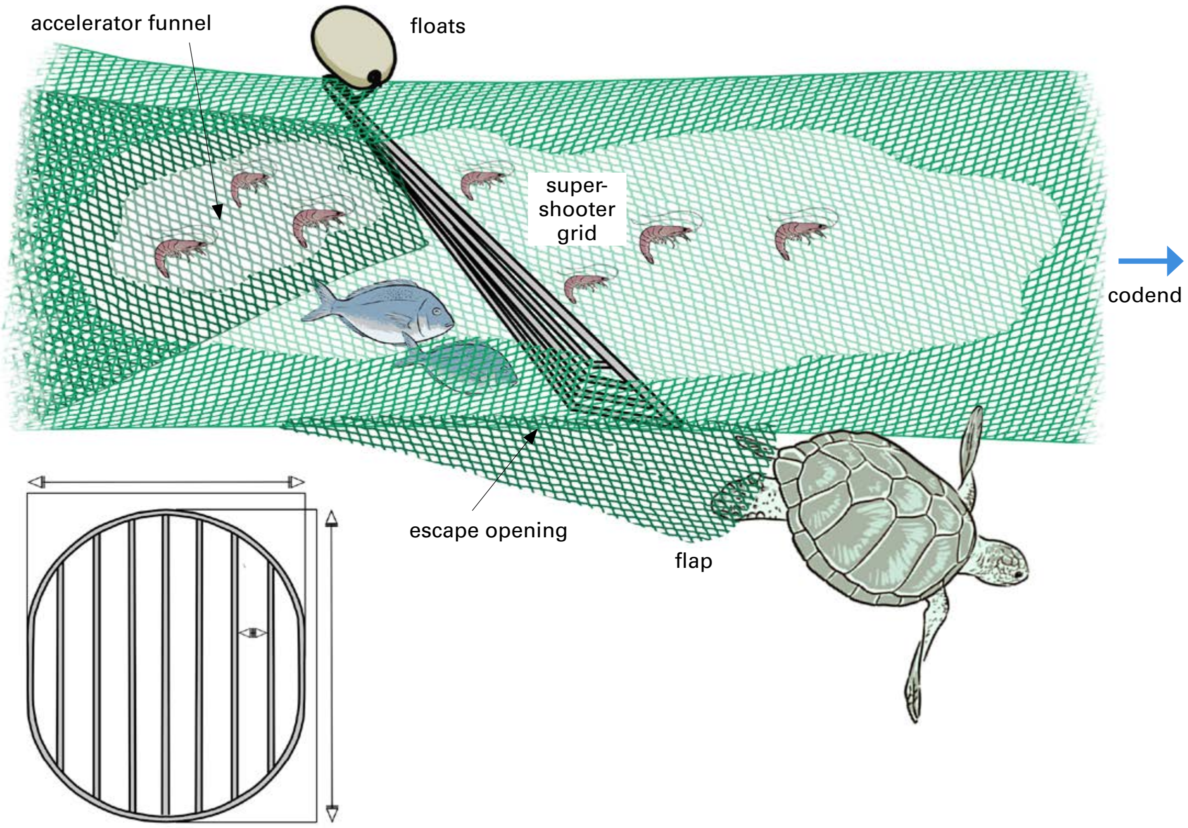
species (including sea turtles, sharks and rays) as well as other commercial fish species which happen to be important resources for coastal small-scale fishers. In order to mitigate bycatch of these unwanted species, a TED adapted to the Guyanese shrimp fishery has been developed. This new device is designed to assist sea turtle escape, reduce shark and large ray bycatch and eliminate marine debris (for example, stones, shells and sponges) (Rieu, 2010; Davies, 2016). Mandated since 2010, the use of trash and TEDs has reduced the total bycatch of the shrimp trawl fishery by around 30 percent without significantly lowering shrimp catches (Davies, 2016).

The trash and TED system (Figure 9) is an adaptation for the French Guyana trawl fishery of the Super shooter grid, with flat bars and a bottom escape opening. To facilitate its implementation, training and technical specifications were provided to fishers and to fishery officers (CRPMEM, 2015).

2.4.2 Setting improvements

Tow duration and depth
When caught by a trawl with too long of a tow duration, sea turtles can drown by forced apnea (i.e. cessation of breathing) or fall into a coma and die later (Casale, 2008). Tow duration is therefore one of the main causes of mortality (Henwood and Stuntz, 1987) and decompression sickness may also occur if the trawl is hauled in too rapidly (García-Párraga *et al.*, 2014).

FIGURE 9
Turtle excluder device for Guyanese shrimp trawling



The super-shooter grid has flat bars spaced 50 mm apart and an inclination angle between 45 to 55 degrees. The flap masks the bottom escape opening. The accelerator funnel directs shrimp away from the escape openings, and through the bars of the TED, and the floats keep the escape opening open.

Redrawn from CRPMRN, 2015.

Season

Mortality has been found to be higher in the winter than in the summer (Sasso and Epperly, 2006), probably depending on the seasonal biological cycle.

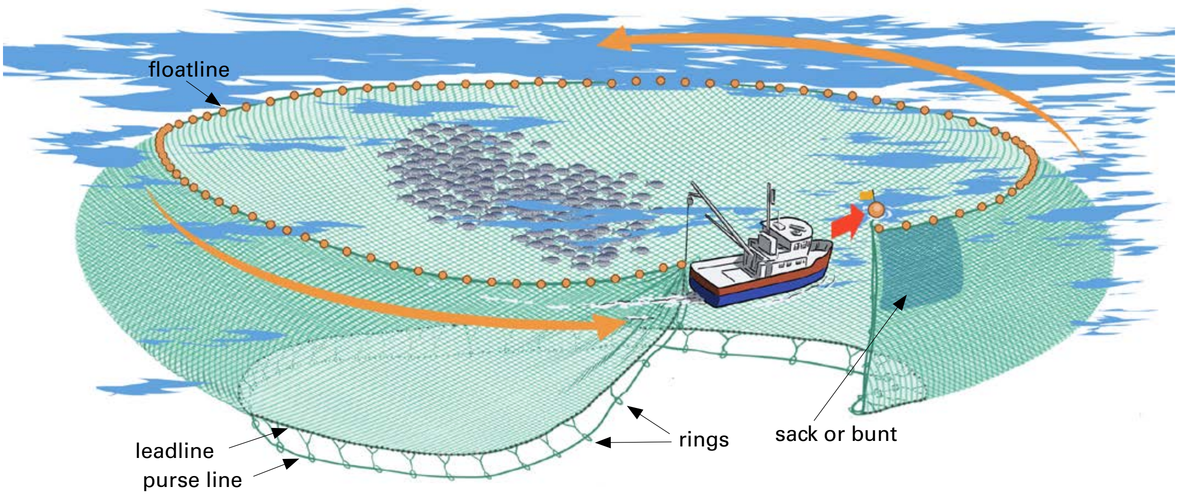
Depth of setting

Atabey and Taskavak (2001) found that most sea turtle bycatch occurs at depths between 11 and 30 m, in particular when the trawling activity took place in coastal areas inhabited by sea turtles (notably during their dormant phase or when in search of food during their demersal phase).

3. Purse seines

Purse seines are mobile fishing gear designed to catch schools of pelagic or midwater fishes by surrounding them. They usually consist of a long wall of netting framed between a lead line and a floatline, with a purse line to close up the bottom of the net to prevent the fish from escaping downwards (Figure 10). Various configurations exist, depending on the target species and the country. Vessels targeting small pelagic fishes generally use lights to concentrate fish schools before encircling them. Tuna purse seiners fish either by spotting free-swimming schools of tuna or by utilizing floating objects, called fish aggregating devices (FADs), to attract fish. When fishing for free-swimming schools, purse seine fishing has an average bycatch rate of less than 1 percent. When utilizing FADs, bycatch rates vary from around 1.75 percent in the western and central Pacific to nearly 8.9 percent in certain ocean regions (ISSF, 2021).

FIGURE 10
Purse seine



Adapted from AFMA, 2021.

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3.1 Marine mammals

In the Atlantic, Indian and Pacific Oceans, purse seine vessels fish either by spotting free-swimming schools of tuna or by using floating objects to attract fish, with either natural objects or manmade ones such as FADs (ISSF, 2019). They can also set the purse seine around tuna schools associated with whale sharks (*Rhincodon typus*), baleen whales or dolphins (Donahue and Edwards, 1996; Hall and Roman, 2013; Hamer, Childerhouse and Gales, 2012; Escalle *et al.*, 2019). The development of purse seining for tuna in the 1950s in the eastern Pacific Ocean had the unwanted consequence of catching many dolphins as bycatch. The mortality rates were not sustainable, and most dolphin populations declined through the late 1970s. Faced with the severity of this problem, the United States of America's purse seining industry sought mitigating solutions or to give up this fishing technique for other alternatives (Hall, 1998).

Since the early 1990s, the use of FADs for tuna fishing has widely and rapidly expanded, especially in the purse seine fleet targeting tropical tunas, such as skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*). Currently, nearly 65 percent of purse seine catch has been secured with the use of floating objects, which leads to 4–5 percent of catch totals consisting of non-target species, including sea turtles, pelagic rays and other fishes, caught as bycatch (Scott and Lopez, 2014). Likewise, for example, the rough-toothed dolphin (*Steno bredanensis*), known in deep and warm tropical waters around the world, is occasionally captured accidentally by purse seining using FADs, as this species appears to have strong associations with floating objects (Hall and Roman, 2013).

Unlike the eastern Pacific tropical tuna fishery, the Mediterranean bluefin tuna fishery does not involve cetacean encirclement and therefore does not result in significant bycatch of dolphins. While there are occasional catches of a few striped dolphins (*Stenella coeruleoalba*), short-beaked common dolphins (*Delphinus delphis*) or long-finned pilot whales (*Globicephala melas*), these very rarely result in deaths (Di Natale, 1997; Silvani, Raich and Aguilar, 1992). As fishing occurs during the daytime, animals can be released alive with more or less difficulty according to their size.

Meanwhile, interactions between cetaceans and purse seiners targeting small pelagic fishes are more frequent. As dolphins search for their main food source of small pelagic fishes, they compete with this activity, and can be caught occasionally, but the mortality rate is low (Goldsworthy, 2018; Marçalo *et al.*, 2015; Benmessaoud *et al.*, 2018).

Depredation of sardine purse seines by some dolphins is a more important issue, mainly involving the bottlenose dolphin (*Tursiops truncatus*). This problem appears to be widespread across the Mediterranean, notably in Greece and Italy (Lauriano *et al.*, 2009), Morocco (Abid *et al.*, 2002), Tunisia (Ben Naceur, 1998; INRH, 2004; Benmessaoud, 2008) and in the Atlantic regions where purse seining is widely used, for instance off Portugal (Wise *et al.*, 2007; Marçalo *et al.*, 2011) and Galicia in northwest Spain (Goetz *et al.*, 2014). This depredation results in the dispersal of small pelagic shoals during net setting and can cause significant tears in the purse seines.

3.1.1 Fishing gear improvements

Backdown and Medina panel

To reduce dolphin mortality in the eastern Pacific Ocean purse seining fishery, one mitigating solution involved the development by tuna fishers of a manoeuvre called backdown (Hall and Roman, 2013; FAO, 2018; Swimmer, Zollett and Gutierrez, 2020). As soon as a group of dolphins is noticed to be encircled, the purse seiner goes into reverse and pulls the net. While the purse seine lengthens, the corkline sinks so that the dolphins can exit the net through the opening. Dolphins most often come into contact with the Medina panels, which consist of small-mesh webbing sewn into the upper part of the purse seine and help to keep dolphins from becoming entangled as well as encourage the corkline to sink.

Net strengthening

For over three decades, the Mediterranean sardine fisheries in Tunisia and Morocco have been affected by a growing problem of depredation by bottlenose dolphins, resulting in a significant loss of income and increase in expenses. The dolphins biting small pockets of enmeshed sardines causes numerous holes in the webbing, requiring expensive repairs and vessel downtime. Within the framework of the project "Mitigating the interactions between endangered marine species and fishing activities" (funded by the MAVA Foundation and coordinated by ACCOBAMS and the GFCM), one action proposed involved the reinforcement of the threads in the weakest parts of the purse seine in order to increase their resistance to the attacks by bottlenose dolphins. The first trials of a modified purse seine began in 2018 for the Moroccan fishing fleet with promising results.

3.1.2 Acoustic or visual mitigation

Banging on the steel hull, fireworks and lasers are usually employed by fishers to deter dolphins during purse seining operations in sardine fisheries, with varying levels of success.

To reduce depredation in Moroccan and Tunisian purse seine sardine fisheries, acoustic deterrents have not yet sufficiently provided reliable evidence of their effectiveness, at least for the bottlenose dolphin.

Northeast of Tunisia, pingers (Aquamark 210) were used as deterrents for bottlenose dolphins interacting with purse seining for small pelagic fishes. The experiments carried out from June to November 2010 showed limited and inconsistent decreases in dolphin attacks (measured by comparing the number of rips in nets) due to the use of pingers (Benmessaoud, 2008; Benmessaoud *et al.*, 2018).

In Morocco, three types of acoustic devices from the same company (SaveWave) with different configurations were tested in 2005 and 2010 without significant results. At the beginning, the experiment with the deterrent effect showed favourable results, but they gradually diminished as the dolphins became accustomed to the signal. Another dolphin deterrent device (DDD) — the DDD H3 from STM — was tested by Moroccan fishers without producing satisfactory results (Najih *et al.*, 2011).

Pinger failure, differences in fishing techniques or bad experimental conditions are among the possible causes of irregular results, but the majority of users point to the additional problem of dolphins' capacity for habituation to signals. The use of new products generating random frequencies and pulse times could delay this behaviour and reduce depredation but will not eliminate it entirely.

Safe release
Sardine purse seining occurs especially at night, so detecting cetaceans near the purse seiner is difficult. Dolphins entering a purse seine can sometimes be detected after hauling begins, or eventually during pursing. In the Portuguese fishery, for example, each encirclement generally involves only one dolphin, and the technical processes required to effectively avoid its capture, such as the backdown manoeuvre, are not possible without costly changes to the seine. The current approach to releasing the dolphin (unfortunately of common use in other fisheries) includes putting a rope around its caudal peduncle[2], and lifting with a crane to release it from the net in a difficult operation (potentially causing both stress and injury to the animal).

Marçalo *et al.* (2015) suggest prioritizing ways to mitigate operational interactions with cetaceans to avoid encirclements and improving and developing new release techniques, including simple tools such as a dolphin release stretcher that not only decreases physical trauma to the dolphins, but also reduces the time required to release them.

3.2 Seabirds

A survey of Portuguese purse seine fishing showed that seabirds were incidentally caught (BirdLife International, 2010). Most purse seine fleets targeting small clupeids (for example, sardines) use light sources to attract the shoals at night before encircling them. During these fishing operations, birds foraging for fish can be attracted and become enmeshed. This problem mainly affects the Balearic shearwater (*Puffinus mauretanicus*), which is on the brink of extinction, the northern gannet

2. i.e. the narrow part of the body to which the tail attaches.

(*Morus bassanus*), Cory's shearwater (*Calonectris borealis*) and the great cormorant (*Phalacrocorax carbo*) (ICES, 2013). Purse seiners operating in the breeding and feeding grounds of endemic species may cause occasional, but significant, bird mortality (Arcos, Louzao and Oro, 2008; Schlatter *et al.*, 2009). Purse seining for small pelagic fishes has also been cited as causing food dependency, similar to that observed with cetaceans, and which may lead, for example, to the expansion of the bird species that feed on them at the expense of other bird populations (Sacchi, 2008).

3.2.1 Setting improvements

Little information is available on the incidental bycatch of seabirds by purse seine techniques. Large numbers of flesh-footed shearwaters (*Ardenna carneipes*) have been caught in a western Australian purse seine fishery targeting pilchards. This bycatch occurs when fishing activities are pursued in close proximity to the birds' breeding grounds and when they are provisioning chicks. Baker and Hamilton (2016) showed that fishing at night and respecting spatial closures could eliminate seabird bycatch in the fishery. Additional mitigation measures, such as spraying water to sink the floatline and create a buffer between the top of the net and the water surface, thus improving the net retrieval phase, have been successful in greatly reducing seabird interaction levels in the western Australian fishery.

Similarly, modifying purse seine nets targeting the Araucarian herring (*Strangomera bentincki*) and Peruvian anchovy (*Engraulis ringens*) in Chile seems to offer a promising method to reduce bycatch of the pink-footed shearwater (*Puffinus creatopus*). A new design, which removes excessive floating mesh was used in sea trials over 93 days by the Albatross Task Force, and resulted in a marked reduction in bycatch of diving and entangled seabirds in the purse seine by 98 percent (Suazo *et al.*, 2018).

3.3 Sharks and rays

Although little information on shark bycatch in purse seining is available from the Mediterranean, it can be assumed that some species, such as the blue shark (*Prionace glauca*), the common thresher (*Alopias vulpinus*) and members of the Dasyatidae, which includes stingrays, are occasionally caught during bluefin tuna or small pelagic fishing trips. Their large size and low commercial value mean that the individuals caught are often released by the crew before the catch is hauled onboard.

On the other hand, tropical tuna purse seine vessels using FADs, floating structures that attract tuna, can result in a large amount of shark bycatch. For example, several species, mainly silky sharks (*Carcharhinus falciformis*), attracted to FADs end up entangled and die in the net structures hung under FADs (Hall and Roman, 2013; Filmalter *et al.*, 2013). Although limited research has been conducted on shark bycatch mitigation in purse seine fisheries, there are a few promising lines of research being pursued, including with ecological FADs and deterrents, (Restrepo, Dagorn and Moreno, 2016; Restrepo *et al.*, 2019), as well as with good onboard practices (Poisson *et al.*, 2016), avoidance of shark areas, restrictions on setting times, and closures at certain times of the year (Kaplan *et al.*, 2014; Forget *et al.*, 2015; Schaefer *et al.*, 2015).

When tuna schools are associated with whale sharks and baleen whales, purse seining may lead to incidental deaths, at least during the manoeuvres to release these large individuals from the net. Nevertheless, Escalle *et al.* (2015, 2019) have shown that whales escape unharmed in the majority of cases. The practice of setting nets where whale sharks are present is increasingly discouraged, however, by regional fisheries management organizations (RFMOs) through regulations, such as the Western and Central Pacific Fisheries Commission (WCPFC) Conservation and management measure for the protection of whale sharks from purse seine fishing operations CMM2012-04

(WCPFC, 2012a) and the Inter-American Tropical Tuna Commission (IATTC) Resolution C-13-04 on Collection and Analyses of Data on Fish-Aggregating Devices (IATTC, 2021).

3.3.1 Excluder devices

An experimental release panel was installed in purse seine nets to determine their ability to release both silky sharks and non-target finfish, i.e. bony and cartilaginous fish. The release panels (5.5 m wide) were installed in a portion of the net that forms a pocket toward the end of net retrieval. Tests were carried out during seven purse seine settings, but only two silky sharks (out of 105) exited through this panel. Despite this failure, the authors consider that refinement of the panel and additional testing are still warranted (Itano *et al.*, 2012).

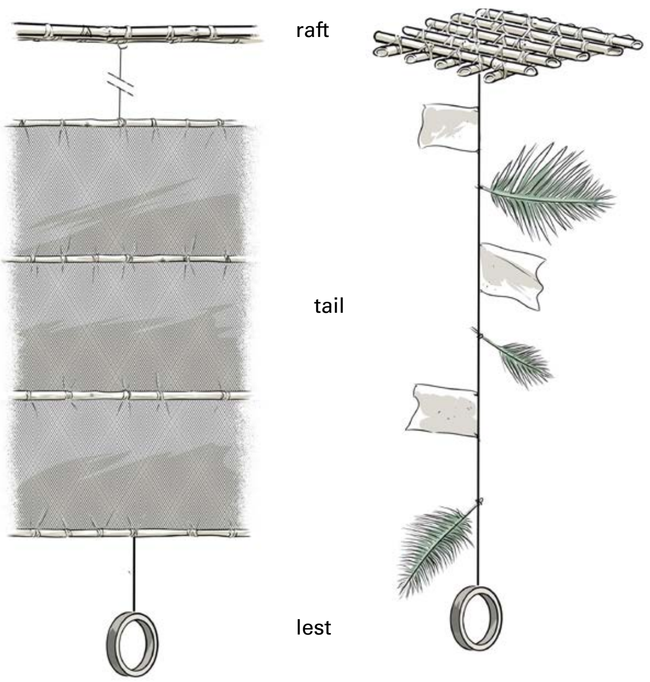
3.3.2 Ecological fish aggregating devices

Fish aggregating devices often represent entanglement hazards, especially when constructed with surplus purse seine netting, as is common in the fishery. This webbing, which hangs in panels suspended below the raft to a depth of 15 m or more, can potentially entangle animals, including sensitive species such as sharks and turtles. Futhermore, when FADs are lost and float adrift, they consequently present an important risk for sharks and pelagic fishes to be caught by ghost fishing.

To resolve this incidental entanglement issue, a number of research projects have investigated several alternative FAD designs (Schaefer and Fuller, 2011; Franco *et al.*, 2012; Lopez *et al.*, 2019). The International Seafood Sustainability Foundation (ISSF) has produced a document summarizing the recommendations for non-entangling FAD construction, i.e. of an ecological FAD (Figure 11), including with the surface structure not covered or only covered with non-meshed material. If the surface structure is covered, log-shaped (i.e. cylindrical) or spherical floats will naturally deter turtles from climbing onto the device, and these should be preferred to flat rafts (ISSF, 2019).

The RFMOs involved in tuna fisheries, such as the IATTC, the Indian Ocean Tuna Commission (IOTC) and the International Commission for the Conservation of Atlantic Tunas (ICCAT) have adopted recommendations on measures for FAD designs that minimize entanglement. The idea of switching to less entangling types of FADs is gradually being embraced by tuna fishers, in the light of experiences showing that reduction of entangling FADs may be a viable and positive option (Murua, Moreno and Restrepo, 2017).

FIGURE 11
Ecological fish aggregating device



Examples of ecological and biodegradable FADs: raft – cover of canvas, tarpaulin, shade cloth, or non-entangling materials; tail – made of ropes, canvas, nylon sheets, palm fronds, etc; lest – made of other non-entangling materials.

Redrawn from ISSF, 2019.

3.3.3 Setting improvements

Setting restrictions are useful management measures when technical solutions are insufficient to reduce bycatch of vulnerable sharks. For example, according to Dagorn (2010), silky sharks appear to move away from FADs at night, and therefore restricting when sets can be made may prove useful (Cosandey-Godin and Morgan, 2011). In the same spirit, the WCPFC and the IOTC have banned the intentional setting of nets around whale shark by precautionary approach considering that they are vulnerable, ecologically important and emblematic species. (WCPFC, 2012b; IOTC, 2019).

3.3.4 Acoustic and chemical mitigation

Preliminary studies are investigating the feasibility of using deterrents, such as sounds and chemicals for keeping sharks, mainly the silky shark, away from FADs, before setting the purse seine, thereby reducing incidental capture (Kondel and Rusin, 2007). Chemical stimuli have been tested more to lure sharks away from FADs before purse seine setting than as repellants. For example, trials were conducted by towing a bag of bait to draw sharks away from a FAD during a scientific cruise in the Indian Ocean (funded by the ISSF Bycatch project[3]). Results were inconclusive, with some sharks following the bait over long distances, while others showed no reaction. Indeed, the FAD remained a very strong attraction stimulus (Dagorn, 2011).

3.3.5 Safe handling and release

Releasing large animals from a purse seine after encirclement is difficult during fishing operations. Poisson *et al*. (2012, 2014) underline in a leaflet of good practices for fishers the adverse conditions that sharks and rays are exposed to during purse seining operations, i.e. when they are brought from the purse seine to the deck before being released at sea. Furthermore, they recommend avoiding the use of hooks, wires or tightening slings, as well as lifting or dragging the animals by the gill slits or cephalic lobes, and propose some simple technical solutions to reduce the risk of mortality after release. Nevertheless, these techniques require some deck management and training for the crew.

The whale shark is a particularly vulnerable species, owing to its biological characteristics (slow growth, late maturation and great longevity), that can be occasionally encircled in tropical tuna purse seining. However, scientific onboard observer programmes and satellite tag results suggest a good chance of survival when they are released through an appropriate method, such as cutting the lacing between the corkline and net, or the net itself, which may be the safest way to release a whale – though for sharks, rolling them out of the end of the net is generally more acceptable and considered safer for the fishers (Escalle *et al*., 2016).

3.4 Sea turtles

The incidental catch of sea turtles is a concern for tuna purse seining. Interactions with purse seining can occur in sea turtles' habitats or along their long oceanic migration routes (Luschi, 2013). Nevertheless, Hall and Roman (2013) showed in their review that purse seine fisheries experience few interactions with marine turtles, and that as bycatch, sea turtles are present in usually less than 1 percent of the nets set.

3. A global, non-profit partnership, among the tuna industry and scientists, which has the goal of improving the sustainability of global tuna stocks by developing and implementing verifiable, science-based practices, commitments and international management measures.

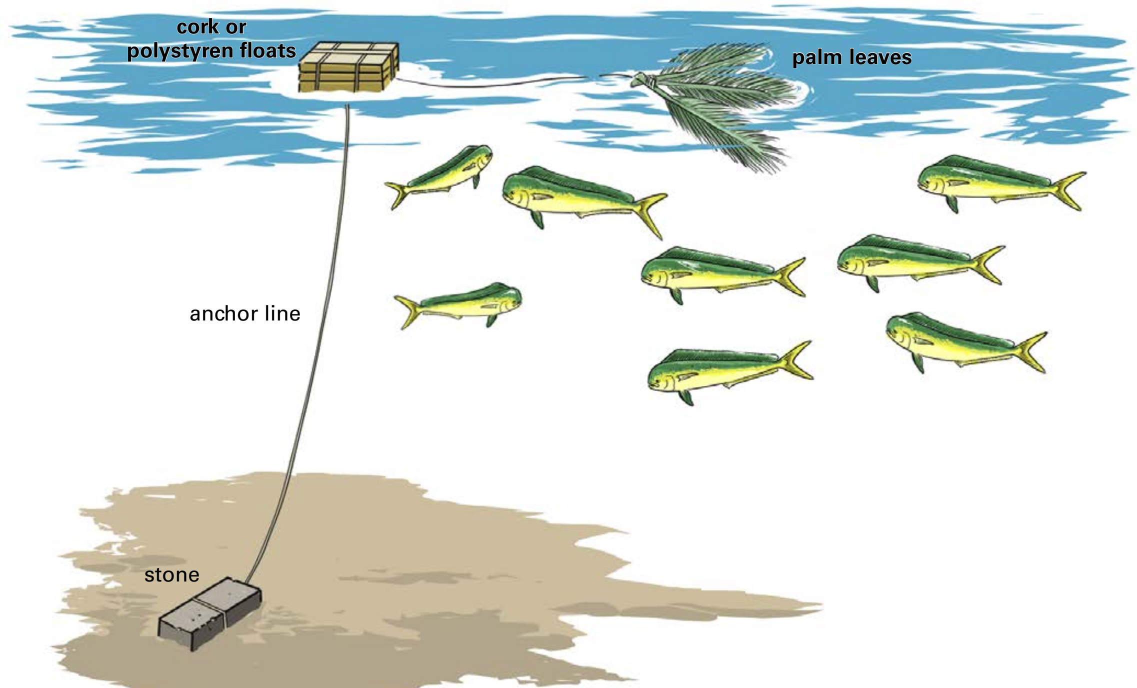
An analysis of 213 000 sets laid by the European purse seine fleets in both the Atlantic and Indian Oceans from 1995 to 2011 did not find any significant correlation between a purse-seine surrounding free swimming schools and a purse seine surrounding school aggregated under a floating object (drifting FAD). The only difference observed was in the Indian Ocean where the annual average sea turtle bycatch per sets on free swimming schools was smaller than with drifting FADs (0.05 and 0.1, respectively) (Bourjea *et al.*, 2014).

Most of the bycatch occurs when the purse seiners encircle tuna schools. Sea turtles are usually found entangled in the net by their flippers but can be released alive when the net is pulled up from the water towards the power block.

Entanglement in the netting materials suspended under FADs to attract fish presents a greater risk for sea turtles, as for small sharks. For example, juvenile sea turtles in their drifting pelagic phase, attracted by FADs for protection, food or a resting site, may become entangled for a long time and die by drowning. Another cause of bycatch mortality is the loss of an unknown number of FADs due to currents, setting them adrift towards the shore and contributing to the phenomenon known as ghost fishing (for example, Chanrachkij and Loog-on, 2003).

Traditional FADs have a long history of use throughout the Mediterranean Sea, mainly in Malta, Tunisia and the Balearic Islands. These devices, called *cannizzati* in Sicily and *kannizzatti* in France (Figure 12), are anchored FADs; currently, only the dolphinfish (*Coryphaena hippurus*) fishery utilizes this under-raft attraction technique. During the fishing season, loggerhead turtles (*Caretta caretta*) moving from neritic to oceanic habitats can become entangled in the anchoring lines of these artisanal FADs, which wrap around their necks and flippers. As with FADs used in tropical tuna purse seining, some of these *kannizzatti* can break away from their anchorages if they are not removed by fishers after the fishing season and consequently represent a potential risk of entanglement (Blasi, Roscioni and Mattei, 2016).

FIGURE 12
Mediterranean anchor fish aggregating device *kannizzatti*



Redrawn from Sacchi, 2008.

3.4.1 Fishing gear improvements

In order to reduce the risk of entanglement of sea turtles and sharks by FADs, the ISSF recommends the use of ecological FADs with hanging panels of nets without large meshes. Furthermore, the surface structure should not be covered or only covered with a mesh material in which the turtles cannot be trapped. If the surface structure is covered, the contours of log-shaped (cylindrical) or spherical floats naturally deter turtles from mounting the device and should be used in preference to flat rafts. In addition, FADs should be constructed as much as possible from biodegradable materials in order to reduce ghost fishing problems and avoid the incidental catch of sea turtles or other vulnerable species when they are lost or abandoned (Restrepo *et al.*, 2017).

For the Mediterranean FAD anchors, Blasi, Roscioni and Mattei (2016) recommend that fishers remove FADs at the end of the fishing season (December) in order to limit potential entanglement on anchor lines by loggerhead turtles.

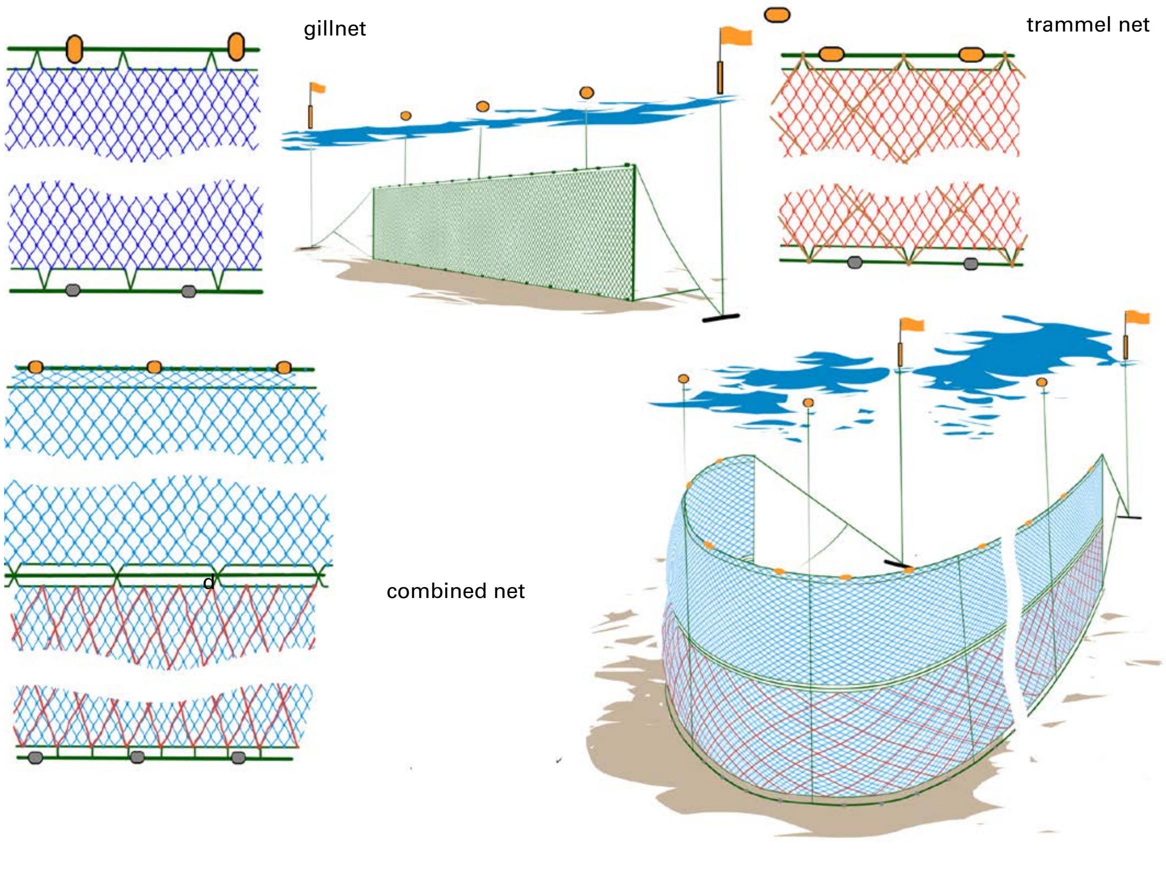
4. Gillnets and entangling nets

The relevant literature includes several descriptions of gillnets and entangling nets (including trammel nets, etc.) along with their designs and their different uses (Nédélec, 1975; Sainsbury, 1996; He, 2006a; Gabriel *et al.*, 2005). They are classified by FAO into seven main types according to their setting modes (Nédélec and Prado, 1990; FAO, 2013).

While gillnets are highly selective in terms of size, they offer limited interspecies selectivity and can catch seabirds, cetaceans, sea turtles and sharks (He, 2006a). Among all fishing techniques, gillnetting represents a particular concern because it is known to be associated with relatively high bycatch mortality of all of the above taxa (Northridge *et al.*, 2016). Set on the seafloor or drifting on the surface, gillnets are one of the most common fishing gear used globally by small-scale fisheries. They generally consist of a single rectangular layer of net (gillnet) or they can come framed by one or two panels of larger mesh (trammel net) (Figure 13); they are mounted vertically between a headline with floats and a weighted bottom line. Some Mediterranean fisheries use combined nets consisting of trammel nets topped with gillnets and are thus referred to as combined gillnets–trammel nets (Figure 13). The webbing hangs from the headline to the bottom line, attached by a hanging twine (staple), which is stitched to the headrope at regular intervals.

Several studies, dealing in particular with selectivity (for example, Baranov, 1948; Hamley, 1975; Sacchi, 2002; Hovgård and Lassen, 2000), show that fish can be caught (Figure 14) either in the mesh of the net (gilled or wedged) or entangled (snagged, hooked or wrapped in the net panel).

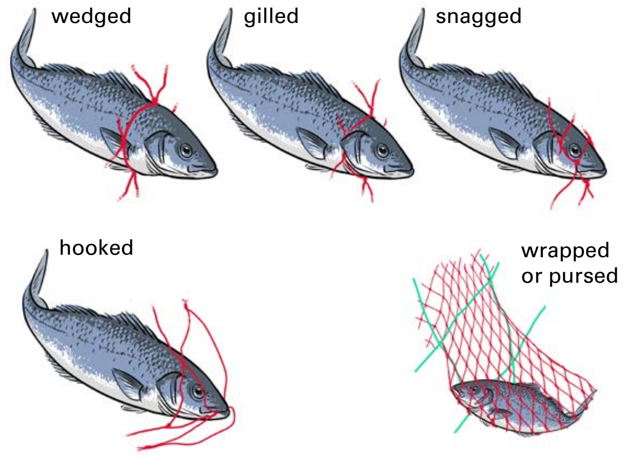
FIGURE 13
Bottom-set nets



Redrawn from Sacchi, 2008.

Depending on the type of species targeted, the fisher will favour one of the two mechanisms (i.e. gilled or entagled fish) for the construction of fishing gear, for example, by using preferably an entangling net for flatfish, large individuals or crustaceans.

FIGURE 14
Fish capture mechanisms



Redrawn from Sacchi, 2008.

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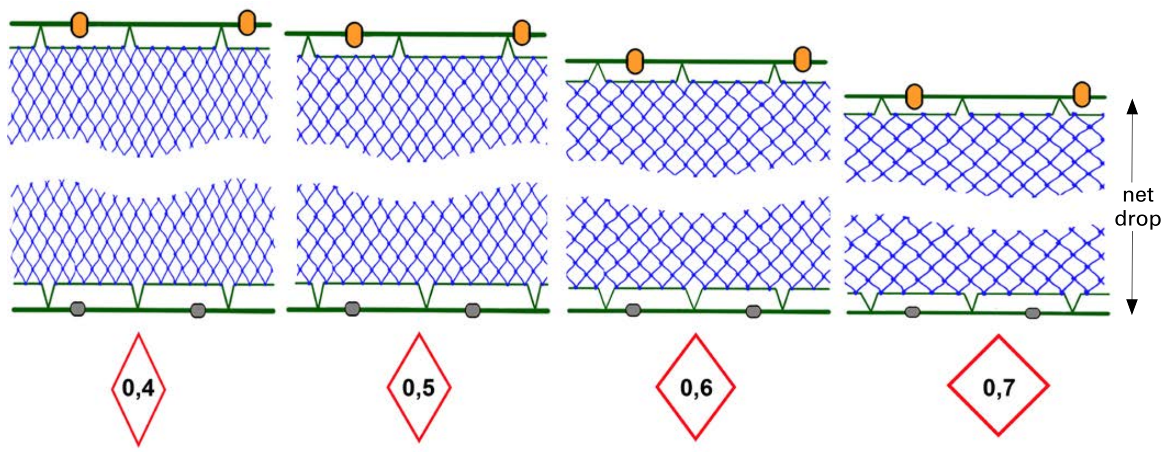
The net depth (D), or the stretched height of the net panel (Figure 15), should not be confused with the net drop (d), which is the vertical distance between the headrope (headline, floatline) and the footrope (lead-line) and determines the theoretical fishing height of a set net (i.e. headline height). The net drop (Figure 15) depends first on the depth and the hanging ratio, then buoyancy and other external factors, such as the catch and water dynamics (tides, currents, etc.). The ratio between the drop and depth determines the slackness (S = d/D) of the net panel.

FIGURE 15
Hanging ratios



Effects of the hanging ratio on mesh opening and on net drop.

Redrawn from Sacchi, 2012.

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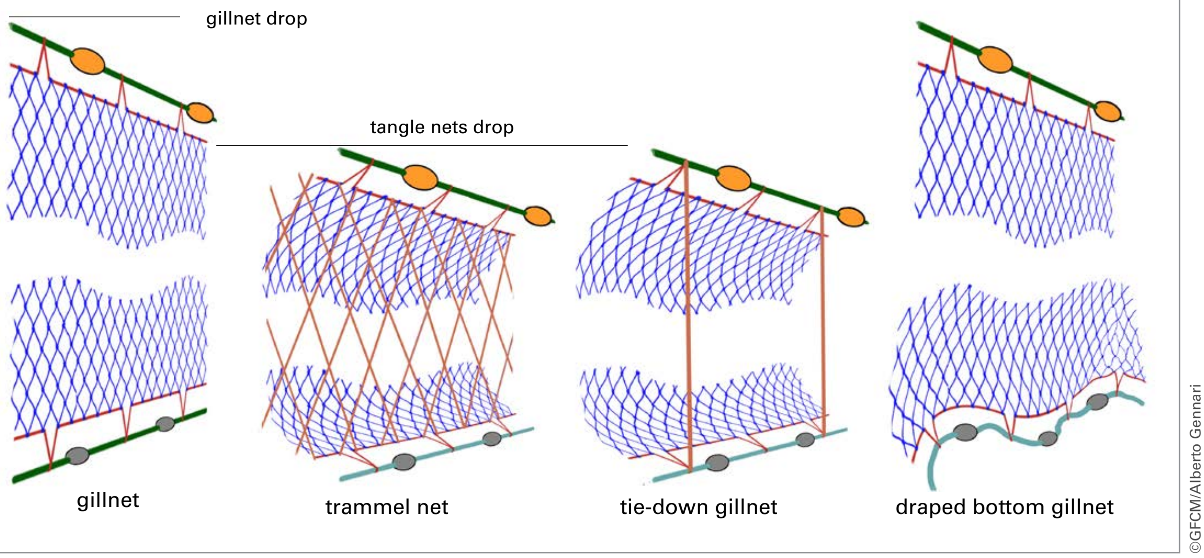
Entanglement can be facilitated by slackness between the headrope and footrope. This slackness (Figure 16) can be created in various ways:

- by reducing the vertical tension on the net panel with fewer or no floats on the headline;
- by reducing the horizontal tension on the net panel by lowering the ratio of the floatline length to the stretched net sheet (hanging ratio), while still keeping a long staple twine. Increasing the hanging ratio alone is not sufficient to reduce entanglement and the risk of catching protected species, as shown by the comparison of monofilament gillnets with hanging ratios of 0.33 and 0.5 used in monkfish (*Lophius americanus*) and ray fisheries in the Gulf of Maine (United States of America) conducted by Schnaittacher (2010);
- by increasing mesh flexibility (adjusting the nature of the thread, decreasing diameter, use of multifilament, etc.);

FIGURE 16
Net slackness



- by increasing the mesh size: the turbot and monkfish fisheries, which generally use very large meshes, are among the fisheries with the highest bycatch rates in the world, as has been demonstrated for Danish fisheries (Vinther, 1999), the Black Sea gillnet fisheries (Bilgin, Kose and Yeşilçiçek, 2018; Birkun *et al.*, 2014) and the monkfish bottom-set net fisheries on the east coast of the United States of America (Wiedenfeld, Crawford and Pott, 2015); and
- by bridling the net panel through the addition of one or two shorter panels (trammel nets) or simply vertical ropes (tie-down gillnets) (Figure 16). In some bottom nets, such as in the Mediterranean coastal fisheries, the footline is longer than the waterline, giving more looseness in the lower part and increasing entanglement (Figure 16).

Nets with high slackness facilitate the entanglement of large individuals or flatfishes (such as turbot, rays, among others), and consequently the retention of small cetaceans, as well as sea turtles and sharks.

4.1 Marine mammals

Reliable bycatch estimates have largely been hindered by a lack of fisheries effort data, especially for gillnets. From the extrapolation of bycatch data in American fisheries (1994–2006) and available metrics of fishing effort from FAO, Read, Drinker and Northridge (2006) estimate that gillnet fisheries are responsible for 84 percent of cetacean bycatch worldwide.

In the Mediterranean and in the Black Sea, several studies (for example, Bearzi, 2002; Birkun *et al.*, 2014) confirm the substantial contribution of gillnets to cetacean bycatch, with numbers of individuals caught in gillnets greatest for those species mainly distributed in coastal and shelf waters (Reeves, McClellan and Werner, 2013). In addition to the problem of incidental catch of cetaceans, some species, such as dolphins, depredate gillnet fisheries, which provide them a more accessible food supply. Reporting mostly from coastal areas, particularly in the Mediterranean (Díaz López, 2006), several authors (Brotons *et al.*, 2008; Lauriano *et al.*, 2009) note that the depredation of gillnets by cetaceans almost always concerns the bottlenose dolphin (*Tursiops truncatus*).

4.1.1 Fishing gear improvements

Net height

As gillnets targeting cod (*Gadus morhua*) catch more harbour porpoises (*Phocoena phocoena*) than trammel nets for sole do, the Ministry of Agriculture, Environment and Rural Areas of the Federal State of Schleswig Holstein has limited the height (drop) of bottom-set gillnets used in the German Wadden Sea National Park to 1.3 m. Nevertheless, further observations showed that this measure was insufficient to avoid incidental catch of harbour porpoises (Pfander, Benke and Koschinski, 2012). In fact, this measure does not appear to take into account other technical aspects of net design (such as the issues of net slackness mentioned above) or even soak time, which is considered the primary predictor of gillnet bycatch (ICES, 2009).

4.1.2 Acoustic mitigation

Developed primarily to deter marine mammals from approaching and interacting with fishing gear or cages, acoustic mitigation devices generally fall into one of two categories: acoustic harassment devices (AHDs), which were initially developed to reduce depredation by pinnipeds, or acoustic deterrent devices (ADDs), designed to mitigate cetacean bycatch (ACCOBAMS, 2010; Mackay and Knuckey, 2013; Northridge, Vernicos and Raitsos-Exarchopolous, 2003; Reeves *et al.*, eds., 1996).

Acoustic harassment devices

Acoustic harassment devices produce intense sounds (above 185 dB re 1 μPa) at a depth of 1 m, sufficiently painful and disturbing to keep animals at a distance, to protect, for example, finfish cage farming. Acoustic harassment devices operate mainly in the 5–30 kHz frequency band. The emitted stimuli produce an immediate response in the animals and induce hazard perception learning over time. Nevertheless, the high-pressure levels pose a risk of permanent damage to cetacean hearing (Gordon and Northridge, 2002), and these devices may exclude some animals from important habitats (Olesiuk *et al.*, 2002).

Acoustic deterrent devices

Acoustic deterrent devices, also called pingers, are acoustic devices emitting middle- to high-frequency stimuli (10–100 kHz) at low intensity (generally below 150 dB re 1 μPa) at a depth of 1 m, with higher harmonic frequencies (up to 160–180 kHz). These harmonic frequencies deter dolphins (Northridge, Vernicos and Raitsos-Exarchopolous, 2003; Reeves *et al.*, eds., 1996); they are unlikely to cause discomfort and their aim is to alert marine mammals to the presence of nets.

Acoustic deterrent devices have been shown to reduce dolphin bycatch in a wide variety of fisheries (Franse, 2005; Mackay and Knuckey, 2013; Gönener and Özsandıkçı, 2017; Reeves *et al.*, eds., 1996; Dawson *et al.*, 2013), but their success varies by species, the technical characteristics of the pingers and their terms of use. Several of these studies show that pingers significantly reduce the bycatch of harbour porpoises and Cuvier's (*Ziphius cavirostris*) and Hubbs' (*Mesoplodon carlhubbsi*) beaked whales.

On the other hand, they show more variable effects on the bottlenose dolphin (Barlow and Cameron, 2003; Carretta and Barlow, 2011; Carretta, Barlow and Enriquez, 2008; Zahri *et al.*, 2004), the short-beaked common dolphin (*Delphinus delphis*), the striped dolphin (*Stenella coeruleoalba*) and the La Plata dolphin (*Pontoporia blainvillei*) (Rossi and Rossi, 2004; Balle, Mackay and Sagarminaga, 2010; Dawson *et al.*, 2013).

Failure to avoid bycatch is often due to the misuse of these devices: attempts to reduce striped dolphin bycatch in the bluefin tuna (*Thunnus thynnus*) driftnet fishery in Provence employing AquaMark® pingers were inconclusive due to the parsimonious use of the devices by fishers, insufficient spacing of the devices and no systematic replacement of used batteries (Imbert *et al.*, 2007).

Habituation to repulsive sounds is often reported in relevant literature (Gordon and Northridge, 2002; Dawson, Read and Slooten, 1998; Reeves, Read and Notarbartolo di Sciara, eds., 2001; Trippel *et al.*, 1999; Cox *et al.*, 2001, 2004) as a leading cause of failure in the use of acoustic repellents.

Long-term deployment of acoustic alarms in several commercial fisheries has not resulted, however, in an increase in cetacean bycatch rates, as long as the nets are properly equipped with functioning pingers (Carretta and Barlow, 2011; Palka *et al.*, 2008; Dawson *et al.*, 2013). Habituation is not always observed and seems to depend on the species. Cox *et al.* (2001) found that non-captive harbour porpoises appear to habituate themselves to Dukane Netmark® 1000 pingers relatively rapidly, after a few days, showing a reduction in the initial avoidance distance by 50 percent. The same experiment conducted later with the same pingers on groups of bottlenose dolphins did not achieve any decisive results (Cox *et al.*, 2004).

The question of habituation arises also with regard to the issue of depredation (or prey removal), particularly by bottlenose dolphins targeting gillnet catch.

Observations of bottlenose dolphin behaviour around nets equipped with pingers suggest that even if the pingers do not completely eliminate the interactions, they can help to reduce the effects. In Greece, Northridge, Fortuna and Read (2003) recorded significantly fewer holes (69 percent) attributed to dolphin depredation in trammel nets equipped with dolphin saver pingers. Similar results were obtained in the Balearic Islands by Gazo, Gonzalvo and Aguilar (2008) and Brotons *et al.* (2008), and Buscaino *et al.* (2009) in Sicily, though differences in interaction rates depended on the devices used.

According to Dawson *et al.* (2013), bottlenose dolphins might take advantage of pingers, showing great enough cognitive ability to associate the sounds with where to find nets and trapped prey and to adapt their foraging behaviour accordingly, assisted by a probable tolerance to higher acoustic pressures than other dolphins (Luís, Couchinho and dos Santos, 2014). Gazo, Gonzalvo and Aguilar (2008) suggest that habituation may occur rapidly if the acoustic disturbance is moderate, and particularly for the bottlenose dolphin, "a species thought to be more adaptable to human impact than many other cetaceans" (Whitehead, Reeves and Tyack, 2000).

Therefore, to reduce the risk of habituation, pingers must emit randomly with pulses selected over a broad frequency spectrum (from 30 to 150 kHz) and with variable 3 to 10 second intervals between signals (Le Gall *et al.*, 2004). This line of research requires further development and at-sea testing. Restricting pinger use to certain periods of time may also represent a viable alternative, as Amano *et al.* (2017) have suggested for reducing bycatch of the endangered finless porpoise (*Neophocaena asiaeorientalis*) (IUCN, 2021) in Omura Bay set net fisheries (Japan).

Other lines of research have also been explored, such as the use of percussion tubes (for example, Zahri *et al.*, 2004) and mimicking killer whale calls (ICES, 2010).

Net acoustic reflectivity

Increasing net reflectivity to echolocation is a passive way to reduce the incidental catch of dolphins and an alternative technical measure to acoustic alarms.

TABLE 1 – Studies on the deterrent performance of some pingers on the bottlenose dolphin (*Tursiops truncatus*)

Pinger	Frequency (khz)	Source level (db)	Response	Location	Author(s)
SaveWave® **Dolphin saver**	30–160	155	Significant reduction in depredation and number of holes in the nets 1 dolphin caught	Aegean Sea (Greece)	Northridge, Vernicos, Raitsos-Exarchopolous, 2003
Aquamark® 210 **Dukane** **Netmark® 1000** **SaveWave®** **Dolphin saver**	5–160	130–155	49% reduction in interactions No impact	Balearic Islands	Brotons *et al.*, 2008
Aquamark® 100	20–160	145	87% fewer holes Depredation rate reduced by about 50%	Balearic Islands	Gazo, Gonzalvo and Aguilar, 2008
DDD 0.2	0.1–200	160	31% fewer holes and 28% more fish	Favignana Island (Italy)	Buscaino *et al.*, 2009
Fumunda (Future Oceans)	10	132	Risk of interactions decreases from 81 to 50%	Hatteras, North Carolina	Read and Waples, 2010
Fumunda (Future Oceans)	70	145	No difference with control nets	Hatteras, North Carolina	Read and Waples, 2010
SaveWave® **Dolphin saver**		155	Significantly fewer interactions	Hatteras, North Carolina	Waples *et al.*, 2013

Source: From Dawson *et al.*, 2013.

Using thicker thread and adding a metallic-based coating (barium sulphate, iron oxide) in the construction of nets increases acoustic reflectivity, potentially reducing the incidental catch of species with echolocation capabilities (Trippel *et al.*, 2003; Cox and Read, 2004; Larsen, Eigaard and Tougaard, 2002; 2007) and increasing the catch of commercial fish species compared to control nets. Larsen, Eigaard and Tougaard (2002) indicate, however, that no significant differences in the acoustic target strength have been noticed between modified and control nets, suggesting that the reduction in bycatch was caused not by an increase in acoustic reflectivity, but rather by the mechanical properties of the thread (e.g. stiffness). Nevertheless, while these material modifications have been shown to be effective in Hawaiian waters for bottlenose dolphins and harbour porpoises (Mooney *et al.*, 2007), experimental trials undertaken at a gillnet artisanal fishery in Argentina did not show a reduction of bycatch of the La Plata dolphin, also known as the franciscana dolphin (Bordino *et al.*, 2013). Trippel *et al.* (2003) conclude that coating to produce thicker twine increases net stiffness, thus reducing entanglement properties. Consequently, increasing net rigidity may help reduce bycatch in some cases, but also risks reducing target species catch and should therefore be complemented by other changes in the net.

Passive acoustic devices

A number of studies have dealt with the use of reflectors as passive acoustic devices in order to make gillnets more acoustically visible to echolocating cetaceans, though they showed mixed results (Goodson, 1997; McPherson, 2011; Koschinski and Culik, 1997; Gordon and Northridge, 2002; McPherson and Nishida, 2010; Goodson, Woodward and Newborough, 2001). These reflector devices (metallic heads, gillnets with barriers and floatlines, among others) could induce avoidance behaviour in some species, or keep dolphins at short distances from the net, but their effects were not consistent across all groups.

4.1.3 Chemosensory mitigation

Cetaceans (Odontoceti), i.e. toothed whales, such as dolphins, do not possess olfactory bulbs or nerves, which are poorly developed in Mysticeti, i.e. baleen whales (Kishida *et al*., 2015a, 2015b). However, cetaceans do have taste buds in the root region of their tongue and research on deterrent solutions using chemoreception appears more promising (Friedl *et al*., 1990). According to studies undertaken on captive animals, i.e. short-beaked common dolphins, bottlenose dolphins and harbour porpoises, this quasi-olfaction (Kuznetzov, 1990), which helps to detect pheromones and induces different chemical cues in the animals (Nachtigall, 1986; Kishida *et al*., 2015a, 2015b), might play a role in reproduction in particular.

4.1.4 Visual mitigation

Few significant studies have been undertaken targeting cetaceans' visual abilities with deterrents in static net fisheries (Childerhouse, Miller and Steptoe, 2013), and indeed visual deterrents have not been extensively tested in cases of marine mammal/fishery conflicts interactions (Schakner and Blumstein, 2013).

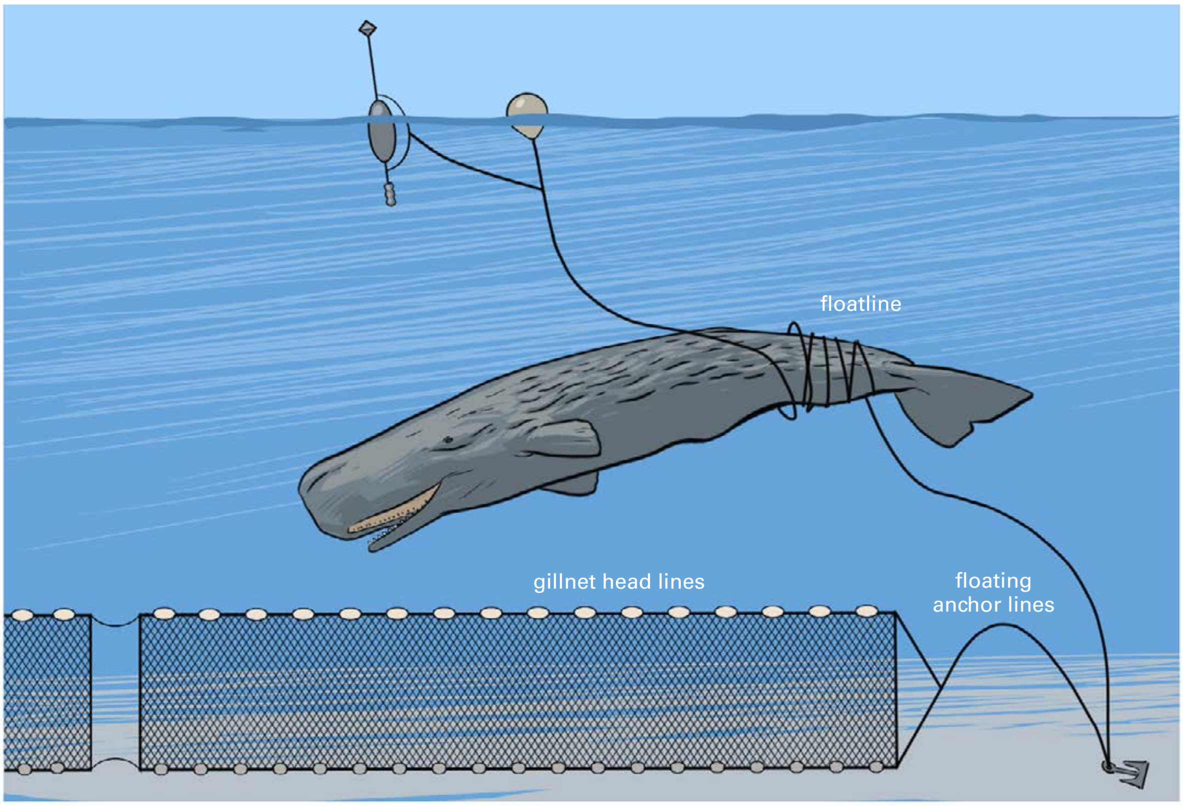
4.1.5 Setting improvements

Buoy rope modification
Entanglement in the buoy lines of nets, as for any static fishing gear (for example, pots, longlines, among others), can cause cetacean bycatch (Figure 17). As shown by Knowlton *et al*. (2016) and the Consortium for Wildlife Bycatch Reduction (2014), entanglement can occur through a variety of ways, though mostly through entanglement of the fins, the mouth – particularly in the baleen whales (Mysticeti) – or the tail. The main technical reason is excessive rope length, resulting in loops in the upper water layer. It is therefore generally recommended to use sinking ropes for the upper two-thirds of the buoy lines and weighted branch lines between the anchor points and the end lines (Johnson *et al*., 2005; FAO, 2018).

Generally, the breaking strength of buoy line ropes should be sufficient to withstand the hauling of fishing gear under normal fishing conditions, while allowing a large cetacean to free itself without too much difficulty in the case of entanglement. For example, Knowlton *et al.* (2016) showed that the use of ropes with breaking strengths of 7.56 kN (e.g. polypropylene with an 8 to 10 mm diameter) could reduce by at least 72 percent the number of entanglements of large cetaceans, such as the North Atlantic right whale (*Eubalaena glacialis*) and the humpback whale (*Megaptera novaeangliae*).

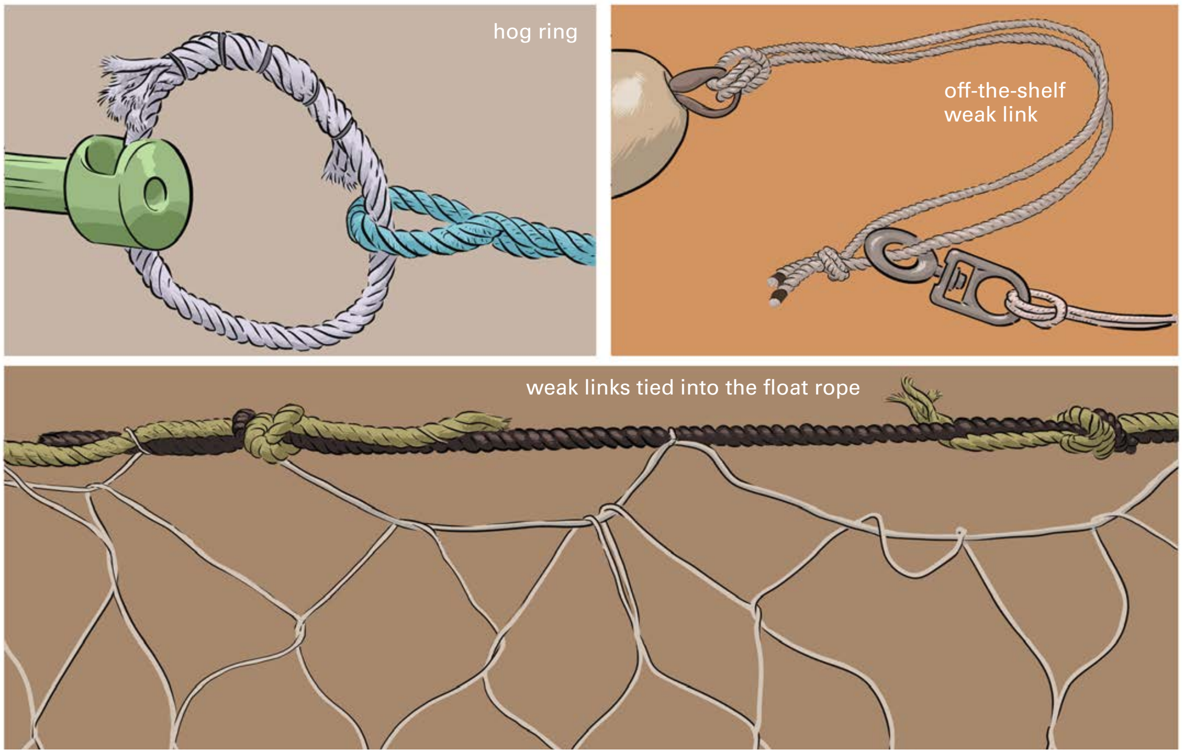
Weak links
The intent is to allow fishers to use weak links for fishing which also allow a large whale to break free if entangled (Figure 18). To this end, various solutions have been proposed (Werner *et al*., 2006) for weak links (including swivels) connecting the set gear (such as gillnets or pots) to the marker buoy line, which would break under any pressure maintained for longer than the time required to haul in the gear, with the idea that broken lines help free entangled animals (Knowlton *et al*., 2016; FAO, 2018).

FIGURE 17
Main risks for whale entanglement



Adapted from Center for Coastal Studies, 2021.

FIGURE 18
Weak links



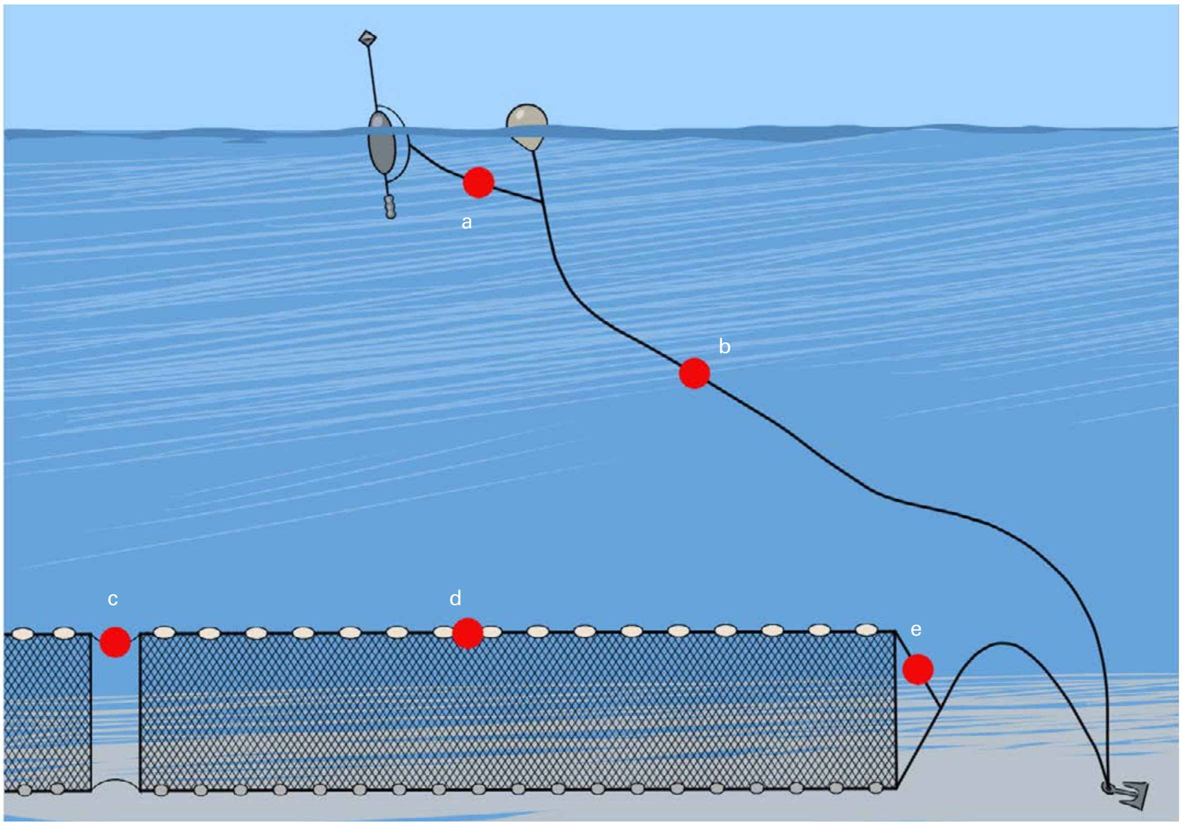
Hog rings can be used to form an eye in the end of a line that will function as a weak link. Weak links tied into the float rope with the fisher's knots can reduce the strength of the rope to about 60 percent of its original strength.

Adapted from NOAA, 2018.

For example, in its plan to reduce the bycatch of large whales by gillnet fisheries in the Atlantic, the National Oceanic and Atmospheric Administration (NOAA) (2018) recommends fixing weak links at specific points along the net and its rigging in order to facilitate the release of a whale (or other large animal) tangled either in part of the net or in the different ropes of the rigging (Figure 19).

Rope visibility
The concept of increasing buoy lines' and anchor lines' visibility to whales at night or in the dark depths of the sea has led to the testing of different coloured or luminescent ropes. According to trials undertaken in Cape Cod Bay (United States of America), using mimic ropes, red and orange ropes appear to be more easily detectable by the North Atlantic right whale than green or black (Kraus *et al.*, 2014).

FIGURE 19
Weak links on bottom gillnets



Preferred positions of weak links on a bottom gillnet: between the flag and the buoy (a); on the buoyline (b); between two panels (c); in the middle of the floatline for net panels greater than 50 m in length (d); on the bridle before the anchor line (e).

Redrawn from NOAA, 2018.

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4.2 Seabirds

In general, knowledge of seabird bycatch in gillnet fisheries is highly fragmentary. Even from regions where numerous reports are available, such as the Baltic Sea, information is often traced to short-term studies and opportunistic observations. However, several regions can be identified as especially deficient in information and where the presence of both susceptible species and gillnet fisheries implies potentially high seabird bycatch (Žydelis, Small and French, 2013). Mainly in shallow waters and coastal areas, gillnets present a major risk for diving seabirds, which can easily get entangled and drown.

A number of factors contribute to bycatch risks, including seabird abundance and species composition, overlap between seabird foraging areas and fishing grounds, fishing gear characteristics, water clarity and meteorological conditions. Some mitigation measures have been suggested in Europe and elsewhere, though few have been applied (Bull, 2007).

More recently, under the aegis of BirdLife International, a workshop was organized in 2015 to examine the mitigation methods best adapted to different vulnerable species caught in gillnets (BirdLife International, 2015; Wiedenfeld, Crawford and Pott, 2015). In addition, the European Union has published within the framework of the Executive Agency for Small and Medium-sized Enterprises a review of mitigating measures applicable to static net fisheries in the European Union's waters (excluding the Mediterranean), including reports on tests of two selected methods conducted in Poland and Portugal (Almeida *et al.*, 2017).

4.2.1 Acoustic mitigation

Avian hearing has been studied in a number of species, but there have been very few investigations on seabirds. Nevertheless, birds are known to be primarily sensitive to sound frequencies between 1 and 5 kHz (Winkler, 2001).

In a previous study, pingers with frequencies adapted to seabirds' audiograms were tested in Puget Sound, Washington, United States of America on common murres (*Uria aalge*) and resulted in a 50 percent reduction in incidental catch, but they had no effect on rhinoceros auklets (*Cerorhinca monocerata*) (Melvin, Parrish and Conquest, 1999).

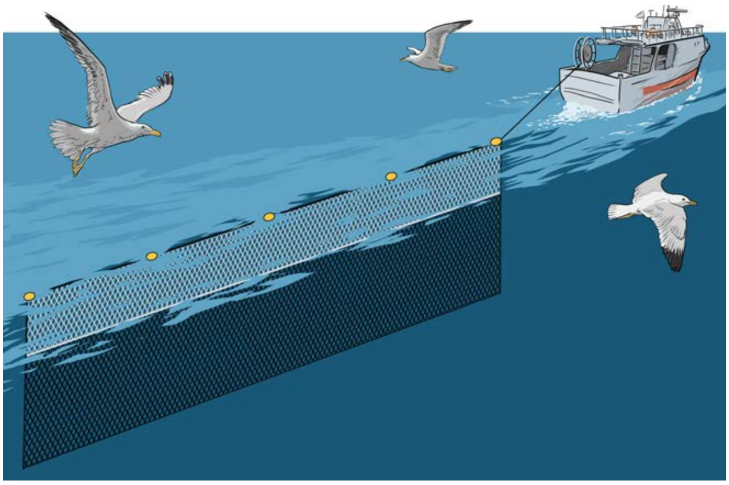
Locating the source of a sound is as important in this context as merely detecting it; the ability of seabirds to locate underwater sources is not well understood and would require further investigation, in particular to determine whether the seabirds would be attracted to such a source instead of avoiding it. Therefore, the use of pingers attached to nets is still of limited application (Martin and Crawford, 2015).

4.2.2 Visual mitigation

Warning net panel

The introduction of monofilament nets has increased seabird bycatch due to their quasi-transparency. Indeed, monofilament nylon gillnets result in a greater bycatch than the traditionally used twined nets (Žydelis *et al.*, 2009). Given their reduced frontal vision, as visual sensitivity has been compromised for better resolution, diving seabirds are unable to see, especially in poor light, the obstacle posed by set gillnets, particularly those of monofilament nylon.

FIGURE 20
Puget Sound warning panel



Warning panel of white braided nylon twine on the upper part of a coastal gillnet for salmon in Puget Sound.

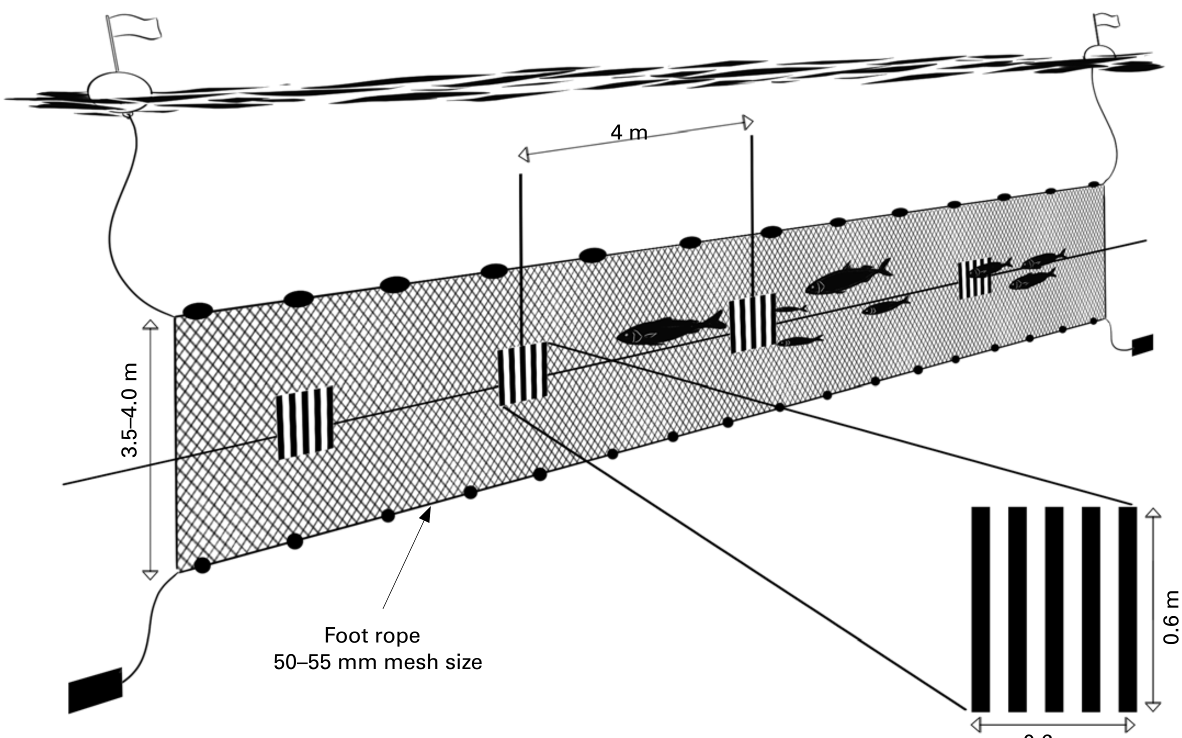
Redrawn from Melvin, Parrish and Conquest, 1999.

Replacing 10 to 25 percent of the monofilament panels of the upper part of the net with a section of more visible white braided nylon twine can offer a sufficiently dissuasive obstacle to prevent birds from getting entangled in the nets as they dive (Figure 20). For example, a significant reduction in seabird bycatch was achieved in the coastal drifting gillnet fishery targeting salmon in Puget Sound, Washington, United States of America, by combining two technical solutions: visual alerts (panels of visible mesh in the top part of the net) and acoustic alerts (pingers). Bycatch of common murres was reduced by 40 and 45 percent in 50- and 20-mesh visual alert nets respectively, while rhinoceros auklet bycatch was reduced by 42 percent only in larger 50-mesh nets (Melvin, Parrish and Conquest, 1999).

The same technique was also tested in a bottom-set gillnet fishery for cod in the Lithuanian Baltic Sea. Standard monofilament gillnets were modified in two ways: either the upper 10 percent of the meshes (equivalent to 40 cm in a net of 4 m height) were replaced with thick white twine or the upper 25 percent of the meshes (equivalent to 1 m in a net of 4 m height) were replaced with the same thick white twine. Although the small number of trials did not allow for statistically significant sample sizes, the limited preliminary evidence suggests that seabirds are still captured in these nets, quite possibly because the deep setting depths of the fishery render the "higher visibility" white netting as imperceptible as the standard monofilament netting (Wiedenfield, Crawford and Pott, 2015).

In a similar vein, other deterrent visual warning techniques have been recently tested in the Baltic Sea. Martin and Crawford (2015) proposed attaching warning panels on nets at regular intervals (Figure 21). They consist of alternating black and white grating, or a checkerboard pattern to achieve maximum contrast. When the weather turns colder, Lithuanian gillnetters target cod closer to the coast and at this time, seabirds are most at risk of capture. According to the authors,

FIGURE 21
Lithuanian warning panels



Net equipped with warning panels in Lithuania.

Redrawn from Martin and Crawford, 2015.

the aim is to deploy visual stimuli along the net to alert birds to its presence rather than distract them away from it. During the winter season of 2015–2016, 53 seabirds were caught in control sets, while only 36 were caught in experimental sets with warning panels without an impact on the commercial catch; long-tailed duck (*Clangula hyemalis*), velvet scoter (*Melanitta fusca*) and common scoter (*Melanitta nigra*) were the most common species captured. Unfortunately, these encouraging results were not confirmed in the winter of 2016–2017 (Tarzia *et al.*, 2017). Indeed, no reduction in seabird bycatch was demonstrated in more conclusive work conducted in the Baltic Sea, which research also paired lighting as a deterrent; some seabirds were even shown to find them attractive (Field *et al.*, 2019).

Net lighting

Though the technique was originally developed for sea turtles (Wang *et al.*, 2013), experiments undertaken on set nets in Peru suggest that increasing nets' visibility using light-emitting diodes (LEDs) significantly reduces seabird bycatch as well, with an 85.1 percent decline in the cormorant catch rate (Mangel *et al.*, 2014). However, Martin and Crawford (2015) noted that diving seabirds may find it harder to detect sections of a net that are not directly illuminated, as acuity (resolution) decreases with light levels. On the other hand, in parallel with the study on the warning panels' efficacy mentioned above, Field *et al.* (2019) tested two types of net lighting: constant green net lighting in the Polish Baltic gillnet fisheries predominantly for cod or herring (*Clupea harengus*) in the Pomeranian Bay, and flashing white net lights in the Lithuanian smelt (*Osmerus eperlanus*) fishery. The results showed that the addition of green net lights had no significant effect on seabird bycatch and, furthermore, that flashing white lights attached to the headline attracted more long-tailed ducks into gillnets than the control nets did.

4.2.3 Setting improvements

Spatio-temporal closures

Numerous authors consider that the spatio-temporal management of fishing effort represents one of the most reliable solutions to mitigate the incidental catch of seabirds in gillnet fisheries. Seabird abundance, and consequently their risk of entanglement, varies by season and over the course of the day, as well as by species. For example, the probability of rhinoceros auklet entanglement is highest at dawn, whereas common murre entanglement is high both at dawn and dusk (Melvin, Parrish and Conquest, 1999).

Temporary fishing closures in important seabird feeding zones (for example, areas adjacent to significant breeding colonies) will reduce accidental bird mortality in those zones.

Although difficult to establish and enforce, spatial and temporal fishery closures are paramount to the management of gillnet bycatch (Regular *et al.*, 2013).

Restrictions on the minimum net-setting depth

The majority of diving seabirds prefer shallow waters and the greatest incidental catch occurs at depths of less than 20 m (Stempniewicz, 1994). Bellebaum *et al.* (2013) noted that the probability of incidental catch declined with increasing depth. In California, a ban on gillnet fishing at depths less than 60 fathoms has almost completely eliminated common murre bycatch (Carretta and Chivers, 2004).

4.3 Sharks and rays

Though some bottom or midwater gillnet fisheries directly target species of sharks in certain families (e.g. Mustelidae, Squalidae, Scyliorhinidae) for commercial purposes, as in the northern Adriatic or in the Gulf of Gabès, off Tunisia (Bradai, Saidi and Enajjar, 2018), most gillnet and trammel net fisheries are also still responsible for impacting vulnerable species through bycatch, including the common eagle ray (*Myliobatis aquila*), bull ray (*Pteromylaeus bovinus*), blackmouth catshark (*Galeus melastomus*), gulper shark (*Centrophorus granulosus*), and various species in the *Carcharhinidae* family, as in the southern Brazilian gillnet monkfish (*Lophius gastrophysus*) fishery (Perez and Wahrlich, 2005). In the Black Sea, the turbot gillnet fishery is associated with high incidental catch rates of demersal sharks, such as piked dogfish (*Squalus acanthias*), as well as of dolphins. Tangle nets target turbot (*Scophthalmus maximus*) in Turkish waters (Kara, 2012), but in the process, unwanted species are caught as bycatch and discarded, including endangered shark species. Indeed, studies on gillnets report high mortality rates for sharks, which, apart from nurse sharks (*Ginglymostoma cirratum*), breathe only by swimming and are consequently critically threatened by entanglement (Thorpe and Frierson, 2009; Cosandey-Godin and Morgan, 2011).

Despite a 1992 United Nations ban, illegal drift nets are still used in some areas, leading to bycatch mainly of large pelagic sharks, such as the blue shark (*Prionace glauca*), shortfin mako shark (*Isurus oxyrinchus*) and the common thresher (*Alopias vulpinus*) or pelagic rays, including the pelagic stingray (*Pteroplatytrygon violacea*) and the devil fish (*Mobula mobular*) (Tudela *et al.*, 2005).

4.3.1 Fishing gear improvements

Enmeshment
Gillnet mesh size, in parellel with hanging ratio, twine material, twine thickness and visibility, has a major effect on fish catch rates and catch composition (size and species) (Hamley 1975). As a result, gillnets can be highly selective for small size classes and certain shark species (Walker, 1998; Carlson and Cortés, 2003; Thorpe and Frierson, 2009). Indeed, the capture of small or juvenile sharks in gillnets is highly dependent on mesh size, as demonstrated for blacknose sharks (*Carcharhinus acronotus*) (Carlson and Cortés, 2003) and juvenile blacktip sharks (*Carcharhinus limbatus*), both captured as bycatch by commercial gillnet fisheries in the Gulf of Mexico (Baremore, Bethea and Andrews, 2011). Likewise, Ceyhan, Hepkafadar and Tosunoglu (2010) have shown the selectivity of trammel net inner mesh sizes in capturing the smooth-hound shark (*Mustelus mustelus*) in small-scale coastal fisheries, through a comparison of trammel nets with two mesh sizes and longline fishing in the Izmir Bay, Aegean Sea.

Therefore, mesh size regulations can provide an effective tool for managing the unintentional catch of threatened sharks or improving juvenile and adult survival rates by limiting the size composition of catch. For instance, to help the recovery of declining stocks of sandbar sharks (*Carcharhinus plumbeus*), which are the dominant bycatch component of a western Australian multispecies demersal gillnet fishery, and to promote a more sustainable management of this fishery, McAuley, Simpfendorfer and Wright (2007) suggest restricting both the fishery's maximum and minimum mesh sizes in order to reduce the bycatch of both larger and smaller sharks.

Nevertheless, in such cases of multispecies fisheries, mesh size modifications must consider the effects on commercial species yields and the possible consequences for other vulnerable species before implementation.

Entanglement
Small demersal sharks, such as the small-spotted catshark (*Scyliorhinus canicula*), and rays are usually observed to be enmeshed in the lower part of nets, while large pelagic and mid-water sharks are often entangled in the middle part. A comparison conducted by He (2006b) in inshore waters of the western Gulf of Maine between small-height cod gillnets and tie-down flounder gillnets show that lowering nets (through the use of tie-downs) reduces the catch of mid-water fishes, such as

cod and piked dogfish, while increasing the catch of flatfishes, such as yellowtail flounders (*Limanda ferruginea*), American plaice (*Hippoglossoides platessoides*), witch flounder (*Glyptocephalus cynoglossus*) and winter flounder (*Pleuronectes americanus*), as well as of skates such as thorny skates (*Amblyraja radiata*).

In order to avoid bycatch, it is important to reduce entanglement rates, notably in the lower part of the net. To the same end, increases are recommended in the tension of the net panel by raising float buoyancy and the lead-rope weight in order to fix the gillnet more securely to the seafloor, thus reducing flexiblility. In such a way, sharks will probably bounce off the webbing, instead of becoming entangled. Indeed, this type of modification with stiffer materials has significantly reduced the number of Atlantic sharpnose sharks (*Rhizoprionodon terraenovae*) caught by gillnetters in the Spanish mackerel (*Scomberomorus maculatus*) fishery off North Carolina, without a significant reduction in commercial catch (Thorpe and Frierson, 2009). Furthermore, loose nets more easily entangle large-bodied species, including shark-like batoids such as *Rhynchobatus* spp. (White *et al.*, 2013).

4.3.2 Magnetic mitigation

Sharks can sense at a short range weak electrical fields as low as 5 nV/m due to sensory organs located on the snout and called the ampullae of Lorenzini. These organs are sensitive to frequencies from 1 to 8 Hz (Haine, Rid and Rowe, 2001). Sharks are consequently capable of detecting weak electric fields generated by the neuromuscular activity of prey in seawater. Laboratory experiments based off this capacity have demonstrated the repellent effect of electromagnetic fields on sharks and the potential utility of tests in limiting bycatch (Brill *et al.*, 2009). With this in mind, Jordan *et al.* (2013) have suggested the use of electrical barriers attached to nets, either powered or magnetic, which could repel sharks, rays and skates, thus preventing entanglement. This repellent solution is disadvantaged, however, by its effectiveness only over short distances and the availability/cost of magnetic materials.

4.4 Sea turtles

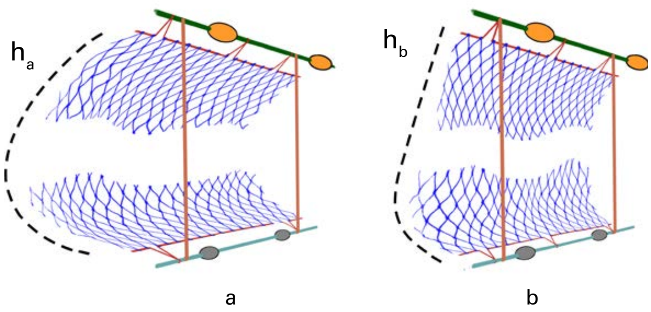
Among the major types of fishing gear, gillnets and trammel nets are of particular concern for sea turtle bycatch, especially when found in coastal waters close to breeding beaches or in foraging and wintering areas (Gilman, 2009; Peckham *et al.*, 2007; Cardona *et al.*, 2009; Wallace *et al.*, 2010; Guebert, Barletta and Costa, 2013; Levy *et al.*, 2015). In addition, since gillnets are left for several hours or even days at sea (for example trammel nets for lobsters or for soles), oftentimes entangled sea turtles cannot easily come to the surface to breathe and die by forced apnea (Casale, 2010; Luchetti *et al.*, 2017). Coastal gillnet fishing can have indirect adverse effects on sea turtles as well, such as through capture in abandoned pieces of net (ghost net fishing) and interference with their critical habitats (feeding and nesting areas).

Four species of sea turtles are mainly affected by interactions with gillnets: the green turtle (*Chelonia mydas*), the loggerhead turtle (*Caretta caretta*), the hawksbill turtle (*Eretmochelys imbricata*) and, at low levels, the leatherback turtle (*Dermochelys coriacea*).

Several studies have been conducted in different countries to reduce these unwanted interactions, both through technical improvements of the fishing gear and improved practices and management measures for the concerned fisheries (Gilman *et al.*, 2009; FAO, 2004, 2009b).

4.4.1 Fishing gear improvements

FIGURE 22
Decreasing net slackness



A decrease in net slackness between (a) and (b) caused by reducing the net height ($h_b < h_a$) while keeping the same tie-down length.

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Net height
Several species of sea turtle, including the loggerhead sea turtle, an endangered species protected by the federal Endangered Species Act, are found off North Carolina. The deep waters of Pamlico Sound, the largest lagoon along the North American east coast, represent an important site in the large-mesh gillnet fishery targeting southern flounder (*Paralichthys lethostigma*), from September onwards, the season when sea turtles start moving away from the bay as the water temperature begins to fall. The concurrence of this autumn migration and the fishing season explains a significant bycatch of loggerhead sea turtles (Price and van Salisbury, 2007).

In order to reduce the impacts of this commercial fishery on sea turtles, a study evaluated the effect of net panel height. The nets comprise 3.6 m panels, which can be reduced to a fishing height of 1.2 m by tie downs (wires stretched vertically between the floatline and the leadline) (Figure 22). This system creates a kind of bag that increases southern flounder entanglement. The study showed that halving panel height (i.e. to 1.8 m) significantly reduced the net slackness and therefore sea turtle bycatch, without affecting the catch rate of target species (Price and van Salisbury, 2007).

Buoyancy
One way to limit the fishing height of a set net without reducing its entanglement capacity for catching large fish is to reduce its buoyancy. An experiment undertaken in the framework of a participatory research programme with fishers from Puerto Lopez Mateos in Mexico showed – based on 136 observations – that removing floats from nets reduced the turtle catch rate (mainly loggerhead turtles) by 68 percent, without affecting the commercial catch of California halibut (*Paralichthys californicus*) and grouper (*Mycteroperca xenarcha*). However, because the market value of the catch from nets without buoys was "marginally but significantly lower," the authors could not recommend this mitigation technique to fishers (Peckham *et al.*, 2016). Other experiments using different techniques in relation to static nets need to be complemented by underwater observations.

Other net modifications
One of the major concerns with gillnet fishing is the low likelihood of survival for animals caught, given their long immersion time. Various strategies have been suggested in the literature to increase the survival rate of turtles caught in nets and to facilitate their release, for example, by setting the net in shallow waters or adjusting the ballast so that the individuals caught may reach the surface to breathe during net immersion (Gilman, 2009; Gilman *et al.*, 2009, 2010).

Gill and trammel nets are the principal fishing techniques used by small-scale Mediterranean vessels. Mainly set in the coastal zone, they present a potential hazard to all endangered megafaunal species. To catch monkfish (*Lophius piscatorius*) and flatfish, Mediterranean fishers mainly use large-mesh trammel nets. The use of these nets results in sea turtle and dolphin bycatch, particularly in the Black Sea. Improving technical characteristics, such as an overall reduction of the entanglement risk, are simple solutions that can be implemented in sensitive areas.

4.4.2 Acoustic mitigation

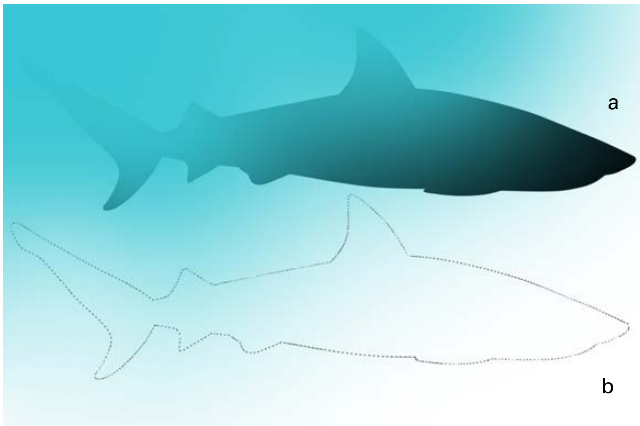
Sea turtles and fish share similar hearing characteristics as low frequency specialists (Swimmer and Brill, 2006; Brill, Swimmer and Southwood, 2004), so much so that any sound produced to limit turtle interactions with fishing gear will also be detected by fish and might frighten away target species (Southwood *et al.*, 2008). Nevertheless, recent work carried out on bottom gillnets, used for catching Californian flounder (also referred to as Californian halibut) in Baja (Mexico), demonstrated that low-frequency ADDs generating 200–500Hz tones (135–140dB re 1 μPa) reduced the catch of green turtles by 60 percent, with no change in commercial catch rates (Piniak *et al.*, 2018).

4.4.3 Visual mitigation

Scarecrows

Following experiments undertaken on set nets along the Mexican coast of the Baja California Peninsula, Wang, Fisler and Swimmer (2010) noted that shark-shaped silhouettes trigger an innate flight reaction in sea turtles bred in captivity and having therefore never been exposed to sharks or other predators. In more recent sea trials, shark shapes helped to reduce the number of turtles caught in nets. However, as these visual deterrents have an impact on target species as well, the authors suggest that differences in the visual aptitude of turtles and fish should be exploited, especially in the ultraviolet (UV) light spectrum, by designing, for example, shark shapes (Figure 23) to absorb UV and show up as visible to turtles only (Wang *et al.*, 2013).

FIGURE 23
Shark silhouettes



Shark silhouettes made of plastic designed to absorb UV light visible to turtles (a) and invisible to fish (b).

Redrawn from Wang, Fisler and Swimmer, 2010.

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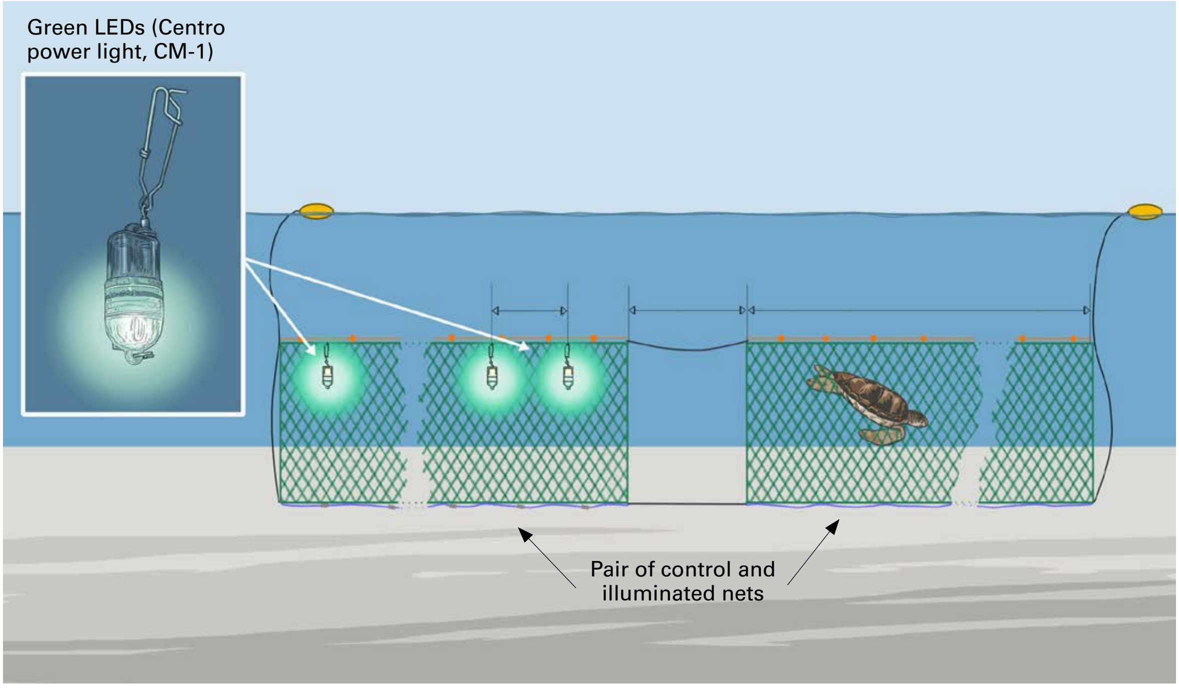
Light sticks and light-emitting diode lamps

Light sticks are known to attract some species. Indeed, Wang *et al.* (2007) have shown through experiments in test tanks that they can also have an attractive effect on certain age groups of sea turtles.

Nevertheless, Wang *et al.* (2013) have also shown that light sources mounted on bottom gillnets targeting flatfish along the Baja California Peninsula (Mexico) decrease green turtle catch rates. Light sticks were fixed 5 m apart on the branch line of an experimental net, while LEDs were placed on another experimental net at 10 m intervals. Each experimental net was paired with an identical control net equipped with the same but inert light devices. The results showed that the catch rate of green turtles fell by 40 percent in LED-illuminated nets and by 60 percent in those equipped with light sticks.

These results suggest that by lighting up the layers of submerged nets, LEDs or light sticks help turtles avoid entanglement. The better results obtained with light sticks may be explained by the fact that the light was emitted over a wider spectrum with less irradiance. The drawback to light sticks is that they deteriorate faster over time (Wang, Fisler and Swimmer, 2010).

FIGURE 24
Green light-emitting diodes



Light-emitting diodes are placed every 10 m along the tested nets' floatline; the control nets are placed 200 m away to avoid the influence of the light.

Adapted from Ortiz *et al.*, 2016.

More recently, research undertaken with an artisanal fleet using gillnets targeting flounder (*Paralichtys* spp.), the flathead guitarfish (*Rhinobatos planiceps*) and several species of rays in Sechura bay (northern Peru) confirmed that adding electroluminescent diodes (LEDs) to gillnets offered an effective way to reduce green turtle bycatch (Figure 24); 114 pairs of control and illuminated nets were deployed, with 125 green turtles caught in the control nets and 62 in the illuminated nets, without a significant reduction in commercial catch. After standardizing the fishing effort in terms of set length and soak time, the authors reported a potential reduction of 202 green sea turtles per 321 caught per year, or a 63 percent reduction in bycatch of green turtles in the illuminated nets (Ortiz *et al.*, 2016).

Further experiments, particularly at sea, are required to confirm these results and evaluate the various strategies that could render light sticks less attractive or less visible to sea turtles (Wang *et al.*, 2007).

Ultraviolet light-emitting diode lamps

Ultraviolet LED lamps, mainly in low water transparency, offer the advantage of providing consistent high-intensity illumination, lasting longer and penetrating deeper into the water compared to common light sticks.

A study was carried out in the summers (June–July) of 2015 and 2016 in the northern Adriatic Sea (central Mediterranean Sea), which is a major feeding habitat for loggerhead turtles, but also a high-risk area for interactions with the local fisheries. In particular, loggerhead turtles are vulnerable to bottom gillnetting, which targets thornback (*Raja clavata*) and starry rays (*Raja asterias*), as well as turbot (*Scophthalmus maximus*) and brill (*Scophthalmus rhombus*) (Lucchetti, Vasapollo and Virgili, 2017). The results showed that only the control nets caught sea turtles (16 loggerheads).

Furthermore, Virgili, Vasapollo and Luchetti (2018) reported similarly positive results, with a bycatch reduction of 100 percent in bottom-set gillnet fisheries using UV light in deep waters (>70 m) and without lowering the commercial catch level.

Although further sea trials are needed, UV LED illumination appears to be a potentially effective tool for deterring sea turtles from approaching set nets in the Mediterranean while maintaining commercial catch levels (Lucchetti *et al.*, 2019).

5. Longlines and lines

Various configurations of longline fishing (or longlining) exist for target species, generally falling into two main categories: bottom longlining targets bottom fishes while pelagic longlining is directed toward the capture of pelagic and midwater fishes. The key components of longline gear include a main line, branch lines, hooks and bait (Figure 25), with type, material and dimensions constituting the main factors determining fishing efficiency. Branch lines are made of nylon, polypropylene, polyester or steel. Hooks are either made of forged metal (steel or alloy) or from metallic wire; they are typically J-shaped or G-shaped (circle hook) and their bend can be

FIGURE 25
Longline components and configurations

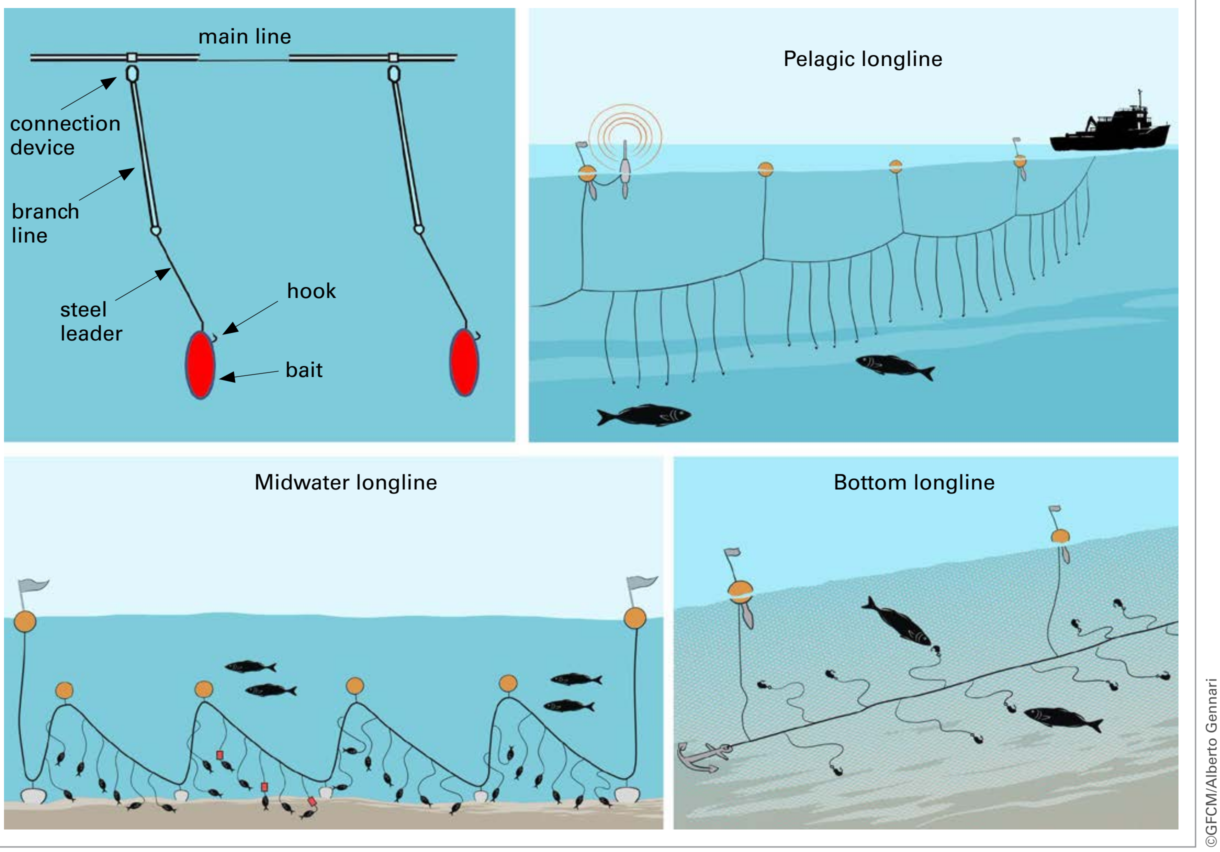
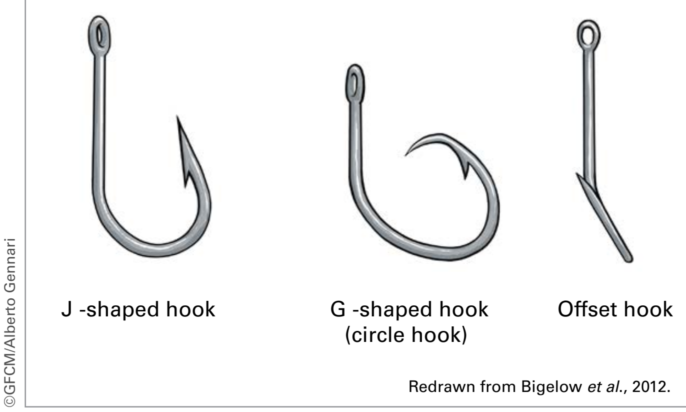


FIGURE 26
Commonly used hook shapes



Redrawn from Bigelow *et al.*, 2012.

offset (offset hook) or in line with the axis of the shank of the hook (non-offset) (Figure 26). Interactions between vulnerable species and longlines concern mainly depredation of captured fish or of the bait and entanglement with the gear.

5.1 Marine mammals

Although dolphins may occasionally become entangled in branch lines, the incidental catch of marine mammals by longlines is often the result of their getting hooked while foraging. This problem mainly concerns the false killer whale (*Pseudorca crassidens*), the killer whale (*Orcinus orca*), pilot whales (*Globicephala* spp.), the common bottlenose dolphin (*Tursiops truncatus*), the dusky dolphin (*Lagenorhynchus obscurus*), the short-beaked common dolphin (*Delphinus delphis*) and the striped dolphin (*Stenella coeruleoalba*) (Clarke *et al.*, 2014).

Bluefin tuna (*Thunnus thynnus*), a common prey of the killer whale in the Strait of Gibraltar, is fished over the summer by small-scale fishing boats using vertical handlines, along the steep continental slope of Morocco and Spain at depths of 200 and 250 m (Pérez Gimeno *et al.*, 2001). Killer whales swimming among the fishing vessels often snatch a part or all of the caught tuna before it can be hauled onboard. The only method fishers can resort to in order to avoid this foraging is to leave the tuna on the seabed attached to a buoy until the killer whales leave the fishing zone (Guinet *et al.*, 2007; Esteban *et al.*, 2016).

In the relevant literature, a number of papers discuss studies and systems seeking to keep cetaceans at a distance from fishing operations (for example, IOTC, 2007; Hamer and Childerhouse, 2012; Mooney, Pacini and Nachtigall, 2009; Rabearisoa *et al.*, 2012; Werner *et al.*, 2015). Three strategies emerge from this literature: 1) developing alternative techniques or modifying the design of fishing gear; 2) reducing the acoustic attractiveness of fishing operations (adjusting engine speed, changing fishing vessels); and 3) regularly shifting the time and duration of fishing in areas shared with killer whales.

5.1.1 Fishing gear improvements

Hook types

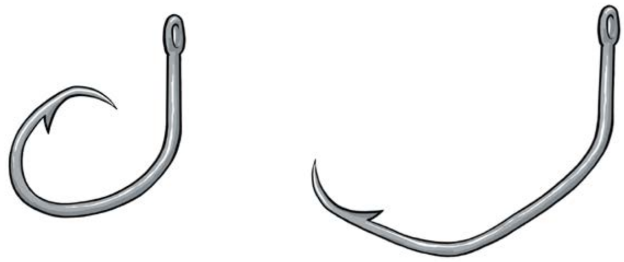
The use of circle hooks has been shown to be effective in reducing sea turtle bycatch, but less so for cetaceans. For these species, other approaches must be identified, such as weak hooks which straighten out more easily (Bigelow *et al.*, 2012).

Weak or breakable hooks

The use of hooks with low mechanical resistance, particularly standard hooks (non-forged), was tested in several pelagic longline fisheries as a selective device to reduce bluefin tuna catch in the albacore (*Thunnus alalunga*) fishery (Foster and Bergmann, 2012). They are made of flexible metal and can be straightened easily when they are bent, which helps large animals to escape more easily.

The use of such hooks (also called whale safe hooks), that are deformable but strong enough to retain target species (Figure 27), may help to reduce the bycatch of cetaceans foraging on bait and catch (Bayse and Kerstetter, 2010; Clarke *et al.*, 2014; FAO, 2018; Swimmer, Zollett and Gutierrez, 2020).

FIGURE 27
Deformable hook



Standard circle hook

The same hook bent by a false killer whale (*Pseudorca crassidens*)

Redrawn from Bigelow *et al.*, 2012.

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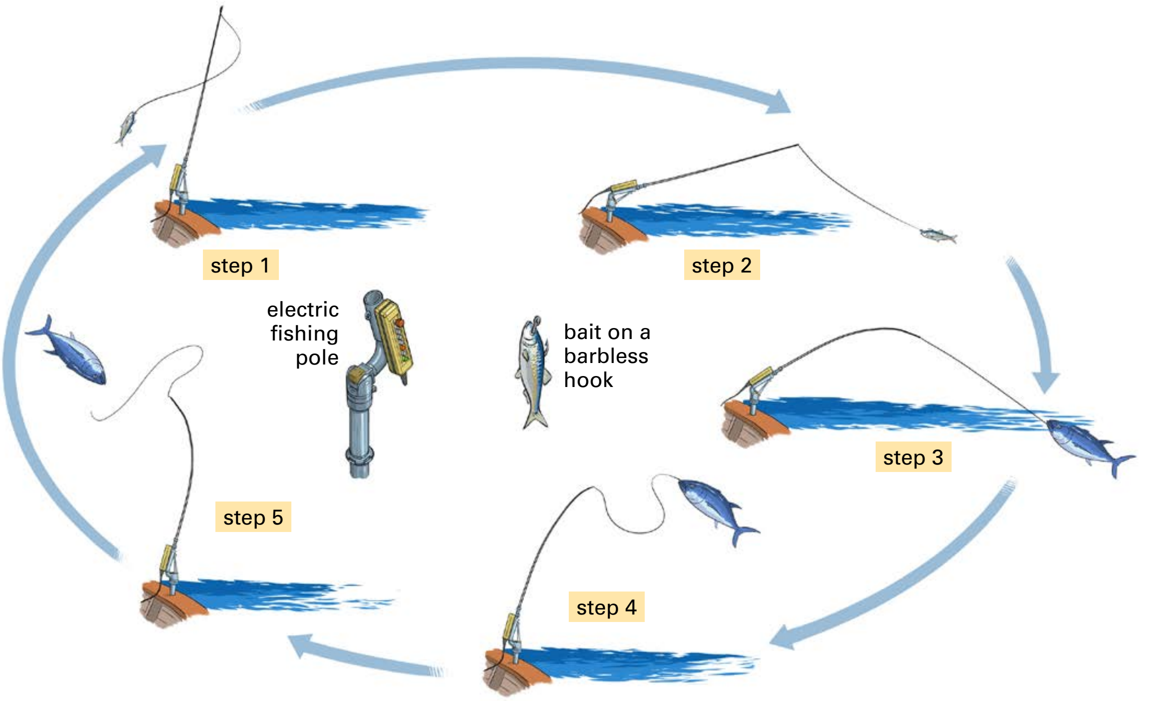
This type of hook has been shown in the laboratory by McLellan *et al.* (2015) to offer the additional advantage of causing little trauma to toothed whales' (odontocetes) mouths, for example, in the short-finned pilot whale (*Globicephala macrorhynchus*), Risso's dolphin (*Grampus griseus*) and the false killer whale (*Pseudorca crassidens*), compared with the injuries caused by forged hooks. The barb of deformable hooks neatly cuts the lip tissue freeing the hook. Forged hooks, on the other hand, are more rigid and do not open completely, thus tearing the flesh irregularly and sometimes leaving the broken barb in the wound.

5.1.2 Setting improvements

Two factors can significantly reduce depredation levels: setting shorter longlines (less than 5 000 m) and hauling lines in as quickly as possible, for example, 50 hooks per minute, according to Tixier (2012), when in the presence of killer whales (Guinet *et al.*, 2007, 2015; Tixier *et al.*, 2010, 2014). Hauling speeds can be increased greatly by using powerful automatic line-haulers, such as the AZTI automatic tuna fishing pole (Figure 28) or automated winding (tuna trolling line). However, this equipment requires vessels over 12 m long with a sufficient source of energy.

FIGURE 28
Automatic tuna fishing pole



Step 1: the line is launched towards the water's surface by motor control. Steps 3–4: a caught tuna tugs on the line and triggers the lifting of the pole. Step 5: passing over the gunwale, the tuna is released from the barbless hook and falls onto the fishing deck.

Adapted from Ferarios *et al*., 2009.

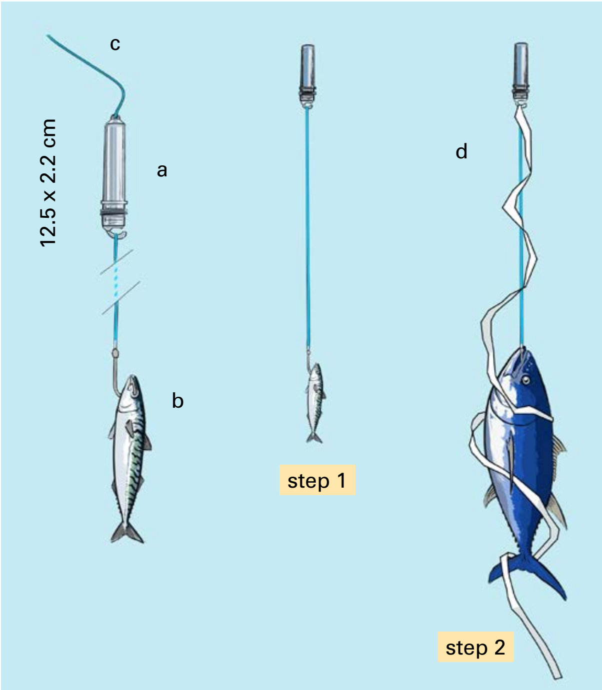
5.1.3 Visual mitigation

Given that the primary function of toothed whales' (odontocetes) vision is to forage fish, visual mitigation devices create a kind of screen preventing the predator from noticing the catch. These systems can additionally be applied to any type of longline or handline fishing. For example, the cage device consists of a functional deterrent structure that will either physically or psychologically deter a depredating toothed whale (Hamer and Childerhouse, 2012).

Streamers

McPherson *et al.* (2008) described a streamer-based system tested in the Coral Sea (off the northeast coast of Australia) for approximately 50 fishing sets. This device can be released from

FIGURE 29
Streamer device



A plastic tube containing the electric fence ribbon (a) is fixed onto the branch line (c) with the hook at 50 cm distance (b). Step 1 – step 2: streamer is released from the tube and surrounds the caught fish (d).

Redrawn from McPherson, 2010.

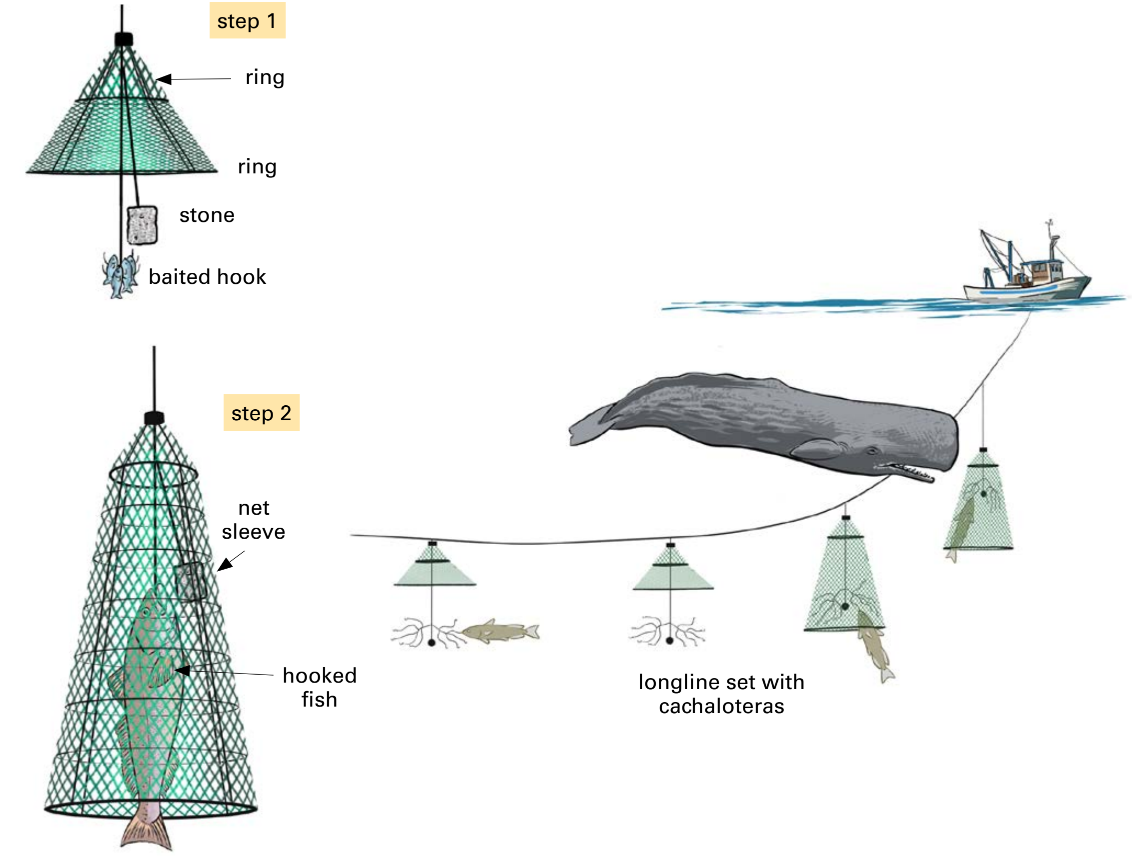
a polycarbonate tube holding coiled wire-embedded electric fence tape reinforced by steel wire to maintain a target strength (Figure 29). When a fish strikes, the streamer is deployed from the tube and tangles around the tuna. At the end of the experiment, it was clear that depredation had been reduced. Following further experimentation, McPherson and Nishida (2010) concluded that the logistics of deployment were not suited to high seas and large-scale longline activity, but the devices could still be useful at a limited scale for longlining and trolling where depredation occurs.

Umbrella or *cachalotera*
This technique (Figure 30), used originally by the Chilean small-scale fleet to reduce depredation by toothed whales, was then adopted by the pelagic longline commercial fleet targeting the Patagonian toothfish (*Dissostichus eleginoides*) with some modifications (Hamer, Childerhouse and Gales, 2012; Moreno *et al.*, 2008; Goetz *et al.*, 2011). The longline is composed of a main polypropylene line supporting several 8 mm polypropylene branch lines, each outfitted with six hooks. Each branch line weighs 8 kg and is equipped with an umbrella, composed of an upper and a lower ring (of a 10 cm and 80 cm diameter, respectively) supporting a cone-shaped net sleeve of 1.5 to 2 m. The positive buoyancy of the rings and the net allow the umbrella to float over the baited hook while the gear is soaking. When the longline is hauled in, the umbrella slides down and covers the baited hook. As depredation takes place primarily during gear retrieval, this mechanism protects caught fish from cetacean foraging.

The system was tested over 297 sets. Although it effectively reduced depredation, it also significantly reduced the catch rate (Goetz *et al.*, 2011).

Other depredation mitigation devices
A French team has tested similar devices in order to reduce depredation during pelagic longlining in the Indian Ocean by bottlenose dolphins, short-finned pilot whales, false killer whales and some pelagic sharks. The first one, called a net sleeve, consists of a textile bag folded up above the baited hook, which slides down when a fish takes the bait, covering it and hiding it from predators. The team developed another device, the spider (Figure 31), made of eight polyester legs designed to cover the catch when a biting fish triggers the system (Rabearisoa *et al.*, 2012). Based on the same technical principle, the DEPRED, made up of eight streamers, gave encouraging results during its first trials conducted at a small scale (Rabearisoa, Bach and Marsac, 2015). Nevertheless, due to difficulties in setting these devices at sea (for example, entanglement problems) these devices require further improvements and additional complementary repellent processes.

FIGURE 30
Longline set with *cachaloteras*



Step 1: soaking – the umbrella covers the baited hook during setting. Step 2: hauling – the umbrella slides down to cover the fish when the line is hauled in.

Adapted from Goetz *et al.*, 2011 and Hamer, Childerhouse and Gales, 2012.

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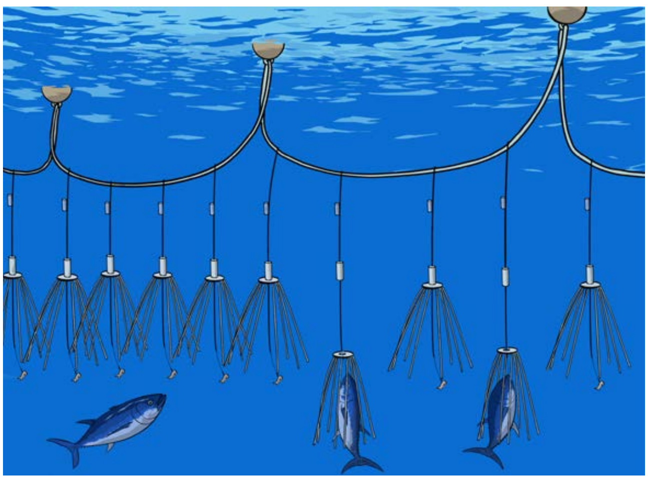
5.1.4 Acoustic mitigation

Active acoustic deterrents

To reduce depredation, various solutions have been proposed by manufacturers and have been tested with mixed results, including standard pingers, i.e. ADDs and louder devices, such as AHDs, emitting sounds at fixed or randomized frequencies, with amplitude modulated or frequency modulated, among others parameters.

FIGURE 31
Spider device



Spider device covering a tuna spider system used on longline.

Redrawn from IOTC, 2007.

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Pingers

The purpose of pingers is to emit a prescribed sound at a defined frequency and noise level in order to alert marine mammals to the presence of a nearby obstacle (Arangio, 2012).

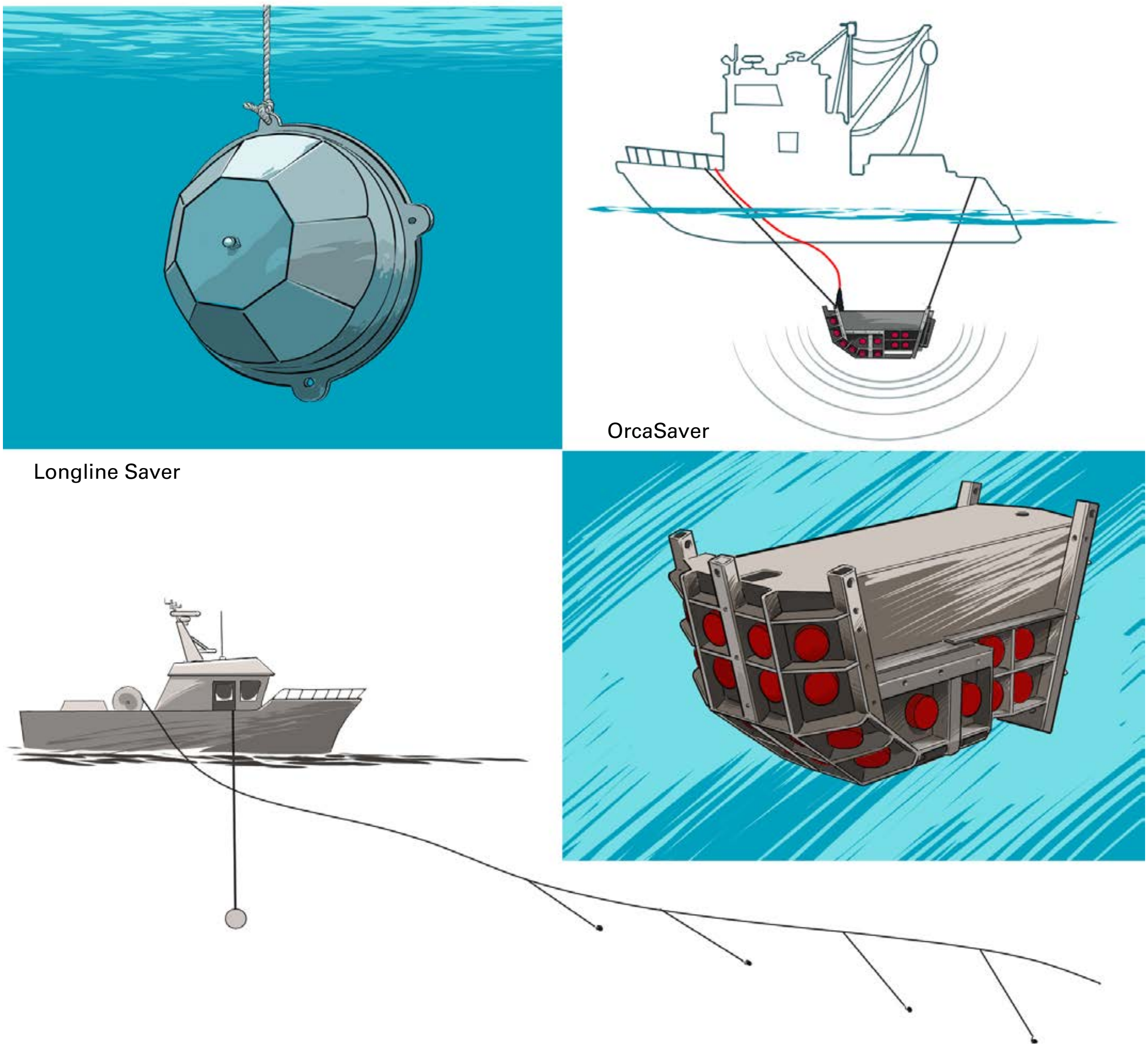
According to a number of authors (Hamilton and Baker, 2019; Hamer, Childerhouse and Gales, 2012; Tixier *et al.*, 2015; Werner *et al.*, 2015), however, no clear evidence exists to show that pingers have a repellent effect on cetaceans.

Nevertheless, Nishida and McPherson (2011) tested the effectiveness of the newly developed DDD pinger in an area of high depredation south of Hawaii. According to the authors, preliminary results suggested that depredation rates by toothed whales (mainly killer and false killer whales) could be reduced with DDD pingers, as well as with dolphin interactive deterrent pingers.

Mixed acoustic deterrents

Combining elements of ADDs with AHDs, a device called the Longline Saver (Figure 32) was developed in 2008 by the Dutch company SaveWave to dissuade false killer whales from coming near pelagic longlines in the north Pacific. This acoustic deterrent can produce a series of complex broadband signals (1–250 kHz) at high intensity levels (up to 195 dB). The device's 2013 version (OrcaSaver) (Figure 32) comprised 40 transducers with three different signal types

FIGURE 32
The Longline Saver



The Longline Saver is hemispherical, with a 38.1 cm diameter, and weighs 24 kg; it is lowered to 10 m below the water's surface and is designed to be activated during hauling of the longline; the larger size (90 × 45 × 35 cm) and weight (150 kg) of the OrcaSaver necessitate a crane for its deployment.

Redrawn from Mooney, Pacini and Nachtigall, 2009.

emitting at 6.5 kHz – the frequency considered to be the most effective – and a sound pressure of 196 ±2dB re 1. However, given its weight and cost, the device can only be used on large longliners in industrial fisheries.

Tested by the Hawai'i Institute of Marine Biology on a captive animal, the Longline Saver was shown to reduce the echolocation performance of the animal by 54 percent at high emission levels, with the animal recovering up to 85 percent of its detection capacity at the end of the experiment (Mooney, Pacini and Nachtigall, 2009).

Trials carried out with a longliner targeting Patagonian toothfish within the Crozet Islands exclusive economic zone in the southern Indian Ocean between 6 February 2011 and 24 February 2011 showed that though killer whales initially responded by fleeing from the vessel due to the high amplitude sounds, this reaction disappeared after ten successive exposures. The authors concluded that this rapid habituation behaviour suggests the device is not efficient enough to reduce depredation by killer whales on longline catch (Tixier *et al.*, 2015).

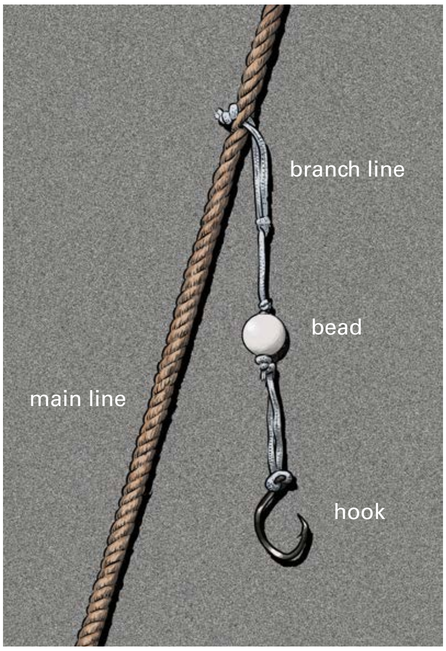
In addition to the limits on its effective duration, the system cannot cover a longline several kilometres long when operated from the vessel. While this configuration might be suitable for vertical longline fisheries, it is too cumbersome and costly for small-scale vessels, such as those targeting bluefin tuna in the Strait of Gibraltar and challenged by killer whale foraging (Esteban *et al.*, 2016).

Passive acoustic deterrents
An alternative to the emission of warning acoustic (pingers) or painful (AHD) signals is to disrupt the cetacean's use of echolocation to detect potential prey.

Beaded gear

In order to reduce the depredation of sperm whales (*Physeter microcephalus*) on sablefish (*Anoplopoma fimbria*) longline fishing in Alaska, O'Connell *et al.* (2015a) attached 25 mm beads above the hooks (Figure 33), predicting that whales echolocation ability to isolate a single sablefish would be impaired by the presence of beads – the bead size being similar to the size of a sablefish swimbladder, each gangion would have a similar acoustic return. Although sablefish catch increased and depredation decreased, the authors found that this experiment was not statistically significant due primarily to the field study design (O'Connell *et al.*, 2015a).

FIGURE 33
Beaded gangion



Adapted from O'Connell *et al.*, 2015a.

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5.2 Seabirds

Seabirds can peck at the bait fixed to longline hooks before they sink and can be dragged underwater and drown during hauling. In the Mediterranean, the most critical area for seabird bycatch is located around the Balearic Islands, where three shearwater species, Scopoli´s shearwater (*Calonectris diomedea*), Balearic shearwater (*Puffinus mauretanicus*) and the great shearwater (*Puffinus gravis*) have been classified as "critically endangered" by the International Union for Conservation of Nature (BirdLife International, 2009). Furthermore, seabird interaction with longlines represents an economic loss, due to the amount of bait consumed and the number of hooks that end up sinking unbaited. Indeed, it is important to avoid conditions in which fishers perceive birds as genuine competitors. The relevant literature (Gilman, Kobayashi and Chalouka, 2008; FAO, 2009b; ACAP, 2011; ICES, 2013; BirdLife International, 2013, 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, etc.) provides descriptions of several effective methods for seabird deterrence in pelagic longline fisheries, including fishing gear modifications, setting improvements and fishing management measures.

5.2.1 Fishing gear improvements

Hooks

Little research has been undertaken on the impacts of the type and dimension of hooks. It appears that the combination of these two characteristics have an effect on seabird bycatch, though they are difficult to dissociate from the influence of the choice of bait, setting conditions and longline design (Li, Browder and Jiao, 2012). Domingo *et al.* (2012) have observed a tendency for J-hooks to catch more albatrosses than circle hooks, though not a statistically significant one; indeed, because the J-hooks were sometimes deployed in daylight and the circular hooks immediately after dusk, the effects of a chosen setting time and a certain hook type may be confused in evaluating the differences observed in albatross bycatch. Nevertheless, a case can be made for the use of circle hooks in that their wide bend inhibits ingestion and as their barbs are turned towards the inside, the risk of hooking the body or the wings is lower, while finally seabirds that are hooked during line-hauling are more easily freed and more likely to survive (FAO, 2009a; BirdLife International, 2013, 2014a, 2014e).

Bait

Condition of the bait

In fisheries adding weights to their branch lines, the use of thawed bait reduces the sink rate. For the same reason, live bait is not recommended as it sinks more slowly than dead bait.

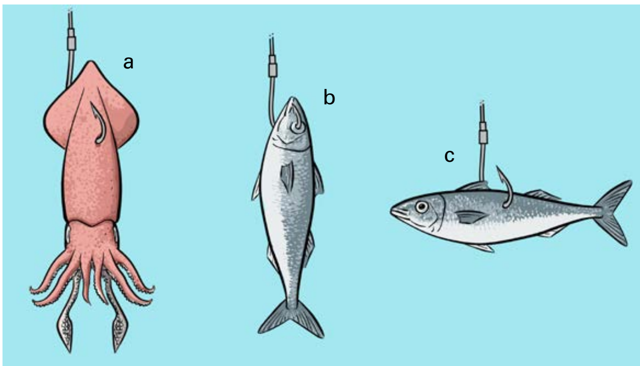
Size and species

Small fish species (for example, sardines and various mackerel species) should be preferred as bait to squid, which sinks more slowly. There is only a small difference in the immersion rates of large and small bait of the same fish species.

Position of the bait on the hook

For faster immersion, the bait should be fixed preferably head-first (fish) or tail-first (fish and squid), rather than by the dorsal part (fish) or the top of the mantle (squid) (Figure 34). However, it should be emphasized that hooking the bait by the dorsal part considerably reduces the risk of a turtle swallowing it and that by this method the bait remains hooked (Figure 34, c).

FIGURE 34
Fixing bait



Different ways of fixing bait: a and b help with the immersion of the baited hook; c helps to reduce marine turtle bycatch.

Source: Sacchi, 2008.

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Dyed bait

In the 1970s, fishers first tested dyed bait to improve their catch. More recently, experiments have been undertaken on the use of blue-dyed bait to reduce seabird bycatch in pelagic longline fisheries. For example, Cocking *et al.* (2008) showed that, over 26 longline sets, the use of blue-dyed squid reduced interactions with foraging wedge-tailed shearwaters (*Puffinus pacificus*) by 68 percent during hauling. During each set, all interactions (e.g. bait strikes, dives, descents, inspections of bait and longline traverses) between seabirds and the baited line were recorded. Among the 1 288 interactions observed, a mean of 37.7 interactions per set were recorded for non-dyed squid and 11.9 interactions for blue-dyed squid bait. Conversely, blue-dyed fish bait had a weaker mitigatory effect, representing 48 to 90 percent of the bait strikes.

In theory, the blue dye should reduce the visual contrast between the surrounding sea water and the bait, making it more difficult to detect (Gilman *et al.*, 2003). Other evaluations suggest that seabirds notice blue-dyed bait as consistently but are simply less interested in the dyed bait than in undyed bait. Indeed, several factors may influence the effectiveness of blue-dyed bait, such as light, water colour, food competition, seasonal food requirements and habituation over the long-term. If blue-dyed bait can complement the effectiveness of other proven seabird bycatch mitigation techniques, including bird scaring lines or weighted lines, several technical issues need to be resolved such as bait preparation and onboard handling in order to promote its use by fishers (BirdLife International, 2014f).

Hook-shielding devices

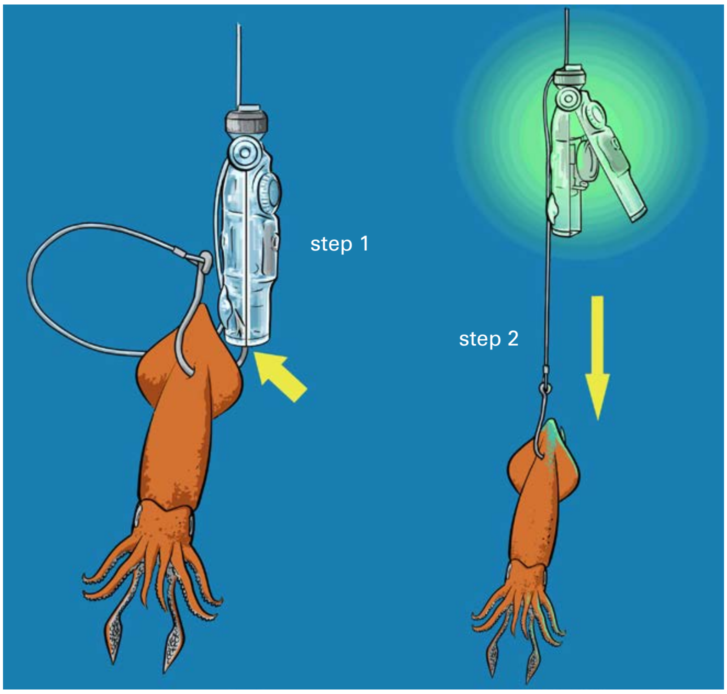
Several authors point out that less seabird bycatch is reported when baited hooks are protected by a hook-shielding device (Barrington, 2016a, 2016b; Baker, Candy and Rollinson, 2016; Sullivan *et al.*, 2018). Two devices are currently available on the market and recommended by the Agreement on the Conservation of Albatrosses and Petrels (ACAP) (ACAP, 2017) to prevent seabird attacks during line setting: the Fishtek Hookpod and the Jusseit Smart Hook (see Smart Tuna Hook section below) (Jusseit, 2010).

The Hookpod

This device is the result of a collaboration between BirdLife International and Fishtek Ltd. The Hookpod is designed to reduce seabird bycatch by encapsulating the barb of the hook when the line is hauled out. Once the branch lines have reached a depth of at least 10 m, the pod opens, releasing the hook (Figure 35). The pod is later recovered during hauling and stored until its next deployment. Different types of bait (large and small fish, live bait and squid) and various positions on the hook have been tested with success. More recently, an LED was integrated into the chamber of the device to replace the chemical light sticks (Sullivan *et al.*, 2018).

Over 18 sea trials, conducted between 2011 and 2015, onboard pelagic longliners targeting tuna

FIGURE 35
Hookpod operation



Step 1: the bait is attached to the hook which is then clipped into the pod; the hook's barb stays secured during the casting out of line, preventing seabirds from being snagged; step 2: at selected depth, water pressure releases the hook and the LED flashes to attract target species.

Adapted from Hookpod, 2014.

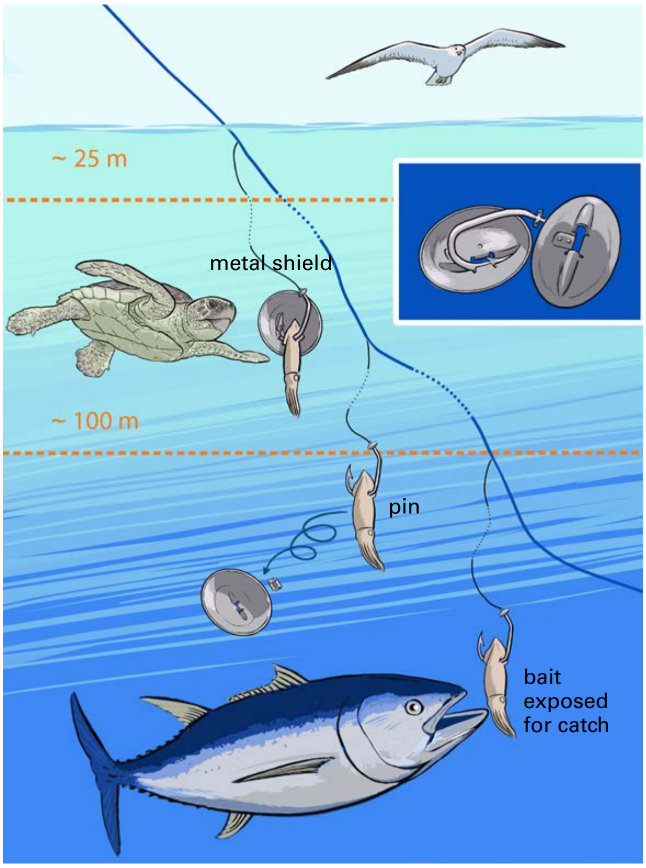
(*Thunnus* spp.) and swordfish (*Xiphias gladius*) in South African, Brazilian and Australian waters only recorded a single seabird mortality on the Hookpod branch lines, in comparison to 24 seabirds caught on the control branch lines. Furthermore, no differences in catch rates of the target fish species were detected between the Hookpod and control techniques (Sullivan *et al.*, 2018; Hookpod, 2014).

Smart Tuna Hook

The Smart Tuna Hook (Figure 36), designed by Hans Jusseit, prevents not only the hooking of seabirds but also of sea turtles during line setting by protecting baited hooks with a metal shield, held in place with a biodegradable pin. The shield and the pin are both made of a metal alloy which dissolves on extended contact with seawater – after about 15 minutes' immersion – exposing the baited hook; the shield sinks to the seabed and corrodes within 12 months. The hook is a modified tuna (or circle) longline hook adapted to the fishery, attached to branch lines in the same way as standard tuna hooks. The protective shield is fixed manually and does not require any particular skill. Once the hook sinks beneath critical depths (i.e. 25 m for seabirds and 100 m for sea turtles), the pin dissolves, the shield falls off and the baited hook is ready to catch fish.

A recent pilot study, funded by the Australian Fisheries Management Authority, demonstrated the effectiveness of the system using a range of bait (fish and squid) and hook types (Jusseit, 2010) with no influence on the results from setting time. The system was also perceived to facilitate baiting and bait retention down to the required depth, thus increasing the catch of target species.

FIGURE 36
Jusseit Smart Tuna Hook



The metal shield of the Smart Tuna Hook protects bait from seabirds within 25 m below the surface and from sea turtles up to a depth of 100 m; the pin dissolves, releasing the shield and exposing the bait for catch.

Redrawn from Jusseit, 2010.

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More recently, experimental research conducted on the South African pelagic longline fishery has confirmed the device's efficacy with two seabirds caught on Smart Tuna Hooks against 11 seabirds captured during the control set (Barrington, 2016a). The use of this kind of system also allows fishing vessels to access restricted zones and eliminates the need for other mitigation methods such as branch line weighting, Tori lines or night setting; it may also improve fisher safety during setting and hauling manoeuvres.

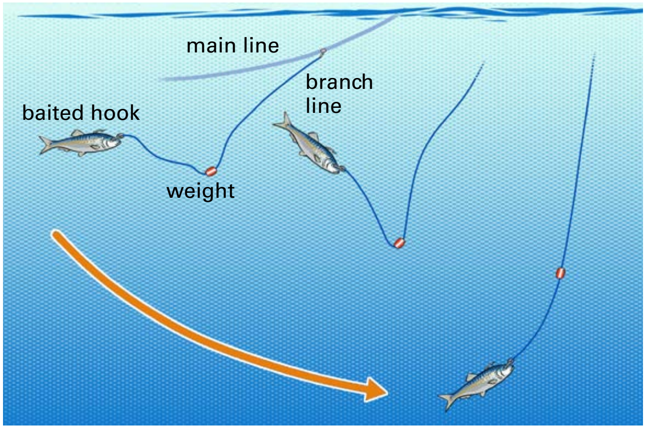
Weighting longlines

In order to minimize bycatch during hauling, baited hooks must reach 10 m below the surface as quickly as possible (Friesen *et al.*, 2017).

In the case of demersal longline fishing, bait depredation by seabirds is fairly rare because the branch lines are short (< 0.6 m) and the main line is often weighted; by contrast, branch lines of pelagic longlines are much longer (15–40 m) and the main line lighter. Weighting the longline (Figure 37) is therefore necessary to reduce incidental catch, mainly occuring during the short period when the baited hooks remain on the surface during setting. In many pelagic longline fisheries, weights are added to branch lines in order to reach the target species depth as fast as possible. During setting, the added weight pulls the lower line and the baited branch line rapidly towards the seabed (Robertson *et al.*, 2010).

Studies have demonstrated that the closer the weights are to the hooks, the more rapidly the line sinks (Barrington, Robertson and Candy, 2016), thereby significantly reducing seabird bycatch (Gianuca *et al.*, 2013; Jiménez *et al.*, 2013, 2019; Santos *et al.*, 2016, 2019). An experiment undertaken in Australia on longlines targeting yellowfin tuna (*Thunnus albacares*) showed that placing 40 g weights about 50 cm from the hooks reduced the sinking time by 25 to 33 percent, while facilitating longline setting without risk of line entanglement or crew injuries (Robertson, Candy and Hall, 2013).

FIGURE 37
Weighted branch line



Working principle of a weighted branch line during setting.

Adapted from Robertson *et al.*, 2010.

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Since 2007, in Australia, line weighting has become a mandatory requisite to apply for fishing permits under the Australian Fisheries Management Act 1991, and as such permit holders are required to equip branch lines with either 60 g swivels within 3.5 m from the hooks, or 100 g swivels within 4 m from the hooks.

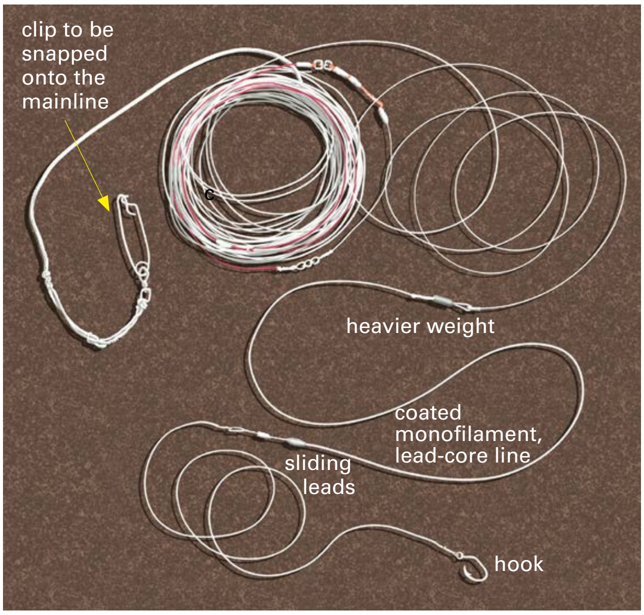
On the other hand, ACAP (2017) recommends a weighted branch line design including a weight of 40 g or greater attached within 0.5 m of the hook or a weight of 60 g or greater attached within 1 m of the hook or a weight of 80 g or greater attached within 2 m of the hook.

In the case of demersal longlining, bait depredation by seabirds is fairly rare since the branch lines are short (< 0.6 m) and the main line is often weighted with leads. Weighted integrated longlines are specially recommended because they sink more uniformly compared to externally weighted lines and are shown to substantially reduce mortality rates of surface foragers and diving seabirds, with no effects on catch rates of target species (Robertson *et al.*, 2006; Dietrich, Melvin and Conquest, 2008). A positive example is provided by the New Zealand demersal longline fishery, where a minimum weighted integrated lines with a lead core of 50g/m is required (ACAP, 2019).

Double-weight branch lines

The technique of weighting branch lines has been improved by adding and placing weights in different ways. The Yamazaki system (Figure 38) designed by Kazuhiro Yamazaki, a captain on a Japanese tuna vessel, calls for two weights placed at each end of an inelastic wire 1 to 1.5 m long, added to a monofilament branch line 2 m above the hook (WWF, 2011). The weight closest to the hook can slide freely along the branch line, while the second one remains fixed. This double-weight system reduces the risk of injury to crew members from fly-backs of lead weights. Additionally, this set-up means that the heaviest weight has to be at 3–3.5 m from the hook, within reach of a crew member as the caught fish comes onto deck. The second, lighter weight, placed 2 m from the hook, fits snugly onto the wire or line but is free to slide.

FIGURE 38
Double-weight branch line



Redrawn from Melvin, Guy and Read, 2014.

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Melvin, Guy and Read (2014) have introduced some improvements to the Yamazaki system, notably in spreading the weight over the weighted section in order to avoid risks of tangling and facilitate the coiling of the branch line. The weighting has evolved from a 12–38 g configuration on 1 m, for a total weight of 65 g, to a 70 g total weight fixed over a 1.5 m-long coated, monofilament, lead-core line (Figure 38).

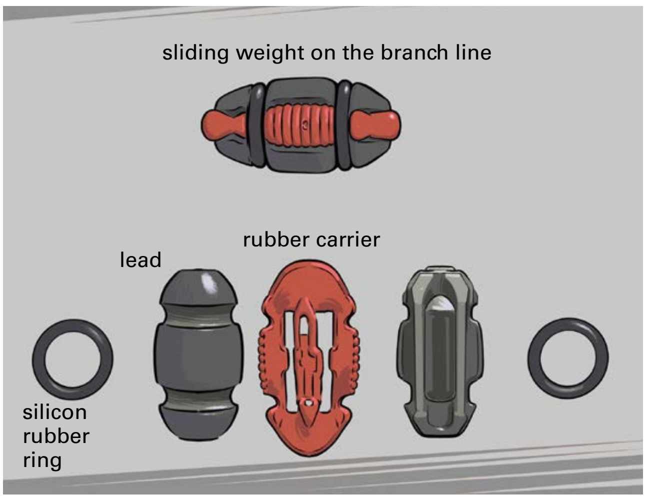
Research carried out in the South African joint venture tuna fishery during the austral winter of 2010, (when seabirds are considered to be most abundant and aggressive) showed that this technique, combined with dual streamer lines, reduced bycatch by 86 percent compared to non-weighted lines, while still maintaining the same catch rate for target species (Melvin, Guy and Read, 2014).

These results were also confirmed in 2011 during an experiment conducted on a longline vessel targeting bigeye tuna (*Thunnus obesus*) off Chile and Peru, with only one seabird caught on weighted branch lines and 11 on unweighted branch lines, thus confirming that the use of weighted branch lines can significantly reduce seabird bycatch (Sato *et al.*, 2016).

Sliding weights

Tested in Australian and South African waters, Safe Leads, a type of sliding weight, represents an alternative line weight to weighted swivels. It is designed to increase the sink rate of the branch line and protect the crew from the risk of injury from the line breaking under stress or from hazardous fly-backs of the branch line when the fish is unhooked (Sullivan *et al.*, 2012). Safe Leads are held in place on monofilament lines by internal forces on the line created by silicon rubber rings squeezing the two halves of the lead weight together (Figure 39). During a bite-off, the line is stretched and the weight slides towards the end of the branch line, greatly reducing the recoil force of the stretched line.

FIGURE 39
Sliding weights



Redrawn from Sullivan *et al.*, 2012.

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The Lumo Lead is a variant on the sliding weight (Figure 39), designed by the Fishtek Marine company working closely with fishers and the Australian Fisheries Management Authority to reduce the incidental catch of albatross. These weights are encased in a luminescent nylon sheath that glows for over six hours, attracting fish and protecting both the crew during fishing operations and the gear rigging (Melvin, Guy and Sato, 2011; Robertson, Candy and Hall, 2013; Gianuca *et al.*, 2013; Jiménez *et al.*, 2013).

Lumo Lead-type sliding weights were tested in 2015 in the Brazilian pelagic fleet during fishing trips in the southwest Atlantic. The longlines are traditionally set at night with branch lines weighted with swivels placed 3.5 m from the hook. Compared to this technique, Lumo Lead sliding weights, placed 1 m from the hook, sink more quickly with no difference in the catch rate of target species. However, seabird mortality rates do not disappear, showing that the combination of night setting and branch line weighting is insufficient. The use of an added deterrent of, for example, the streamer line type, might reduce the incidental catch of seabirds to acceptable levels in this fishery (Santos *et al.*, 2016, 2019).

5.2.2 Setting improvements

Different setting techniques may contribute in various ways to reducing the incidental catch of seabirds. Bull (2007), Brothers, Cooper and Løkkeborg (1999) and ACAP (2011) have described in their reviews some of these techniques, aimed at hiding baited hooks from seabirds and facilitating their immersion.

Day or night setting
In the Mediterranean, the most effective way to reduce the incidental catch of seabirds is to avoid setting longlines at sunrise or sunset, when the seabirds usually feed (Belda and Sánchez, 2001). Night setting requires no gear modification and must simply be undertaken during hours of darkness. The effectiveness of this tactic is considerably reduced during moonlit periods with some species such as Cory's shearwater (*Calonectris borealis*) and Audouin's gull (*Ichthyaetus audounii*) also feeding at night, especially during a full moon (Cortés and Gonzalez-Solis, 2015).

It is therefore recommended to start setting the longlines at least one hour after dusk and to finish at least one hour before dawn. The deck must be sufficiently lit to ensure safe handling but must not illuminate the line being deployed. These recommendations may be restrictive, however, especially because they reduce the duration of setting (BirdLife International, 2013).

Side-setting
Traditionally, longlines are deployed from the stern. When deployed from the side, seabirds are less eager to approach the vessel to forage for bait. Moreover, side-setting (Figure 40) avoids the issue of setting baited hooks in the propeller wash, which slows their sink rate, as occurs with stern-setting. Indeed, the lines are deployed just as rapidly as in stern-setting. This method was tested on small vessels in the north Pacific and proved to be more effective than other measures, such as blue-dyed bait (Gilman *et al.*, 2003).

FIGURE 40
Side-setting protected by a bird curtain

Adapted from BirdLife International, 2014e.

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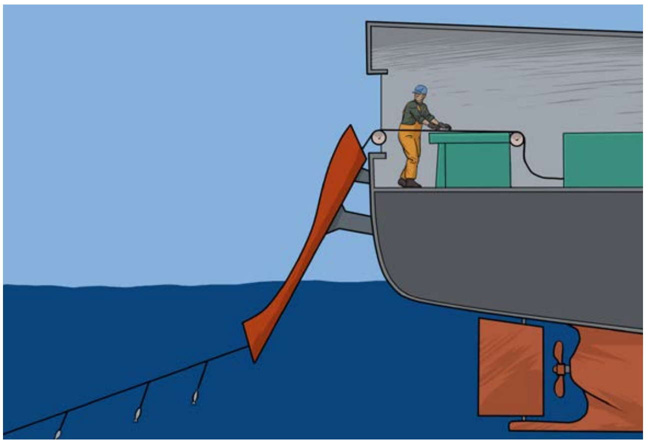
Bird curtain
A bird curtain is a pole with streamers attached, which can be deployed during setting or hauling of the longline in order to prevent seabirds from attacking the

baited hooks, thus reducing the risk of their capture (Figure 40). Research in Hawaiian longline fisheries has demonstrated the efficacy of combining seabird bycatch mitigation methods, which include a bird curtain (for example, Brothers and Gilman, 2006; Gilman, Kobayashi and Chaloupka, 2008; Gilman *et al.*, 2016a); however, the single-factor effect of a bird curtain during setting has not been assessed.

Similar bird exclusion devices were experimented in the longline fisheries of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), in this case geared to protect the hooks still baited from seabirds during the hauling-in phase rather than during the setting phase; they consist of booms with single or multiple suspended objects placed around the vessels' hauling spots (Reid, Sullivan and Clark, 2010).

FIGURE 41
Underwater setting system using a chute



Adapted from BirdLife International, 2014b.

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Underwater setting
This system enables the deployment of longlines underwater and out of sight of seabirds. It is traditionally performed using a chute (Figure 41) fixed at the stern of the vessel and extending 1 to 2 m underwater. As with many mitigation measures, environmental and operational factors affect the chute's effectiveness. In heavy seas, for example, the pitching of the vessel may raise the end of the chute clear of the water surface, rendering it less effective (Williams *et al.*, 2017).

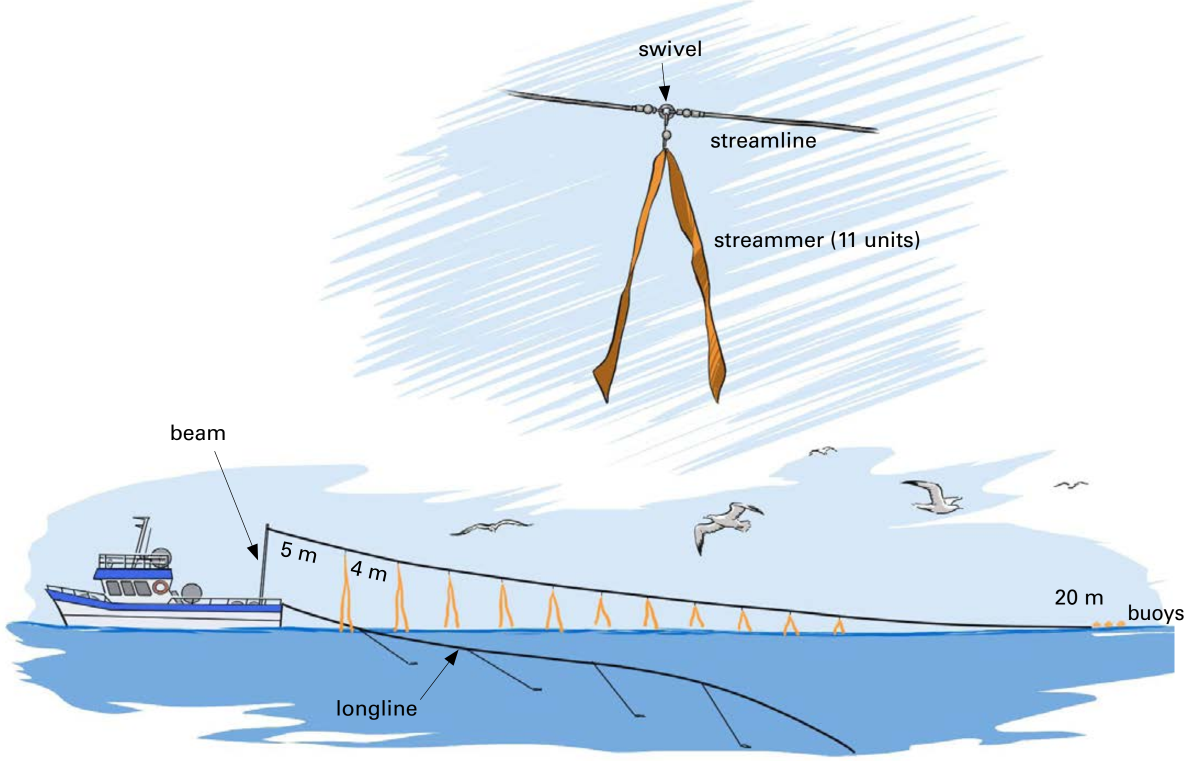
Branch line hauler
In longline fisheries, branch lines can reach 40 m in length. During hauling, seabirds may forage on baited hooks as they come to the surface. Using a line hauler speeds up the branch line hauling process.

Line shooter
By decreasing the tension in the longline, this hydraulically operated mechanism is designed to deploy the main line forward at a greater speed than the moving vessel, so that the main line enters the water faster and the baited hooks sink more quickly and deeper (Robertson *et al.*, 2010). However, the WCPFC stipulates that line shooters alone cannot be considered a sufficient mitigation measure and must be used in conjunction with at least one other such measure (WCPFC, 2012b). This system, tested in demersal longline fisheries in Norway, has proved to be less effective than underwater or side-setting (Løkkeborg, 2003).

5.2.3 Visual mitigation

Streamer lines
Streamer lines, also called Tori lines and scaring lines, appear to be one of the most effective systems to keep seabirds away from baited hooks during longline setting (Figure 42). They consist of one or two lines, with brightly-coloured streamers attached at regular intervals, mounted on a high vantage point at the stern and towed behind the vessel when the longline is deployed. An object attached at the end of the line ensures sufficient tension in the system. The aim is to keep the streamer line above the sinking area of the bait so that seabirds deterred by this kind of scarecrow cannot forage on baited hooks and get caught.

FIGURE 42
Streamer line for longliners



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It has been shown that the use of streamer lines alone can reduce seabird mortality by more than 70 percent (Boggs, 2001; Domingo *et al.*, 2011). However, it is strongly recommended to combine their use with other methods, such as night setting and weighted branch lines (Melvin, Guy and Read, 2013).

Several documents provide detailed recommendations for their design (Bull, 2007; Melvin, Guy and Read, 2010, 2014; BirdLife International, 2014c, 2014d). Here are presented only the specifications given in the good practice guide (Figure 42) prepared for the Balearic longliners (Cortés and Gonzáles-Solis, 2015).

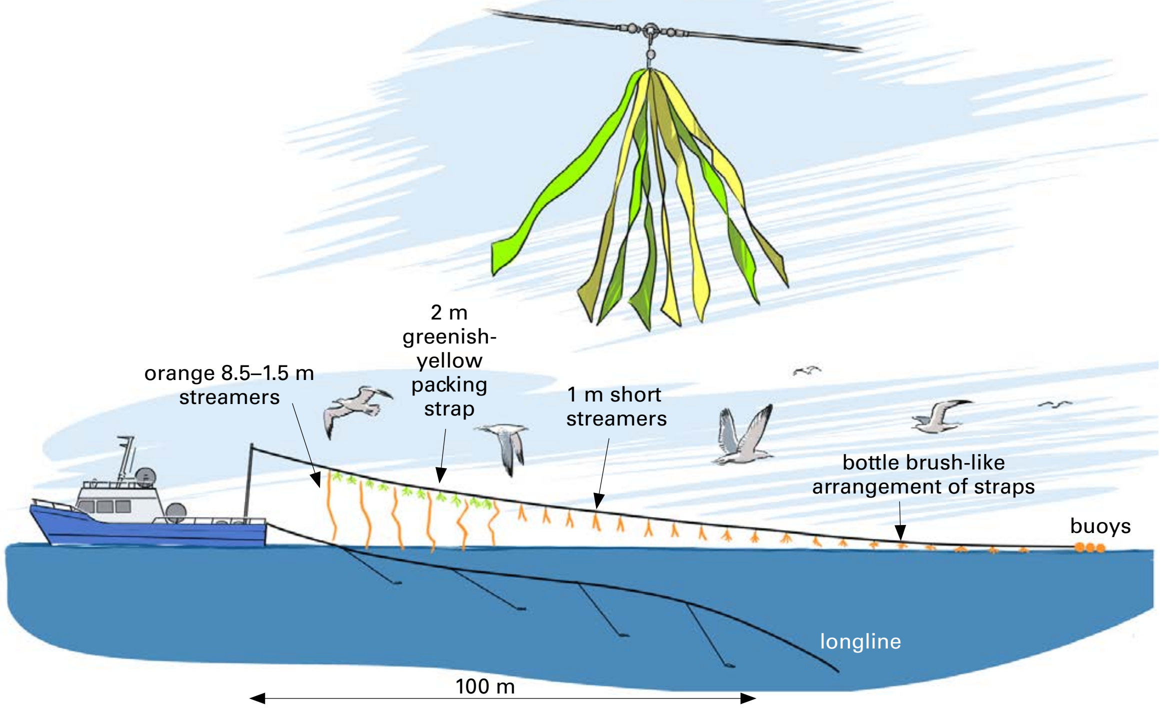
A standard streamer line (Figure 42) comprises a 70 m wire of 6 mm diameter on which brightly-coloured PVC light streamers of decreasing lengths are attached every 3 to 4 m; a buoy used as a weight is fixed at the end of the wire, about 20 m away from the last streamer. The other end of the wire is fixed to a pole at over 5 m above sea level (Cortés and Gonzáles-Solis, 2015).

The streamers must protect the baited hooks until they sink out of seabird reach (around 10 m below the surface) (Melvin, Guy and Read, 2010). Weighting the branch lines makes it possible to reach this depth more rapidly.

The setting operation starts with the launch of the buoy while the boat is moving. Once the streamer line is entirely deployed, the longline can be set. At the end of setting it has to be hauled in before the streamer line (Cortés and Gonzales-Solis, 2015).

Generally, pelagic longlines are set at a rate faster than the vessel speed and the hooks sink more slowly than those on demersal longlines. This increases the distance to be protected behind the vessel.

FIGURE 43
Hybrid streamer lines



Redrawn from Melvin, Guy and Read, 2014.

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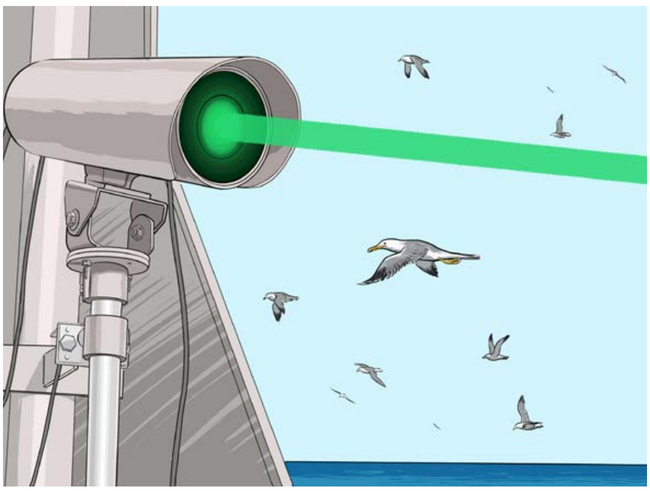
In calm situations, this deterrent system may be ineffective as the streamer lines fail to flutter and frighten the seabirds. Meanwhile, in crosswind conditions, the streamer lines have to be adjusted to deter seabirds, which usually fly close to the wind, from foraging on baited hooks (Domingo *et al.*, 2011; Gianuca *et al.*, 2013).

A hybrid Tori line (Figure 43) has also been developed, combining long streamers (8.5 m to 1.5 m long) with short streamers (2 m). Additionally, in order to create drag on the line in the water, clusters of three 1 m streamers are used to avoid tangling on surface floats (Melvin, Guy and Read, 2013, 2014).

Laser beams

The use of the SeaBird Saver laser beam (Figure 44), designed by the Mustad Autoline (Mustad Autoline, 2014) and SaveWave (SaveWave, 2021; New Zealand Department of Conservation, 2014) to keep seabirds away during longline setting, was first tested in 2014 onboard an Icelandic vessel fishing for cod (*Gadus morhua*) with

FIGURE 44
Seabird Saver visual deterrents



Marketed by the Norwegian company Mustad, Seabird Saver visual deterrents produce a broad laser beam especially effective in darkness; they can be operated as a static or sweeping laser beam and be combined with an optional sound system.

Redrawn from SaveWave, 2021 and Mustad Autoline, 2014.

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a bottom longline. The trial lasted five fishing days, covering a total of five sets of a 2 500-hook longline. The system is built to produce a visual deterrent especially effective during low visibility conditions (i.e. dawn, dusk, rain and fog) with a broad light beam to reduce the risk of eye damage in seabirds. During the trials, the SeaBird Saver effectively warded off Northern Fulmars (*Fulmarus glacialis*), which were present at some distance from the vessel stern in the critical area where baited hooks are immersed. The laser can be coupled with acoustic stimuli creating a dual deterrent. In the future, it was recommended that this system be complemented with a sound component mimicking a mixture of predator and distress calls (Van Dam, Schrijver and Sorensen, 2014).

However, according to Parker (2017), evidence lacks to confirm that the system works without injuring seabirds. Trials carried out in trawl fisheries in Alaska (Melvin *et al.*, 2016) showed in particular that the device is not effective during daylight, with varying levels of efficacy at night for seabirds.

Additional experimental research is needed in other fisheries to show that laser beams could have a statistically significant effect in reducing seabird bycatch. The Australian Fisheries Management Authority recently undertook trials of lasers in a bottom longline fishery, but the results have not yet been reported (Parker, 2017).

5.2.4 Acoustic mitigation

Acoustic deterrents currently used range from firing shotguns or cannons and beating on the steel hull to commercial devices emitting loud, high-frequency noises or distress signals (Bull, 2007). However, these devices appear to be largely ineffective and should be used sparingly in order to avoid any habituation (Brothers, Cooper and Løkkeborg, 1999).

5.3 Sharks and rays

In a recent study on reducing the risks of shark bycatch and mortality in New Zealand longline fisheries (Howard, 2015), 20 methods were identified and ranked according to how quickly they could be applied in commercial fisheries. The highest-ranked methods were large hooks, nylon leaders, squid bait and non-forged hooks (weak hooks). Other parameters, such as the depth and timing of setting, depend on the species and environmental conditions in the fishery, or may be controversial, as in the use of circle hooks.

5.3.1 Fishing gear improvements

Hook

Circle hooks

Circle hooks have a circular shape with the tip perpendicular to the shank and they are designed for hooking in the corner of the mouth of the fish, ensuring great hooking efficiency and reducing the risk of deep hooking. This type of hook is considered as a practical and economical measure to reduce mortality in tuna-like longline fisheries (Promjinda *et al.*, 2008; Afonso *et al.*, 2011; Graves, Horodysky and Kerstetter, 2012; Gilman, Chaloupa and Musyl, 2018).

According to different studies comparing the efficacy of circle hooks and J-hooks in pelagic longline fisheries in reducing shark and ray bycatch (Bolten and Bjorndal, 2005; Yokota, Kiyota and Minami, 2006; Ward *et al.*, 2009; Fernandez-Carvalho *et al.*, 2015), the authors did not find significant differences between the two types of hooks on bycatch and mortality of sharks and rays – notably for blue sharks (*Prionace glauca*) – regardless of the bait. On the contrary, Afonso *et al.* (2011, 2012) found that significantly high mortality rates for blue sharks, silky sharks (*Carcharhinus falciformis*) and oceanic whitetips (*Carcharhinus longimanus*) resulted from using J-hooks vs circle hooks. Gilman *et al.* (2016b) indicate that certain species of sharks are captured more frequently with circle hooks compared to J-hooks or tuna hooks.

Several authors (Watson *et al.*, 2005; Gilman *et al.*, 2007; Patterson and Tudman, 2009; Afonso *et al.*, 2011, 2012) suggested that the observation of increased blue shark catches using circle hooks may be due to unrecorded instances of sharks dehooking themselves from longlines coupled with monofilament branch lines, which can be cut by sharks deep-hooked by J-hooks, allowing them to escape before being hauled on board.

In the Mediterranean, the pelagic stingray (*Pteroplatrygon violacea*) represents the primary bycatch of swordfish longline fisheries. Circle hooks appear to be more effective than J-hooks, showing an 80 percent reduction in stingray bycatch, thus supporting the adoption of this type of hook to reduce the fishing's environmental impact (Piovano, Clò and Giacoma, 2010).

Domingo *et al.* (2012) also observed a decrease in the catch of pelagic stingray when using circle hooks compared to J-hooks (always using the same bait for the two types) in their trials on the Uruguayan pelagic longline fleet targeting swordfish, tunas (*Thunnus* spp.) and pelagic sharks (mainly the blue shark). Similarly, Fernandez-Carvalho *et al.* (2015) confirm for the Portuguese pelagic longline fishery targeting swordfish in the tropical northeastern Atlantic that the pelagic stingray was only captured with J-hooks.

Nevertheless, other factors must be taken into consideration in choosing a hook type, such as mortality after release and catch value. Thus, experiments in test tanks on pelagic stingray, caught by French Mediterranean bluefin tuna longlining showed that J-hooks showed a faster self-shedding rate than circle hooks of a similar size, thereby resulting in minimal injury and a quick resumption of feeding by pelagic stingray, as well as a better chance for survival (Poisson *et al.*, 2019).

For most longline fisheries targeting swordfish, squid-baited J-hooks are a commonly used combination; authors like Sales *et al.* (2010), Fernandez-Carvalho *et al.* (2015) point out that the catch of swordfish decreases when switching from the traditional J-hook baited with squid to other combinations including the circular hook, which tradeoff can be problematic from a fishery management point of view.

Apart from the effects of the bait or branch, other parameters of the hook should be considered; from their experiences, Piovano, Cló and Giacoma (2010), noting a relationship between the size of the stingray mouth opening and the size and shape of the hook, suggest further study of the effects of hook size on reducing the impact on vulnerable bycatch, while maintaining the profitability of fishing.

The use of weak hooks to reduce the catch of large specimens is a simple measure to implement, but it has not yet been shown to be effective in reducing shark bycatch.

Corrodible hooks

These hooks are made of metals other than stainless steel, such as different alloy compositions with various coatings conditioning their durability. They decay more or less rapidly following their ingestion according to their diameter and composition (ranging from a couple of days to a few months). Their use is of interest, as they reduce the mortality rates of animals freed with a hook still in place. While the need to replace the hook more frequently can present a drawback, manufacturing this kind of hook is technically simple and therefore less costly (Patterson and

Tudman, 2009; McGrath *et al.*, 2011), thus justifying a preliminary economic evaluation before its application in a fishery.

Branch lines

As noted above, the type of branch lines and the equipment used play an important role in catching sharks and rays. In some longline fisheries, notably those targeting sharks, branch lines are made of steel wire (Vega and Licandeo, 2009; Watson *et al.*, 2005).

To assess the performance of wire conductors, Ward *et al.* (2008) conducted experiments off northeastern Australia on commercial vessels, comparing wire (leader) branch lines of cabled stainless-steel wire to nylon (polyamide) monofilament branch lines covered with an outer nylon skin. Using the same Japanese tuna hook and the same frozen bait (sardine, *Sardinops* spp.), tests showed that the catch rates of many species, including of sharks, snake mackerel (*Gempylus serpens*), lancet fish (*Alepisaurus* spp) and wahoo (*Acanthocybium solandri*), were higher on wire branchelines than on the nylon monofilament ones; the catches of sharp-toothed species, such as sharks and snake mackerel, are lower on nylon branch lines since the animals are able to sever them and escape. Furthermore, the authors noted that the J-hooks used in their study often became embedded in the throat or gut, thereby exposing the branchelines to abrasion against the teeth. It can therefore be estimated that J-hooks on nylon branches may lead to higher shark loss rates than circle hooks on nylon branchelines. Consequently, Ward *et al.* (2008) conclude that there are real benefits to banning wireline branching in longline fishing in order to reduce bycatch of sharks and other species.

More recently, from experiments conducted in the southwest Indian Ocean on a commercial fishing vessel in the Portuguese pelagic longline fleet over two trips, Santos, Lino and Coelho (2017) observed higher biteoff rates on nylon monofilament branch lines, likely owing to the escape of species with sharp teeth, such as sharks, and moreover noted that a larger mean size of blue sharks was recorded on wire branch lines.

Several countries, including Australia, Ecuador, the Federated States of Micronesia, New Caledonia, Papua New Guinea, South Africa, Tonga and Republic of the Marshall islands, have already prohibited the use of wire leaders in their longline fisheries (Gilman *et al.*, 2008; Lack and Meere, 2009).

Bait

Bait type

According to Fernandez-Carvalho *et al.* (2015), bait type has a stronger influence than the hook style on shark catch. Bait used for longline fishing must be attractive to the target fish, should remain on the hook for either the entire duration of fishing or until a fish is hooked, be available in large (and regular) quantities, be inexpensive and should deliver the best economic returns to the fishers (Kumar, Pravin and Meenakumari, 2016).

Mackerel, sardines and squid are the primary baits used for longlining (Foster *et al.*, 2012; Løkkeborg *et al.*, 2014); several field experiments have attempted to determine their selective effects on non-target species such as sharks, rays and sea turtles (for example, Santos *et al.*, 2012).

For a number of authors (Galeana-Villasenor, Galvan-Magana and Santana-Hernandez, 2009; Cosandey-Godin, Carlson and Burgener, 2012; Watson *et al.*, 2005; Gilman *et al.*, 2007, 2008) using fish such as mackerel or mullet as bait rather than squid reduces pelagic shark bycatch, including of the blue shark.

Conversely, other studies revealed high bycatch rates with mackerel bait for the blue shark and the bigeye thresher shark (*Alopia superciliosus*) (Foster *et al.*, 2012; Amorim *et al.*, 2015).

To explain this divergence, it is important to underline that a catch rate is not the result of only the attractiveness of the bait but also of the ability of the fish (here the shark) to ingest it entirely with the hook. The texture, shape and size of the dead baits affect longline efficiency and selectivity, in terms of species and size of the targeted fish (Løkkeborg and Bjordal, 1992; Løkkeborg, Bjordal and Fernö, 1989; Johannessen, Fernö and Løkkeborg, 1993). As such, according to their hook-holding properties, squid was found to be superior to fish (Ward and Myers, 2007), such as mackerel, and fresh bait more efficient than frozen bait (Løkkeborg *et al.*, 2014).

Foster *et al.* (2012) conclude that if blue sharks simply bite the mackerel bait halfway instead of ingesting it whole with the hook, the probability of their being caught diminishes, resulting in a high proportion of hooks without catch and consequently a low catch rate.

In addition, the choice of bait selectivity may lead to opposite effects, depending on the species of shark. Studies conducted by Foster *et al.* (2012) have shown that mackerel used as bait decreases the hooking rate of the blue shark, while significantly increasing the bycatch of the porbeagle (*Lamna nasus*) and shortfin mako (*Isurus oxyrinchus*). The use of fish in place of squid bait has been shown to be effective in reducing the bycatch of sea turtles and seabirds but may increase the catch of some shark and ray species (Kumar, Pravin and Meenakumari, 2016).

The main issue in determining the selective effect of a certain bait in sea trials is the difficulty of dissociating its influence on a longline's catch from those of the hook type, the setting mode and a range of environmental factors. Consequently, as Gilman *et al.* (2016b) emphasize, there is a need to observe the fishing process in captive conditions, preferentially focusing on a single variable at a time.

Artificial bait

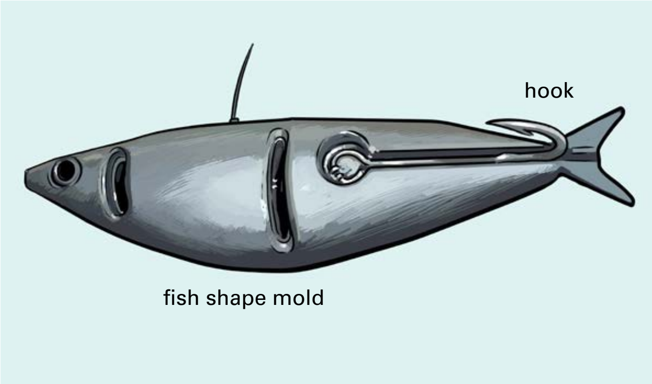
The development of different kinds of artificial bait undertaken in the 1980s aimed to both free longline fishers from natural bait supply constraints and recycle waste from the processing industry (Løkkeborg *et al.*, 2014). Designs should meet three requirements: a synthetic attractant, preferably as effective as the natural bait commonly used; a support sufficiently strong to keep it on the hook, while capable of diffusing the attractant throughout the setting; and a product that is easily stored without being significantly more expensive than natural bait (Le Gall, 2008). The challenge is to design bait which will attract only target species and consequently reduce the catch of unwanted species.

Several studies demonstrate great potential for the use of baits or extract mixtures to attract specific target species to an odour source. These properties of feeding attractants should form the basis for the development of species-selective bait-fishing methods (Løkkeborg *et al.*, 2014). For example, Erickson and Berkeley (2008) used artificial bait made from products derived from fish waste incorporated into a gum-based matrix. When tested on bottom longline fishing gear targeting the Pacific halibut (*Hippoglossus stenolepis*) in Alaska, this bait significantly reduced bycatch of the piked dogfish (*Squalus acanthias*) and the longnose skate (*Raja rhina*). Halibut catch was unaffected, though cod catch fell substantially. This artificial bait has the advantage of maintaining its attractiveness to target species for two hours more than herring bait while avoiding catching sharks and rays, which are much more attracted by herring bait (Erickson and Berkeley, 2008; Erickson, Goldhor and Giurca, 2000).

Trials on pelagic longlines have indicated that it is also possible to reduce ray bycatch with artificial bait. Januma, Miyajima and Abe (2003) have developed an artificial bait using squid liver for tuna longline fisheries; they observed that fewer sharks and rays were caught by the artificial bait than by squid bait, without a significant difference in tuna catch between the artificial and squid bait. However, they did not find obvious causes for this reduction in bycatch.

In the southwestern Indian Ocean, a prototype called ecological-based artificial bait (EBAB), which combines a fish-shaped mold (Figure 45) with tuna flesh pulp, was tested from May to August 2012 during 46 fishing operations of commercial longliners targeting tuna and swordfish. During the trials, only two shark species, the blue shark and the oceanic whitetip shark were captured with EBAB, versus seven species of sharks and rays caught with natural bait. Furthermore, no sea turtles were caught with EBAB and only one Risso's dolphin was accidentally hooked by its pectoral fin (Bach *et al.*, 2012).

FIGURE 45
Ecological-based artificial bait



Redrawn from Bach *et al.*, 2012.

Other research includes examining the possibility of using artificial bait designed to both repel sharks or other unwanted bycatch – by using, for example, necromones (i.e. pheromones given off by a dead organism) – and improve selectivity for target species (Clarke *et al.*, 2014).

Nevertheless, Kumar, Pravin and Meenakumari (2016) emphasize that most studies, with the exception of those examples presented above, indicate greater effectiveness of natural bait over artificial bait for target species. Although artificial bait has the potential to reduce bycatch, no effective substitute for natural bait satisfying the fishing industry has been developed so far.

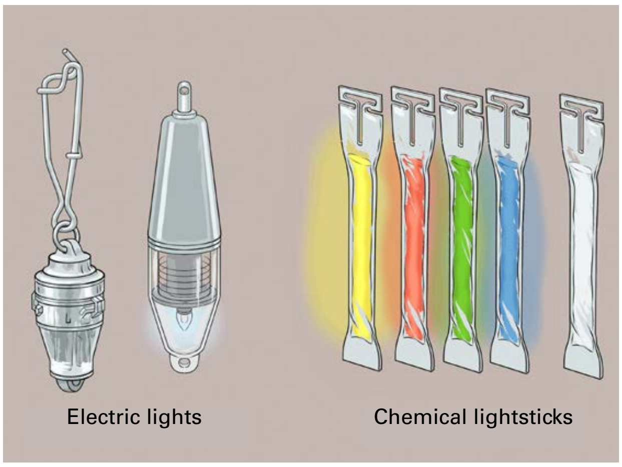
Luminous lures

Lightsticks (Figure 46) attract small fish and squid as well as predators to bait by creating a lighted environment and a shaded area around branch lines (Hazin *et al.*, 2005) and are thus responsible for high catches of sharks and rays.

Many fishers believe that the use of light sticks may increase shark bycatch, but do not agree on the colours that are most attractive to sharks. Little is known about the responses of sharks and rays to the light lures used by longliners. According to a study undertaken on the swordfish longline fishery in the Strait of Sicily, light lures appear to have little impact on the catch rate of the pelagic stingray (Piovano, Clò and Giacoma, 2010).

Nevertheless, they are increasingly considered to be harmful to the marine environment because they are suspected to attract sharks, rays and sea turtles, and the chemical lightsticks, in particular, are potentially toxic to marine organisms when they are released at sea due to their contents (Pinho, Ihara and Fillmann, 2009).

FIGURE 46
Light-emitting diodes and light-sticks



Redrawn from Beverly and Park, 2009.

Removing lightsticks could offer a simple mitigation measure, but it is unlikely to produce significant results despite the positive correlation reported in the relevant literature between their use and shark bycatch (Gilman *et al.*, 2007, 2008; Poisson *et al.*, 2010).

Branch lines

Both nylon and stainless-steel wire branch lines (Figure 47) are used indifferently in various longline fishing activities (Beverly and Park, 2009). Nevertheless, Stone and Dixon (2001) have shown that the use of monofilament lines in pelagic swordfish longline fisheries increases the catch of target and bycatch species, such as sharks, by a similar extent.

FIGURE 47
Different types of material used for longlines

Redrawn from Beverly and Park, 2009.

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Sharks free themselves with less difficulty from monofilament branch lines, which they can more easily break, than from steel lines (Gilman *et al.*, 2008; Ward *et al.*, 2008). Although this leads to an apparent decrease in shark catch, it does not necessarily signify reduced mortality rates, as hook will remain attached to the freed shark's esophagus or jaw. This dynamic was observed in the Brazilian longline fishery, where 97 percent of escapees had been caught with nylon branch lines; the difference between nylon and steel branch lines was only significant for those equipped with J-hooks. The use of steel branch lines therefore does not necessarily mean higher shark catch rates (Afonso *et al.*, 2012; Clarke *et al.*, 2014).

The branch line length may also affect shark survival rates; too short of a length will restrict the swimming motion required for ram ventilation (i.e. ventilating the gills by swimming fast with an open mouth) and may lead to asphyxia in captured individuals (Gallagher *et al.*, 2014).

Furthermore, in 2013 and 2014, 40 g and 60 g Lumo Leads were tested on New Zealand tuna and swordfish longliners. The recorded bycatch of blue sharks was significantly lower than with normal longlines, with no impact on the catch of target species (Pierre, Goad and Abraham, 2015).

5.3.2 Setting improvements

Time and duration of the setting

The duration and the time of setting and hauling affect catch rates, presumably because of differences in the environmental conditions determining shark behaviour. This issue has been the subject of little research, however, and the research that has been conducted tends not to differentiate between the impacts of the timing and duration of the setting.

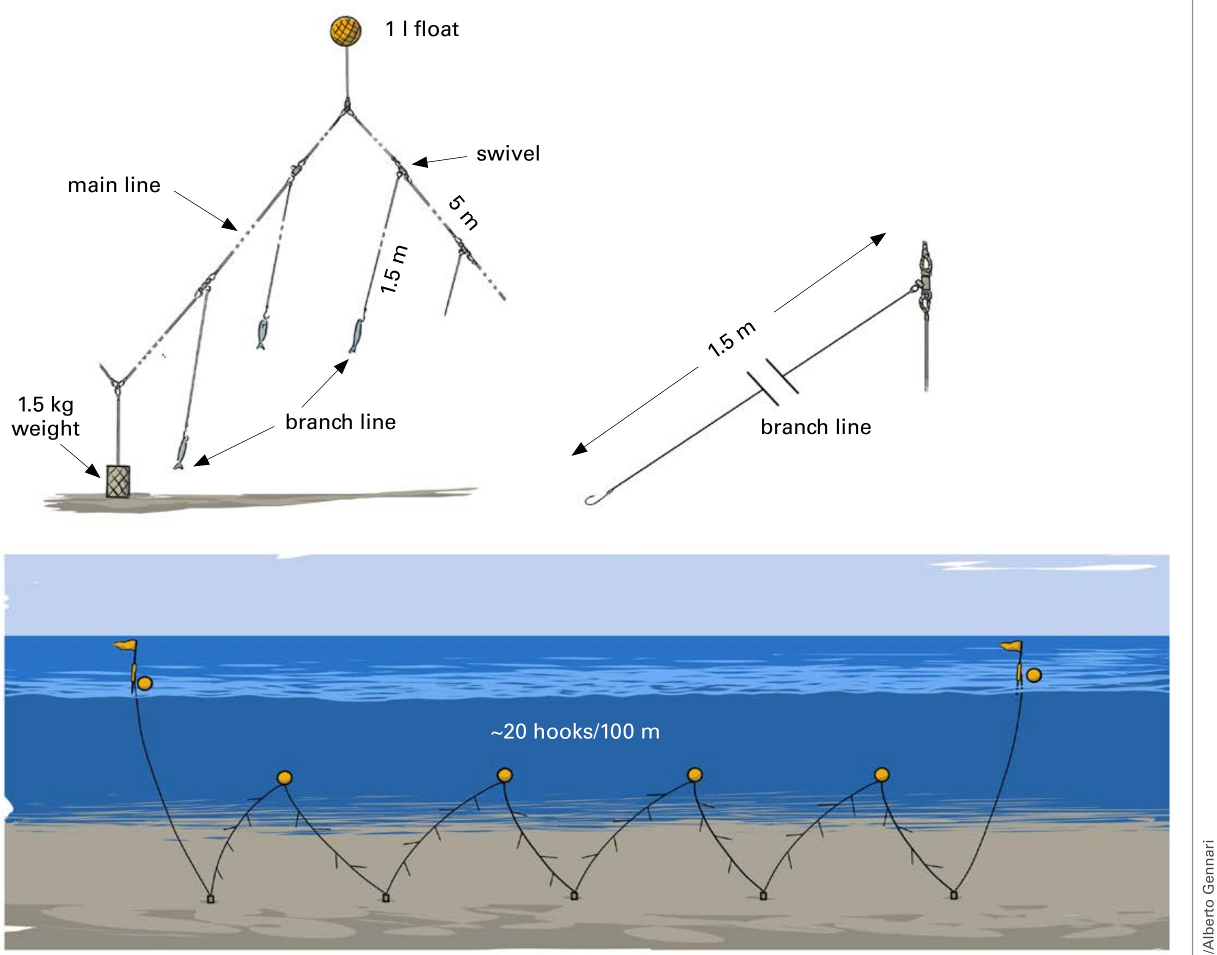
Setting depth

The bigeye thresher (*Alopias superciliosus*) catch rate in the longline fishery of the Marshall Islands is higher during shallow night setting and deeper day setting (Bromhead *et al.*, 2012).

Changing the setting depth may thus represent an effective way to reduce shark bycatch in longline fisheries. However, even if the longline is rigged for deep-sea fishing, some parts can remain in the surface water layer for a period of time, depending on the sink speed of the longline. In order to reduce the risk of interactions with surface-swimming pelagic sharks, a few simple ways to increase this speed include weighting the branch lines and deploying the longline at a faster rate than the vessel speed (Beverly, 2005).

In the case of longline fishing for demersal species, the use of longlines, where the main line floats above the seafloor (Figure 48) so that baited hooks do not touch the bottom, reduces the risk of depredation by demersal sharks, such as the small-spotted catshark (*Scyliorhinus canicula*) or by invertebrate scavengers. The drawback of this longline is that it takes longer to sink during deployment, increasing the risk of incidental seabird catch. Coelho *et al.* (2005) have shown that by removing the lower three hooks in the hake (*Merluccius merluccius*) semi-pelagic longline fishery in the Algarve, the number of sharks caught decreases by 16 percent to 33 percent, depending on the species. Hoey and Moore (1999) also found that reducing the number of hooks or setting the gear farther from the seafloor achieved a reduction in shark bycatch.

FIGURE 48
Semi-pelagic hake longline



Semi-pelagic hake longlines, known as "piedras-bolas", are used for example in the Catalan Sea.

5.3.3 Acoustic mitigation

Sharks, like pelagic teleosts, are known to be sensitive to low frequencies (Southwood *et al.*, 2008). Silky sharks and oceanic whitetip sharks are attracted to low-frequency sounds within the range of 25 to 1 000 Hz, with attraction increasing as sound frequency decreases. Irregularly pulsed sounds, similar to those produced by struggling prey, are more attractive than regularly pulsed sounds. Sudden transmission of high-intensity sound at close range prompts an immediate and rapid withdrawal in sharks, though this effect does not last long, as they rapidly habituate to such signals.

5.3.4 Chemosensory mitigation

Sharks display attraction to odors deriving from fish and invertebrates as a signal of potential prey, particularly those from stressed fish; this draw represents one of the main reasons behind shark bycatch during longline fishing. Red Sea soles (Pardarchirus spp.) are known to secrete a surfactant-like substance containing pardaxin, a natural shark repellent (Clark and George, 1979). However, its potential use is hindered by its difficult synthesis and its extreme liability. This line of research was pursued further by Stroud *et al.* (2014), but the dissuasive effect of semi-chemical substances derived from decaying shark tissue appears to be of limited interest to longliners for the time being, given the large quantities and concentrations required for them to be effective. Nevertheless, sea trials using squid treated with a chemosensory substance showed a 37 percent reduction in shark bycatch in surface longlines (NOAA, 2013).

Concerning predation, chemoreception is most likely the dominant detection system in sharks. Jordan *et al.* (2013) have carried out a comprehensive review on how the sensory biology of sharks is linked to bycatch reduction.

For example, using aerosol canisters at the surface to deliver a substance produced by putrefied shark tissue induced an immediate flight reaction in the Caribbean reef shark (*Carcharhinus perezi*) and the blacknose shark (*Carcharhinus acronotus*) populations at South Bimini in the Bahamas. By contrast, no aversion response was detected in the teleosts also present (Stroud *et al.*, 2014), i.e. the potential target fish species.

Shark Defense Technologies (Sharkdefense, 2001), a company based in New Jersey, has developed a series of chemical repellent polymers supposed to deter a wide variety of shark species from approaching baited hooks. SuperPolyShark is a time-release pellet, constructed as a paper tube enclosing a polymer infused with a synthetic semi-chemical. In swordfish longline fisheries, it can be inserted under the mantle of a squid before baiting the hook. According to the company, "this repellent is non-toxic and biodegradable and target species catch rates are maintained. It dissolves completely within 16 hours of contact with water. This nontoxic and biodegradable repellent has achieved a 71 percent difference in shark catch between treated and control baits over a four-hour window." Though the device was awarded as a runner-up of the World Wildlife Fund (WWF) International Smart Gear Competition in 2014 (WWF, 2015), no research has yet been published to verify the manufacturer's claims.

5.3.5 Magnetic or electropositive mitigation

Permanent magnets have been demonstrated to produce a repellent effect on sharks by creating an abnormally strong electrical stimulus, which overwhelms the sharks' acute electro-sensory system. The use of rare earth metals, such as lanthanides, were introduced into longlines in 2006 by the winner of the WWF Smart Gear competition, Michael Herrmann, as a means of keeping sharks away from baited hooks. These magnets, sometimes simply called rare earth metals, are either added to the line in the form of metal discs or directly incorporated into hooks. A New Jersey company (Shark Defense) developed a magnetic hook called the SMART Hook, coated with a special polymer and metal creating a 1.05 V galvanic cell in seawater (Figure 49). According to the National Science Fondation (2011), the hook loses its electromagnetic property after five days as the metal dissolves rapidly.

An experiment carried out on longlines in the Gulf of Maine showed that SMART hooks decreased the capture of piked dogfish by 28.2 percent after 26 days of longline gear deployment; however, the SMART hooks did not show any influence on thorny skate (*Amblyraja radiata*), barndoor skate (*Dipturus laevis*) or teleost capture (O'Connell *et al.*, 2014).

FIGURE 49
Shark Defense SMART Hook with galvanic coating

Source: Sharkdefense, 2001.

O'Connell *et al.* (2011) reviewed the different studies on the impacts of permanent magnets and lanthanides on various shark species and concluded that the deterrent effect varied according to the studied species (Table 2). While the deterrent effect of magnets or electropositive metals has often come through in controlled laboratory conditions, field trials have experienced varying degrees of success depending on the application. In the laboratory, the scalloped hammerhead (*Sphyrna lewini*)

TABLE 2 – Impacts of magnetic materials on some shark species

Authors	Species	Material	Approach		Avoidance	
			Control	Magnet	Control	Magnet
O'Connell *et al.*, 2010	I) *Dasyatis americana*	Barium ferrite	20	18	5	49
O'Connell *et al.*, 2010	II) *Ginglymostoma cirratum*	Barium ferrite	6	8	2	20
O'Connell *et al.*, 2011	III) *Carcharhinus limbatus*	Barium ferrite	16	2	N/A	N/A
O'Connell *et al.*, 2011	IV) *Carcharhinus plumbeus*	Barium ferrite	4	7	N/A	N/A
O'Connell *et al.*, 2011	V) *Dasyatis americana*	Neodymium-iron-boron	10	5	N/A	N/A
O'Connell *et al.*, 2011	VI) *Mustelus canis*	Neodymium-iron-boron	10	1	N/A	N/A
O'Connell *et al.*, 2011	VII) *Raja eglanteria*	Neodymium-iron-boron	4	1	N/A	N/A
O'Connell *et al.*, 2014	I) *Carcharhodon carcharias*	Barium ferrite	66	2	6	20
O'Connell *et al.*, 2014	II) *Squalus acanthias*	Neodymium-iron-boron	1 296	930	N/A	N/A
O'Connell *et al.*, 2014	III) *Tetronarce nobiliana*	Neodymium-iron-boron	1	0	N/A	N/A
O'Connell *et al.*, 2014	IV) *Lamna nasus*	Neodymium-iron-boron	1	0	N/A	N/A
Rigg *et al.*, 2009	V) *Carcharhinus amblyrhyncos*	Ferrite	388	302	51	109
Stone and Kaimmer, 2008	VI) *Squalus acanthias*	Neodymium-iron-boron	79	64	N/A	N/A

Data from several studies on the use of magnets as repellents. The "Approach" column indicates the number of times an animal approached the experimental apparatus, bit at the hooks, took bait from them or was caught on a line. The "Avoidance" column indicates the number of times an animal showed a definitive action to try to avoid a magnetic field (modified from O'Connell *et al.*, 2011).

(Hutchinson *et al.*, 2012), piked dogfish (*Squalus acanthias*) (Stoner and Kaimmer, 2008), the southern stingray (*Dasyatis americana*) and the nurse shark (*Ginglymostoma cirratum*) (O'Connell, Stroud and He, 2014; O'Connell *et al.*, 2010) showed significant sensitivity to lanthanides.

In field trials, Brill *et al.* (2009) showed that electropositive metals (mixtures of lanthanide elements), placed within 10 cm of bottom longline hooks, reduced the catch of sandbar sharks (*Carcharhinus plumbeus*) by around two thirds compared to the catch on hooks with a placebo.

Similarly, experiments conducted in 2010 in the waters of South Bimini (Bahamas) by O'Connell *et al*. (2015b) show that the great hammerhead shark (*Sphyrna mokarran*) behavior is significantly altered in the presence of barium-ferrite, displaying significantly increased avoidance frequency.

On the other hand, sea trials conducted on the Scotian Shelf, southwest of Nova Scotia, Canada (Cosandey-Godin *et al.*, 2013) did not show any reduction in the bycatch of the blue shark or of any other common shark species. Furthermore, a study carried out during commercial longline fishing operations in the northeastern Atlantic, onboard a longline fishing vessel, showed that neodymium magnets (model 8850 Gauss and model 4640 Gauss) do not reduce blue shark catch rates, even showing an attractive effect at times (Bitón Porsmoguer *et al.*, 2015).

These examples corroborate the conclusion that results contrast greatly between laboratory and field experiments, between species and according to the electro-magnetic system used. O'Connell, Stroud and He (2014) also noted that after dissection, sharks that had avoided capture showed higher levels of satiation. Concerning their sea trials on the great hammerhead shark, O'Connell *et al.* (2015b) observed an important decrease in feeding frequency under the electro-magnetic treatment.

These observations show that biological and environmental variables may influence shark behavior towards magnetic stimuli and further findings could greatly benefit the understanding of what conditions yield maximum deterrent efficacy.

Nevertheless, the main weakness of permanent magnets lies in their short range of efficacy: all the above trials showed that avoidance responses only occur within approximately 1 m of the magnetic field source (O'Connell, Stroud and He, 2014).

5.4 Sea turtles

Between small craft and large industrial vessels with processing facilities, longline (mainly pelagic longline) fisheries are responsible for significant bycatch of sea turtles, including of both juveniles and breeders. Of the seven species of sea turtles in the world, the loggerhead (*Caretta caretta*) and the leatherback (*Dermochelys coriacea*) represent the most affected species and are of particular concern due to their vulnerability status. Gilman and Huang (2017) provide an overview of various mitigation solutions, including both the improvements in fishing gear and adaptations of fishing strategies.

5.4.1 Fishing gear improvements

Hooks

The most important parameters determining the hooking process are the overall hook width, which can be better accommodated for turtle mouth dimensions, the distance between the point and the shank, which ensures deeper penetration of the point and provides better holding power, and its shape, which can influence the hooking position (Lucchetti and Sala, 2010).

The hook size influences the probability of the hook being swallowed and thereby the rate of delayed mortality after release. Jribi and Bradai (2008), Alós *et al.* (2008), and Jribi *et al.* (2008) found that large hooks reduce the incidence of hooking injuries, with only a small reduction in catch rates.

According to Santos *et al.* (2012), while leatherback sea turtles are mostly hooked externally by the flippers, loggerhead turtles are mainly hooked by the mouth. Specifically, loggerhead turtles most often swallow J-hooks, which hook them internally, probably the most lethal form of hooking (Watson *et al.*, 2005).

Circle hooks

An increasing number of studies tend to show that circle hooks are more effective than J-hooks in reducing sea turtle bycatch, as their greater width prevents deep hooking and their curved shape reduces external hooking.

Piovano, Swimmer and Giacomi (2009) stress that circle hooks significantly reduce bycatch of juvenile loggerhead turtles, without substantially affecting the target species catch rate in swordfish longline fisheries in the Strait of Sicily.

In the Brazilian longline fishery operating in the southwest Atlantic Ocean, Sales *et al.* (2010) showed that the use of circle hooks instead of J-hooks reduced bycatch of loggerhead turtles by 55 percent and of leatherback turtles by 65 percent. Furthermore, deep hooking was reduced from 25 to 5.8 percent with circle hooks, thereby increasing survival rates after dehooking.

In a similar way, Santos *et al.* (2013) studied the effects of changes in hook style and bait type on sea turtle bycatch in the Portuguese commercial longline fishery targeting swordfish in the south Atlantic. Three different styles of hooks were tested, a traditional J-hook and two circle hooks of varying dimensions, but with only one type of bait (Scomber spp. or Illex spp.). Two species of sea turtles were captured, the leatherback turtle and the loggerhead, with most loggerheads hooked by the mouth, while leatherback turtles were mainly hooked externally by the fins. The highest mean bycatch per unit effort occurred with J-hooks baited with squid. Overall, 85 percent of leatherback turtles and 63 percent of loggerheads were released live at sea. From these results, the authors suggest that a significant reduction in incidental catches of sea turtles in swordfish longline fisheries could be achieved by replacing J-hooks with circle hooks, especially if baited with mackerel.

As for sharks and rays, the use of circle hooks decreases light hooking (mouth) and deep hooking (esophagus) and therefore the post-release mortality rate. However, circle hooks with high offset (for example, greater than ten) are likely to behave similarly to J-hooks, increasing the proportion of caught turtles that are deeply (esophagus) or lightly (mouth) hooked (Coelho *et al.*, 2015; FAO, 2009b).

Based on the conclusions of the Subgroup on bycatches of turtles in the European Union longline fisheries of the Scientific, Technical and Economic Committee for Fisheries of the European Union (Camiñas, Di Natale and Munch-Petersen, 2005) as well as on research by Watson *et al.* (2005) and Gilman *et al.* (2006), hook shapes do not appear to have consistent effects on sea turtle bycatch reduction across different fisheries; bait and hook size, branchline length and immersion depth are likely more important. According to these authors, the attenuation effects of these technical factors should be studied separately for each fishery concerned by bycatch issues, over a sufficiently long period of time and taking into account the consequences on other taxa.

Corrodible hooks

This type of hook offers the same advantages for sea turtles as for sharks (see Section 5.3.1).

Bait

Bait type

As mentioned already for sharks, it is difficult to analyse separately the selective effects of bait, disassociated from those of hooks, so they are generally studied together.

However, various studies have shown that bait type remains a determining factor in sea turtle bycatch, potentially more important than the choice of hook (Read, 2007; Watson *et al.*, 2005). Squid, considered to be the most effective bait for swordfish fishing, holds more firmly onto the hook than mackerel due to its texture and turtles are therefore able only to swallow it, whereas they can easily tear the flesh off of mackerel bait with very little risk of ingesting the hook (Figure 50). The horizontal position of the bait on the hook may contribute an added positive effect without modifying the effectiveness of the longline (Broadhurst and Hazin, 2001).

Fishing trials carried out by Coelho *et al.* (2015) in the tropical northeastern Atlantic Ocean with a Portuguese longline vessel between August 2008 and December 2011 showed that the use of J-hooks baited with mackerel reduced the bycatch of hard-shell sea turtles, notably loggerhead, olive ridley (*Lepidochelys olivacea*) and Kemp's ridley (*Lepidochelys kempii*) sea turtles. Although the sample size of these hard-shell sea turtle species was relatively low (42), the results obtained from 202 pelagic longline sets were found to be consistent with those of previous studies (Yokota, Kiyota and Okamura, 2009; Watson *et al.*, 2005; Báez *et al.*, 2009; Foster *et al.*, 2012; Santos *et al.*, 2012). Conversely, the leatherback, the only sea turtle without a hard bony carapace (shell), was the most frequently caught species (183 out of a total of 225 turtles), caught almost exclusively by hooked flippers and/or entanglements in branch lines, while the hard-shell turtles were mainly hooked by the mouth and esophagus.

As was pointed out for sharks, the differences in results between existing studies may be related to the specificities of fisheries (for example, different seasons, areas or setting modes). Therefore, studies in captive conditions as suggested by Gilman and Huang (2017) are needed to better distinguish the effects of the bait from the other parameters involved in the longline fishing system.

However, an integrated understanding is also required of the impacts different choices of bait and hooks can have on other vulnerable species (Santos *et al.*, 2012) and on the reduction in target species and discarded fish catch (Báez *et al.*, 2009).

Dyed bait

Blue-dyed bait can dissuade seabirds from taking the bait. However, there is no concrete evidence to show that this method might also reduce interactions between fishing gear and sea turtles. Colour preferences shown in laboratory settings, i.e. avoidance of blue-dyed bait by loggerhead and Kemp's ridley sea turtles could not be verified in the field (Swimmer *et al.*, 2005). Nevertheless, laboratory trials with loggerhead sea turtles do suggest individual colour preferences (Piovano, Farcomeni and Giacoma, 2013).

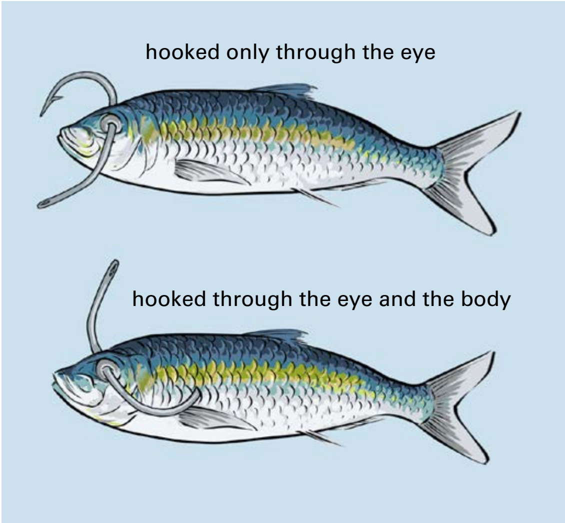
Location of the bait

A laboratory study showed that the probability of sea turtles attempting to swallow threaded baits was 2.5 times greater than for single baits (Figure 50), possibly because they are more difficult to tear off the hook (Stokes *et al.*, 2011).

Branch lines

There are no clear differences in bycatch risks between monofilament and steel branch lines. The monofilament used in surface longline fisheries is less supple than multifilament, which has a tendency to loop, significantly increasing the risk of bycatch by entanglement. On the other hand, the less flexible monofilament lines disentangle easily when no longer under tension (Boggs and Swimmer, 2007; Mug, Hall and Vogel, 2008).

FIGURE 50
Ways to hook bait



Adapted from Stokes *et al.*, 2011.

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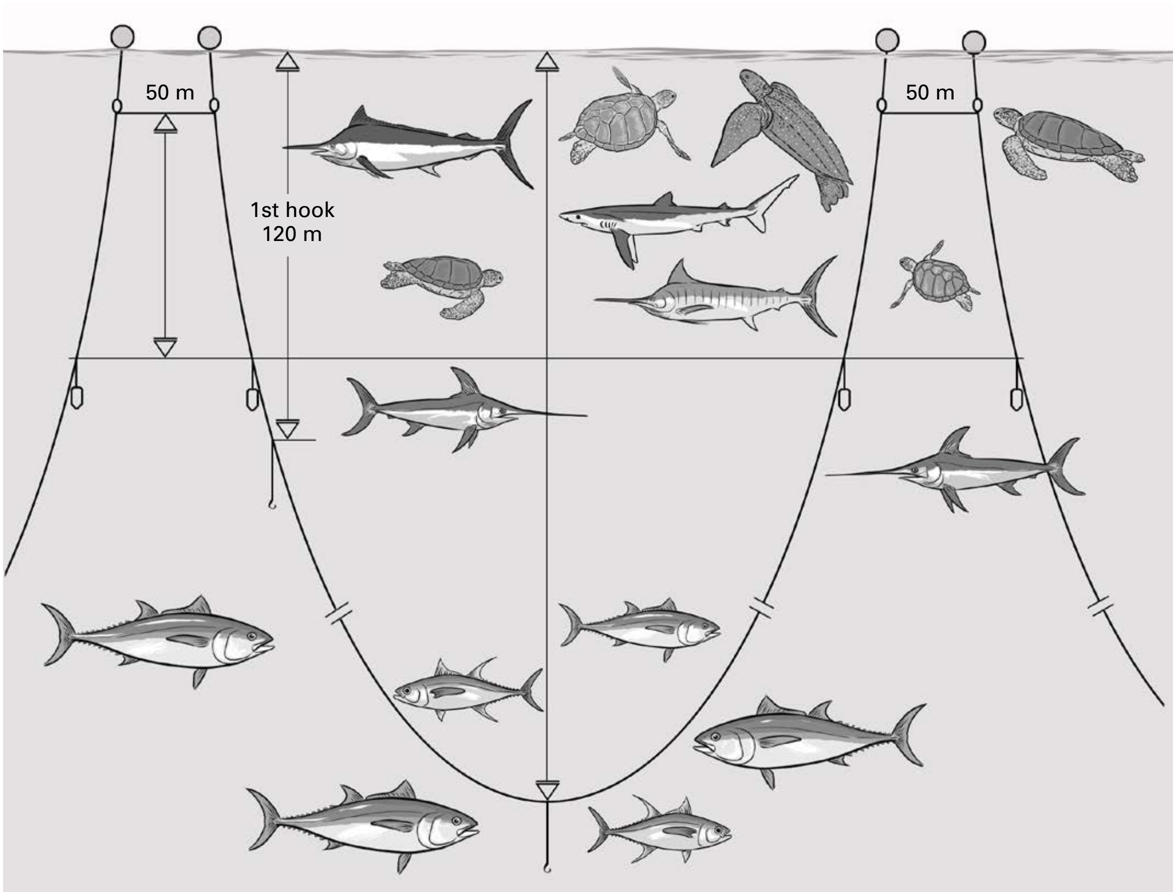
An example of efforts to tackle these issues comes from Steve Beverly, a fisher from Australia who won the first WWF International Smart Gear Competition in 2005 for his innovative deep-setting strategy aimed at limiting sea turtle interactions (SPC, 2005). He proposed several modifications for longlines targeting bigeye tuna. In particular, in order to avoid tangles, floats were set in pairs (Figure 51) separated by 50 m of blank main line without any baited branch lines (Beverly and Robinson, 2004).

FIGURE 51
Smart Gear longline 2005



Adapted from Beverly and Robinson, 2004.

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5.4.2 Setting improvements

Hook setting depth

Billfish (for example, sailfish, marlin and swordfish) or tuna pelagic longline hooks can be set at variable depths depending on the strategy adopted to catch target species, though all run the risk of significant bycatch. Even with deep-setting, a good portion of the baited hooks are left in shallow water within reach of sea turtles and non-target species.

Loggerhead turtles are known to spend 90 percent of their time less than 40 m from the surface (Polovina *et al.*, 2004), and leatherback turtles mostly swim less than 100 m from the surface, though tracking has shown that they can dive to depths greater than 600 m (Hays *et al.*, 2004); in areas where these species are highly abundant, pelagic longlines should be rigged so that hooks are out of their reach in order to avoid the risk of bycatch.

Steve Beverly, in his proposal for longline modification described above, suggested that the baited hooks be placed below the first critical 100 m (Figure 51). In order for deep-setting of the longline, the parts of the main line holding the hooks are connected to long sections of unhooked main line, loaded with 3 kg weights at each end and suspended by ordinary floats (Beverly and Robinson, 2004).

Setting time

Gilman (2011), and Gilman and Huang (2017) suggested that the timing of gear setting, soak and hauling may contribute to interactions between sea turtles and longlines. However, this has not been clearly demonstrated as the effects of these parameters cannot be differentiated from those related to depth (Clarke *et al.*, 2014).

In the Mediterranean, line and longline fishing are part of the seasonal activities of small vessels targeting, in particular, demersal species in the coastal zones and the more specialized activity of some 1 500 vessels over 12 m long selecting large pelagic fishes. Extended soak durations and short depths of demersal longlines result in much higher mortality rates than with pelagic longlines targeting bluefin tuna or swordfish. Efforts must therefore first focus on avoidance techniques (such as zone closures, side-setting, deterrent devices, required set depths and proper choice of bait). These measures are equally applicable to both demersal and pelagic longlines.

5.4.3 Visual mitigation

Light sticks and light-emitting diode lamps

In some longline fisheries targeting swordfish, light sticks are attached to branch lines in order to attract fish into the vicinity of baited hooks (Hazin *et al.*, 2005; Bigelow *et al.*, 2006). Unfortunately, sea turtles such as loggerheads may be also attracted by light sticks and can be inadvertently caught. The attraction of young loggerhead turtles to luminous lures has been shown in laboratory experiments, but no significant differences have been found between bright green, blue and yellow chemical light sticks or by orange LEDs (Lohmann *et al.*, 2006; Wang *et al.*, 2007) to show they are useful enough toward reducing the risks of interaction. Consequently, the authors suggest further studies are needed using the same experimental methodology to test the efficacy of modified light sticks designed to be less attractive to sea turtles (Wang *et al.*, 2007).

5.4.4 Acoustic mitigation

As mentioned, any sound emitted to keep sea turtles away would have the same effect on longline target species (Bartol and Ketten, 2006; Southwood *et al.*, 2008). It has been noted that loggerhead sea turtles submitted to repetitive sounds over short periods initially avoided the noise source but then fairly quickly grew accustomed to it (Bartol *et al.*, 1994). On the other hand, sea turtles may also be attracted to the sound produced by longline floats. In order to reduce interactions, Bartol and Ketten (in Brill, Swimmer and Southwood, 2004) proposed studies to determine the sound spectrum and sound pressure levels produced by both hard and soft floats used in longline fishing.

6. Pots and traps

Pots, also known as traps, are the simplest and probably the oldest traps known to fishers, allowing animals to enter and then impeding their escape. Built to catch crustaceans, mollusks or fish, they are designed in the form of cages or baskets with one or more openings or entrances and made of various materials (Figure 52).

Compared to other fishing techniques, pots have a weaker impact on vulnerable species, due less to their catch mode than to their mode of setting. Most of them are set on the bottom, usually with bait or a lure – single or in strings connected to a main line system – and they are attached by a rope to a buoy on the surface of the water, called the mooring line or buoy line (FAO, 2021d).

FIGURE 52
Lobster trap string

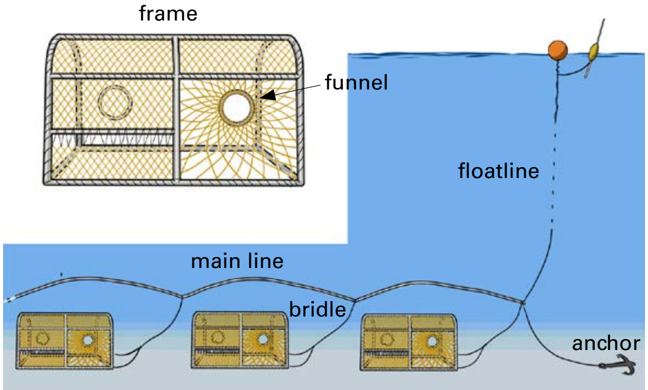

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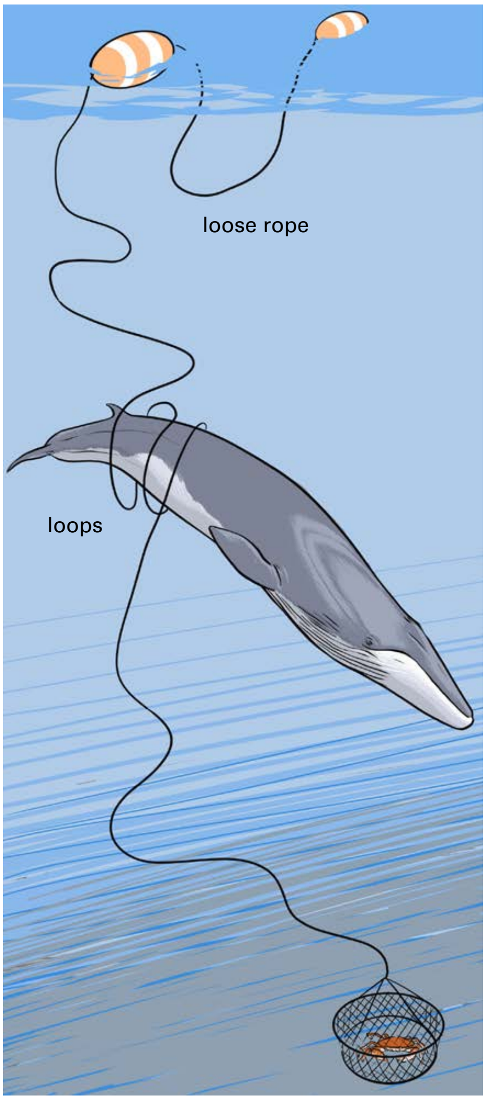
FIGURE 53
Whale entanglement in a floatline



A loose rope can cause loops, in which whales can become entangled.

Adapted from Center for Coastal Studies, 2021.

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6.1 Marine mammals

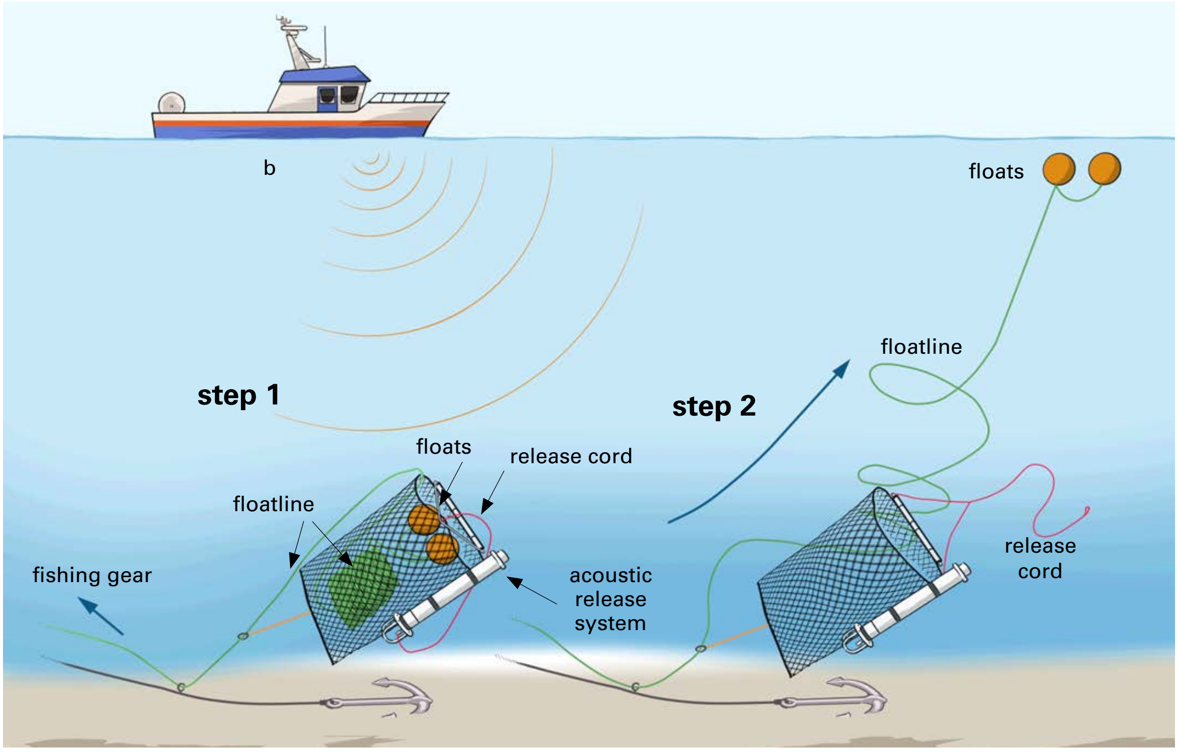
As noted for gillnets, the vertical line running from the trap to the surface buoy can entangle not only sea turtles (particularly leatherback turtles), but also whales (Figure 53). By increasing the tension of these lines, it is less likely that whales become entangled (FAO, 2018).

6.1.1 Ropeless system

To reduce the risk of entanglement in floatlines, the fishing industry has considered various solutions, such as minimising line lengths (How *et al.*, 2016), using breaking links or ropeless systems combining coiling lines and time release devices. The most sophisticated of these was proposed by the RopeLess consortium and combines the use of an acoustic and electronic control system and a releasing bag (Baumgartner *et al.*, 2018).

An acoustic release mechanism is fixed on the side of a hard, plastic mesh bag, holding coiled rope and buoys, and can be remotely triggered via a sonar transducer (Figure 54). The system is connected to a smartphone or tablet application which allows for virtual marking of the fishing gear position.

FIGURE 54
Desert Star ropeless system



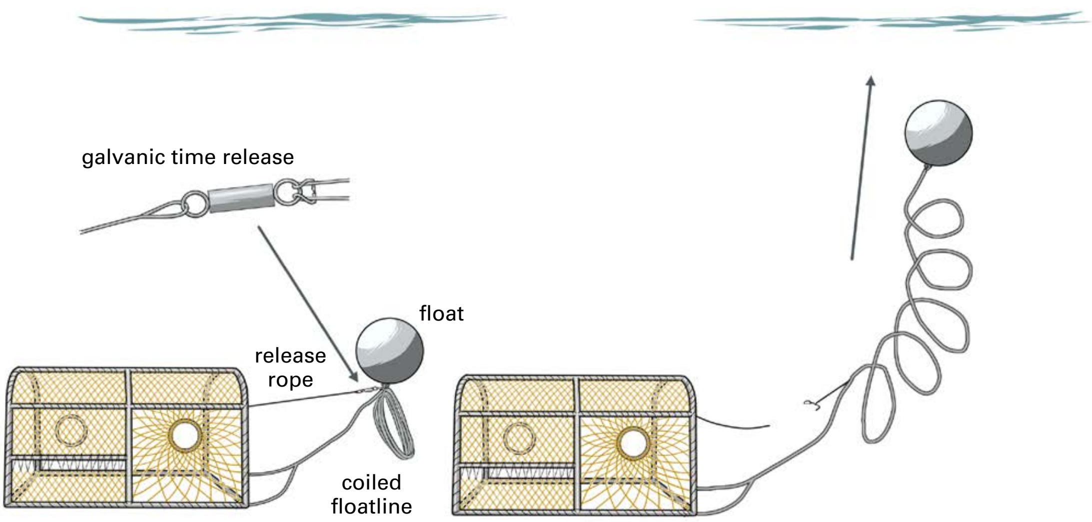
Step 1: the floatline is coiled up in a storage bag, which is closed by a stainless steel retainer and a release cord. Step 2: the emission of an acoustic signal by the vessel triggers the release of the release cord and allows the floatline to deploy towards the surface with the help of the floatation force of the floats.

Adapted from Baumgartner *et al.*, 2018 and Desert Star Systems, 2012, 2020.

6.1.2 Galvanic time releases

As part of this device, galvanic swivels can be used to tighten the buoy ropes when they are set (Werner *et al.*, 2006; Neptune Marine Products, 2017a). First designed to avoid ghost fishing by pots, galvanic time releases (Figure 55) consist of anodes joining together two stable metal eyelets,

FIGURE 55
Galvanic time release used for traps



After a set period of time, the galvanic device dissolves and releases the floatline.

Adapted from Neptune Products, 2017b.

which function as cathodes and at a specific time disintegrate in sea water allowing the release of whatever was being held. Moreover, these delayed-release devices serve as an effective way to reduce the risk of incidental catch by nets that have been abandoned or soaking for an excessively long time.

6.2 Sharks and rays

6.2.1 Magnetic mitigation

In New South Wales (Australia), the fish trap fishery targeting snapper (*Pagrus auratus*) catches large numbers of benthic sharks, including the blind shark (*Brachaelurus waddi*), electric ray (*Hypnos monopterygius*) and Port Jackson shark (*Heterodontus portusjacksoni*), (Uhlmann and Broadhurst, 2015; Foged and Powter, 2015). The fish traps traditionally used are large, made of hexagonal wire mesh, with three funnel entrances.

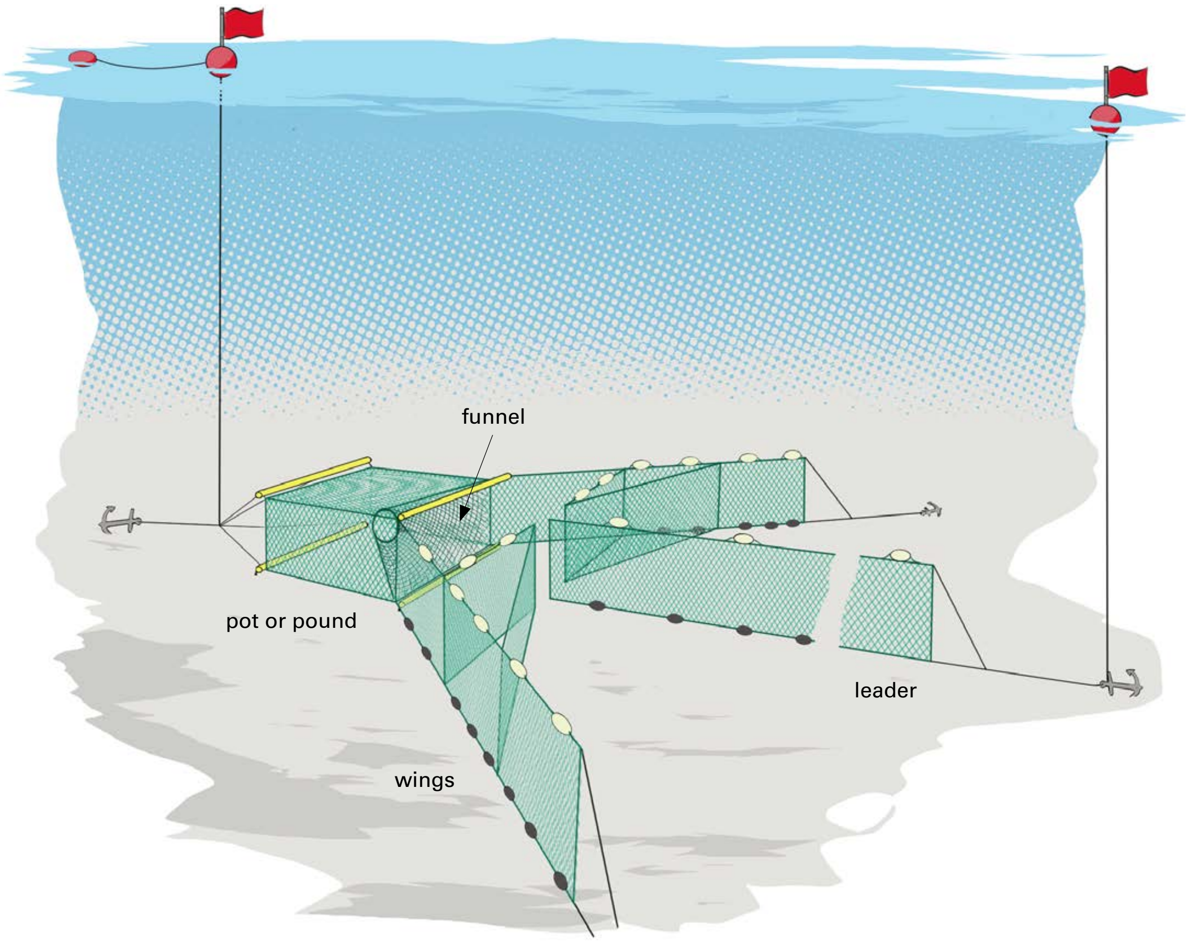
In sea trials conducted by the University of Newcastle (Australia), four permanent ferrite magnet bars with high gauss (G) strength (25 G at 10 cm) were attached to each of the funnels within the experimental group. The comparison with a control group of non-modified traps showed that the incorporation of ferrite magnets lowers the catch rate of sharks and rays by more than 30 percent and increases catches of targeted fish by the same amount (Richards *et al.*, 2018), probably in part due to less depredation of the bait by sharks entering the traps.

Considering these results, the authors assess that these deterrent devices could offer a cost-effective, widely applicable tool to reduce shark and ray bycatch in trap-based fisheries. Nevertheless, since these magnets or electropositive metals are still expensive and have a relatively short lifespan, fishers may be reluctant to use them on a large scale.

7. Trap nets

Trap nets (Figure 56), also known as *dalyan* (in Turkish), *tonnara* (in Italian), *kaky-ami* (in Japanese), pound nets, fyke nets and stow nets or weirs, are fixed fishing gear of various shapes that usually consist of one or two barriers or fences (leaders or wings) guiding the fish to a final compartment (chamber, trap or pound), from which the fish cannot escape, and they usually target migrating schools of midwater or pelagic fishes in estuarine or coastal waters, such as eels (*Anguilla anguilla*), sparids (Sparidae), salmon (*Salmo salar*), whitefish (*Coregonus lavaretus*), herring (*Clupea harengus*), capelin (*Mallotus villosus*) and cod (*Gadus morhua*). Anchored to the bottom and perpendicular to the shore, the netting usually reaches above the waterline; the final compartment is either covered or open-air. Under a variety of configurations, trap nets can be responsible for a range of harmful interactions with vulnerable species, such as collisions, entanglements in the nets of the leader or entrapment in the pound, which may be fatal for the animals.

FIGURE 56
Trap net



Redrawn from Sea Grant Institute, 2011.

7.1 Marine mammals

In Newfoundland and Labrador, Lien *et al.* (1992) observed that humpback whales (*Megaptera novaeangliae*) frequently collide with inshore trap nets due to their inability to detect the presence of the net. In the Kattegat and Baltic Sea, harbour porpoises (*Phocoena phocoena*) sometimes get trapped or entangled in pound nets, as well as in the Canadian herring weirs of the Bay of Fundy

(Canada), though they can usually be recovered and released alive (Scheidat, Bos and Geeelhoed, 2016; European Commission, 2002). Finless porpoises (*Neophocaena phocaenoides*) are also known to be frequently found caught in stow nets in China (Zhou and Wang, 1990) and in Korea (Kim *et al.*, 2013; Leaper and Calderan, 2017).

7.1.1 Fishing gear improvements

Mesh size effect

The mesh netting of the leader of a trap net can behave like a gillnet, potentially entangling small coastal cetacean species, such as bottlenose dolphins (*Tursiops truncatus*). If the animals are trapped for too long underwater, they are unable to breathe at the surface when they need to and can drown. As noted by Todd and Nelson (1994), traps using smaller mesh sizes (for example, capelin traps) lead to fewer collisions and entanglement than traps with large mesh sizes, such as trap nets targeting cod.

Furthermore, the use of stiffer netting in the wings and middle chambers to prevent fish entanglement, thereby reducing their vulnerability to predation by cetaceans, was demonstrated by Suuronen *et al.* (2006) in a coastal trap net fishery in the northern Baltic Sea.

7.1.2 Acoustic mitigation

Lien *et al.* (1992) tested an acoustic alarm producing a 3 or 6 s sound at 4 kHz peak frequency with intensity of 135 dB (re 1µ Pa at 1 m) on a cod trap net and noted a significant decrease in collisions and entrapment rates of whales without reducing target species (cod) catch over the test period.

Although pingers may offer the potential to deter dolphins from trap nets, whales' reactions to acoustic repellents have shown them to be of variable effectiveness. In Australia, while southward migrating humpback whales exhibited aversion behaviour to acoustic stimuli (Dunlop *et al.*, 2013), northward migrating whales showed no detectable response to pingers (Harcourt *et al.*, 2014; Pirotta *et al.*, 2016). If there were any indications that pingers could potentially deter grey whales (*Eschrichtius robustus*) from high-risk coastal areas, the results were inconclusive due to insufficient sample sizes, especially during experimental periods (Lagerquist, Winsor and Mate, 2012).

7.2 Seabirds

7.2.1 Fishing gear improvements

Escape windows

Bundgarn is a type of pound net used in the Danish, German and Swedish Baltic Sea to catch migrating fishes such as herring (*Clupea harengus*), mackerel (*Scomber scombrus*), cod (*Gadus morhua*), garfish (*Belone belone*) and eels (*Anguilla anguilla*) (Gabriel *et al.*, 2005). Since these trap nets are set in shallow waters, cormorants and herons may be attracted by concentrations of fish and drown if the catching chambers are closed above (Erdmann *et al.*, 2005).

This type of bycatch can, however, largely be avoided by means of escape windows allowing birds to return to the surface (ASCOBANS, 2012).

Similarly, in the Great Lakes (Evers, 2014), common loons (*Gavia immer*) can be caught in commercial trap net fisheries using nets with covered hearts. Common loons, attracted by fish, dive into the trapnet and readily enter the heart, which is enclosed on top and submerged in deep areas; when the loons attempt to surface they become entangled in the top part of the net and drown.

Trials increasing mesh size in the top of the hearts to 15.2 cm, instead of the usual 10.2 cm bar meshes, resulted in 80 percent of loons escaping with no reduction in commercial fish catch (Carey, 1992; Christiansen and Robinson, 1997).

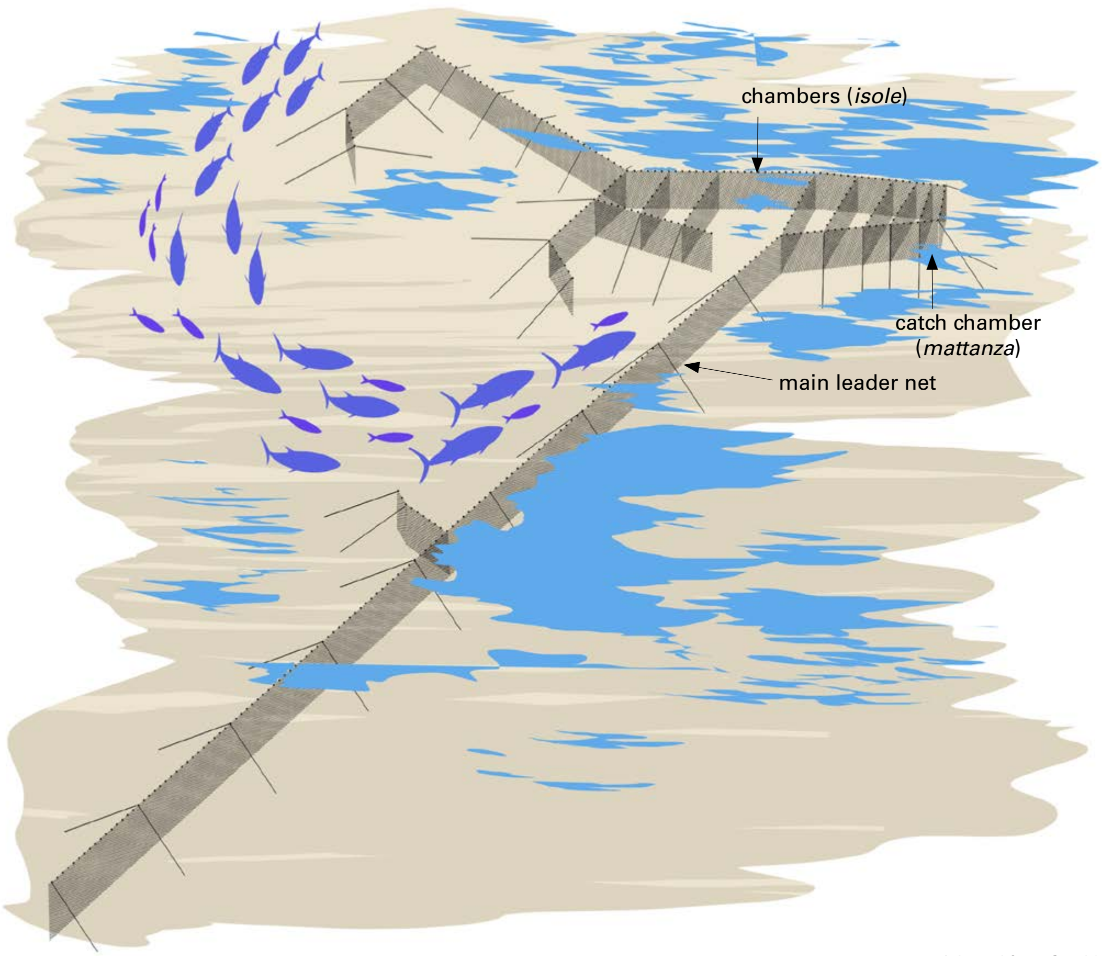
7.3 Sharks and rays

The relevant literature provides little information on the incidental capture of sharks by trap nets, except in those used for tuna (Figure 57).

Mediterranean tuna traps (*mattanza, almadraba*) targeting bluefin tuna (*Thunnus thynnus*) consist of a large wing (*coda* in Italian) set perpendicular to the shore, which serves to lead tuna schools towards a series of successive chambers (*isole*), the last of which concentrates the catch (*mattanza*). These traps were formerly widespread in the Mediterranean, though nowadays little more than 15 are in activity, off Portugal, Morocco, Spain and Italy.

Tuna traps incidentally catch some specimens of large sharks and rays, including common thresher sharks (*Alopias vulpinus*), basking sharks (*Cetorhinus maximus*), blue sharks (*Prionace glauca*), giant devil rays (*Mobula mobular*), and sometimes even great white sharks (*Carcharodon carcharias*) (Bradai, Saidi and Enajjar, 2012; Vacchi *et al.*, 2002; Storai *et al.*, 2011). However, such bycatch in tuna traps is insufficiently reported in the Mediterranean Sea.

FIGURE 57
Mediterranean tuna trap for bluefin tuna



Adapted from Sacchi, 2008.

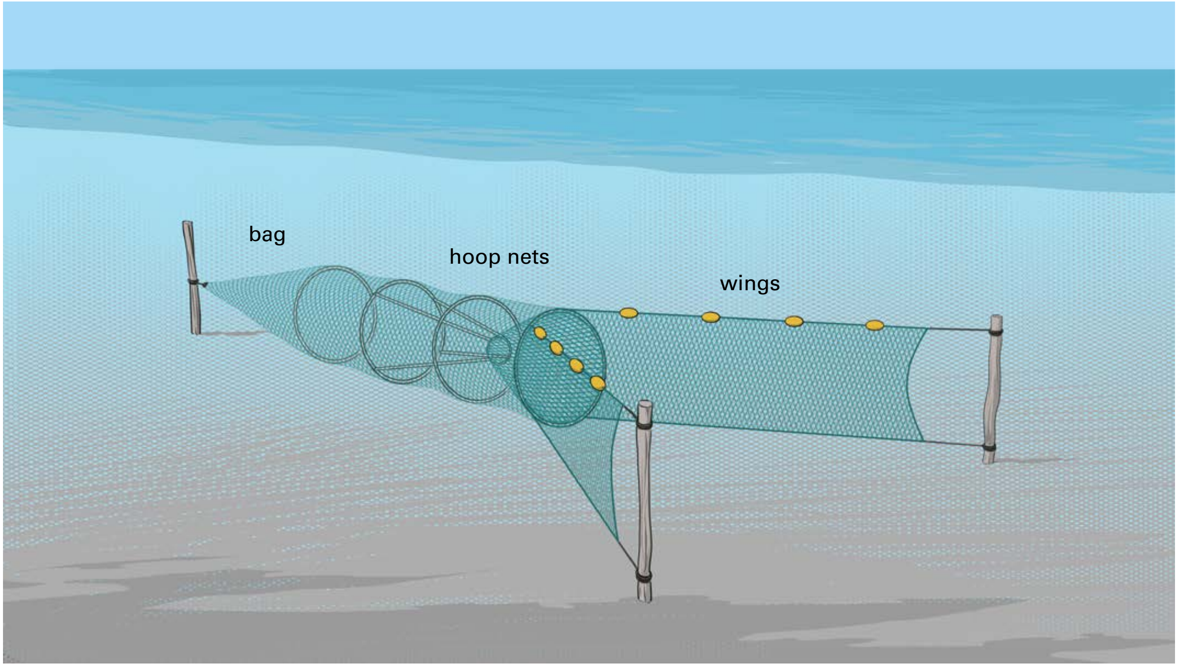
7.4 Sea turtles

7.4.1 Fishing gear improvements

Gap entrance modification

A fyke net (Figure 58) is a kind of trap net consisting of cylindrical or cone-shaped netting bags mounted on rings or other rigid structures. Its wings, or leaders, guide the fish towards the entrance of the bags. This type of trap is mainly used for freshwater fishing in inland waters, in river mouths, but also for amphyhaline fish such as eels in estuaries or lagoons, like those of the Mediterranean sometimes frequented by sea turtles.

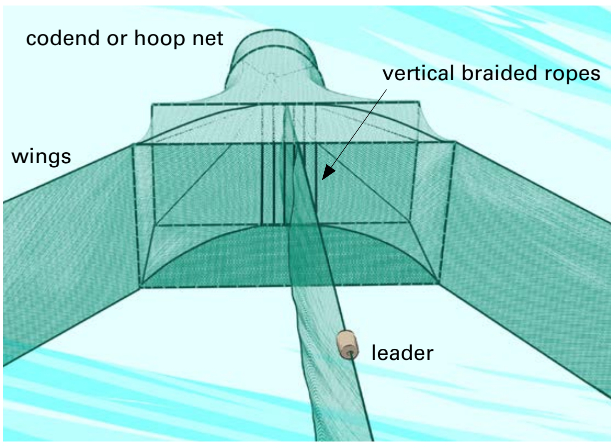
FIGURE 58
Fyke net



Adapted from Seafish, 2021.

Most of the BRDs for fyke nets concern freshwater turtles, but they could be also judiciously applied to fyke nets in lagoons to avoid accidental catch of sea turtles. Fratto, Barko and Scheibe (2008) have therefore designed and tested a BRD for Wisconsin-type fyke nets, which reduces turtle bycatch without affecting fish capture. The BRD consists of four lines added in the vertical gap of the net (Figure 59). Similar modifications have been tested on fyke nets used in the inland fishery in southeastern Ontario, Canada, using exclusion bars attached to the first hoop of the net in order to avoid bycatch of freshwater turtles, such as painted turtles (*Chrysemys picta*) (Larocque, Cooke and Blouin-Demers, 2012).

FIGURE 59
Wisconsin-type fyke net



Design of the modified Wisconsin-type fyke net, illustrating the pattern of braided rope configurations and the placement of modifications. The vertical braided ropes are fixed in front of the gap.

Redrawn from Fratto, Barko and Scheibe, 2008.

Pound net leader modification

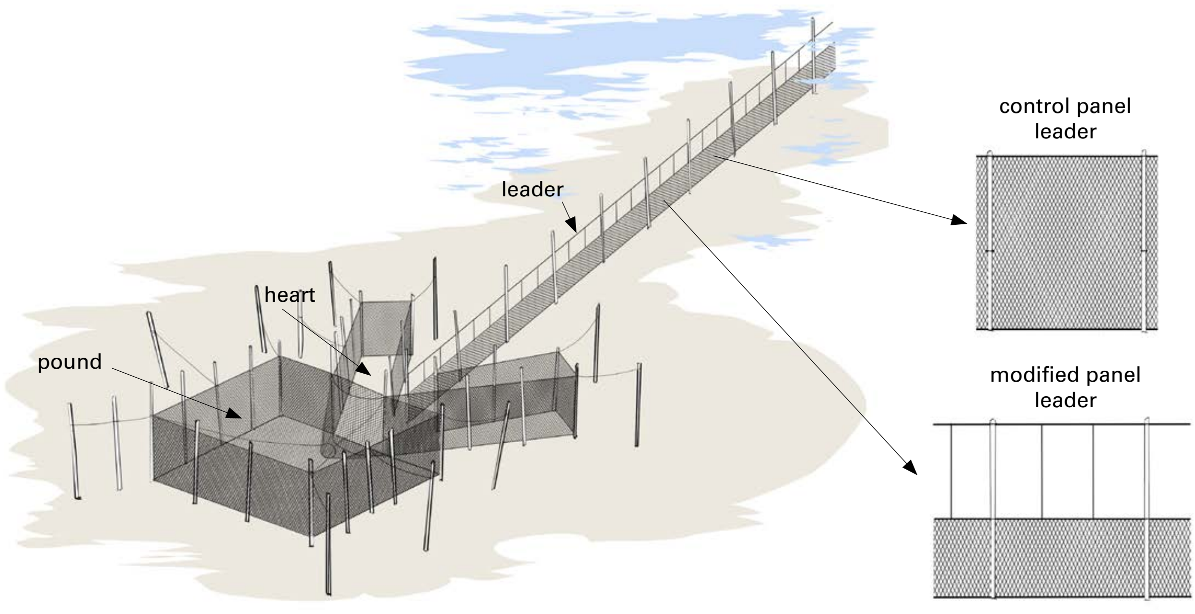
Pound nets are composed of three primary components: a leader, a heart, and a pound. Generally suspended from anchored poles, the leader is a wall of mesh webbing extending vertically from the sea floor to approximately the sea surface and running up to several hundred metres in length. Located at the deep end of the leader is the heart, the funnel and the pound, in which the fish are trapped (Figure 60). The offshore pound net fishery in the southern portion of Chesapeake Bay (United States of America, mid-Atlantic) mainly fishes for Atlantic thread herring (*Opisthonema oglinum*), butterfish (*Peprilus triacanthus*), Atlantic croaker (*Micropogonias undulatus*) and weakfish (*Cynoscion regalis*).

Sea turtles can be either entrapped in the pound or entangled in the leader and may drown if they cannot reach the surface to breathe. Surveys initiated by NOAA in 1979 noted that this type of gear was responsible for 3 to 33 percent of stranded sea turtles in the Bay (i.e. between 6 and 165 turtles annually, and mainly in May and June), most of which were loggerhead (*Caretta caretta*) and Kemp's ridley (*Lepidochelys kempii*) sea turtles (DeAlteris and Silva, 2007).

In response to a closure of the fishery mandated in 2004 by the National Marine Fisheries Service, fishers and researchers decided to test an experimental leader by replacing the upper two-thirds of the leader with rigid vertical ropes with enough spacing between them (61 cm) to allow sea turtles to pass through without being tangled and adopting a smaller mesh (20 cm) for the lower third, to reduce any risk of entanglement (Figure 60).

Without significantly affecting the fish catch, the reduction in sea turtle mortality attributed to the experimental leader was large enough for resource managers to allow restricted pound net fishers to use the leader of the experimental net. These regulations were implemented on 23 June 2006 (Silva, DeAlteris and Milliken, 2011).

FIGURE 60
Experimental leader modification in a pound net



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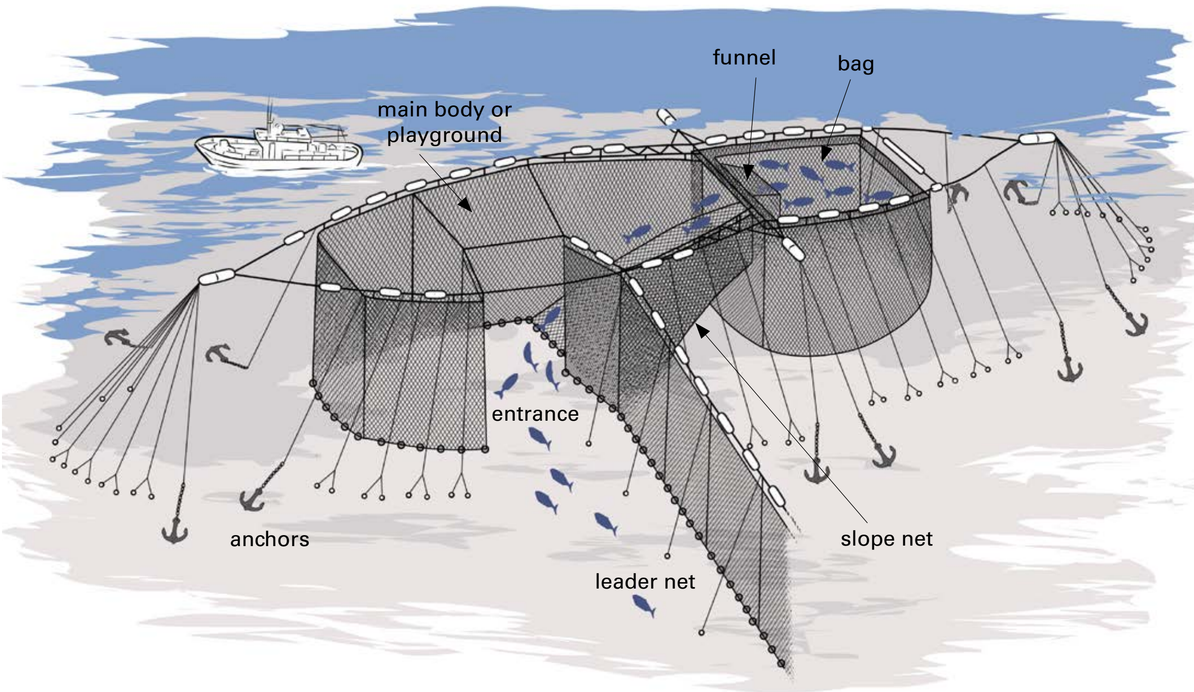
Turtle reduction device

The set net (*Teichi ami*) is an important type of coastal fishing gear in Japan (Figure 61), and this type of trap net occasionally catches sea turtles in some coastal regions; some of the nets are set in waters deeper than 27 m. In particular, set nets with an open bag chamber result in substantially lower sea turtle mortality rates than those with closed ones. In these types of set net, which are fully submerged, sea turtles accidently entering into the set net bag chamber tend to push up the upper net in trying to take breaths and often drown (Ishihara, 2007).

Several experiments found that the use of a rectangular, pyramid-shaped bag net with a top part angled at 20 degrees toward the apex (Figure 62) may be effective at directing sea turtles to an excluder device fixed on the upper part of the cone, while only allowing a small amount of target fish to escape (Abe and Shiode, 2009; Takahashi *et al.*, 2008; Shiozawa *et al.*, 2019). Sea trials were performed with loggerhead turtles, which entered into the submerged bag net (30 m x 10 m x 10 m) equipped with an experimental excluder device consisting of a 1 m square escape vent and a flap door, designed to automatically close after a turtle has pushed through it, permitting the turtle to escape, while preventing fish loss. If loggerhead turtles can manage to escape through the turtle reduction device, their survival time within the submerged bag net might be shorter, after consuming a greater amount of oxygen during movement due to stress (Shiozawa *et al.*, 2019).

FIGURE 61
Tosa-Otoshi ami

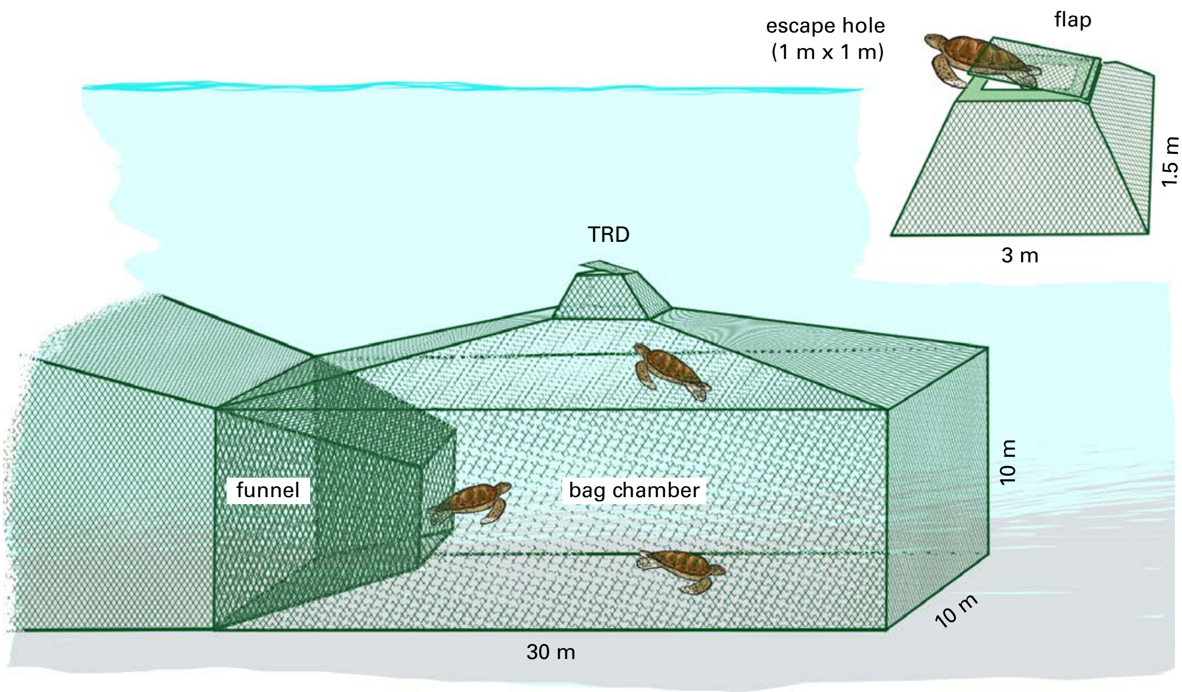


An example of a Japanese set net, the Tosa-Otoshi ami.

Adapted from Kask, Hiyama and Kita, 1947; Arimoto, 2007 and FAO, 2015.

On the other hand, the authors underline the need to assess the validity of this system by using much larger bag nets in further trials and observing turtle behaviour to prepare for a practical application (Shiozawa *et al.*, 2019).

FIGURE 62
Turtle reduction device



Adapted from Shiozawa *et al.*, 2019.

8. Non-technical measures for reducing bycatch

Since fishing effort determines the level of commercial and incidental catch, the use of mitigation techniques must be accompanied by fisheries management measures, such as limits on fishing units and fishing gear, reductions in the duration of operations, seasonal closures of sensitive areas or changes in harvesting techniques or in fishing activities.

According to Melvin, Parrish and Conquest (1999), a combination of changes in gear, abundance-based fishery openings and hourly restrictions can reduce seabird bycatch by up to 70–75 percent without reducing commercial catch.

Fishing effort restrictions in small-scale fisheries are constrained by the risk of fishers dipping below a minimum catch threshold, after which they may redirect their effort to other fishing techniques with potentially more serious consequences.

For instance, monkfish (*Lophius* spp.) fisheries, which show high bycatch ratios of sea turtles and marine mammals, such as the monkfish (*Lophius americanus*) set net fishery off the east coast of the United States of America studied by Wiedenfeld, Crawford and Pott (2015), require soak times of several days. Therefore, in this case, changing the soak time does not represent a feasible option for the viability of these fisheries.

Changing the technique is often regarded as a satisfactory mitigation measure in multispecies and multi-purpose Mediterranean fisheries, where it is much easier to implement than in highly specialized fisheries. However pre-conditions must be met to prevent undesired consequences caused by changes in technique, such as increasing the risk of capturing other vulnerable species or of producing negative socio-economic impacts if the new mitigation measures prove to be more costly and more restrictive than previous ones.

The substitution techniques should be those having tried and tested mitigation methods. Gillnetting, the most common fishing technique in small-scale fisheries, unfortunately presents fewer possibilities for technical modification. On the other hand, pots and traps and longlines can sometimes provide sound alternatives to gillnets or trammel nets, if operated in such a way as to maintain their profitability. To a lesser extent, lines and longlines also experience depredation and bycatch problems, but they boast the advantage of various reliable solutions available for adaptation.

The temporary closure of protected zones and restrictions on fishing effort are also effective tools to reduce bycatch of vulnerable species, particularly in areas where, and during the periods when, bycatch risk is significant (Cambiè, 2011; Murray, Read and Solow, 2000; Lewison *et al.*, 2014; Van Beest *et al.*, 2017), especially in set net fisheries (Childerhouse, Miller and Steptoe, 2013). These measures require a spatial and temporal definition of at-risk areas, using an overlay map of fishing activities and the sensitive phases of vulnerable species. This process, which was undertaken comprehensively in the Adriatic under the framework of the European project NETCET (Network for the Conservation of Cetaceans and Sea Turtles in the Adriatic) (Fortuna, Holcer and Mackelworth, eds., 2015), can help define strategies for the reduction of cetacean and sea turtle bycatch, for example. These types of measures must, however, take into account potential shifts of effort to neighboring zones, as well as impacts on other threatened species as bycatch.

A dynamic management approach is necessary to adapt to changing circumstances. For example, Australian fishery managers have adopted a real-time spatial management support tool using a habitat prediction model to reduce unwanted bycatch of southern bluefin tuna (*Thunnus maccoyi*) incidentally captured by longline fishery targeting tropical tuna and billfish year-round along Australia's southeastern seaboard (Hobday and Hartmann, 2006). This process allows for the definition of management zone boundaries and for their routine updating, according to changes in southern bluefin tuna habitat distribution.

Another example of dynamic management is provided by McClellan *et al.* (2009), who describe the use of a spatially explicit predator-prey model to study real-time interactions between sea turtles and the winter flounder fishery in Pamlico Sound (North Carolina). Combining data on the distribution of fishing effort and observations of the distribution of bycatch species derived from satellite telemetry, this tool can be used to define effective bycatch reduction measures, such as the establishment of spatio-temporal closures.

The Turtle Watch programme proposed a dynamic and holistic approach (Howell *et al.*, 2008) to help reduce interactions between the Hawaiian pelagic longline fishery and loggerhead sea turtles. By matching logbook fishing data from between 1994 and 2006 and satellite data from tagged turtles with sea surface water temperatures, the study determined that a temperature of about 18.5°C could be used as a thermal warning band for shallow water fishing. Today, NOAA uses this tool to display maps of sea surface temperatures, predicting the location of waters preferred by turtles. By providing these maps to longline fishers, NOAA hopes to decrease the likelihood of interactions during, for example, the first quarter of the swordfish fishing season (NOAA, 2019b).

More recently, Hazen *et al.* (2018) used a data-driven, multispecies predictive habitat modelling framework (EcoCas) to create predictive surfaces quantifying relative target catch and bycatch probabilities for a specific fishery. When applied to the Californian drift gillnet fishery, responsible for the bycatch of vulnerable species including sea turtles, blue sharks and dolphins, among others, this programme found that dynamic closures could cover areas two to ten times smaller than existing static closures, while still providing adequate protection of endangered species.

These dynamic approaches have the advantage of offering fast and flexible tools, thus facilitating better decision-making in fisheries management, while resulting in more economically robust fisheries with less impact on the environment.

Safe handling and release refer to using best practice methods for dealing with bycatch species in order to maximize their chances of survival after interactions with fishing gear. These procedures may include vessel manoeuvering to avoid capturing vulnerable species, as well as following advice on good onboard practices. To this end, several programmes have developed good practice guides, offering suggestions on the best ways to free the animals from nets, without risking injury to them or the crew, such as FAO and ACCOBAMS have done for Mediterranean fishers (FAO and ACCOBAMS, 2018a, 2018b, 2018c, 2018d).

9. Discussion and conclusions

Analysis of the relevant literature shows that mitigation measures may be described as having one or both of two major objectives: 1) to avoid incidental catch of vulnerable species; and 2) to reduce post-catch mortality rates. They are of either a technical or a management-related nature. Therefore, given these principles, for any fishing technique faced with issues of vulnerable species bycatch, potential solutions include:

- reducing the attractiveness of fishing gear by using all necessary means, including alarm or scaring systems;
- modifying the gear in order to reduce the risk of bycatch or to facilitate the release of caught animals; and
- reducing or avoiding fishing effort in sensitive areas or at sensitive times, where and when a higher concentration of endangered species is present (GFCM, 2012).

The different systems used to reduce bycatch of each group include gear modifications, setting strategies, acoustic, visual, magnetic and chemosensory deterrents, and management measures. Some of the mitigation techniques presented here are already implemented while others are still under development. Table 3 below summarises the state of advancement on the different solutions without prejudging their effectiveness, since many show inconsistent results, depending on the species concerned, the fishery concerned and/or the trial conditions.

Thus, better understanding of the nature and the circumstances of interactions is required, involving new means of observing the behaviour of vulnerable species.

Most authors agree, however, that no measure is sufficient on its own and strongly recommend combining measures for greater effectiveness.

Strategies to manage interactions must take into account that some of the measures discussed may result in opposing effects depending on the species to be protected. It would be useful therefore to apply a multi-taxon approach to any strategy aimed at improving the selectivity of fisheries.

Depredation is an issue discussed by a number of authors: it affects all fishing techniques and concerns all species. It is likely the main cause of vulnerable species bycatch, regardless of fishing technique. Examples drawn from the relevant literature show that all deterrents lead to habituation in the animals that they are intended to keep away. Therefore, it would appear that depredation results from a habituation to a particular fishing activity, for a number of reasons (such as the availability of a more easily-accessible resource), and affects all groups of vulnerable species. More aggressive strategies are being considered, based on the hypothesis that while fear induces a flight reaction, anxiety generates wariness and therefore avoidance (Dawson *et al.*, 2013). This idea has prompted the development of systems (in particular, acoustic systems) inducing anxiety (for example, producing a startled reaction) which may help depredators learn to recognize the clues or contexts which precede painful stimuli, thereby encouraging avoidance of these situations (Schakner and Blumstein, 2013).

Along the same lines, some conservation measures may also produce conflicting effects, such as the European discard ban (Regulation (EU) No 1380/2013 of the European Parliament and of the Council of 11 December 2013) or the ban on sunday trawling and purse seining, which have tended to shift seabirds towards longliners and increase their bycatch rate (García-Barcelona *et al.*, 2010; Soriano-Redondo *et al.*, 2016).

In fact, most of the measures described here are simply non-restrictive recommendations from RFMOs. The only regulatory measures discussed are the European Union ban on drift-netting and the compulsory use of TEDs to reduce sea turtle bycatch in Australia, the United States of America, French Guyana and Europe.

In the Mediterranean, no mitigation measure is currently implemented to reduce seabird, turtle or shark bycatch.

In practice, these mitigation measures can therefore only be implemented within a global management framework for fishing activities and at a regional level. In this context, the action plans relating to the protection of the four species groups in the Mediterranean propose a strategy describing main priorities and the measures to be implemented gradually (UNEP MAP RAC/SPA, 2003, 2007, 2009, 2020).

The Sea Turtle Action Plan (UNEP MAP RAC/SPA, 2007) illustrates this strategy. It defines the fishing conditions (season, depth) best suited to high-concentration areas and suggests how to modify fishing methods and gear and train fishers in the release of animals.

The Plan of Action for reducing the incidental catch of seabirds in fishing gears adopted by the Council of the European Union in 2013 highlights the need to evaluate the impact of these measures and the scientific data on the extent of the problem.

Some RFMOs, such as ICCAT (ACAP, 2011) and the GFCM, have adopted various restrictive recommendations (Recommendations GFCM/35/2011/3 on reducing incidental bycatch of seabirds in fisheries in the GFCM area of application, GFCM/35/2011/4 on the incidental bycatch of sea turtles in fisheries in the GFCM area of application, GFCM/35/2011/5 on fisheries measures for the conservation of the Mediterranean monk seal in the GFCM area of application, GFCM/36/2012/2 on mitigation of incidental catches of cetaceans in the GFCM area of application) (GFCM, 2019) establishing measures to reduce the incidental catch of seabirds, sea turtles, monk seals and cetaceans during fishing activities.

Most of these measures have been integrated into European legislation and aim to ban the use of unauthorized fishing gear, such as the use of drift nets for large pelagic species, in order to reduce the bycatch of cetaceans (Recommendation GFCM/36/2012/2) (GFCM, 2019) and fishing activity in protected areas, including through a ban on trawling within three nautical miles off the coast in order to protect coastal sharks (Recommendation GFCM/36/2012/3 on fisheries management measures for the conservation of sharks and rays in the GFCM area of application) (GFCM, 2019).

Furthermore, the Scientific Advisory Committee on Fisheries of the GFCM recommended that, before any restrictive recommendation be implemented, the application of some of the mitigation techniques described here should be investigated: the use of acoustic devices and nets with acoustic reflectivity to deal with cetacean bycatch in the fishing gear, bans on stainless steel hooks and metallic branch lines in bottom and demersal longline fisheries, and reductions in the size of bottom nets or limits on their soak times.

Finally, no mitigation measure can be effective if it is not fully accepted by commercial fishers and the fishing industry, which requires taking into account all fisheries socio-economic constraints and technical fishing conditions and encouraging awareness-raising measures.

TABLE 3 – Overview of mitigation measures, by fishing gear and group of vulnerable species

TRAWLS					
MITIGATION MEASURES		CETACEANS	SEABIRDS	SHARKS AND RAYS	SEA TURTLES
Gear modification		Escape devices		Escape devices tickler chain	TEDs
Setting			Avoid breeding areas, discarding fish at sea		Tow duration, season and depth
Deterrents	**Acoustic**	Acoustic deterrents			
	Visual		Streamline		
			Laser beam		
Effort and strategy		Regulations on: licence number, horsepower, setting duration, tows number, spatio-temporal closures			
PURSE SEINES					
MITIGATION MEASURES		CETACEANS	SEABIRDS	SHARKS AND RAYS	SEA TURTLES
Gear modification Backdown, net strengthening		Purse seine strengthening	Escape devices		
Setting Avoid setting under whales				Implementation of ecological FADs	
		Avoid breeding areas, discarding fish at sea	Avoid setting under whale sharks		
Deterrents	**Acoustic**	Acoustic deterrents	Acoustic deterrents		
	Chemosensory			Attract sharks out of purse seining area	
	Visual		Visual scarers		
GILLNETS AND TRAMMEL NETS					
MITIGATION MEASURES		CETACEANS	SEABIRDS	SHARKS AND RAYS	SEA TURTLES
Gear modification		Slackness reduction		Slackness reduction	
Setting		Break links		Minimum set depth	
Deterrents	**Acoustic**	Acoustic deterrents	Acoustic alarm		Acoustic deterrents
	Chemosensory	Chemical deterrents		Chemical deterrents	
	Visual	Visual deterrents	Net panel visibility		Luminous or visual deterrents
	Magnetic			Magnets or electro-acoustic deterrents	
Effort and strategy		Regulations on: licence number, horsepower, setting duration, tows number, spatio-temporal closures			

methods used and applicable

methods under development

methods subject of ongoing research

TABLE 3 (Continued)

LINES AND LONGLINES					
MITIGATION MEASURES		CETACEANS	SEABIRDS	SHARKS AND RAYS	SEA TURTLES
Gear modification		Type of hook	Hook, bait, hooking position, weighting branch lines	Hook, bait, branch lines	Hook, bait, hooking position
Setting		Hauling speed	Side or underwater setting; line shooter and hauler	Hook depth, setting time, Soak-time	
Deterrents	**Acoustic**	Acoustic deterrents	Acoustic scarers	Acoustic deterrents	
	Chemosensory			Chemosensory repellents	
	Visual	Masking devices	Hookpods, scarers	Luminous lures	Deterrents and luminous lures
	Magnetic			Magnetic or electropositive hooks	
Effort and strategy		Regulations on: licence number, horsepower, setting duration, tows number, spatio-temporal closures			
POTS AND TRAPS					
MITIGATION MEASURES		CETACEANS	SEABIRDS	SHARKS AND RAYS	SEA TURTLES
Setting		Galvanic or breaking links, ropeless system			Galvanic or Breaking links, Ropeless system
Deterrents	**Magnetic**			Permanent magnets	
TRAPNETS					
MITIGATION MEASURES		CETACEANS	SEABIRDS	SHARKS AND RAYS	SEA TURTLES
Gear modifications		Mesh size, trap net design			Escape devices, gap entrances
Deterrents	**Acoustic**	Acoustic deterrents			
	Visual		Visual mitigation		

methods used and applicable

methods under development

methods subject of ongoing research

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11. Glossary

In most cases, the definitions presented here have been obtained from the FAO TERM Portal (FAO, 2021e) and from the FAO Fisheries Division Glossary (FAO, 2021f).

Abundance-based fishery openings: Fishery openings could be scheduled based on the relative abundance of both target and bycatch species or, at least focused on the peak abundance of target species, minimizing the total time that fishing gear would be deployed (Melvin, Parrish and Conquest, 1999)

Acoustic netsounder: Electro-acoustic sounders are used to measure the vertical opening of a trawl and its distance from the seafloor (see also FAO, 2021g)

Apnea: A turtle found stranded or caught in a net may appear to be dead, in a coma, or in shock, having suffered from apnea and lost or suppressed reflexes and showing no signs of breathing. Most turtles caught by, for example, shrimp trawlers, under conditions of forced submergence, have not drowned but are in a coma.

Beta pin: Also known as a Clevis Pin, R-key, bridge pin, hairpin cotter pin, hairpin cotter, bridge pin, hitch pin or spring cotter pin, a Beta pin is a fastener made of a springy material, commonly in the shape of the letter "R" or the greek letter "Beta".

Bycatch: The part of the catch that is unintentionally captured during a fishing operation in addition to the target species. It may refer to the catch of other commercial species that are landed, commercial species that cannot be landed (e.g. undersized, damaged individuals), non-commercial species, as well as to the incidental catch of endangered, vulnerable or rare species (e.g. sea turtles, sharks, marine mammals).

Catch rate: Sometimes catch rate is defined as the amount of catch per unit time and sometimes as catch per unit effort.

Cetacea: The scientific name for the animal group containing whales, dolphins and porpoises. The English names whale and dolphin apply to the larger and smaller cetaceans, respectively, but do not have strict scientific meaning. Biologically, two groups of cetaceans exist: the filter-feeding baleen whales and the toothed whales (which include everything from the sperm whale down to the smallest dolphins and porpoises). The smaller toothed whales include the killer whale and the false killer whale, which belong to the family Delphinidae and are therefore, strictly speaking, dolphins. For this reason, it is often appropriate to talk of small cetaceans rather than dolphins.

Chondrichthyan (or chondrichthian): (class Chondrichthyes) Any member of the diverse class of cartilaginous fishes that includes the two subclasses Elasmobranchii (sharks, skates, rays and sawfish) and Holocephali (chimaeras).

Clupeids: Any widely distributed soft-finned bony fish of the family Clupeidae, typically having oily flesh, including herrings and sardines, among others. The clupeids include many of the most important food fishes in the world.

Codend: The end of a trawl net retaining the catch and the part of the net where most size-selection takes place.

Demersal fish, or groundfish: Live and feed on or near the seabed.

Depredation: An interaction between marine animals (e.g. cetaceans, seabirds, sea turtles, sharks and rays) with different types of fishing gear considered to be a source of food. Depredatory behaviour can have consequences on fisheries through the removal of bait or caught fish from hooks, nets or traps, thereby reducing commercial catches (i.e. income) or damage done to fishing gear. Depredation can also impact animals, who can suffer mortality and injuries from these interactions. Impacts caused by damages to fishing gear and the loss of catches can lead to hostile dynamics between fishers and those groups of species.

Derelict fishing gear: Nets, lines, crab/shrimp pots, and other recreational or commercial fishing equipment that has been lost, abandoned, or discarded in the marine environment.

Discard: To release or return fish to the sea, dead or alive, whether or not such fish are brought fully onboard a fishing vessel.

Elasmobranch: A group of fish without a hard, bony skeleton, including sharks, skates, and rays.

Fishing unit: Can comprise, for example, an individual, community, vessel or fleet.

Ghost fishing: Occurs when lost or discarded fishing gear that is no longer under a fisher's control continues to trap and kill fish, crustaceans, marine mammals, sea turtles and seabirds.

Gillnet: With this type of fishing gear, fish are gilled, entangled or enmeshed in the netting, which may be either single (gillnets) or triple (trammel nets). Several types of nets may be combined in one gear (for example, a trammel net combined with a gillnet). These nets can be used either alone or, as is more common, in large numbers placed in line (fleets of nets). According to their design, ballasting and buoyancy, these nets may be used to fish on the surface, in midwater or on the bottom.

Habituation: Non-associative learning involving a reduction in behavioural response after repeated exposure to stimuli, not due to sensory fatigue (Groves and Thompson, 1970).

Incidental catch or accidental catch: Non-target species captured during their attempts to take bait or other species already caught by fishing gear or taken simply through proximity to the fishing gear. See bycatch.

Lazy line: A slack line attached from a vessel to a cable under tension set at sea (trolling line, streamer lines, etc.) to allow for easy retrieval from the vessel deck.

Mesh size: The size of holes in a fishing net. Minimum mesh sizes are often prescribed by regulations in order to avoid the capture of young valuable species before they have reached their optimal size for capture.

Mitigation measures: Modifications to fishing practices and/or equipment that reduce the likelihood of incidental catch.

Mobile gear: Fishing gear that requires the movement of the fishing vessel to be deployed.

Netsonde: See acoustic netsounder.

Neritic: Relates to the ocean domain above the continental shelf and top edge of the continental slope. Corresponds to nearshore waters.

Pelagic: Relating to, living or occurring in the open sea.

Pinniped: Of the suborder (Pinnipedia) of aquatic carnivorous mammals (such as the walrus or seals) with all four limbs modified into flippers.

Prawns: Colloquial term which is used for large swimming shrimps.

Safe Lead: An alternative line weight in longline fishing, the Safe Lead is designed to slide down, or off of, the line, in the event of a bite-off, significantly reducing danger to the crew from fly-backs of line weights (Sullivan *et al.*, 2012).

Selective gear: A gear which allows fishers to capture few (if any) species other than the target species.

Soak time: Time calculated from the point in which each individual unit of fishing gear has been set, to the time when removal of the same unit begins. It can also be considered as the length of time fishing gear is submerged between hauls; reducing it appears to change bycatch probabilities.

Static/passive gear: A collective term for gear set to allow fish to swim into it, often through the encourament of attached bait, i.e. nets, long lines and traps.

Teleosts: Of or belonging to the Teleostei, a large group of fishes with bony skeletons, including most common fishes. The teleosts are distinct from the cartilaginous fishes such as sharks, rays and skates.

Trolling: Towing, close to the surface or in midwater, one or more lines with hooks holding an attractive bait or lure behind a moving boat.

Turtle excluder device (TED): A grid of bars with an opening either at the top or the bottom of the trawl net. The grid is fitted into the neck of a shrimp trawl. Small animals such as shrimps pass through the bars and are caught in the bag end of the trawl. When larger animals, such as sea turtles and sharks, are captured in the trawl, they strike the grid bars and can leave through the opening.

Vulnerable species: A taxon is considered vulnerable when it faces a high risk of extinction in the wild in the medium-term future. For the purpose of this document, the lists of seabirds, sea turtles, marine mammals and shark species included in Appendix II (endangered or threatened species) and Appendix III (species whose exploitation is regulated) of the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (the Barcelona Convention), together with elasmobranch species included in the IUCN Red List of Threatened Species, and benthic species pertaining to vulnerable marine ecosystems have been used.

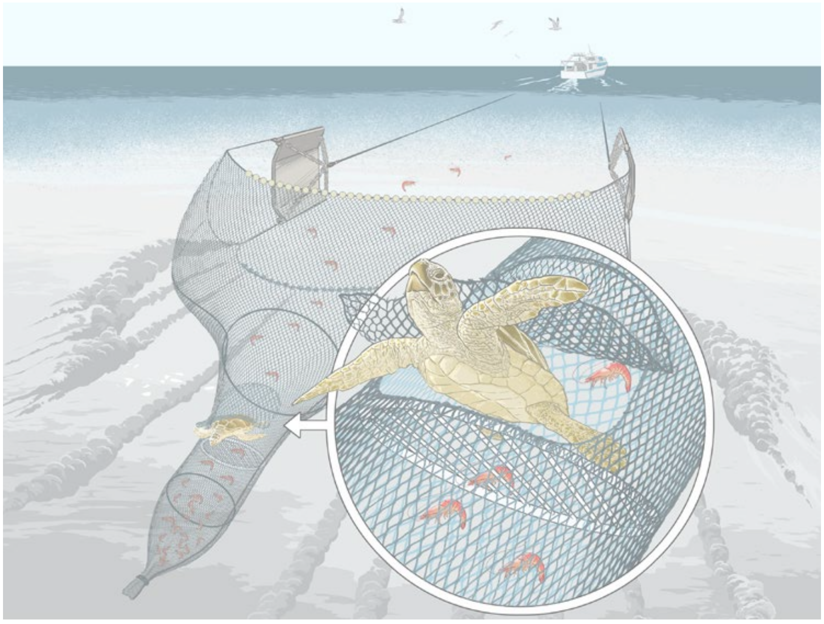
Warp cable: Fishing gear consisting of a trawl net attached to a wire warp, which is in turn fixed securely to the winch drum.

OVERVIEW OF MITIGATION MEASURES TO REDUCE THE INCIDENTAL CATCH OF VULNERABLE SPECIES IN FISHERIES

Potentially harmful contact between fisheries and marine vulnerable species represents a global conservation issue and efforts to mitigate the negative repercussions of these interactions belong in strategies for ensuring the sustainability of fisheries.

This literature review offers a survey of mitigation measures and techniques that have been developed and tested around the world, aiming to address both the incidental catch of highly mobile species – specifically, cetaceans, seabirds, sharks and rays, and sea turtles – and depredation caused by dolphins. Based on research detailed in over 300 documents, including peer-reviewed publications, reports from international organizations and papers available on the internet, most of the mitigation techniques illustrated are still under development, with only a few already adopted through legislation.

The selected mitigation measures are grouped by main types of fishing gear – gillnets and trammel nets, longlines and lines, trawls, purse seines, traps and pots – and further subdivided according to which of the four main groups of vulnerable species – cetaceans, seabirds, sharks and rays, or sea turtles – they are designed to protect. Preventive and curative approaches covering both technical measures (gear modifications, strategies, as well as acoustic, visual, magnetic and chemosensory deterrents) and management measures are described.



ISBN 978-92-5-134539-9 ISSN 1020-9549

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CB5049EN/1/06.21