Reducing sea turtle by-catch in pelagic longline fisheries

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Abstract

Reducing by-catch of sea turtles in pelagic longline fisheries, in concert with activities to reduce other anthropogenic sources of mortality, may contribute to the recovery of marine turtle populations. Here, we review research on strategies to reduce sea turtle by-catch. Due to the state of management regimes in most longline fisheries, strategies to reduce turtle interactions must not only be effective but also must be commercially viable. Because most research has been initiated only recently, many results are not yet peer-reviewed, published or readily accessible. Moreover, most experiments have small sample sizes and have been conducted over only a few seasons in a small number of fisheries; many study designs preclude drawing conclusions about the independent effect of single factors on turtle by-catch and target catch rates; and few studies consider effects on other by-catch species. In the US North Atlantic longline swordfish fishery, 4.9-cm wide circle hooks with fish bait significantly reduced sea turtle by-catch rates and the proportion of hard-shell turtles that swallowed hooks vs. being hooked in the mouth compared to 4.0-cm wide J hooks with squid bait without compromising commercial viability for some target species. But these large circle hooks might not be effective or economically viable in other longline fisheries. The effectiveness and commercial viability of a turtle avoidance strategy may be fishery-specific, depending on the size and species of turtles and target fish and other differences between fleets. Testing of turtle avoidance methods in individual fleets may therefore be necessary. It is a priority to conduct trials in longline fleets that set gear shallow, those overlapping the most threatened turtle populations and fleets overlapping high densities of turtles such as those fishing near breeding colonies. In addition to trials using large 4.9-cm wide circle hooks in place of smaller J and Japan tuna hooks, other fishing strategies are under assessment. These include: (i) using small circle hooks (≤ 4.6-cm narrowest width) in place of smaller J and Japan tuna hooks; (ii) setting gear below turtle-abundant depths; (iii) single hooking fish bait vs. multiple hook threading; (iv) reducing gear soak time and retrieval during daytime; and (v) avoiding by-catch hotspots through fleet communication programmes and area and seasonal closures.

Keywords by-catch, leatherback, loggerhead, longline fisheries, sea turtle

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Introduction

Many sea turtle populations have dramatically declined in recent decades because of several anthropogenic mortality sources (Spotila *et al.* 1996, 2000; Kamezaki *et al.* 2003; Limpus and Limpus 2003; FAO 2004a,b). As a result, six of the seven recognized marine turtle species are endangered (three of those critically endangered), while there is insufficient information to determine the conservation status of the seventh marine turtle species (IUCN 2003). Based on the observed dramatic declines in nesting turtles in the last two decades, leatherback (*Dermochelys coriacea*) and loggerhead (*Caretta caretta*) sea turtles could disappear from the Pacific Ocean in the near future unless major changes occur soon (Spotila *et al.* 2000; Kamezaki *et al.* 2003; Limpus and Limpus 2003).

The capture of sea turtles in pelagic longline fisheries, although only one of the threats faced by these species, has gained recent international attention (FAO 2004a,b). Loggerhead and leatherback turtles are the primary species caught in the pelagic longline gear. Olive ridley (*Lepidochelys olivacea*), green (*Chelonia mydas*), hawksbill (*Eretmochelys imbricata*) and Kemp's ridley (*Lepidochelys kempii*) turtles are also captured (Ramirez and Ania 2000; Polovina *et al.* 2003). Some groups have proposed a global ban on pelagic longlining (Anonymous 2003a,b; Ovetz and Steiner 2004). The Hawaii longline swordfish fishery was closed for over 4 years and is now subject to strict management measures, including prescribed use of large circle hooks and fish bait, restricted annual effort, annual limits on turtle captures and 100% onboard observer coverage because of turtle interactions (US National Marine Fisheries Service 2004a). Similar restrictions have been implemented in the western North Atlantic. An area of over 7.7 million km^2, including the productive Grand Banks, was partially closed to the US pelagic longline fleet in 2000, and completely closed in 2001 because of problematic turtle by-catch levels (US National Marine Fisheries Service 2000, 2001a,b). The Grand Banks were reopened to this fleet in the summer of 2004 after regulations were amended to require the use of recently tested turtle by-catch avoidance methods (US National Marine Fisheries Service 2004c). In concert with initiatives to address other priority threats to sea turtles, actions to abate longline fisheries by-catch of sea turtles can contribute to the recovery of turtle populations (FAO 2004a).

Pelagic longline fishing has been used worldwide since the 19th century and ranges from small-scale domestic artisanal fisheries to modern mechanized industrialized fleets from distant water fishing nations. Pelagic longlining, where gear is suspended from line drifting at the sea-surface, mainly targets large tunas (*Thunnus* spp.), swordfish (*Xiphus gladius*), other billfishes (*Istiorphoridae* spp.) and dolphinfish (mahimahi) (*Coryphaena* spp.). Pelagic longline fleets employ a range of different fishing practices and gear configurations. Pelagic longlines can be up to 100-km long and carry up to 3500 barbed hooks deployed at the terminus of attached branch lines (Brothers *et al.* 1999).

Pelagic longline industries are in a good position to find practical ways to minimize turtle mortality in longline gear. Unlike some other gear types, pelagic longlines do not touch the seafloor and do no direct damage to habitat. Pelagic longlining is generally more selective than bottom trawls and gillnets (Alverson *et al.* 1996; Cook 2001). Techniques for longline vessels to avoid and minimize interactions with sea turtles and other sensitive species such as seabirds are being proactively developed by industies and scientists, and implemented in some fisheries (e.g. Brothers *et al.* 1999; Gilman *et al.* 2005; Watson *et al.* 2005).

Strategies to abate turtle by-catch in longline fisheries include: (i) regulatory controls on fishing effort, seasonal by-catch levels, fishing areas, and fishing seasons; (ii) changes in fishing gear and methods; (iii) voluntary industry fleet communication programmes to avoid by-catch hotspots; and (iv) handling and release practices to increase the survival prospects of captured turtles. This paper discusses all strategies but focuses on reviewing results of completed research involving changes in fishing gear and methods, identifies relevant studies that are in progress or planned, and recommends directions for future research. Most information on studies to minimize turtle capture and injury in pelagic longline fisheries is in the grey literature, and except for USA government documents, there have been no previous reviews of this collective body of information to guide planning for future research or commercial implementation.

Research results and discussion

Table 1 summarizes results from studies on how differences in fishing gear and practices affect sea turtle by-catch and catch of target species in pelagic longline gear. Studies are grouped by the following parameters assessed: hook type, setting depth plus day vs. night setting, bait type, blue-dyed vs. untreated bait and others. Studies are listed from larger to smaller sizes. Fig. 1 shows most of the hooks used in these experiments, identifying each hook's narrowest width. Results from some of these studies have yet to be peer reviewed and published, and for some studies, principal investigators requested that specific details on methods and results not be included so as to maintain the originality of the unpublished results. Table 2 summarizes studies on sea turtle by-catch mitigation methods that are planned or in progress.

The primary goal of identifying methods to reduce sea turtle by-catch in longline fisheries is to contribute to the reversal of turtle population declines and prevention of species extinctions. To achieve this goal, it is necessary to consider both the effectiveness of both methods in reducing turtle capture and injury in longline fisheries as well as commercial viability. Most longline fisheries lack effective frameworks to manage by-catch. For longline fisheries that do have provisions to manage by-catch, resources for enforcement tend to be insufficient to ensure compliance. Given this context, it is critical to account for the commercial viability of by-catch reduction methods to achieve longline industry changes that abate turtle by-catch (FAO 2004b). Methods shown to be effective at reducing by-catch in research experiments may not be employed as prescribed or at all by fishers if they are not convenient and economically viable, or better yet, provide operational and economic benefits. Thus, we report results on effectiveness and commercial viability when available.

Circle hooks vs. smaller J and Japan tuna hooks

Using 4.9-cm wide 'G'-shaped 18/0 circle hooks significantly reduced turtle captures compared to 4.0-cm wide 9/0 J hooks in the US Northwest Atlantic longline swordfish fishery (Watson *et al.* 2004, 2005).* The point on circle hooks is turned in towards the hook shank and, depending on the size of hooks being compared, the gap between the circle hook's point and shaft is smaller than J and tuna hooks (Fig. 1). Watson *et al.* (2004, 2005) found that non-offset 18/0 circle hooks with squid bait reduced loggerhead and leatherback captures by 74% and 75%, respectively, compared to conventional 25° offset 9/0 J hooks with squid bait. In another experiment by Watson *et al.* (2004), 10°

*Currently there is no standardized, consistent, protocol for measuring the sizes and categorizing the shapes of hooks. The narrowest width of a hook and orientation of the point are likely the most important dimensions to document for research on strategies for reducing capture and hooking position of sea turtles. Standardization of terms and of measurements is a priority.

Table 1 Summary of studies assessing the effects of variations in pelagic longline fishing gear and practices on turtle by-catch and target species catch per unit of effort (CPUE).

Fishery or captive turtle species	Experimental treatment	Control treatment	Study size	Period	Results summary and comments
HOOK TYPE					
US Gulf of Mexico longline tuna and swordfish fisheries	None	Analysis of observer data: 16/0 circle hooks, 7/0, 8/0 and 9/0 J hooks with squid and sardine as bait	864 000 hooks (1729 sets)	1992–2002	Confounding factors of bait type, night vs. day setting, and depth gear is set prevent assessment of the independent effect of hook type on turtle capture. Leatherback by-catch rate was significantly lower for sets employing J hooks with sardine bait soaked during the day vs. J hooks with squid bait soaked at night. Loggerhead by-catch rate for sets with J hooks with fish bait soaked during the day was lower than for sets with J hooks with squid bait soaked at night. Leatherback by-catch rate was lower for sets employing circle hooks with sardine bait soaked during the day vs. sets with circle hooks with squid bait soaked at night (Garrison 2003)
Canadian Northwest Atlantic longline tuna and swordfish fisheries	None	Analysis of observer data. Offset and non-offset 9/0 J hooks and non-offset 16/0 circle hooks with a mixture of squid, mackerel, and herring as bait	534 057 hooks, 283 057 hooks in 2001 and 251 000 hooks in 2002	2001–2002	The study assessed nine hook and bait configurations. Results do not allow independent assessment of the effect of hook or bait type on turtle by-catch. The significance of differences in turtle by-catch rates by gear configurations is not available. In 2001 of 28 caught leatherbacks, 42.8% were entangled in gear, 29.3% were foul-hooked, 3.6% was hooked in the mouth, and none swallowed the hook. Of 199 hard-shelled turtles caught in 2001, 92.5% were caught in the mouth, 4.5% swallowed the hook, and 2.5% were foul-hooked or entangled. In 2002, of 33 leatherbacks captured, 12% were hooked in the mouth, 27% swallowed the hook, 6% were foul-hooked, and 52% were entangled. Of 145 hard-shelled turtles caught in 2002, 32% were hooked in the mouth, 66% swallowed the hook and 1% was entangled (Javitech Limited 2002, 2003)
US Northwest Atlantic longline swordfish fishery	10° offset Lingren-Pitman 18/0 circle hooks with mackerel bait	25° offset 9/0 J hooks with squid bait	486 554 hooks	2001–2003	The experimental treatment significantly reduced leatherback and loggerhead capture rates by 63% and 88%, respectively, increased swordfish CPUE by 19%, and decreased bigeye tuna CPUE by 80% compared to the control. Loggerheads were more likely to be hooked in the mouth with the experimental treatment, and more likely to swallow the hook with the control; 60.2% of loggerheads caught on J hooks swallowed the hooks, 80.0% of loggerheads caught on circle hooks were caught in the mouth and 20.0% swallowed the hooks. The majority of leatherbacks caught on either J hooks (96.5%) or circle hooks (85.7%) were hooked externally (Watson *et al.* 2003a, 2004, 2005; Shah *et al.* 2004)

Table 1 *(Continued).*

Fishery or captive turtle species	Experimental treatment	Control treatment	Study size	Period	Results summary and comments
US Northwest Atlantic longline swordfish fishery	Non offset Lingren-Pitman 18/0 circle hooks with squid bait	25° offset 9/0 J hooks with squid bait	225 191 hooks	2001–2003	The experimental treatment significantly reduced the leatherback and loggerhead capture rates by 75% and 74%, respectively, reduced swordfish CPUE by 25%, and resulted in an insignificant increase in bigeye tuna CPUE compared to the control. Most captured loggerheads were hooked in mouth with the experimental treatment, and swallowed the hook with the control; 60.2% of loggerheads caught with J hook swallowed hooks, 14.3% of loggerheads caught on circle hooks swallowed hooks and 75.0% of loggerheads caught on circle hooks were caught in the mouth. The majority of leatherbacks caught on either J hooks (96.5%) or circle hooks (75%) were caught externally (Watson *et al.* 2003a, 2004, 2005; Shah *et al.* 2004)
Azores Eastern Atlantic longline swordfish and blue shark fishery	Non-offset Mustad 16/0 circle hook with squid bait, 25° offset and non-offset 9/0 J hooks with squid bait	None	138 121 hooks (93 sets)	2000	There was no significant difference in the total number of turtles caught by each of the three hook types. There was a significant difference between the three hook types in location of turtle hookings; 57% of loggerheads caught on the two types of J hooks were hooked in the oesophagus, 81% of loggerheads caught on circle hooks were hooked in the mouth. Circle hooks caught significantly fewer swordfish than J hooks. Offset J hooks caught significantly fewer blue sharks than the other two hook types. Turtle capture rate increased significantly as the hour of day of gear hauling i ncreased (Bolten and Bjorndal 2002, 2003)
Azores Eastern Atlantic longline swordfish and blue shark fishery	Non-offset Mustad 16/0 and non-offset 18/0 circle hooks with squid bait, non-offset 9/0 J hook with squid bait	None	88 150 hooks (60 sets)	2001	There was no significant difference between the three hook types in the number of loggerhead turtles caught. When data from research conducted in 2000 (Bolten and Bjorndal 2002) is combined with this study's results, there was a significant difference in the position of turtle hooking for each hook type: 60% of loggerheads caught on J hooks were hooked in the oesophagus, and 9% of loggerheads caught on circle hooks were hooked in the oesophagus. There was no significant difference in the number of blue sharks caught between 16/0 and 18/0 circle hooks. The non-offset J hook caught significantly fewer blue sharks than the two circle hooks (Bolten and Bjorndal 2003)

Table 1 *(Continued)*.

Fishery or captive turtle species	Experimental treatment	Control treatment	Study size	Period	Results summary and comments
US Hawaii longline swordfish fishery	Non offset Lingren-Pitman 18/0 circle hooks with squid bait	Non-offset 9/0 J hooks with squid bait	78 071 hooks (95 sets and 7 trips)	2002	Experimental treatment was 40% and 94% as effective at catching swordfish and tuna, respectively, compared to the control. The circle hook caught significantly fewer numbers of swordfish than the J hook. Differences between the sizes of swordfish caught on circle hooks and J hooks was significant (Boggs 2003, 2004).
Azores Eastern Atlantic longline swordfish and blue shark fishery	Offset and non-offset Mustad 16/0 circle hooks and offset 18/0 circle hook with squid bait	None	75 511 hooks (48 sets)	2002	There was no significant difference between the three hook types in the number of loggerhead turtles caught. Using combined data from research conducted in 2000, 2001, and this study shows that turtles were captured in clusters. Combined data from three studies from 2000 to 2003 show a significant difference in position of turtle hooking for each hook type: 60% of loggerheads ingesting J hooks were hooked in the oesophagus, 12% of loggerheads ingesting circle hooks were hooked in the oesophagus. There was a significant difference in the number of blue sharks caught among the three hooks: non-offset 16/0 circle hooks had a higher blue shark CPUE than offset 18/0 circle hooks, which had a higher blue shark CPUE than offset 16/0 circle hooks. Significance of the effect of hook type on swordfish CPUE is not reported (Bolten and Bjorndal 2004)
Japan Northwest Pacific shallow set longline tuna and swordfish fishery	18/0 10° offset and non-offset circle ring hooks, Tokkan type 5.5 sun circle hook, and Tokkan type 4.3 sun circle hook	Japanese tuna hook 3.8 sun	40 000 hooks (47 sets, 2 trips)	2004	Results on significance of differences in loggerhead capture rates by hook type are not available. There was a nominal difference in tuna and swordfish CPUE between Japan 3.8 sun tuna hooks and Tokkan type 4.3 sun circle hooks (Kiyota *et al.* 2003; Nakano 2004; Nakano *et al.* 2004)
US Gulf of Mexico longline tuna fishery	Non-offset 18/0 circle hook with sardine bait	Non-offset 16/0 circle hooks with sardine bait	29 570 hooks	2004	Three leatherback turtles were captured by being foul hooked, two on 18/0 circle hooks and one on a 16/0 circle hook; 18/0 circle hooks resulted in a 25.7% reduction in the number and weight of target yellowfin tuna captured compared to 16/0 circle hooks (Watson 2004)

Table 1 *(Continued).*

Fishery or captive turtle species	Experimental treatment	Control treatment	Study size	Period	Results summary and comments
Japan Northwest Pacific shallow set longline tuna and swordfish fisheries	Tankichi type 3.8 sun circle hook	Japanese tuna hook 3.8 sun	28 000 hooks (33 sets, 1 trip)	2003	Results on the significance of differences in loggerhead turtle by-catch rates and target species CPUE by the experimental and control treatments are not available. The ratio of mouth to oesophagus-hookings was higher for the circle hook than the tuna hook. Japanese tuna hooks resulted in about 52% of loggerhead turtles being hooked in the mouth, 40% in the oesophagus, and 8% in the flipper. Circle hooks resulted in about 67% of loggerhead turtles being hooked in the mouth, 25% in the oesophagus, and 8% in the flipper. Catch rates of target fish species (bigeye tuna, albacore tuna, yellowfin tuna, and swordfish) were not substantially different between the circle and tuna hooks (Nakano 2004; Nakano *et al.* 2004)
US California/Hawaii Eastern Pacific longline swordfish fishery	16/0 circle hook with squid bait	9/0 J hook with squid bait	16 065 hooks	2000	Ten swordfish were caught on circle hooks (4.5 swordfish/1000 hooks) and 119 on J hooks (8.6 swordfish/1000 hooks). Four tuna were caught on circle hooks (1.8 tuna per 1000 hooks) and 7 on J hooks (0.5 tuna per 1000 hooks) (LaGrange 2001)
Venezuela Caribbean longline tuna fishery	16/0 circle hook with live bigeye scad (*Decaoturus* spp.) bait	7/0 J hook with live bigeye scad bait	2105 hooks (6 sets, 1 trip)	1999	Target species CPUE with circle hooks of 3.33 yellowfin tuna/100 hooks was significantly higher than 1.33 yellowfin tuna/100 hooks on J hooks. The number of target species captured was not large enough to provide considerable power to the statistical analysis (Falterman and Graves 2002)
Captive loggerhead turtles	Modified 16/0 circle hook with squid bait	Modified 9/0 and 10/0 tuna hooks and 9/0 J hooks with squid bait	45 hooks	2003	Experimental treatment (4.6 cm narrowest width) significantly reduced the incidence of swallowing the baited hook compared to the control (narrowest width between 3.3 and 4.0 cm) for loggerhead turtles 44–58.8 cm in straight line carapace length (Watson *et al.* 2003b)
DEPTH OF SETTING AND DAY VS. NIGHT SETTING					
Western tropical Pacific longline tuna fisheries	None	Analysis of observer data. Hooks set shallower than 100 m predominantly at night and hooks set deeper than 150 m predominantly in daytime	7 387 054 hooks (6408 sets)	1990–2000	Shallow set hooks set primarily at night resulted in a turtle by-catch rate of 0.061 captures per 1000 hooks. Deep-set hooks set primarily during the day resulted in a turtle by-catch rate of 0.012 captures per 1000 hooks (Secretariat of the Pacific Community 2001)
US Northwest Atlantic longline swordfish fishery	Shorter daytime gear soak time	Longer daytime gear soak time	427 385 hooks	2002	The effect of total soak time on loggerhead catch rate was highly significant. The effect of daylight soak time on loggerhead capture was varied and inconclusive. For leatherbacks, neither total soak time nor daylight soak time had a significant effect on catch rates (Watson *et al.* 2005)

Table 1 *(Continued)*.

Fishery or captive turtle species	Experimental treatment	Control treatment	Study size	Period	Results summary and comments
US Northwest Atlantic longline swordfish fishery	Branch lines set 60 m from buoy lines	Branch line located directly under each buoy (conventional gear design)	164 429 hooks (186 sets)	2001	The experimental treatment did not result in a significantly different loggerhead capture rate, and increased leatherback capture compared to the control (Watson *et al.* 2002). The experimental treatment deviated from the planned research design, placing the shallowest hooks deeper than the control shallowest hooks, but leaving more baited hooks above 40 m than the control (Boggs 2003, 2004)
US Hawaii longline swordfish fishery	Deep daytime sets	Shallow night sets	52 618 hooks (66 sets)	2002	No turtles were caught on hooks of the experimental treatment, one loggerhead was caught in control treatment gear. The experimental treatment caught 85% fewer swordfish and reduced overall revenue by 71% compared to the control. The research vessel setting gear deep only got the hooks to a mean depth of 244 m, while the research design called for these hooks to be set to a mean depth of 400 m (Boggs 2003, 2004)
East coast Australian longline tuna and swordfish fishery	Gear with lead weights and portions of the main line used as float lines (Fig. 2)	Gear suspended between two floats sagging in a catenary curve (conventional gear design)	6270 hooks (6 sets)	2004	Experimental treatment hooks reached depths between 120 and 340 m, control treatment hooks reached depths between 0 and 300 m. CPUE of target species were unchanged or enhanced by the experimental treatment compared to the control (Beverly and Robinson 2004)
Japan longline tuna fishery	Gear with one or two mid-water floats attached to the main line	Gear without mid-water floats	15 hooks (3 baskets)	2004	The difference between the shallowest and deepest hook depths in a basket was 4.9 m in gear with two mid-water floats, 26.2 m in gear with one mid-water float, and 55.1 m in control treatment gear. Results demonstrate it is possible to set all hooks in a basket at almost the same depth. There was no significant difference in hook sink rates for experimental and control treatments (Shiode *et al.* in press).
BAIT TYPE					
US Gulf of Mexico longline tuna and swordfish fisheries	None	Analysis of observer data. 16/0 circle hooks and 7/0, 8/0 and 9/0 J hooks with squid and sardine bait	864 000 hooks (1729 sets)	1992–2002	Confounding factors of night vs. day gear soaks, depth gear is set, and hook type prevent assessing the independent effect of bait type on turtle capture rates. Results are summarized under Hook Type entry (Garrison 2003)
Japan Northwest Pacific shallow set longline swordfish and tuna fishery	Mackerel bait	Squid bait	100 000 hooks (118 sets, 5 research fishing trips)	2002–2004	Results are being analysed (Nakano *et al.* 2004)

Table 1 *(Continued)*.

Fishery or captive turtle species	Experimental treatment	Control treatment	Study size	Period	Results summary and comments
BLUE-DYED VS. UNTREATED BAIT					
US Northwest Atlantic longline swordfish fishery	Blue-dyed squid bait	Untreated squid bait	164 429 hooks (186 sets)	2001	Blue-dyed squid bait did not result in a significantly different loggerhead and leatherback turtle capture rate compared to the control (Watson *et al.* 2002)
Japan Northwest Pacific shallow set longline swordfish and tuna fishery	Blue-dyed squid and mackerel bait	Untreated squid and mackerel bait	18 000 hooks (19 sets, 1 research fishing trip)	2003	Analysis using a generalized linear model showed that there was no statistically significant effect associated with dyed or untreated bait (Clarke 2004)
Costa Rica longline dolphinfish fishery	Blue-dyed squid bait	Untreated squid bait	12 834 hooks (22 sets)	2003	Blue-dyed bait did not result in significantly different olive ridley and green turtle capture rates compared to a control. Turtle capture rates were 8.4 and 8.1 turtle captures/1000 hooks for untreated and blue bait respectively (Programa Restauracion de Tortugas Marinas 2004; Swimmer *et al.* 2004)
Captive green and loggerhead turtles	Blue-dyed squid bait	Untreated squid bait		2001	Green and loggerhead sea turtles would not attempt to consume the blue-dyed bait for up to 10 days, after which the turtles would consume the dyed and non-dyed bait at the same rates (Swimmer and Brill 2001; Swimmer *et al.* 2002a)
OTHER PARAMETERS					
Captive green turtles	Bait soaked in alternative substances [quinine hydrochloride, lactic and citric acid, urea (shark smell), squid ink, garlic, jabanero chili extract, cilantro, sea hare (*Aplysia*sp.) ink]	Untreated bait			There was no difference in green turtle feeding behaviour between experimental and control treatments (US National Marine Fisheries Service, Pacific Islands Fisheries Science Center, unpublished data).
US Hawaii longline swordfish fishery	Countershaded floats (blue on the bottom, orange on the top), dark grey lines, hardware painted to remove metallic shine, down-welling narrow-frequency yellow electronic diode lightsticks, and blue-dyed bait	Orange buoys, uncoloured monofilament lines, unpainted hardware, green fluorescent lightsticks, and untreated bait (conventional gear)	53 483 hooks (66 sets)	2002	No turtles were caught on hooks of the experimental treatment, one loggerhead turtle was taken on the control treatment. The experimental treatment caught significantly fewer swordfish than the control treatment reducing revenue by 39% (Boggs 2003, 2004)

Studies are grouped by parameter assessed: hook type, depth of setting plus day vs. night setting, bait type, blue-dyed vs. untreated bait, and other parameters. When possible, studies are listed in order from larger to smaller study sizes. Figure 1 shows most of the hooks used in these experiments and identifies each hook's narrowest width.

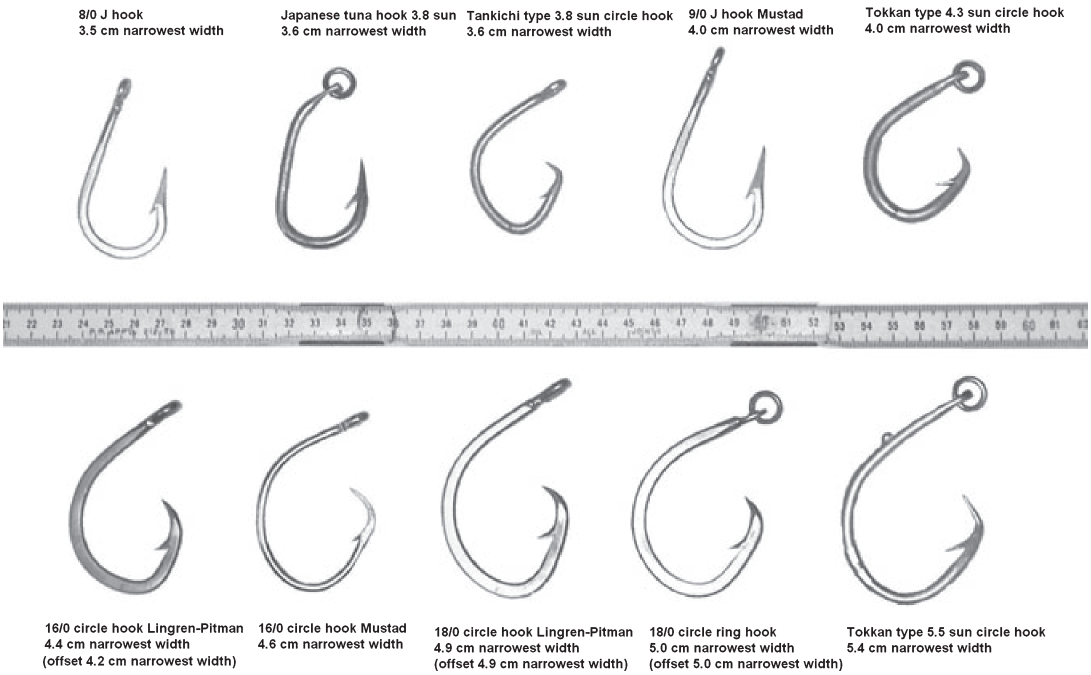

Figure 1 Some of the hooks used in referenced research. Displayed hooks are non-offset except for the Japanese tuna hook 3.8 sun. Hooks are arranged from smallest to largest width measured at the narrowest point. Widths of offset hooks are reported when these hooks were included in experiments included in Table 1. Hooks are oriented so that the narrowest width is horizontal. Measuring tape is in cm. Differences in hook designs other than narrowest width (i.e. orientation of point, length, gape and bite) and materials are not described. These may be important variables to document for research on strategies to reduce capture and hooking position of sea turtles.

offset 18/0 circle hooks with mackerel bait significantly reduced loggerhead and leatherback captures by 88% and 63%, respectively, compared to conventional J hooks with squid bait in the US Atlantic pelagic longline swordfish fleet.

However, in the Azores longline swordfish and blue shark fishery, Bolten and Bjorndal (2003) found no significant difference between 16/0 circle hooks, 18/0 circle hooks and 9/0 J hooks with squid bait in the number of loggerhead turtles caught. The reason for different results between Watson *et al.* (2004, 2005) and Bolten and Bjorndal (2003) might be due to the small size of the Azores experiment (88, 150 hooks) and small number of loggerheads captured (44). Results from the US North Atlantic and on captive turtles suggest that large circle hooks are effective at reducing hard-shelled turtle captures primarily as a result of the size of the hook relative to the size of the turtle (small turtles <65 cm straight carapace length are prevented from swallowing hooks >4.6-cm wide) (Watson *et al.* 2004, 2005). Loggerhead and other hard-shelled turtles tend to get caught in longline gear by biting a baited hook while soft-shelled leatherback turtles by getting entangled in line or foul-hooked on the body (Bolten and Bjorndal 2002, 2003; Javitech Limited 2002, 2003; Watson *et al.* 2003a). Leatherbacks apparently become entangled before they can bite the bait perhaps because they are less manoeuvrable than hard-shelled turtles (Davenport 1987). Circle hooks may be effective at reducing leatherback captures primarily because of the hook's shape.

Studies comparing small circle hooks (≤4.6-cm width) to smaller J-shaped hooks (≤4.0-cm width) conducted in the Azores longline swordfish and blue shark fishery and on captive turtles found that loggerhead turtle by-catch rates between the hook types were not significantly different (Bolten and Bjorndal 2002, 2003; Watson *et al.* 2003b). Yet, Watson *et al.* (2003b) found that 4.6-cm wide circle hooks significantly reduced the incidence of loggerhead turtles swallowing the hook compared to J hooks with a width between 3.3 and 4.0 cm. These results support the hypotheses that small circle hooks are too small to deter large loggerhead turtles from fitting them in their mouths and getting

Table 2 Planned or in progress research on strategies to reduce sea turtle by-catch in pelagic longline gear.

Fishery	Experimental treatment	Control	Status
Ecuador longline dolphinfish and tuna fisheries	14/0, 16/0 and 18/0 circle hooks with squid bait	Dolphinfish fishery: Mustad 4, 5 and 6 J hooks with squid bait Tuna fishery: Japanese tuna hook 3.8 and 4.0 sun	Initiated in March 2004, in progress (Hall 2003)
Azores longline swordfish and blue shark fishery	Non-offset 16/0 circle hooks and non-offset 18/0 circle hooks with squid bait	Offset Japanese tuna hook 3.6 sun with squid bait	Results are not yet available. Research was conducted from 2000 to 2003 as a continuation of research reported by Bolten and Bjorndal (2002, 2003), funded by the US National Marine Fisheries Service (Watson 2004)
Japan longline shallow-set fishery and Hawaii longline deep-set tuna and shallow-set swordfish fisheries, joint study	(a) Japanese shallow-set longline fishery: Tokkan type 4.3 and 5.2 sun circle hooks with squid bait, (b) Hawaii longline swordfish fishery: 18/0 circle hooks with fish bait; and (c) Hawaii longline tuna fishery: 14/0 and 15/0 circle hooks with fish bait	(a) Japanese shallow-set longline fishery: Japanese tuna hook 3.8 sun with fish and squid bait; (b) Hawaii longline swordfish fleet: Reference to historical turtle capture rates on 9/0 J hooks with squid bait conventionally used; and (c) Hawaii longline tuna fishery: Japanese tuna hook 3.6 sun with fish bait	In progress (US Western Pacific Regional Fishery Management Council 2004)
Japan longline tuna fisheries	Deep pelagic longline gear with the entire basket of hooks set at the same depth using longer float lines and mid-water floats attached to the main line	Conventional pelagic longline gear without mid-water buoys	Planned joint study by Tokyo University of Marine Science and Technology and Japan National Research Institute of Far Seas Fisheries (Nakano *et al.* 2004; Nakano 2004)
Costa Rica longline dolphinfish fishery	Non-offset vs. 10° offset 14/0 circle hooks		In progress (Swimmer *et al.* 2004)
Government of Brazil research vessel using pelagic longline gear and methods	Baits soaked in alternative dyes and odors	Untreated bait	Research is completed. A report will be available by the end of 2005 (US National Marine Fisheries Service, Pacific Islands Fisheries Science Center, unpublished data)
Peru longline dolphinfish and shark fisheries	Shark fishery: 18/0 circle hook Dolphinfish fishery: 16/0 circle hook	None	Planned by US National Marine Fisheries Service, IMARPE, and Associacion Pro-Delphinus (Peter Dutton, US National Marine Fisheries Service Southwest Fisheries Science Center, personal communication, January 2005)
Chile longline swordfish fishery	18/0 circle hook	9/0 J hook	Initiated in 2004 by US National Marine Fisheries Service Southwest Fisheries Science Center and Instituto de Fomento Pesquero (Peter Dutton, US National Marine Fisheries Service Southwest Fisheries Science Center, personal communication, January 2005)
Hawaii longline tuna and swordfish fisheries	Vessels participating in fleet communication programme to avoid turtle and albatross by-catch hotspots	Vessels not participating in fleet communication programme	One-year pilot fleet communication project is planned to be initiated in late 2005 (Sean Martin, Hawaii Longline Association, personal communication, August 2005)

hooked, but they reduce the incidence of being swallowed by loggerheads.

While large circle hooks were economically viable in the US Northwest Atlantic longline swordfish fishery, they may not be in longline fisheries with smaller or different target species. The limited sample sizes of completed research on small circle hooks warrants additional research. Several such experiments are in progress (Table 2). It is hypothesized that use of small circle hooks may decrease turtle by-catch and injury compared to J hooks and Japanese tuna hooks of the same size or smaller for three reasons:

1. Circle hooks may reduce foul hooking because of the hook's shape (orientation of the point and size of the gap);
2. Hard-shelled turtles caught on circle hooks are more likely to be hooked in the mouth vs. swallowing the hook (Bolten *et al.* 2001; Watson *et al.* 2003a,b; Bolten and Bjorndal 2002, 2003, 2004; Nakano *et al.* 2004; Watson 2004);
3. Watson *et al.* (2003b) observed the behaviour of loggerhead turtles 44–58.8 cm in straight line carapace length to determine that circle hooks with a width of 4.6 cm are more effective at reducing turtles swallowing baited hooks than smaller hooks. Circle hooks narrower than 4.6 cm may effectively avoid capture of turtles smaller than the size observed in this study.

The US fishery management authorities hypothesize that mouth-hooked turtles have higher post-hooking survival prospects than more deeply hooked turtles. Current practice for turtle mortality estimates in longline fisheries by the US fishery management authorities considers whether gear is removed or not from a turtle before release (US National Marine Fisheries Service 2004c), which is more readily accomplished with mouth-hooked vs. more deeply hooked turtles. Post-release mortality of loggerhead and leatherback turtles was estimated to be 40% and 32%, respectively, resulting from interactions with US North Atlantic pelagic longline swordfish gear using J hooks, assuming that fishers remove gear from and release light-hooked turtles and the deeper hooking causes greater mortality (US National Marine Fisheries Service 2004c). Chaloupka *et al.* (2004) found that light-hooked loggerhead turtles had significantly longer time-to-failure of satellite transmitters vs. deep hooked turtles within 90 days of release. But the cause of transmitter failures is not known, preventing reliable estimates of mortality based on these observations (Swimmer *et al.* 2002b; Chaloupka *et al.* 2004). Also, none of the turtles released in the light-hooked sample included turtles released with a hook retained in the mouth, instead, all light-hooked turtles were hooked in the body and there was a small sample size (40 turtles, 27 deep hooked and 13 light hooked) (Chaloupka *et al.* 2004; Parker *et al.* 2005). Even if injury to mouth-hooked turtles is lower than more deeply hooked turtles, this is a benefit only in shallow setting fisheries, as most turtles hooked in deep setting fisheries would drown regardless of where they are hooked.

Bait and baiting techniques

There is a need for additional research comparing bait types, sizes and baiting techniques to determine effects on target and turtle catch per unit of effort (CPUE). Watson *et al.* (2004) found no significant difference in turtle capture rate reductions between squid and mackerel bait when used with 18/0 circle hooks. Mackerel bait significantly reduced turtle interactions compared to squid bait when used with J hooks (Watson *et al.* 2004, 2005). Garrison (2003) found significantly lower leatherback by-catch rates for 7/0, 8/0 and 9/0 J hooks with sardine bait vs. 7/0, 8/0 and 9/0 J hooks with squid bait. However, there were confounding factors of differences in the time of day of sets and possibly the depth of gear deployment, which prevent the determination of the independent effect of bait type. Watson *et al.* (2004) found 10° offset 18/0 circle hooks with mackerel bait significantly reduced loggerhead and leatherback captures by 88% and 63%, respectively, compared to J hooks with squid bait in the US Atlantic pelagic longline swordfish fleet, but again it is not possible to determine the single factor effect of bait type.

Preliminary research indicates that single-hooked fish baits on circle hooks may result in higher target swordfish CPUE and lower incidence of loggerhead turtles swallowing the baited hook than when the circle hook is threaded through the fish bait multiple times (Watson *et al.* 2002). Feeding studies are in progress to test this hypothesis. It has been observed in feeding studies that fish bait tends to come free of the hook while being progressively eaten by the turtle in small bites, while squid bait holds much more firmly to the hook and tends to result in turtles gulping down the hook with the entire squid (Fig. 2). It is also hypothesized that using larger bait may make it harder for turtles to swallow the bait and thus the hook, but this remains to be tested.

Figure 2 Observations of foraging captive turtles indicate that fish bait tends to come free of the hook while being progressively eaten by the turtle in small bites, while squid bait holds much more firmly to the hook and tends to result in more turtles consuming the hook with the squid. More research is needed (photos courtesy of US National Marine Fisheries Service Southeast Fisheries Science Center).

Economic viability of circle hooks and fish bait

Large circle hooks (≥4.9-cm width) and usage of fish instead of squid for bait have shown to effectively reduce turtle by-catch in one fishery without adverse effect on commercial viability for some target species. This suggests that broad implementation may be realistic for longline fleets where use of the large hook is economically viable, but fleet-specific trials over several seasons are needed to determine if this would apply elsewhere. Small circle hooks (≤4.6-cm width) have had mixed results on the capture rate of target species when compared to smaller (≤4.0-cm width) J-shaped hooks. The size of hook and type and size of bait that will be economically viable for an individual longline fishery will likely depend on the sizes and species of the target fish.

Watson *et al.* (2005) found that, in the US Northwest Atlantic longline swordfish fishery, non-offset 18/0 circle hooks with squid bait reduced the target swordfish CPUE by weight by 25% and resulted in a nominal increase in bigeye tuna CPUE compared to a control of 25° offset 9/0 J hooks with squid bait. A 10° offset 18/0 circle hook with mackerel bait increased target swordfish CPUE by weight by 19% and decreased bigeye tuna CPUE by weight by 80% compared to a control of 25° offset 9/0 J hooks with squid bait. Boggs (2003, 2004) found that, in the Hawaii longline swordfish fishery, non-offset 18/0 circle hooks with squid bait were 40% as effective as a control of non-offset 9/0 J hooks with squid bait at catching swordfish and the circle hook was 94% as effective as the J hook at catching tuna.

Watson (2004) found that use of an 18/0 circle hook with fish bait resulted in significantly lower target CPUE by weight than a smaller 16/0 circle hook also with fish bait in the US Gulf of Mexico longline yellowfin tuna fishery. Studies comparing small circle hooks of 4.6 cm narrowest width to smaller J hooks and a Japan tuna hook (≤4.0-cm width) produced mixed results for effect on target CPUE. Nakano *et al.* (2004) found that there was no substantial difference in tuna and swordfish CPUE between Japan 3.8 sun tuna hooks and Tokkan type 4.3 sun circle hooks nor between the Japan 3.8 tuna hooks and Tankichi type 3.8 sun circle hooks in the Japanese longline tuna and swordfish fisheries. Non-offset 16/0 circle hooks resulted in significantly lower swordfish CPUE than offset and non-offset 9/0 J hooks and significantly higher blue shark CPUE in a 2000 study in the Azores longline swordfish and blue shark fishery, but blue sharks were not being targeted this year because of low market demand (Bolten and Bjorndal 2002). In a 2001 study in the Azores longline swordfish and blue shark fishery, when blue sharks were being targeted, there was no significant difference in the number of blue sharks caught between non-offset 16/0 and non-offset 18/0 circle hooks, but these two circle hooks caught significantly more blue sharks than a non-offset 9/0 J hook (Bolten and Bjorndal 2003). In a 2002 study in the Azores longline swordfish and blue shark fishery, when blue sharks were being targeted, non-offset 16/0 circle hooks had a higher blue shark CPUE than offset 18/0 circle hooks, which had a higher blue shark CPUE than offset 16/0 circle hooks (Bolten and Bjorndal 2004). LaGrange (2001) found that a 16/0 circle hook caught fewer swordfish than a 9/0 J hook in the US eastern Pacific longline swordfish fishery. Falterman and Graves (2002) found that the target CPUE using 16/0 circle hooks in the

Venezuela Caribbean longline yellowfin tuna fishery was significantly higher than fishing with conventionally used 7/0 J hooks.

While J hooks and Japanese tuna hooks used by the majority of longline vessels around the world are available at relatively low prices, comparable or larger sizes of circle hooks tend to be either much more expensive or weaker. Hooks are largely a disposable, high turnover item and many longline vessels select cheap, short-life hooks. However, hopefully if demand for circle hooks increases, supply of strong, affordable circle hooks will follow. In the interim, researchers and managers have the opportunity to provide an incentive for fishers by offering to exchange valuable extra-strength circle hooks for smaller circle, J and tuna hooks as a part of programmes to study the impact of the exchange, as is being conducted in four South American longline fleets (Table 2).

Offset vs. non-offset hooks

Results from research comparing 25° offset and non-offset 9/0 J hooks in the Canadian Northwest Atlantic longline tuna and swordfish fishery and analysis of observer data comparing 10° offset and non-offset 16/0 circle hooks in the US Atlantic longline swordfish fishery found no significant differences for turtle hooking location between the offset and non-offset hooks (Javitech Limited 2002, 2003; Watson 2004). Results from research conducted in the Azores longline swordfish and blue shark fishery also found no significant difference in loggerhead capture rates for 25° offset vs. non-offset 9/0 J hooks and offset vs. non-offset 16/0 circle hooks (Bolten *et al.* 2001; Bolten and Bjorndal 2002, 2004). Watson *et al.* (2004) found no significant difference in turtle capture rates between 10° offset and non offset 18/0 circle hooks in the US Northwest Atlantic longline swordfish fishery; however, statistical power was very low.

Gear depth and day vs. night setting

Sea turtles spend a majority of their time at depths <40 m (Swimmer *et al.* 2002b; Polovina *et al.* 2003, 2004; Watson *et al.* 2003a) indicating that setting longline gear deeper than 40 m will reduce turtle captures.

There is clear evidence that deep-set fisheries have lower turtle catch rates than shallow-set fisheries in US, Japan, Spain, Costa Rica and Western tropical Pacific pelagic longline fisheries (US Western Pacific Regional Fishery Management Council 1993; Arauz 2000; Secretariat of the Pacific Community 2001; US National Marine Fisheries Service 2001c, 2002). Analysis of fishery observer data from Hawaii longline fisheries found that deep day-set fishing targeting tuna had a rate of sea turtle interactions orders of magnitude lower than shallow night-set fishing targeting swordfish (0.006 vs. 0.15 captures per 1000 hooks respectively) (US National Marine Fisheries Service 2001c, 2002). However, given the number of other differences between the Hawaii longline tuna and swordfish fisheries besides depth and timing of gear setting (i.e. location of fishing grounds, hook and bait type), the effect of depth and timing of gear setting alone is unclear. The Secretariat of the Pacific Community (2001) analysed observer data from the Western tropical Pacific longline tuna fleets and concluded that shallow-set hooks (<100 m), set primarily during the night resulted in a higher turtle by-catch rate (0.061 captures per 1000 hooks) than deep set hooks (>150 m), set primarily during the day (0.012 captures per 1000 hooks). Also, observer data from the Hawaii longline fleet (Kleiber and Boggs 2000) and results of Watson *et al.*'s (2002) experiments showed that a higher proportion of leatherback turtles are taken on the shallowest branch line closest to floats than on deeper branch lines.

Empirical evidence directly demonstrating the turtle avoidance effectiveness of modifying longline gear configuration to set gear deeper is currently lacking. This is a research priority. The experimental treatment in Watson *et al.* (2002) could not achieve the depths that might have reduced turtle capture as suggested by Boggs (2003). Other studies of deeper gear alternatives were not designed to test effectiveness at reducing turtle interactions (Boggs 2003, 2004; Beverly and Robinson 2004; Shiode *et al.* in press). Instead, these were preliminary short-term trials of commercial viability and gear design feasibility.

The effect on target species CPUE in longline swordfish and tuna fisheries from moving all baited hooks below 40–100 m is fishery-specific. For instance, it is not commercially viable for the Ecuadorian longline dolphinfish and tuna fisheries to set gear below 40 m, while the Hawaii pelagic longline tuna fishery is expected to be able to set all gear below 100 m with no noticeable change in target fish CPUE. In longline fisheries where setting

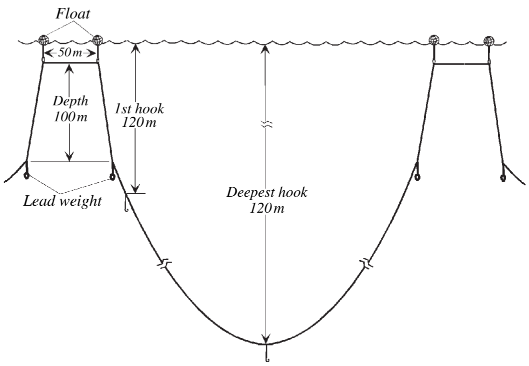

Figure 3 Configuration of weighted gear used by Beverly and Robinson (2004) with 20 hooks per basket and target depth for shallowest hook of 120 m.

deeper than 100 m is economically viable, at a minimum, vessels should use longer branch lines adjacent to buoys, which are the shallowest set hooks or leave a gap on each side of the buoy line. Longliners should be encouraged to minimize all gear between 0 and 100 m to reduce risk of entangling turtles. This can be accomplished by increasing the length of buoy lines rather than having short buoy lines and longer branch lines, however this comes at a cost of increasing the risk of drowning caught turtles as they will be less likely to be able to reach the sea surface. Lead weights can be used to sink the entire fishing portion of the line to a selected depth (Fig. 3) (Beverly and Robinson 2004). Mid-water floats can be attached to the main line to place the hooks at the same depth vs. having the hooks in a catenary curve (Shiode *et al.* in press).

Soak time

Watson *et al.* (2005) found the effect of total soak time (period that fishing gear is in the water) on loggerhead catch rate to be highly significant. The effect of daylight soak time was varied and inconclusive. Bolten and Bjorndal (2003) documented a significant increase in loggerhead capture rate with increased length of daytime line hauling. For leatherbacks, neither daylight nor total soak time had a significant effect on leatherback catch rates (Watson *et al.* 2005). Research with hook timers indicates that leatherbacks are hooked more frequently at night (Watson *et al.* 2004). This suggests that reducing total soak time and daytime retrieval can reduce loggerhead capture.

Sea temperature

Watson *et al.* (2005) found increased loggerhead catch at temperatures above 22.2 °C and an increase in leatherback catch at temperatures above 20 °C. Javitech Limited (2003) reported the highest loggerhead sea turtle CPUE at 23.8 °C. Target fish CPUE had a contrasting trend. Higher swordfish CPUE by weight occurred in waters at temperatures below 20 °C (Watson *et al.* 2005). For some fisheries, a promising strategy to decrease sea turtle by-catch while increasing target species catch could be to fish in water with temperatures below 20 °C (Watson *et al.* 2002; Javitech Limited 2003).

Blue-dyed bait

Blue-dyed bait has not resulted in a significantly different sea turtle capture rate than untreated bait based on research results from longline fisheries from the US Atlantic, Costa Rica and Japan and on captive green and loggerhead turtles (Swimmer *et al.* 2002a, 2004; Swimmer and Brill 2001; Watson *et al.* 2002; Clarke 2004; Programa Restauracion de Tortugas Marinas 2004). Furthermore, because of the expense of dyeing bait and fishers' perception that dyeing bait is impractical, industry acceptance of blue-dyed bait is expected to be low, unless competitively priced pre-dyed bait becomes commercially available (Gilman *et al.* 2003b).

Practices to handle and release captured turtles

Much progress has been made to identify best practices to handle and release turtles captured in longline fisheries (e.g. Epperly *et al.* 2004; Gilman 2004; McNaughton and Swimmer 2004; US National Marine Fisheries Service 2004b). A high proportion of turtles caught on shallow-set longlines can survive the gear soak and are alive when brought to the vessel during gear haulback (Witzell 1994). While empirical evidence is lacking showing that without better handling and release practices that captured and released turtles have a higher risk of dying, these efforts to minimize injury and risk of mortality from capture might increase turtles' post-hooking survival prospects.

Additional research directions

New hook designs, bait and baiting techniques are being assessed to determine effectiveness at reducing turtle interactions with longline gear. A small commercial demonstration of 'stealth' gear, designed to be less detectable by turtles, including gear with countershaded floats (blue on the bottom half, orange on the top half), dark grey lines, dulled hardware (painted to remove the metallic shine), lightsticks shaded on the upper half, and lightsticks with more narrow light frequency found it was not economically viable in the Hawaii longline swordfish fishery (Boggs 2003). Lightsticks that flash intermittently were found not to attract captive loggerhead turtles (Wang *et al.* 2005). Another study has investigated the effects of other modifications to buoys (orange bullet, white bullet and orange poly); presence or absence of AK snaps below buoys; placing devices (e.g. funnel and soda bottle) above or around the baited hook; and using various colours, stiffness and diameters of monofilament branch lines on the behaviour of captive turtles (Hataway and Mitchell 2003).

Scientists are also testing methods to deter turtles from eating baited hooks, including acoustic deterrents and soaking bait in various substances. Results to date have not shown these methods to be effective (US National Marine Fisheries Service, Pacific Islands Fisheries Science Center, unpublished data). One research group is attempting to identify shark characteristics that produce avoidance behaviour in captive turtles (Higgins *et al.* 2005).

New ways of altering hook and bait designs may reduce turtle capture, injury and death. Some ideas include using artificial lures and placing a device near or over the baited hook to physically protect the baited hook from turtles. For instance, 'weedless' hooks have a device that covers the point of the hook to avoid foul hooking turtles but moves away from the point when a fish bites the hook (Hataway and Mitchell 2003). 'Whisker' hooks could have added material to increase the dimension of a hook, such as by adding a ring to the hook below the barb where monofilament can be threaded through, to make the hook sufficiently thick to prevent turtles from being able to swallow it. 'Smart' hooks could have a device added to the hook that conceals the point of the hook when at a shallow depth or warm sea temperature that moves away from the point of the hook when at depth or in colder water. One way to rig a smart hook might be to use a bimetallic strip to cover or expose the hook point as a function of temperature.

Methods to avoid turtle by-catch hotspots

Fleet communication programmes and area and seasonal closures are management tools that can enable a longline fleet to avoid by-catch hotspots that can complement employment of other strategies to reduce turtle by-catch. Observations from the US Hawaii and North Atlantic longline fisheries and Canadian Northwest Atlantic longline fisheries indicate that, in longline fisheries where turtle interactions are relatively rare events, if a vessel catches a turtle, avoiding fishing at this area will reduce the chance of having another turtle interaction (Javitech Limited 2002, 2003; Gilman *et al.* in press). Fleet communication programmes can report real-time observations of by-catch hotspots to be avoided by vessels in a fleet (Gilman *et al.* in press). For instance, the US North Atlantic longline swordfish industry instituted a voluntary fleet communication programme to report real-time sea turtle encounters, sightings of clusters of sea turtles and specific oceanographic features known to be correlated with high abundance of sea turtles, as a means to avoid exceeding a government established cap on turtle by-catch. The programme is inferred to have reduced turtle CPUE by 50% based on analysis of observer data from before and after industry instituted the fleet communication programme (Gilman *et al.* in press).

Area and seasonal closures are another approach for pelagic longline fisheries to avoid peak areas and periods of sea turtle foraging, nesting and migration (Kleiber and Boggs 2000). Closed areas can have substantial adverse economic effects on industry, but remain an available tool to fishery managers if alternative methods are lacking. It may also be a more desirable option than a closed fishery. However, resource use restrictions of a marine protected area may displace effort to adjacent and potentially more sensitive areas, especially if an effective management regime does not exist for these other areas (Gilman 2002). For instance, closure of the Northwest Atlantic to the US pelagic longline swordfish fleet may have had negative consequences for some sea turtle populations by displacing longline effort to alternative grounds such as the South Atlantic (Kotas *et al.* 2004). Also instituting a closure for one longline fleet may result in an increase in effort by another nation's longline fleet with fewer controls to manage turtle by-catch. For example, during the 4-year closure of the Hawaii longline swordfish fishery, swordfish supply to the US marketplace traditionally met by the Hawaii fleet was replaced by imports from foreign longline fleets, including from Mexico, Panama, Costa Rica and South Africa, which lack measures to manage turtle interactions and have substantially higher ratios of sea turtle captures to unit weight of swordfish catch (Bartram and Kaneko 2004; Sarmiento 2004).

Establishing protected areas containing turtle nesting colonies and adjacent waters is potentially an expedient method to reduce interactions between sea turtles and commercial fisheries. However, establishing high seas marine protected areas to restrict fishing in sea turtle foraging areas and migration routes, which would require extensive and dynamic boundaries defined in part by the location of large-scale oceanographic features and short-lived hydrographical features such as eddies and fronts, and would require extensive buffers, may not be a viable short-term solution. This is due in part to the extensive time anticipated to resolve legal complications with international treaties, to achieve international consensus and political will, and to acquire requisite extensive resources for enforcement (Thiel and Gilman 2001).

Conclusions and recommended next steps

Most studies on methods to reduce turtle by-catch in longline fisheries have been small, conducted over short time periods, and in a small number of fisheries. The confounding effect of comparing multiple factors in most reviewed studies makes it difficult to draw conclusions about the effectiveness and commercial viability of specific factors.

Available information indicates that using 18/0 circle hooks in place of narrower Japan tuna and J hooks, and using fish instead of squid for bait, may significantly reduce the turtle capture rates, the proportion of hardshell turtles that swallow the hook vs. get hooked in the mouth, and maintain or increase CPUE of target species in some fisheries. However, this might not apply in all fisheries. Because of differences in fishing gear (e.g. amount and location of weights, length of branch lines, size of hooks, type and size of bait), methods (e.g. day vs. night setting), size and species of turtles, turtle abundance at fishing grounds, location of fishing grounds, and size and species of target fish, turtle avoidance methods found suitable for one fishery may not be effective and commercially viable in others. It may be necessary to assess the fleet-specific effectiveness and commercial viability of turtle avoidance methods. Progress is being made towards this end, as numerous strategies are undergoing assessment.

Assessments of turtle by-catch avoidance methods need to be conducted over several seasons to determine whether the methods are consistently effective and commercially viable under variable conditions over time. Such trials also have the benefit of developing industry familiarity with modified fishing gear and methods to develop support for fleet-wide use.

Research on turtle by-catch avoidance should be designed to assess effects on other sensitive by-catch species. It is important to identify any conflicts as well as mutual benefits of by-catch reduction strategies among species groups. For instance, when researchers design deep-setting gear to attempt to reduce turtle by-catch, in fisheries where seabird by-catch occurs, the gear design needs to consider effects on seabird interactions. Changes in line weighting that reduce the sink rate of baited hooks could result in substantial increases in seabird capture rates (e.g. Gilman *et al.* 2005).

Longline fishers likely have a large repository of knowledge and information related to sea turtle by-catch, which can be tapped to contribute to finding effective and practical solutions. This has been demonstrated by successful collaborative research in the US Atlantic longline swordfish fishery (Watson *et al.* 2005), US Hawaii longline fishery (Gilman *et al.* 2003a) and various industry-led fleet communication protocols to reduce by-catch (Gilman *et al.* in press). Fishers and longline associations are encouraged to become active participants to address turtle by-catch problems by participating in research and commercial demonstrations, implementing best practices, and supporting adoption of regulations based on best available science before restrictions, embargos and possible closures are imposed on them.

Pelagic sea turtles are highly migratory species with breeding and foraging distributions in multiple nations and the high seas. Consequently, a collaborative and integrated approach to management among nations is essential to recover depleted sea turtle populations.

The majority of leatherback, loggerhead and olive ridley by-catch in observed US Pacific and Atlantic pelagic longline fisheries were by vessels targeting swordfish, likely because gear is set shallower than by vessels targeting tuna overlapping more with the depths occupied by turtles, squid is the primary bait, gear soaks into the day and is hauled during the day, and lightsticks are deployed near baited hooks (Polovina *et al.* 2000, 2003, 2004; US National Marine Fisheries Service 2002). Similar order of magnitude higher sea turtle by-catch rates have been observed in shallow vs. deep-set longline fisheries of Japan, Spain, Costa Rica and the Western tropical Pacific (US Western Pacific Regional Fishery Management Council 1993; Arauz 2000; Secretariat of the Pacific Community 2001). Hence, there is a high priority to identify sea turtle avoidance methods that are effective and commercially viable specifically for use in shallow-setting longline fisheries. Taiwan, Japan and Spain were the leading nations landing swordfish in 1997, accounting for more than half of global landings (Ward and Elscot 2000).

While the large industrialized pelagic longline fleets from distant water fishing nations are hypothesized to cause relatively high turtle mortality levels, some coastal artisanal and small domestic commercial shallow-setting longline fleets may also cause relatively high turtle mortality and mortality of critically threatened turtle populations as a result of the location of their fishing grounds and their fishing methods and gear. For instance, the artisanal Ecuadorian longline fisheries for dolphinfish, swordfish and bigeye tuna use relatively small J hooks and Japanese tuna hooks, set gear shallow, and overlap with high densities of East Pacific leatherback sea turtles and olive ridley turtles, which migrate through waters around the Galapagos Islands after nesting in Mexico and Costa Rica (Eckert 1997; Spotila *et al.* 2000; Hall 2003). Also, for example, olive ridley sea turtle capture rates in the Costa Rica longline dolphinfish surface fishery are very high (Programa Restauracion de Tortugas Marinas 2004), and Alfaro-Shigueto *et al.* (2004); Alfaro-Shigueto *et al.* in press a; Alfaro-Shigueto *et al.* in press b) describe large leatherback and loggerhead turtle interactions with the Peruvian coastal, artisanal, longline dolphinfish and shark fisheries. FAO (2004a) identified the pelagic longline fisheries of the Eastern Pacific and Mediterranean as the highest priority pelagic longline fisheries threatening turtles based on the location of the most threatened sea turtle populations.

Results of completed research studies and the large number of new, candidate turtle avoidance methods undergoing assessment warrant cautious optimism that sea turtle mortality in pelagic longline fisheries can be substantially reduced. The source and extent of sea turtle longline mortality can be determined. Efforts need to continue to identify fisheries posing the greatest threat to priority turtle populations. Management authorities exist, there are internationally accepted principles on the problem, and it is probable that commercially viable solutions exist. Critical next steps include multilateral contribution to the identification, testing, improvement and broad uptake of effective and commercially viable turtle avoidance methods by pelagic longline fleets with sea turtle by-catch problems.

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