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Fisheries Bycatch of Sharks: **Options for Mitigation**

THE PEW ENVIRONMENT GROUP

Fisheries Bycatch of Sharks: **Options for Mitigation**

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INTRODUCTION

Bycatch (see definition below) is one of the most significant issues in the management and conservation of global fisheries (Hall et al. 2000, Kelleher 2005, Lewison et al. 2004) and has been identified as one of the leading causes of shark population declines. Sharks are susceptible to high fishing mortality rates because of their life history characteristics, which include slow growth, late ages at maturity, and the production of a limited number of young over a lifetime (Cortes 2002, Heppell et al. 1999, Cortes 1999). In addition, research has shown that several species of sharks have very high rates of mortality associated with the fishing process (Morgan and Burgess 2007, Mandelman et al. 2008), and it has been estimated that species such as sandbar shark (*Carcharhinus plumbeus*) (Sminkey and Musick 1994, Cortes 1999) and dusky shark (*Carcharhinus obscurus*) (Simpfendorfer 1999) increase their population sizes so slowly that they are considered particularly vulnerable to mortality from fishing activities (Musick et al. 2000a). For example, Cortes et al. (2006) found that if fishing for dusky shark stopped for 30 years, their population in the Northwest Atlantic would still be depleted.

Over the past two decades, serious population declines have been reported for a number of shark species in several regions around the world (Baum et al. 2003, Ferretti et al. 2008, Robbins et al. 2006, Ferretti et al. 2010, Clarke 2011) and are attributed to both targeted and incidental capture. According to the International Union for Conservation of Nature (IUCN) and other sources, bycatch is one of the primary threats facing sharks (Musick et al. 2000b, Lewison et al. 2004).

Despite widespread recognition of shark bycatch issues (Food and Agriculture Organization [FAO] 1999; FAO 2010), few mitigation actions have been established, and there are no clear guidelines about which mitigation actions would be most effective. In addition, there are very few management measures requiring actions to mitigate shark bycatch. However, it is clear that managers and fishermen must aim to reduce both bycatch rates and the harmful effects from bycatch (e.g., injuries from capture on fishing gear). Based on the best available information, this review provides a summary of the current knowledge and understanding of shark bycatch and discusses available management options and technical measures aimed at reducing both the rate at which sharks encounter fishing gear and the associated damaging effects.

SHARK BYCATCH: WHY IS IT A PROBLEM?

Since the 1990s, the growing markets for shark products, specifically shark fins (Clarke et al. 2007), has resulted in greater demand for and utilization of sharks (Walker 1998, Kelleher 2005, Fowler et al. 2005). A study commissioned by FAO estimated that in the late 1980s and early 1990s, nearly a third of all reported shark catches were landings from bycatch fisheries (Bonfil 1994). More recently, Stevens et al. (2000) suggested that sharks taken as bycatch could account for as much as 50 percent of all shark landings. The increased economic incentive to land sharks that are incidentally caught alongside targeted species, in addition to targeted shark fisheries, has complicated efforts to reduce shark bycatch. For

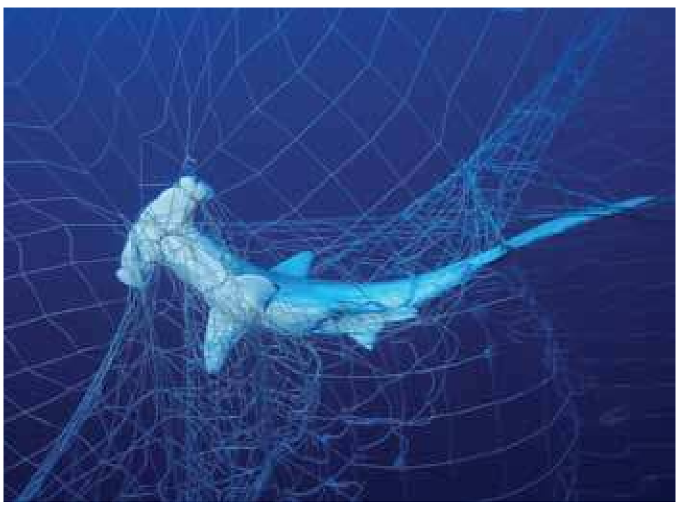
What is Bycatch?

Bycatch defined here refers to the incidental take of undesirable size or age classes of the target species, or to the incidental take of other non-target species or protected, endangered, or threatened species (FAO 2010). Bycatch can be sold, or it may be unusable or unwanted for a number of regulatory and economic reasons and therefore thrown back to sea (i.e., discarded), either alive with injuries or dead (Harrington et al. 2006, FAO 2010). Mortality of sharks caught as bycatch can be caused by the physical trauma of fishing (e.g., internal hooking) or from physiological stress associated with the capture and handling process. In addition, this mortality could occur at the time of capture (at-vessel mortality) or at some point after the sharks are returned to sea (Davis 2002).

bycatch mitigation measures to work, there generally must also be a reduced incentive to incidentally capture and land sharks.

In some regions of the world, even though sharks are not the primary target of fisheries, they make up a majority of the total catch (i.e., all fish caught and discarded). For example, in the Atlantic Ocean (north and south), large pelagic sharks amount to roughly 70.3 percent of the total landings in weight in the Spanish surface longline fleet targeting swordfish (*Xiphias gladius*) (Mejuto et al. 2006). In the U.S. Atlantic, sharks made up 25 percent of the total catch of the pelagic longline fishery between 1992 and 2003 (Abercrombie et al. 2005). The sharks caught in these fisheries are often unmanaged, because regulations typically focus on the target species (e.g., tunas and swordfish) (Stevens et al. 2000).

Bycatch of sharks results in a substantial number of sharks being discarded dead or dying every year. However, quantifying total shark mortality from bycatch is challenging because comprehensive data on these discards are unavailable. Most monitoring focuses primarily on fishing effort and landings of target species, and few fisheries have onboard observer programs (FAO 2009).



A hammerhead shark caught in a fishing net.

Moreover, although capture mortality can be readily assessed when species are hauled onboard, post-release mortality rates for sharks that are released alive but that subsequently die from stress or injuries related to the fishing process are difficult to quantify. In some cases, post-release mortality rates have been identified through the use of satellite tags, or through the collection of blood samples to determine the shark's stress response to capture (Moyes et al. 2006). However, this information is rarely available for pelagic shark species.

Even so, evidence does suggest that discard mortality rates can be very high. For example, recent research on blue sharks (*Prionace glauca*) calculated discards in the North Atlantic solely from pelagic longline fisheries at about 57,000 metric tons (mt) annually (Campana et al. 2009). Of this, total dead discards were estimated at 20,000 mt, corresponding to an estimated 860,000 blue sharks, a number equal in magnitude to the nominal catch (catch excluding discards) reported to the International Commission for the Conservation of Atlantic Tunas (ICCAT) (Campana et al. 2009). In other words, the inclusion of discard mortality may have doubled the total fishing mortality estimate for this species.

Similarly, the total number of sharks captured in the Central Pacific was estimated recently at 696,401 and current fishing mortality at 189,791 sharks per year, mainly from the tropical shallow surface longline fisheries (Molony 2005). However, because the level of observers reporting the condition of discarded sharks is low, Molony (2005) suggested that annual fishing mortality could be significantly higher, perhaps even closer to total catches. This researcher also concluded that discard mortality could triple the total fishing mortality estimate for sharks in this particular region. The large number of discarded sharks and the scarcity of information on these discards (e.g., number, species, mortality rates, size) preclude comprehensive analysis of the global scope of shark bycatch in fisheries.

DIFFERENCES IN SHARK BYCATCH AND SURVIVAL BY FISHING GEAR

Many different types of fishing gear (Figure 1) incidentally capture sharks, including longlines, gillnets, trawls, and purse seines, particularly those fishing on fish aggregating devices (FADs). Shark "catchability," selectivity (likelihood that a fish of any given size coming into contact with fishing gear will be retained by it) (Pope et al. 1975), and post-release mortality vary greatly, depending on which of these gears is used (Table 1).

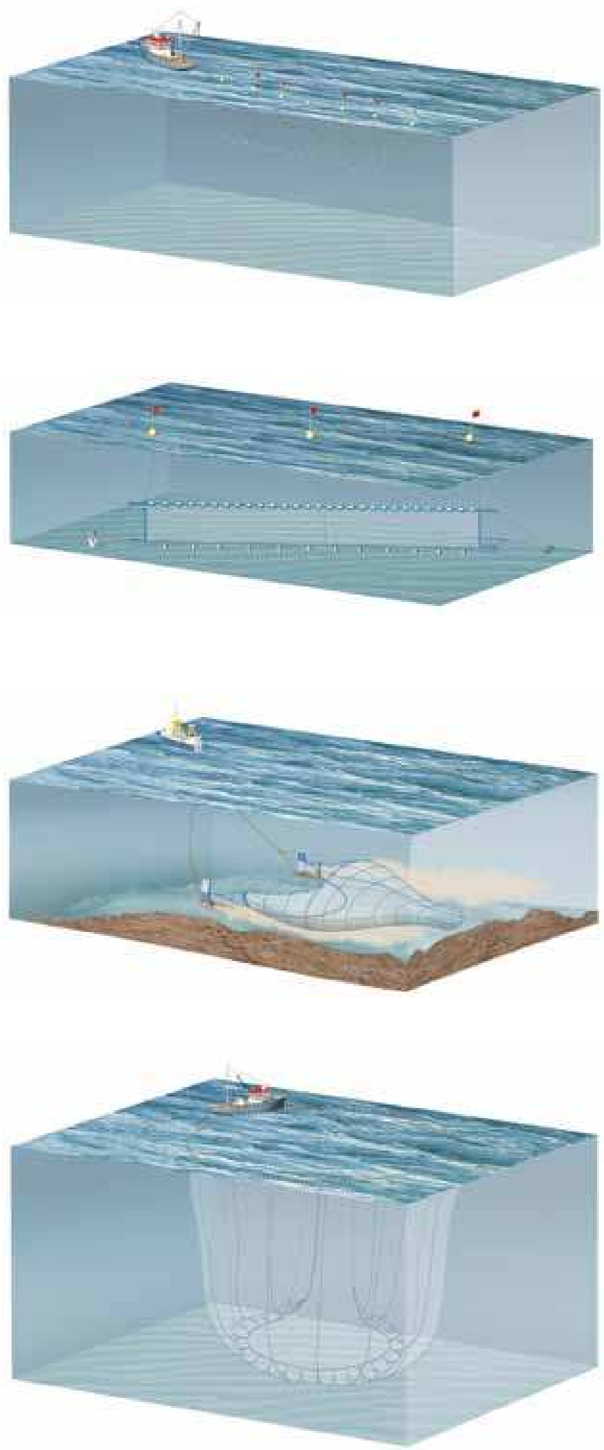
Pelagic longline gear

Pelagic longline fisheries are a significant source of bycatch for many species of sharks (Mandelman et al. 2008, Gilman et al. 2007a, Bonfil 1994). Pelagic longlines consist of a mainline that can stretch for tens of kilometers suspended by floats with branchlines, which are vertical lines attached to the mainline by a clip or swivel with a hook suspended below (Brothers et al. 1999) (Figure 1a). Shark catch-per-unit-of-effort (CPUE), the number of sharks

Table 1: Estimated capture mortality rate during haulback of elasmobranch species.

Gear type	Capture mortality (percent)	References
Pelagic longline gear	<30	Diaz and Serafy 2005, Campana et al. 2006, Francis et al. 2001, Megalofonou et al. 2005
Bottom longline gear	15–90	Morgan and Carlson 2010, Rulifson 2007
Gillnet gear	>70	Manire et al. 2001, Rogan and Mackey 2007, Thorpe and Frierson 2009
Trawl gear	0–60	Rulifson 2007, Rodríguez-Cabello et al. 2005, Mandelman and Farrington 2007, Enever et al. 2009, Stobutzki et al.
Purse seine gear	Estimated to be very high, maybe 100	Molony 2005

Figure 1: Sharks are often caught in various types of fishing gears including (a) longlines, (b) gillnets, (c) trawls, and (d) purse seines.



a

b

c

d

per 1,000 hooks, varies greatly among pelagic longline fisheries, individual vessels, seasons, and years, but sharks often make up 15 to 25 percent of the total catch of specific fisheries (Williams 1999, Gilman et al. 2008, Matsunaga and Nakano 1999, Beerkircher et al. 2002). For example, sharks made up 16.2 percent of the total number of fish caught in the South African tuna and swordfish longline fishery from 1998 to 2005 and more than 25 percent of the Fiji tuna longline fishery in 1999 (Gilman et al. 2007a). In the Hawaiian swordfish longline fishery, sharks represent about 32 percent of the total catch (Gilman et al. 2008). Blue shark is typically the most commonly caught species, probably because of its worldwide distribution (Compagno 1999), and often accounts for 50 to 90 percent of the total reported shark catch on high-seas longlines (Campana et al. 2006, Francis et al. 2001, Megalofonou et al. 2005, Gilman et al. 2008). In 2005, incidental catch of blue shark totalled 145,685 lbs in the Atlantic and Gulf of Mexico pelagic longline fishery (NMFS 2011a).

Pelagic longlines tend to have lower shark mortality rates for some species such as blue and tiger sharks (Beerkircher et al. 2002). More than 70 percent of blue sharks survive after being hooked on a longline and brought onboard (Francis et al. 2001, Diaz and Serafy 2005, Campana et al. 2006, Megalofonou et al. 2005), and an additional 80 to 95 percent of the discarded blue sharks are expected to survive the release process (Moyes et al. 2006, Campana et al. 2009). In the U.S. Atlantic, pelagic longline fishery survival rates are even higher, with 97 percent of tiger sharks (*Galeocerdo cuvier*) and 87.8 percent of blue sharks surviving the fishing process (Beerkircher et al. 2002). However, several species have very high mortality rates on pelagic longline gear (Beerkircher et al. 2002), including the night shark (*Carcharhinus signatus*) (80.8 percent), silky shark (*Carcharhinus falciformis*) (66.3 percent), and bigeye thresher shark (*Alopias superciliosus*) (53.7 percent).

Bottom longline gear

In addition to pelagic longlines, bottom longlines, which are similar to pelagic longlines but are weighted so they are close to the bottom, can also incidentally capture sharks. For example, the Chilean bottom longline fishery that targets pink cusk eel and yellownose skate frequently captures sharks, including the redspotted catshark (*Schroederichthys chilensis*) and dusky catshark (*Halaelurus canescens*) (Valenzuela et al. 2008). Other examples include the South African and Namibian bottom longline fisheries that target hake (Basson et al. 2007). It has been estimated that 374,060 sharks, mostly dogfish species, are incidentally caught each year in the South African fishery and 1,081,600 in the Namibian fishery (Bassoon et al. 2007). In the U.S. Gulf of Mexico reef fish bottom longline fishery, a variety of shark species were incidentally caught in 2005, including 798 dusky sharks, 304 sandbar sharks, and an additional 1,242 unidentified sharks and rays (NMFS 2011a).

In bottom longline fisheries, capture mortality rates for sharks (the percentage dead when brought on board) can vary by species. For example, Morgan and Carlson (2010) found high capture mortality rates in the U.S. Atlantic for Atlantic sharpnose (*Rhizoprionodon terraenovae*) (91 percent) and blacktip sharks

(*Carcharhinus limbatus*) (85 percent). However, the sandbar shark (21 percent) and the bull shark (*Carcharhinus leucas*) (15 percent) had much lower mortality rates. Long soak times (the length of time a fish is kept on fishing gear before being brought up) in bottom longline fisheries have also been linked to higher mortality rates among some shark species (Morgan and Burgess 2007, Morgan and Carlson 2010).

Gillnet gear

A gillnet is a type of fishing gear designed to entangle or ensnare fish by keeping the net near or at the surface with floats and allowing it to freely drift with the currents (Hovgard and Lassen 2000) (Figure 1b). Despite a 1992 United Nations ban on high-seas drift gillnets (U.N. Resolution 46/215), these fisheries continue to be a threat to vulnerable species in some regions. Drift gillnets can still be used in national waters, and they are allowed to float in the water, catching animals that come into contact with them. For example, in the Moroccan large-scale driftnet fleet operating in the Alboran Sea and nearby Straits of Gibraltar, the ratio of swordfish to sharks caught is approximately 2 to 1 in number of individuals (Tudela et al. 2005). In the Japanese flying squid drift gillnet fishery, blue sharks and salmon sharks (*Lamna ditropis*) are common bycatch species (McKinnel and Seki 1998).

Bottom and mid-water gillnets, which are weighted so they fish at or near the bottom and are generally anchored to prevent drifting, can also catch a variety of shark species as bycatch. For example, sharks make up a portion of the bycatch in the south Brazilian gillnet monkfish fishery (Perez and Wahrlich 2005). In the Canadian halibut gillnet fishery, black dogfish (*Centroscylium fabricii*) are caught in large numbers, as are piked dogfish (*Squalus acanthus*) in the cod and redfish gillnet fisheries (Benjamins et al. 2010).

Studies on gillnets report high mortality rates, especially among certain species of the requiem (Carcharhinidae) and hammerhead (Sphyrnidae) shark families. These sharks breath by swimming, and entrapment in gillnets inhibits their normal reliance on this mechanism (Manire et al. 2001, Rogan and Mackey 2007, Thorpe and Frierson 2009). It was also estimated that 31 percent of blacktip sharks (*Carcharhinus limbatus*) and 40 percent of bonnetheads (*Sphyrna tiburo*) released after being caught in gillnets died of injuries or stress sustained during the capture process (Hueter et al. 2006).

Trawl gear

Trawls are cone- or funnel-shaped nets that also catch sharks as bycatch (Figure 1c). Towed by one or two boats, these nets have two wings of varying lengths that extend the net opening horizontally, and they can be pulled along the bottom or any level in the mid-water, including the surface water (Hovgard and Lassen 2000). Sharks are caught as bycatch in Australia's northern prawn trawl fishery (Stobutzki et al. 2002) and the Gulf of Mexico shrimp trawl fishery (Shepherd and Myers 2005). Additionally, the blackmouth catshark (*Galeus melastomus*), velvet belly shark (*Etmopterus spinax*), and spotted dogfish shark (*Scyliorhinus canicula*) are commonly caught bycatch species in the Balearic Islands in the western Mediterranean (Carbonell et al. 2003).

In trawl fisheries, survival is affected by several factors, including the duration of the trawl, the size of the catch, and the amount of time used to sort the catch. Within-net mortality varies greatly but tends to remain relatively low, particularly among smaller size species, such as piked dogfish (Stobutzki et al. 2002, Rodríguez-Cabello et al. 2005, Rulifson 2007, Mandelman and Farrington 2007).

Purse seine gear

In tuna purse seining operations, a large net is used to capture fish by encircling schools (Figure 1d). These fisheries pose a growing threat to sharks throughout tropical and subtropical waters of the Indian, Pacific, and, to a lesser degree, Atlantic Oceans (ICCAT 2011). Sharks CPUE (number per set) varies in these fisheries but is usually less than 5 percent of the total catch (Amande et al. 2008, Watson et al. 2008, Molony 2005). Nonetheless, the total shark catch can be quite large, although not as large as in other fisheries. For example, Molony (2005) estimated that the total shark catch by the purse seine fishery in the Western and Central Pacific Fisheries Commission (WCPFC) area varied but could be as much as 80,000 sharks per year, which is a large number but relatively small compared to other fisheries such as pelagic longline fisheries operations.

Silky sharks (*Carcharhinus falciformis*) are usually the most commonly caught species, followed by oceanic whitetip sharks (*Carcharhinus longimanus*) (Amande et al. 2011, Inter-American Tropical Tuna Commission [IATTC] 2009, Secretariat of the Pacific Community [SPC] 2008). In the Indian Ocean, 1,385 immature silky sharks were observed caught by the French tuna purse seine fishery from 2005 to 2008 (Amande et al. 2008).

To capture tunas, some purse seine vessels use FADs, floating structures that attract fish (Bromhead et al. 2003) and can result in a large amount of shark bycatch. For example, from 2003 to 2005, 40 percent of sets made on FADs in the western-central Pacific Ocean captured sharks (Scott 2007). In the Indian Ocean, silky sharks were caught in about 24 percent of purse seine sets, with higher catch rates occurring around FADs (Amande et al. 2008).

Although mortality rates of sharks incidentally caught in purse seines has not been thoroughly studied, some research suggests high (75 percent) mortality rates, such as in the Atlantic menhaden purse seine fishery (de Silva et al. 2001).

HOW CAN SHARK BYCATCH AND POST-RELEASE MORTALITY BE REDUCED?

Shark bycatch in fishing operations can be mitigated through the implementation of policy and management measures (e.g., input and output control measures, such as limit reference points) or through technological changes to the fishing gear and/or fishing practices (e.g., bait restrictions). Table 2 summarizes these techniques and indicates if they have been empirically tested specifically on sharks and whether there is evidence that the measures can be feasibly implemented. Each of the techniques is also discussed in further detail below.

Table 2: Summary of methods used to reduce shark interactions or increase the likelihood of survival of sharks in fisheries.

Measure to reduce shark interactions or injury in fisheries	Empirical evidence of shark avoidance or reduced injury efficacy	Empirical evidence of economic and practical viability
Policy and management measures		
Effort limitations	Y	Y
Banning finning	Y	Y
Handling and release practices	Y	Y
Time and area closures/marine protected areas	Y	Y
Interaction cap	N	N
Technological changes in gear and fishing procedures		
Pelagic longline gear		
Use of circle hooks	Y	Y
Bait restrictions	Y	N
Banning wire leaders	Y	Y
Hook depth	Y	Y
Temperature avoidance	Y	N
Reducing soak time	Y	N
Repellents	Y	N
Bottom longline gear		
Reducing the number of hooks	Y	N
Reducing soak time	Y	N
Repellents	Y	N
Gillnet gear		
Mesh size regulations	Y	Y
Tensioning gillnet	Y	N
Trawl gear		
Bycatch reduction devices (BRDs)	Y	Y
Filter grid	Y	N
Purse seine gear		
Ecological FADs	in trials	in trials
Deterrents	Y	N
Restricting set times	N	N
Restricting sets on FADs and other floating objects	N	N
Multiple FADs	Y	N

Shark bycatch policy and management measures

Management of sharks varies greatly between countries and is non-existent, of low priority, or in the early stages of development in many (Gilman et al. 2007a, Camhi et al. 2009). Additionally, no regional fishery management organizations (RFMOs), international organizations that manage the fishing of high seas stocks, have developed management plans for sharks or set catch limits. Some RFMOs have, however, implemented mandatory species-specific reporting of shark landings, placed bans on finning, called for reductions in fishing mortality, encouraged the live release of sharks (Camhi et al. 2009), or prohibited the retention of certain species (ICCAT 2010). Shark bycatch rates and associated mortality in commercial fisheries could be reduced in many areas through the implementation of the types of management measures discussed in detail below.

Effort limitations

Limits on the number (Camhi et al. 2008) and size (capacity) (Dulvy et al. 2008) of vessels allowed to participate in a fishery and limits on catch are both tools that can be used to reduce fishing effort, subsequently leading to a reduction in the overall mortality of sharks. Shark mortality and fishing effort can also be reduced by prohibiting the fishing of certain or all shark species such that any possession, landings, or sales are illegal (Camhi et al. 2008). Another alternative is to have a limit on the bycatch-to-target species ratio allowed in a fishery. For example, the South African longline tuna and swordfish fishery limits shark landings to 10 percent of the total catch (Gilman et al. 2007a). Although catch limits have been implemented in some countries, the same cannot be said for the high seas, where a number of shark species susceptible to over-exploitation are commonly caught as bycatch (Dulvy et al. 2008).

Banning finning

Finning, the practice of removing and retaining shark fins while discarding the remainder of the carcass at sea, is widespread (Clarke et al. 2007). Protective shark finning policies, such as banning finning or the sale and possession of fins, have been shown to reduce the mortality associated with this practice (Camhi et al. 2008) in fisheries that are heavily monitored through surveillance and enforcement or in areas where there is little to no market for shark meat and therefore no incentive to fish for sharks (Gilman et al. 2008, Walsh et al. 2009).

Finning bans are now widely used in many countries as well as by some RMFOs, and strict regulations, such as requiring the whole shark to be landed (with fins naturally attached) allow for better enforcement and data collection (Hareide et al. 2007, Dulvy et al. 2008). However, a number of countries still rely instead on a fin-to-carcass ratio, typically 5 percent. This presents many problems, including differences in the fin-to-carcass ratio between species, different cuts of the fin between fisheries, discarding of low-value but heavy carcasses and retention of high-value fins (e.g., those of hammerhead sharks), problems with enforcement (e.g., species identification) (Hareide et al. 2007), the inability to actually reduce shark bycatch rates or mortality, and increased challenges in species-specific identification and data collection.

Handling and release practices

Injuries sustained by sharks during the fishing and handling process, including those suffered during removal of hooks and gaffing (hooks with handles commonly used by fishermen to bring large fish onboard), can severely impair survival of sharks upon release (Campana et al. 2009). The development and enforcement of protocols or best practices for safe handling and release of sharks could greatly reduce post-release mortality rates (Gilman et al. 2008), and scientists have suggested that the live release of unwanted shark bycatch should be mandatory (Musick et al. 2000b). For example, the United States has recently begun encouraging the live release of shortfin mako (*Isurus oxyrinchus*) sharks to mitigate the effects of overfishing on this population (National Marine Fisheries Service [NMFS] 2011b).

Time and area closures and marine protected areas

The protection of sharks through time and area closures, sanctuaries, or marine protected areas (MPAs) in shark "hot spots" or critical habitats have great conservation promise. Such areas can be used to protect sharks and aid in rebuilding shark populations because fishing is either altogether prohibited or fishing for targeted species is restricted (e.g., Garla et al. 2005, Barker and Schluessel 2005, Stevens 2002, Heupel and Simpfendorfer 2005). For example, tagging and telemetry data from both inside and outside the Fernando de Noronha archipelago's MPA show that shark abundance and activity is greatest along the coastline that is least disturbed by human activity (Garla et al. 2005). In the Great Barrier Reef MPAs, Robbins et al. (2006) showed that whitetip and grey reef sharks were 80 to 97 percent more abundant in no-entry zones compared with fished zones. Demographic modeling of sandbar sharks and other large coastal sharks has shown that population growth rates are sensitive to juvenile survivorship, and thus protection of nursery areas can be a means of rebuilding stocks (Cortes 2002, Cortes 1998, Cortes 1999).

For such closures to be a viable management tool, the cost to fishermen and the consequences of fishing reallocation (e.g., fishermen moving to another location to continue fishing) need to be carefully evaluated. Few examples exist of fisheries closed to reduce shark bycatch. In the eastern Pacific tuna purse seine fishery, Watson et al. (2008) evaluated potential spatial closures to reduce silky shark bycatch. Overall, they found that the spatial patterns of silky shark bycatch were persistent and that some of these regions were spatially distinct from regions with the greatest tuna catch. Several area closures could reduce total silky shark bycatch by as much as 33 percent (Watson et al. 2008).

TECHNOLOGICAL CHANGES IN GEAR AND FISHING PROCEDURES

Pelagic longline gear

Use of circle hooks

A large percentage of shark bycatch research has focused on pelagic longlines because this gear has the highest rate of shark bycatch globally. In particular, research has focused on the effect of circle hooks, which have shown significant success in mitigating marine turtle bycatch and injury (Watson et al. 2005, Gilman et al. 2006, Read 2007).

Figure 2: J hooks (a), commonly used in fisheries, can be replaced by circle hooks (b). The impact of using circle hooks to reduce shark bycatch has been variable.

a

b

The effects of hook type (e.g., circle versus J-shaped and minimum width [Figure 2]) on shark catch rates remain unclear. Many studies report no statistically significant difference in shark catch rates between circle versus J-shaped or tuna hooks (Ward et al. 2009, Watson et al. 2005, Kerstetter and Graves 2006, Yokota et al. 2006, Galeana-Villasenor et al. 2008, Galeana-Villasenor et al. 2009, Ward et al. 2009, Curran and Bigelow 2011, Pacheco et al. 2011, Promjinda et al. 2008, Cosandey-Godin et al. In Press). However, some studies report lower catches of sharks when circle hooks are used (Kim et al. 2006, Gilman et al. 2007b, Promjinda et al. 2008, Curran and Bigelow 2011), while others suggest that circle hooks lead to higher shark catch rates (Bolten et al. 2005, Watson et al. 2005, Kerstetter and Graves 2006, Kim et al. 2007, Ward et al. 2009, Sales et al. 2010, Alfonso et al. 2011). For example, Curran and Bigelow (2011) found that shark catch rates declined by 17.1 to 27.5 percent when circle hooks were used instead of J hooks. A decrease in blue shark catch rates of 36 percent was observed in the Hawaii pelagic longline fishery after regulations requiring the use of circle hooks and bait restrictions (see below) were implemented (Gilman et al. 2007b). In contrast, Sales et al. (2010) found that the use of circle hooks in the Brazilian pelagic longline fishery increased catch rates of blue sharks as well as sharks from the genus Carcharinus.

As is the case with sea turtles, circle hooks do appear to decrease mortality of hooked sharks, because most individuals are externally hooked in the mouth or jaws, in contrast with J and tuna hooks (Watson et al. 2005, Carruthers et al. 2009, Campana et al. 2009, Alfonso et al. 2011). Circle hook capture is also associated with less internal injury and a higher chance of survival (Campana et al. 2009, Carruthers et al. 2009, Cosandey-Godin et al. In Press).

Bait restrictions

Squid is commonly used as bait in pelagic longline fisheries targeting swordfish (SPC 2009). Empirical studies and interviews with fishermen suggest that large reductions in blue shark catch rate can be achieved when squid is replaced with fish baits (Watson et al. 2005, Gilman et al. 2007b, Petersen et al. 2009, Galeana-Villasenor et al. 2009). For example, in the Hawaiian swordfish longline fishery, shark catch rates (all species combined) dropped considerably (36 percent for blue sharks) when the fishery was required to switch from using J hooks with squid baits to wider circle hooks with fish bait in order to reduce marine turtle interactions (Gilman et al. 2007). Historically, blue sharks made up more than 90 percent of total shark catch in this fishery, and the apparent drop in shark catches was primarily attributed to the change of bait. However, the effect of baits on other species is still largely unknown, and probably varies among species.

Bans on wire leaders

Longline hooks are attached to vertical lines (called branchlines) that are attached to the mainline suspended by floats. Most lines are made of heavy-duty nylon monofilament (from a single fiber of plastic), but sometimes wire leaders are used for a proportion of the branchlines (Ward et al. 2008, Gilman et al. 2007a). Information collected through interviews with fishermen revealed that where there is no regulatory framework and where the market is profitable for shark products, fishermen will often use wire leaders to maximize shark catch (Gilman et al. 2007a). Sharks are less able to escape from wire leaders than from monofilament nylon leaders, which they can sever or break with their sharp teeth (Vega and Licandeo 2009, Ward et al. 2008).

Ward et al. (2008) provided a comprehensive analysis of the biological and socio-economic impacts of banning wire leaders, which are associated with higher shark catch rates. Their conclusions are promising; overall, this gear alteration (replacement with monofilament line) increased the catchability of target species (in this case bigeye tuna) while decreasing shark catch rates by 58 percent, and the increased returns outweighed the costs of replacing and repairing gear damaged by sharks (Ward et al. 2008).

Avoiding certain materials for branchlines could also influence shark bycatch rates. For instance, multifilament (a braided line made of polyethylene) as opposed to monofilament has been shown to lead to lower catch rates of sharks in some cases (Stone and Dixon 2001, Branstetter and Musick 1991), and higher in others (Varghese et al. 2007). More research is clearly needed on multifilament versus monofilament line.

Hook depth

Interviews conducted with longline fishermen reveal that most believe that the depth of baited hooks and the length of time the gear soaks influence shark catch rates (Gilman et al. 2007a). Setting baited hooks below a threshold depth has been shown to reduce catches of several species of sharks. For example, in the western and central Pacific pelagic longline tuna fisheries, Williams (1999) found that blue shark, silky shark, and oceanic whitetip shark catches were higher in shallow-set gear (one to nine hooks between floats) versus deep-set gear (at least 10 hooks between floats). Ward and Myers (2005) had similar results with oceanic whitetip shark and dusky shark in the Pacific Ocean. Using ecosystem modeling in the north Pacific and eastern tropical Pacific Ocean, Hinke et al. (2004) evaluated the ecological outcomes of longlining and found that restrictions on both shallow-set longline gear and on shark finning together may do more to recover top predators than simple reductions in fishing effort.

One technique for reducing shallow-set hooks in longline fishing involves lowering the mainline by using weighted sections (Beverly et al. 2009, Beverly and Robinson 2004). This configuration requires additional gear and more time allocated to set and haul back the gear and has not yet been found to significantly reduce the interactions and impacts on sharks. Additional trials and better understanding of the main shark bycatch species' vertical habitat preferences are needed.

Temperature avoidance

Sea surface temperatures, topographic features such as shelf breaks and seamounts, and oceanographic features such as currents, fronts, and gyres, may affect shark interactions with fishing gear. For example, interviews with longline fishermen have revealed that many believe setting their gear in specific water temperatures, such as the colder side of fronts, reduces shark bycatch levels (Gilman et al. 2007a). More comprehensive studies on shark species distributions according to water column temperature profiles and thermocline dynamics are necessary before fishing practices are amended in accordance with patterns in sea-surface temperatures.

Reducing soak time

On both pelagic and bottom longlines, catch rates of sharks (Morgan and Carlson 2010, Ward et al. 2004), as well as mortality rates (Diaz and Serafy 2005, Morgan and Burgess 2007), increase with soak time, or more precisely with increasing time that the species spends on a hook (Morgan and Carlson 2010). Reducing soak times will probably result in fewer interactions and reduced mortality rates, particularly among species that require swimming for effective respiration, such as many species of Carcharhinid sharks (Carlson et al. 2004). In some regions where information on soak time is available, this measure could potentially be implemented in a relatively short period of time. However, the impact on the fishery has to be evaluated; if this measure would result in increased fishing effort (i.e., increase in number of sets) it probably would have little effect on mitigating shark bycatch and total fishing mortality.

Repellents

Electrochemical permanent magnets or electropositive metals and semiochemical repellents are promising shark deterrents that have received more attention in recent years. Semiochemicals are deterrents that use chemical messengers that sharks can detect in their environments. Certain chemicals can trigger a flight reaction in sharks (Sisneros and Nelson 2001, Swimmer et al. 2008), including ammonium acetate, a major component in decaying shark flesh and other semiochemicals emitted from predators (Sisneros and Nelson 2001). Recent advances in these chemical repellents have produced environmentally benign compounds that do not affect other fish and are highly specific to sharks, making them useful for future application in commercial fisheries.

Permanent magnets and electropositive or rare earth metals (a mixture of the lanthanide elements lanthanum, cerium, neodymium, and praseodymium) create an electric field that perturbs the electro-sensory system in sharks, causing the animals to exhibit aversive behaviors (Swimmer et al. 2008, Brill et al. 2009). Rare earth metals have shown repulsive effects on many species of sharks, including juvenile sandbar sharks, lemon sharks (*N.egaprion brevirostris*), nurse sharks (*G.inglymostoma cirratum*), and piked dogfish (*Squalus acanthias*) (Kaimmer and Stoner 2008, Stoner and Kaimmer 2008, Swimmer et al. 2008, Brill et al. 2009).

Field experiments have also shown that rare earth metals attached near hooks reduced piked dogfish catch by 19 percent on bottom longlines (Kaimmer and Stoner 2008) and, in laboratory studies, reduced the frequency at which piked dogfish attached to and consumed baited hooks (Stoner and Kaimmer 2008). However, rare earth metals incorporated into longlines have been shown to have no effect in reducing catches of piked dogfish (Tallack and Mandelman 2009). Rare earth magnet discs have reduced bait depredation by Galapagos sharks (*Carcharhinus galapagensis*), although this effect was diminished when high densities of sharks were present (Robbins et al. 2011). The use of any electrochemical deterrent in commercial fisheries will have significant cost, however, and currently is not an economically viable option. In addition, there are issues with the high dissolution rates of the metals (requiring continual replacement), safety in handling the metals, and environmental hazards caused by these metals. Therefore more research is needed to develop effective designs and evaluate the impact of these deterrents on target and other non-target species.

Bottom longline gear

Reducing the number of hooks

Although many bycatch reduction measures that have been found useful with pelagic longlines could potentially be effective in bottom longline fisheries, very little research has been conducted on this topic. Coelho et al. (2005) evaluated the effect of removing the lower three hooks in the hake near-bottom longline fishery in the Algarve in southern Portugal, where deep-water sharks are the most significant portion of bycatch. This gear design did reduce the number of sharks that were caught by 16 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. These measures show that better and more selective gear can be also be adapted for other longline fisheries and warrant additional research.

Gillnet gear

Mesh size restrictions

In gillnets, the mesh size, hanging ratio, twine material, twine thickness and visibility, and fish morphology and behavior can have an effect on fish catchability (Hamley 1975). Gillnet mesh sizes have a major effect on catch composition and catch rate, with particular mesh sizes exhibiting a high selectivity for certain shark species (Walker et al. 2005, Carlson and Cortes 2003). Therefore, mesh size regulations can be an effective tool for managing unintentional catches of threatened sharks or enhancing juvenile and adult survival by limiting the size composition of catches (e.g., Carlson and Cortes 2003, McAuley et al. 2007).

Tensioning gillnet

New methods that have been investigated for reducing shark bycatch include increasing the tension on gillnets by increasing float buoyancy and lead-core lead-line weights. Thorpe and Frierson (2009) have demonstrated that these modified gillnets have the potential to reduce shark bycatch rates and mortality, especially for species such as the blacktip shark (Carcharhinus limbatus). These sharks become entangled more easily and therefore have higher mortality rates. If gillnets have more tension, more sharks will probably bounce off the webbing instead of being entangled (Thorpe and Frierson 2009). This modification is costly to fishermen (Thorpe and Frierson 2009), but where shark interactions are high, the initial cost could be outweighed by the costs of replacing and repairing damaged gear (Trent et al. 1997).

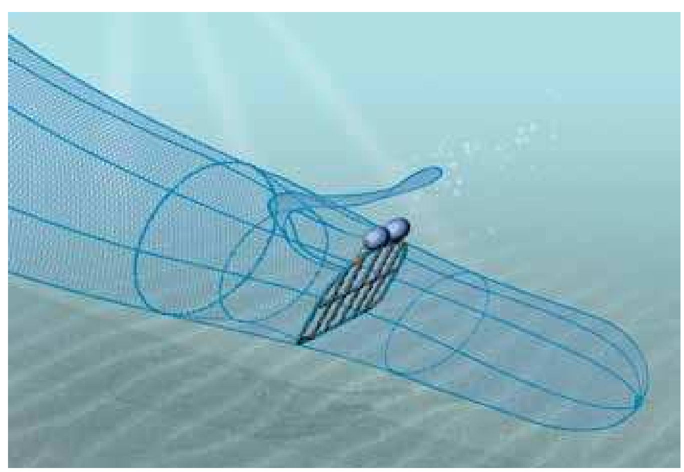
Trawl gear

Bycatch reduction devices

Numerous bycatch reduction devices (BRDs) have been developed to increase the selectivity of trawl fisheries. These include turtle excluder devices (TEDs) (Figure 3), which consist of grid bars fitted into the neck of a trawl net with an opening at either the top or the bottom, allowing large animals to escape through the openings as they strike the grid bars while target species pass through the grids and are subsequently captured in the net. The successful development of such devices has resulted in BRDs and TEDs becoming mandatory in a number of prawn and shrimp fisheries worldwide (Hall and Mainprize 2005).

The excluder devices may have an indirect influence on reducing shark bycatch. For example, Brewer et al. (2006) assessed modified trawls using different combinations of BRDs, including TEDs, during commercial operations in Australia's northern prawn fishery. Overall, any nets with such modification caught significantly fewer (86 to 94 percent) large shark species (Brewer et al. 2006). For example, TED devices, particularly those with upward excluders, reduced the numbers of larger sharks (those greater than one meter in length) by 86 percent (Brewer et al. 2006). However, more extensive research on the use of excluder devices to reduce shark bycatch is still needed. In addition, the effectiveness of any TED in reducing shark bycatch will be dependent on proper use of the devices.

Figure 3: Bycatch reduction devices such as turtle excluder devices, which consist of grid bars fitted into the neck of a trawl net with an opening at either the top or the bottom, can allow large animals to escape through the openings as they strike the grid bars while target species pass through the grids and are subsequently captured in the net.



Filter grid

The "tunnel excluder" is another trawl modification that holds promise for large sharks (Figure 4). A filter grid, which allows fish that are too big to pass through the grid and exit through an escape hatch, slopes downward 20 degrees and forces larger non-target species downward to the tunnel entrance. This configuration has shown a 20 to 100 percent reduction in the bycatch of the most vulnerable species, including sharks (Zeeberg et al. 2006). In addition, a 250 by 250 millimeter shark filter grid has been shown to allow 25 percent of the hammerheads, particularly mature specimens, to escape (Zeeberg et al. 2006).

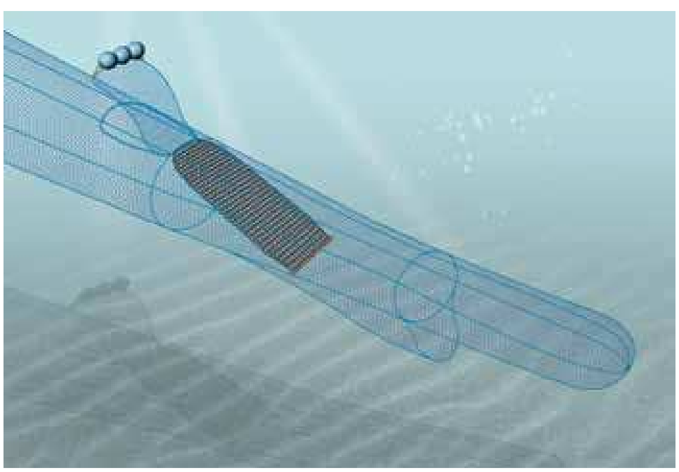
Purse seine gear

Although little research has been conducted on shark bycatch mitigation in purse seine fisheries, there are a few promising ideas, including ecological FADs, deterrents, restrictions on set times, restrictions on sets on FADs and other floating objects, and avoidance of sharks.

Ecological FADs

Research into the use of ecological FADs has been initiated in the equatorial eastern Pacific Ocean and Atlantic Ocean (Franco et al. 2011, Schaefer and Fuller 2011). These FADs are designed to reduce the potential entanglement of sharks (and other bycatch species). The designs currently being tested include FADs made from natural biodegradable material such as bamboo (Franco et al. 2011) and FADs with a smaller stretch purse seine mesh net hung from them. Preliminary tests have resulted in no bycatch of sharks (Schaefer and Fuller 2011).

Figure 4: A filter grid allows fish that are too big to pass through the grid and exit through an escape hatch.



Deterrents

Various ideas that have been proposed for deterring shark bycatch include bait stations and the use of sounds and chemicals that could lure sharks away from FADs before the set is made, therefore reducing incidental capture of sharks (Dagorn 2010, Kondel and Rusin 2007). Preliminary studies investigating the feasibility of deterrents are currently being conducted in areas such as the eastern Pacific Ocean (Kondel and Rusin 2007).

Restrictions on set times

Some research has shown that silky sharks appear to move away from FADs at night, and therefore restricting when sets can be made may prove useful (Dagorn 2010). However, much more research needs to be conducted on additional species and in other locations (Dagorn 2010).

Restrictions on sets on FADs and other floating objects

Managers could prohibit the setting of purse seines around FADs or other floating objects in an effort to reduce the bycatch, including that of sharks (WCPFC 2004). Such prohibition of setting on FADs have been initiated during time and area closures in the Atlantic Ocean (ICCAT 1999) and on floating objects in the western and central Pacific Ocean (Parties to the Naura Agreement [PNA] 2010). In addition, the Forum Fisheries Agency (FFA), which was developed to assist 17 Pacific Island nations in the sustainable management of their fishery resources, has recently adopted a management measure that prohibits purse seine fishing around whale sharks (FFA 2011).

Multiple FADs

Another possible way of reducing shark bycatch in purse seine FAD fisheries that is being investigated to reduce small tuna bycatch is using stacking or double FADs, whereby two FADs are placed in close proximity, thereby increasing the potential for segregation by certain species (ISSF 2011). Research in the equatorial eastern Pacific Ocean is currently being conducted to determine whether such species-specific aggregations occur (Schaefer and Fuller 2011).

CONCLUSION

The drastic declines in shark populations over the past few decades are a result of the capture of these animals in both targeted and bycatch fisheries. Although bycatch, capture, and post-release mortality rates differ among fisheries, it is clear that managers and fishermen must begin to mitigate bycatch mortality of sharks. To achieve this goal, encounter and discard mortality rates must be reduced, and technological changes to gear and fishing practices should be implemented through requirements and incentives, particularly when shark survival rates are low, such as in the bottom longline and gillnet fisheries. It has been proposed that fishing mortality of sharks can be greatly reduced through a combination of changes in fishing regulations and gear and fishing practices (Worm et al. 2009). For example, Kaplan et al. (2007) demonstrated that a management policy combining the mandatory use of circle hooks and the subsequent immediate release of sharks caught on them leads to an increase in shark abundance. However, for these measures to be successful, they

generally must be accompanied by a reduction in the economic incentives for fishermen to incidentally capture and land sharks.

Measures such as banning the use of wire leaders on pelagic longlines and mandating the use of BRDs, particularly TEDs, in trawls have already been implemented in several fisheries, and could be implemented elsewhere. In some regions, where adequate onboard observer information is available, reductions in gear soak time and time and area closures could also potentially be implemented. Although methods of reducing shark bycatch in purse seine fisheries, such as the use of attractants or deterrents that keep sharks away from floating objects before the purse seine is set, are currently being investigated, it is an area of study that requires more scientific examination. Other bycatch mitigation measures, such as the use of chemical deterrents, have shown great results and with improved technology might in the near future be viable to implement in commercial fisheries.

The majority of research on bycatch mitigation measures applies to pelagic longline fisheries, probably because of their very high shark bycatch rates. In addition, the issue of shark bycatch mortality is complicated by the fact that capture and post-release mortality rates also differ significantly among species, highlighting the importance of species-specific studies in fisheries that capture sharks incidentally. More attention needs to be given to the development of mitigation measures for bottom longline, gillnet, trawl, and purse seine fisheries, which also capture a large number of sharks incidentally and have high shark bycatch mortality rates.

The success of any bycatch solution will greatly depend on the species involved in the fishery and the dynamics of the fisheries, ecosystem, and governance regimes. Examples presented in this review show that over the past few years, several promising mitigation measures have been tested and shown to result in reductions in shark bycatch rates in several different fisheries. However, these reductions will be successful only if they are implemented worldwide. Addressing the challenge of shark bycatch requires that fisheries managers implement mitigation measures demonstrated to be useful in reducing shark bycatch and associated mortality.

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