Mitigating sea turtle by-catch in coastal passive net fisheries

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Abstract

There is growing evidence that small-scale, coastal, passive net fisheries may be the largest single threat to some sea turtle populations. We review assessments of turtle interactions in these fisheries, and experiments on gear-technology approaches (modifying gear designs, materials and fishing methods) to mitigate turtle by-catch, available from a small number of studies and fisheries. Additional assessments are needed to improve the limited understanding of the relative degree of risk coastal net fisheries pose to turtle populations, to prioritize limited conservation resources and identify suitable mitigation opportunities. Whether gear technology provides effective and commercially viable solutions, alone or in combination with other approaches, is not well-understood. Fishery-specific assessments and trials are needed, as differences between fisheries, including in gear designs; turtle and target species, sizes and abundance; socioeconomic context; and practicality affect efficacy and suitability of by-catch mitigation methods. Promising gear-technology approaches for gillnets and trammel nets include: increasing gear visibility to turtles but not target species, through illumination and line materials; reducing net vertical height; increasing tiedown length or eliminating tiedowns; incorporating shark-shaped silhouettes; and modifying float characteristics, the number of floats or eliminating floats. Promising gear-technology approaches for pound nets and other trap gear include: replacing mesh with ropes in the upper portion of leaders; incorporating a turtle releasing device into traps; modifying the shape of the trap roof to direct turtles towards the location of an escapement device; using an open trap; and incorporating a device to prevent sea turtle entrance into traps.

Keywords By-catch, gillnet, passive net fisheries, pound net, sea turtle, small-scale fisheries

Introduction

The Millennium Ecosystem Assessment found that overexploitation, including from by-catch, currently is the most widespread and direct driver of change and loss of global marine biodiversity, with habitat destruction, pollution, outcomes of climate change and spread of exotic species being additional major drivers (Pauly *et al.* 2005; Brander 2008). Cumulative and synergistic effects of myriad human-induced stressors are causing extinctions and altered marine biodiversity, including reduced species diversity, reduced abundance, changes in distribution (latitudinal and depth), altered age and sex structures, altered temporal and spatial spawning patterns, reduced viability of offspring, reduced genetic diversity and altered evolutionary characteristics of populations (Jackson *et al.* 2001; Pauly *et al.* 2002). Sea turtles, cetaceans, seabirds, elasmobranchs and other fish species, are particularly vulnerable to overexploitation and slow to recover from large population declines; by-catch in marine capture fisheries is putting some species in these groups at risk of extinction (FAO 1999a,b, 2005, in press; Gilman and Lundin 2009).

The expansion in fishing activities in coastal areas and in the high seas during the second half on the twentieth century is believed to have contributed to the declines of several sea turtle populations (FAO, 2004, 2005, in press). Sea turtle by-catch is known to be problematic in pelagic longline, gillnet, pound net, set-net, trawl, purse seine and demersal longline fisheries operating in areas that overlap with the distribution of sea turtles (primarily in the tropics and subtropics; Crowder and Murawski 1998; Lewison *et al.* 2004a,b; Gilman *et al.* 2006a; Gilman and Lundin 2009; FAO, in press). There has been substantial progress to identify effective and commercially viable methods to reduce sea turtle capture and mortality in coastal trawl and pelagic longline fisheries (FAO, 2005; Eayrs 2007; Gilman *et al.* 2006a, 2007a,b; FAO, in press), although lack of uptake of these best practice by-catch reduction techniques remains a governance deficit (Gilman *et al.* 2007a). Limited progress has been achieved in the other gear types (Gilman and Lundin 2009; FAO, in press).

Coastal passive net fisheries use gillnets, trammel nets, pound nets, fyke nets and other net gear that catch and in some cases, drown turtles. Nedelec and Prado (1990) provide a description of the range of coastal passive net gear designs and fishing methods. The understanding of the relative risks of the full suite of mortality sources for individual turtle populations is generally poor (Chaloupka 2007, 2009). However, there is growing evidence of relatively high sea turtle mortality in coastal passive net fisheries from various regions, and coastal passive net fisheries are now understood to be a large anthropogenic mortality source (Chan *et al.* 1988; Frazier and Brito 1990; Julian and Beeson 1998; Mansfield *et al.* 2001, 2002; Gearhart 2003; Price 2004; Alfaro-Shigueto *et al.* 2005, 2007, 2008; Lee Lum 2006; FAO, 2007, in press; Gearhart and Eckert 2007; Ishihara 2007; Peckham *et al.* 2007; Pilcher *et al.* 2007; Price and Van Salisbury 2007, SIRAN, 2007).

Small-scale fisheries have substantial socio-economic importance and have the potential to contribute to sustainable economic development

(FAO, 2008b). However, to secure their long-term economic viability and to ensure conformance with international guidelines for the conduct of responsible fisheries, these fisheries need to mitigate the problematic by-catch of sea turtles and other sensitive species groups [e.g. marine mammals (e.g. Kraus *et al.* 1997; Alfaro-Shigueto *et al.* 2007), seabirds (Strann *et al.* 1991; Darby and Dawson 2000; Tasker *et al.* 2000; Melvin *et al.* 2001; Price 2008), sharks (e.g. Alvarez and Wahrlich 2005) and dugong (*Dugong dugon*) (Pilcher *et al.* 2007)]. Preventing the overexploitation of all species subject to fishing mortality, including all retained and discarded catch, as well as unobserved fishing mortalities, is an integral component of implementing the ecosystem approach to fisheries management (FAO, 2003). The Food and Agriculture Organization of the United Nations' (FAO) Code of Conduct for Responsible Fisheries (CCRF) calls for the sustainable use of aquatic ecosystems and requires that fishing be conducted with due regard for the environment (FAO, 1995). The FAO Article 7.2.2 d of the CCRF specifically addresses biodiversity issues and conservation of endangered species, calling for minimizing the catch of non-target species, both fish and non-fish species.

A range of natural and anthropogenic factors adversely affect sea turtles, including predation at nesting beaches, land uses, climate change outcomes (e.g. erosion, rise in sand and sea surface temperatures), marine pollution and fisheries by-catch (e.g. Carr 1987; Gardner *et al.* 2003; Hitipeuw and Pet-Soede 2004; Hitipeuw *et al.* 2007; Peckham *et al.* 2008;). As a result, many sea turtle populations have dramatically declined in recent decades, and people have driven most populations to ecological extinction (Chan and Liew 1996; Sarti *et al.* 1996; Spotila *et al.* 1996, 2000; Eckert and Sarti 1997; Jackson *et al.* 2001; Kamezaki *et al.* 2003; Limpus and Limpus 2003; Pandolfi *et al.* 2003; FAO 2004, 2005, Dutton *et al.* 2007; Hitipeuw *et al.* 2007). Consequently, all sea turtle species whose conservation status has been assessed are categorized as threatened or endangered (IUCN, 2008).

Evidence suggests that depleted sea turtle populations can recover when major anthropogenic mortality sources are adequately reduced. Nesting beach data document some turtle population recoveries, inferred to have resulted from reduced anthropogenic mortality pressure: green sea turtles (*Chelonia mydas*) at six major nesting sites (Chaloupka *et al.* 2008); olive ridleys (*Lepidochelys*

olivacea) at Oaxaca, Pacific Mexico (Márquez *et al.* 1998); leatherbacks (*Dermochelys coriacea*) at St Croix, US Virgin Islands (Dutton *et al.* 2005); Kemp's ridleys (*Lepidochelys kempii*) at Rancho Nuevo, Atlantic Mexico (Márquez *et al.* 1998) and at Padre Island, Texas (Shaver 2005) and loggerheads (*Caretta caretta*) in Brazil (Marcovaldi and Chaloupka 2007). The capacity to recover populations of sea turtles and other marine megafauna from ecological extinction provides cautious optimism that it may be possible to rehabilitate degraded coastal and marine ecosystems. This is because marine megafauna, once recovered to relatively pristine pre-human conditions, would resume their roles in coastal and marine ecosystem functioning and structure (Jackson *et al.* 2001; Leon and Bjorndal 2002; Bjorndal and Bolten 2003; Pandolfi *et al.* 2003; Moran and Bjorndal 2005, 2007; Stokstad 2006; Worm *et al.* 2006; Chaloupka *et al.* 2008).

This article is the first review of assessments of turtle interactions in coastal passive net fisheries and experiments that investigated the potential for modifications to fishing gear and methods to mitigate sea turtle by-catch these fisheries. Other approaches to mitigate (avoid, reduce and offset) sea turtle by-catch in marine capture fisheries are reviewed in Table 1 (Gilman *et al.* 2006a,b; Gilman and Lundin 2009; FAO, in press). This study was conducted, in part, to provide a starting point for discussion at the *Technical Workshop on Mitigating Sea Turtle By-catch in Coastal Net Fisheries*, convened 20–22 January 2009 in Honolulu (Gilman 2009).

Assessments

There are a growing number of studies documenting relatively high levels of sea turtle capture in coastal net fisheries (Table 2). To provide an understanding of current relative degrees of risk, Table 2 summarizes the methodologies and findings of some of some of these studies, focusing on those implemented in the last few years, which were conducted in gillnet and pound net fisheries.

Gear-technology research

Gillnet fisheries

Table 3 summarizes research involving modifications to gillnet and pound net gear designs, conducted in an effort to identify methods that effectively reduce sea turtle catch rates without

Table 1 Practices to avoid, reduce and offset the capture of sensitive species groups and reduce injury and mortality from gear interactions in coastal net passive fisheries and other marine capture fisheries.

Modifications to fishing gear and methods	Gear technology (changing the design of the fishing gear, e.g. altering net mesh size) and altered fishing methods (e.g. changing the timing of fishing operations) can reduce by-catch, the focus of this article
Gear restrictions	Restrictions on gear designs, in some cases with spatial or temporal measures, can reduce by-catch [e.g. ban on large mesh ray (order Rajiformes) drift gillnets in Malaysia, Yeo *et al.* 2007; mesh size restrictions in gillnets, Price and Van Salisbury 2007; seasonal restriction on pound net leader use and designs, DeAlteris and Silva 2008]
Input and output controls	Input controls include limiting the amount of fishing effort or capacity (e.g. limiting vessel numbers of a specified size, prohibiting new entrants, instituting buy-back schemes, limiting the length of gear soak time, eliminating subsidies that contribute to overcapacity) (Pauly *et al.* 2002, 2005; Beddington *et al.* 2007; Sumaila *et al.* 2008). Output controls include limiting catch through, for example, total allowable catch or quotas of target, incidental or discarded by-catch species; individual transferable quotas and rights-based allocation frameworks have been used , for example, to limit catch levels and address overcapacity issues (e.g. Beddington *et al.* 2007; Costello *et al.* 2008; FAO, in press), and quotas and performance standards for by-catch levels and rates, respectively, have been used to manage by-catch of sensitive species groups (e.g. Environment Australia,2006; Gilman *et al.* 2007b)
Compensatory mitigation	Individual vessels or a fisheries association could meet by-catch mitigation requirements through compensation used to mitigate non-fishery threats. Alternatively, management authorities could create a fee and exemption structure, similar to a "polluter pays" system. For instance, governments could reduce or withhold subsidies, charge a higher permit or license fee, or use a higher tax rate if by-catch thresholds are exceeded. Or, the fee structure can provide a positive incentive, where a higher subsidy, lower permit or license fee, or lower tax applies when by-catch standards are met. Compensatory mitigation programmes likely require 100% observer coverage, a substantial limitation. Problems with lack of performance and off-site and out-of-kind mitigation could occur when compensatory mitigation, a longstanding practice in U.S. wetlands management (Environmental Law Institute 2006), is applied to fisheries by-catch, such as when conservation activities are conducted at a nesting colony not part of the population interacting with the fishery, or conserving different age classes than affected by the fishery. The concept holds promise if used to complement and not detract from actions to first avoid and minimize by-catch (Zydelis *et al.* 2009; FAO, in press)
Marine-protected areas	Spatial and temporal restrictions of fishing, especially in locations and during periods of high concentration of by-catch species groups, can contribute to reducing fisheries by-catch. For instance, managers could reduce or eliminate fishing effort during seasons associated with relatively high by-catch rates and/or areas that are consistent by-catch hotspots (time/area closures; Cheng and Chen 1997; Gearhart 2003; Lee Lum 2006; Maldonado *et al.* 2006). Establishing protected areas containing sea turtle nesting and coastal foraging areas may effectively reduce turtle by-catch, and in some cases, might be socially and economically acceptable to local communities (e.g. Peckham *et al.* 2007, 2008). The establishment of a representative system of protected area networks on the high seas also holds promise. However, this will require extensive and dynamic boundaries, defined, in part, by the location of large-scale oceanographic features and short-lived hydrographic features, and would require extensive buffers (e.g. Hyrenbach *et al.* 2000). Extensive time will likely be required to resolve legal complications with international treaties, to achieve international consensus and political will, and to acquire requisite extensive resources for monitoring and enforcement
Fleet communication	Fleet communication programmes can report real-time observations of temporally and spatially unpredictable by-catch hotspots to be avoided by vessels in a fleet (Gilman *et al.* 2006b). Fleet communication may be successful when there are strong economic incentives to reduce by-catch, by-catch rates of sensitive species are rare events and adequate onboard observer coverage exists
Industry self-policing	Self-policing uses peer pressure from within the industry to criticize bad actors and acknowledge good actors (e.g. Fitzgerald *et al.* 2004). A fishing industry can create a programme where information for individual vessel by-catch levels, compliance with relevant regulations, and other relevant information, is made available to the entire industry. This is especially effective where regulations contain industry-wide penalties if by-catch rates or caps are exceeded

Table 1 Continued.

Changing gear	It may be commercially viable to change to a different fishing gear that results in a lower by-catch -to-target catch ratio than the conventional gear (e.g. replace Trinidad gillnet with troll gear, Eckert and Eckert 2005; Eckert *et al.* 2008)
Handling and release best practices	Much progress has been made to identify best practices to handle and release turtles captured in longline fisheries (e.g. FAO, in press). Some aspects may be applicable to coastal net fisheries, for instance, dipnets to bring turtles onboard, general techniques for turtle handling while onboard, techniques to remove water from a turtle's lungs, removing as much gear as safely possible before release, and use of line cutters
Market-based mechanisms	Eco-labelling and other certification programmes for marine capture fisheries, and employment of sustainable seafood sourcing policies by retailers and seafood buyers, provide large market-based and social incentives for some fisheries to meet sustainability criteria (e.g. FAO, 2008a; Gilman 2008). Fisheries in developing countries have been underrepresented in eco-labelling programmes, in part, because of insufficient fisheries management frameworks, insufficient data and high costs of assessment and maintaining certification. However, the Marine Stewardship Council, the largest global eco-labelling organization for marine capture fisheries, has developed a risk-based framework to apply their assessment process to data-deficient fisheries, and is now testing these protocols through pilot studies (Marine Stewardship Council, 2009)

compromising economic viability. Gillnets and trammel nets are the two static net gear types where fish are gilled, entangled or enmeshed in netting (Nedelec and Prado 1990). In demersal gillnet fisheries, there is empirical evidence that the use of narrower (lower profile) nets is an effective and economically viable method for reducing sea turtle by-catch rates (Price and Van Salisbury 2007). This may be due to the combined effect of: (i) The net being stiffer, thereby reducing the entanglement rate of turtles that encounter the gear, as sea turtles that do interact with the gear to "bounce out" and free themselves more readily than with conventional gear and (ii) the net being shorter, thereby reducing the proportion of the water column that is fished and so reducing the likelihood of turtles encountering the fishing gear (Price and Van Salisbury 2007). Furthermore, lower profile nets may reduce mortality rates when turtles are captured by reducing disentanglement time and effort, which also results in less gear damage (Gearhart and Eckert 2007; Eckert *et al.* 2008).

Increasing tiedown length, or avoiding the use of tiedowns, has also been shown to decrease turtle entanglement rates in demersal gillnets (Fig. 1; Price and Van Salisbury 2007). In demersal gillnet fisheries, tiedowns are typically used to maximize the catch of demersal fish species. Tiedowns are lines that are shorter than the fishing height of the net and connect the float and lead lines at regular intervals along the entire length of the net. This net design creates a bag of slack webbing which aids in "entangling," rather than "gilling," demersal fish species (Price and Van Salisbury 2007). The shorter the length of tiedowns, the deeper the webbing pocket is. Unfortunately, this technique also poses an entanglement hazard to sea turtles that encounter the gear. Several studies in North Carolina's flounder (*Paralichthys lethostigma*) gillnet fishery found that lower profile nets without tiedowns resulted in a significantly lower incidence of sea turtle entanglement, compared with traditional gillnets containing twice as much webbing (twice the number of meshes) and containing tiedowns regularly placed throughout the gear (Price and Van Salisbury 2007). Research has also demonstrated that entangled turtles have a higher rate of escape when longer tiedowns are used (Gearhart and Price 2003). In a 2005 study by Maldonado *et al.* (2006) in a Mexico demersal gillnet fishery, 44% *shorter* tiedowns were trialled in an attempt to

Table 2 Examples of assessments of sea turtle by-catch in coastal gillnet and pound net fisheries.

Fishery	Monitoring methodology	Affected turtle population(s) and age class	Findings	Citation(s)
Greater Caribbean region				
Trinidad Spanish mackerel (*Scomberomorus brasiliensis*) and king mackerel (*S. cavalla*) surface gillnet fishery	Interviewed fishers from Matelot, June to July 1998. Interviewed 126 fishers from 27 landing sites, March 2001 to February 2002	Adult egg-bearing female leatherback turtles, and to a lesser extent, green, hawksbill (*Eretmochelys imbricate*), and olive ridley turtles	Matelot fishers reported catching 10 leatherbacks per 61 m of horizontal net per day. Fishers from 27 landing sites reported catching 3796 sea turtles in 2000, of which 73% were released alive. Extrapolating fleet-wide, 6996 turtles were captured in 2000	Eckert and Lien (1999); Lee Lum (2006); Gearhart and Eckert 2007
Eastern Pacific region				
Chile San Antonio swordfish (*Xiphias gladius*) coastal gillnet fishery	Interviewed fishers from San Antonio seaport from 1988–1989	Subadult and adult leatherbacks	Fishers reported catching 28 leatherback and 2 green turtles. Extrapolating fleet-wide, 250 leatherbacks were caught annually in 1988 and 1989 by 250 artisanal gillnet swordfish vessels from this seaport, and several hundred leatherbacks may have been caught in all Chilean gillnet fisheries combined	Frazier and Brito (1990)
Mexico Baja California Sur halibut (*Paralichthys californicus*), grouper (*Mycteroperca* sp.) and shark demersal longline and demersal gillnet fisheries	Observers collected data on gillnet vessels in June–July 2005, July–August 2006, and August to September 2007, and on longline vessels in September 2005 and August 2006. The two fisheries were selected because of the overlap of their fishing grounds with a high density loggerhead foraging area. Shoreline surveys were conducted to count stranded loggerheads from 2003 to 2007 along 43 km of Playa San Lazáro, the coastline adjacent to the fishing grounds of the two observed fisheries, and 12 additional shoreline areas around Baja California Sur	Large juvenile North Pacific loggerhead turtles	Twenty-eight loggerheads were observed captured during 94 gillnet fishing day-trips, resulting in a catch rate of 0.37 loggerheads per km of horizontal gillnet. 68% were dead upon gear retrieval. All loggerhead gillnet captures occurred during 35 sets made in deeper water (32–45 m), resulting in a by-catch rate of 1.04 loggerheads per km of net when including just the deeper sets; none were caught in shallower sets (5–32 m). (Subsequent observations in 2008 also found loggerheads being captured at shallower depths). In the demersal longline fishery, 48 loggerheads were observed captured during 8-day-long trips, during which a total of 1636 hooks were set, resulting in a catch rate of 29 loggerhead captures per 1000 hooks. 90% of the loggerheads were dead upon gear retrieval. Extrapolating fleetwide for the demersal gillnet fishery, an estimated 547 (356–777 95% CI) loggerheads were killed per year between 2005 and 2007. Extrapolating fleetwide for the demersal longline fishery, 1635 (1160–2174 95% CI) loggerheads were killed in 2005 and 2006. Combined, 2182 (1516–2951 95% CI) loggerheads were killed per year 2719 loggerhead carcasses were observed stranded along beaches adjacent to the grounds of the two fisheries. Of the loggerhead carcasses observed stranded along Playa San Lázaro, 70% were found from May through September, the same season of operation as coastal gillnet and longline fisheries	Peckham *et al.* (2007, 2008)

Table 2 Continued.

Fishery	Monitoring methodology	Affected turtle population(s) and age class	Findings	Citation(s)
Peru				
Mahi mahi (*Coryphaena hippurus*), shark and ray coastal gillnet and longline fishery	Reviewed data on sea turtle captures in Peruvian coastal fisheries from unpublished materials held by the Peruvian Center for Cetacean Research (1985–1999). Reviewed findings from surveys conducted by Van Bressem *et al.* (1998) and Van Waerebeek *et al.* (1999). Conducted dockside observations at six seaports (2000–2003). Collected onboard observer data from 2000–2007 from 239 longline and 89 gillnet fishing trips operating in waters off of Peru and northern Chile, based from 11 ports	Adult and sub-adult leatherback, juvenile loggerhead, green, olive ridley and hawksbill sea turtles	From 1985 to 1999, 33 leatherbacks were observed caught in longline and gillnet fisheries. From 2000 to 2003, 101 leatherback sea turtles were observed caught in artisanal gillnets and 32 on longlines. 41% were released alive and 59% were retained for human consumption. Based on the onboard observations, 323 loggerhead turtles were captured, 99% in longline gear and 1% in gillnet gear. 92% of the captured loggerheads were juveniles	Alfaro-Shigueto *et al.* (2007, 2008)
East and Southeast Asia				
Japan				
Coastal pound net fisheries	Interviewed fishers from October 2006 through September 2007 to obtain information on sea turtle interactions. Monitored pound nets in three fishing villages [Miyama (Mie), Muroto (Kochi) and Nomaike (Kagoshima)]	North Pacific loggerhead and green turtles. Age classes not reported	87 sea turtles were reported by fishers to have been captured in pound nets over the 1-year period. 1824 turtles were observed captured in pound nets in the three monitored fishing villages, of which 18% were dead. No sea turtles captured in the Nomaike pound nets died, where all pound nets employed an open trap design. 97% of caught turtles were dead in the Miyama pound nets, which all employ a closed trap design. About 13 000 pound nets are set off Japan's coastline	Ishihara (2007)

Table 2 Continued.

Fishery	Monitoring methodology	Affected turtle population(s) and age class	Findings	Citation(s)
Malaysia Ray coastal drift gillnet and other coastal fisheries (purse seine, trawl, longline, trap) of the east coast of Peninsular Malaysia	Interviewed 207 mainland and 6 islander drift net vessel owners and/or operators from 20 September 2005 through 24 March 2006	Green and hawksbill sea turtles. Age classes not reported	Fishers reported observing between 1 and 2.5 turtles caught in their gear in 2005. Extrapolated fleetwide, in all gear types, an upper estimate of 140 turtles were caught annually in 2005 and 2006. Green and hawksbill turtles were reported to be most frequently caught. Gillnets with >25.4 cm mesh size, used to target rays, have been illegal since 1989, but remain in common use	Yeo et al. (2007)
Malaysia Coastal fixed and drift gillnet and other artisanal fisheries of Sabah	Interviewed 2670 fishers from April through August 2007, of which 738 were gillnet fishers from 317 vessels, from 161 coastal communities	Not reported	29% of gillnet fishers reported regularly catching turtles. 25% of total respondents reported catching turtles, and catching an average of 10 turtles per vessel per year, for a total of 4490 turtles per year. Respondents reported that all caught turtles were released alive	Pilcher et al. (2007)
Taiwan/Chinese Taipei I-Lan County, eastern Taiwan coastal pound net and gillnet fisheries	Monitored by-catch at monthly or more frequent intervals in 25 pound nets from October 1991 to October 1992. Observed turtles for sale at the Nanfango Fish Market and interviewed turtle dealers from October 1991 to April 1995	Large juvenile, subadult and adult green turtles (66% of 90 documented captures); subadult and adult logger head turtles, juvenile hawks bill turtles, subadult olive ridley turtles, and leatherback sea turtles (age class not reported)	A total of 90 sea turtles were captured during the study period, 83 in pound nets, and 7 in gillnets. By-catch rates in terms of catch per unit of effort were not reported. The majority of turtle captures occurred from November to December and February to March. All caught turtles were alive when gear was retrieved: fishers retrieve the catch two or three times per day, and traps are typically set in ≤20 m depth, enabling caught turtles to reach the surface and breath. Of the caught turtles, 3% were released, 88% were retained for periods lasting as long as months and later released during Buddhist ceremonies, and 8% were killed for consumption or stuffing. At the time this study was conducted, there were 107 pound nets operating off Taiwan, of which 86 operated in coastal waters off eastern Taiwan, and 25 operated in I-Lan County (north eastern Taiwan)	Cheng and Chen (1997)

Table 2 Continued.

Fishery	Monitoring methodology	Affected turtle population(s) and age class	Findings	Citation(s)
USA Atlantic				
North Carolina Pamlico Sound large mesh (>12.7-cm stretched mesh) southern flounder gillnet fishery and small mesh (<12.7-cm stretched mesh) spotted seatrout (*Cynoscion nebulosus*) gillnet fisheries	The North Carolina sea turtle stranding network records observations of stranded turtles along the North Carolina coastline. The North Carolina Division of Marine Fisheries, Fisheries Management Section, conducts at-sea monitoring of gillnet vessels	Juvenile/sub-adult loggerhead, Kemp's ridley and green turtles are predominately observed captured in gillnets and stranded. From 2001 to 2007, loggerheads comprised 62% of total strandings	Prior to 1995, annual turtle stranding along North Carolina's coastline averaged fewer than 200. Strandings reached their highest level in 2000 with 831 turtles reported statewide. Strandings throughout North Carolina have remained relatively consistent since that time with an average of 399 strandings per year from 2001 to 2007. During the 2007 season, there were 1620 large mesh gillnet trips along the Outer Banks, setting 1829 km of net, of which 133 trips (8%) were observed. There were a total of 237 small mesh gillnet trips, of which 10 trips (4%) were observed. There were no turtle captures observed in the small mesh fishery in 2007. There were 20 sea turtle captures (19 green turtles and one loggerhead turtle) in the large mesh fishery, of which 15 were released alive, and 5 green turtles were dead. Extrapolating fleet-wide from cumulative data from 2005 to 2007, about 125 live green turtles, 30 dead green turtles, 4 live Kemp's ridley, 23 live loggerhead and 4 dead loggerhead turtles were estimated to have been observed in the large mesh gillnet fishery in 2007, resulting in a by-catch rate of about 0.3 turtle captures per 914 m (1000 yards) per day	Price (2008)
Virginia Chesapeake Bay pound net fishery	Aerial surveys, surface vessel surveys and SCUBA surveys have been conducted since 1983 to assess levels of sea turtle capture in pound net leaders. A 900 kHz side scan sonar 'tow fish' was trialed, but was unsuccessful in distinguishing entangled turtles form other objects	Juvenile loggerhead and Kemp's ridley turtles and infrequent by-catch of leatherback and green turtles	Pound nets are responsible for 3–33% of stranded turtles in the Bay (6–165 turtles annually), most of which are loggerhead and Kemp's ridley turtles. Each year, 200–500 sea turtles strand in the lower portion of the Bay, with the greatest number occurring in late May and June, when loggerhead and Kemp's ridley turtles migrate into the Bay. Most observed turtle captures were reported from the Virginia portion of the Bay, in the upper 3 m of large mesh (>30 cm) or string leaders, in areas that experience strong currents	Musick *et al.* (1984); Lutcavage and Musick (1985); Bellmund *et al.* (1987); Mansfield *et al.* (2001, 2002); Swingle *et al.* (2004); DeAlteris and Silva (2008)

CI, confidence interval.

Table 3 Research of modified coastal gillnet and pound net gear to assess efficacy at reducing sea turtle by-catch and economic viability.

Fishery	Experimental Design	Findings	Citation
Gillnets			
North Carolina flounder demersal gillnet fishery	Three experiments, conducted in 2001, 2004 and 2006, compared an experimental design low-profile (half the panel height) demersal gillnet without tiedowns to the historical design (control) used in the fishery (4 m panel height, 1-m long tiedowns). The three experiments included 501 paired sets of the experimental and control treatments. Buoys are not conventionally used and were not used in the experimental treatment	Combining data from the three experiments, the experimental treatment significantly reduced the sea turtle by-catch rate ($P < 0.01$) by 80% (15 turtle captures in the control net, 3 in the experimental net; 7 alive, 11 dead). The turtle entanglement and escapement rates were inversely proportional to the tiedown length. The experimental treatment also resulted in a significantly lower by-catch rate by number of individual by-catch species of fish and crabs caught ($P < 0.001$). The difference in target species catch rates between the treatments was also significant ($P < 0.01$): the experimental design resulted in a reduced target catch rate but at an acceptable level to the industry	Gearhart and Price (2003); Brown and Price (2005); Price and Van Salisbury (2007)
Trinidad Serra Spanish mackerel and King mackerel surface drift gillnet fishery	In 2006, 30 fishing trips were conducted from the seaport of Matelot, 26 from Balandra, using a matched pair experimental design, to compare the catch rates of an experimental mid-water drift gillnet deployed at a depth of 5–15 m and a control treatment employing traditional gear deployed at a depth of 0–10 m. The control deployed a floatline every fathom. The experimental gillnet deployed a floatline every three fathoms	Target catch rates by weight were significantly lower in experimental nets in sets from both seaports (75% reduction in Matelot, 70% in Balandra). Total (target and incidental) catch by weight was also significantly reduced by 23% in Balandra. Total catch in Matelot was reduced by 36% but the difference was not significant. Experimental nets caught a larger proportion of demersal species. There was no significant difference in sea turtle catch rates between the two treatments. Results suggest that target species can be caught in the upper 5 m of the water column	Gearhart and Eckert (2007)

Table 3 Continued.

Fishery	Experimental Design	Findings	Citation
Trinidad mackerel surface drift gillnet fishery	In 2007, paired control and experimental treatment gillnets were compared for differences in leatherback sea turtle and fish catch rates. Experimental low profile 50 mesh deep nets were compared to controls consisting of traditional 100 mesh deep nets. Net profiles were 9.1 m (30 feet) deep for traditional gear and 4.6 m (15 feet) deep for experimental gear (Fig. 4). A total of 60 fishing trips were conducted. Each set consisted of 800 m of net composed of four 100 m experimental nets alternated along the set with four 100 m control nets. This design resulted in matched pairs with experimental nets consisting of half the area of controls	29 turtles were captured in the experimental net, 92 in the control net. The experimental net significantly reduced the leatherback turtle capture rate by 32% where the turtle CPUE is calculated as the number of caught turtles/m²/hr soak. Turtles were observed to be easier to release when entangled in the experimental lower-profile net. It was 2.5 times more costly to repair damaged control nets. There was no significant difference in target species CPUE, calculated as weight/m²/h soak, between treatments	Eckert *et al.* (2008); Gearhart *et al.* 2009;
Trinidad mackerel surface drift gillnet fishery	In 2008, sea turtle and finfish catch rates were compared between 50-mesh nets marked with experimental long wavelength red monochromatic gear marker lights and controls marked with broader-spectrum white gear marker lights. Two standardized marker lights were attached at predetermined positions along the gear above the sea surface for each set. A total of 60 fishing trips were conducted. Each set consisted of 1000 m of 50-mesh net	There was no significant difference in turtle and fish catch rates between nets with white marking light and those using red lights	Gearhart *et al.* 2009

Table 3 Continued.

Fishery	Experimental Design	Findings	Citation
Baja California Sur, Mexico halibut and elasmobranch demersal gillnet fishery	A controlled experiment was conducted in July 2006, May through September 2007 and July 2008, near Punta Abreojos, Baja California Sur, at the location of a sea turtle monitoring programme, where very high turtle abundance occurs. The study sought to compare sea turtle catch rates in an experimental net where shark silhouettes were attached at 10-m intervals along the float line next to the net vs. a control with no shark silhouettes. Shark silhouettes, with a 150 cm fork length, were suspended 60 cm below the surface, positioned 1.5 m away from the net, using a 30 cm orange bullet float. The control net also contained the orange floats, but not the shark silhouettes. A second controlled experiment was conducted during the summer of 2008 during commercial fishing operations at conventional fishing grounds near Bahia de los Angeles to compare target species catch rates of nets with and without the shark silhouette. During this second trial, the shark silhouettes were attached directly to the gillnet float lines, again at 10-m intervals. Both experiments were conducted during the daytime	Results of the experiment conducted at the turtle monitoring programme site found that placing shark silhouettes near the gillnets resulted in a significant ($P < 0.01$) 54% decrease in sea turtle catch rate (from 24.2 to 11.2 turtle captures per 24 h soak per 100 m of horizontal netting). Commercial gillnets with incorporated shark silhouettes also resulted in a significant ($P < 0.02$) 55% decrease in the target species catch rate (from 21.2 to 11.6 number of target species per 24 h soak per 100 m of horizontal netting). No sea turtle captures were observed during the study of the commercial gear	Wang *et al.* 2009;

Table 3 Continued.

Fishery	Experimental Design	Findings	Citation
Baja California Sur, Mexico halibut (*Bothidae* spp. and *Pleuronectidae* spp.) and elasmobranch [guitarfish (*Rhinobatidae* spp.) and rays] demersal gillnet fishery	A controlled experiment was conducted in July 2006, May through September 2007 and July 2008, near Punta Abreojos, Baja California Sur (the location of a sea turtle monitoring programme, where very high turtle abundance occurs) to compare green sea turtle catch rates in an experimental net incorporating battery-powered green LED lightsticks (Fig. 3) placed at 10-m intervals, and a control net with inactivated lightsticks also located at 10-m intervals along the net. A second controlled experiment was conducted during the summer of 2008 during commercial fishing operations at traditional fishing grounds near Bahía de los Angeles (on the Gulf of California coast of Baja California) to compare target species catch rates of nets with activated and inactivated lightsticks. Both experiments were conducted at nighttime	Results of the experiment conducted at the turtle monitoring programme site found that illuminating nets with battery-powered LED lightsticks significantly ($P < 0.05$) reduced the catch rates of green sea turtles by 40% (from 24.8 to 14.9 turtle captures per 24 h soak per 100 m of horizontal netting) compared to the control net. Illuminating nets used in the commercial bottom gillnet fishery did not result in a significant difference in the catch rates of target species (target species CPUE of 22.5 vs. 22.1 target species by number per 24 h soak per 100 m of horizontal netting for control vs. experimental nets respectively). No sea turtle captures were observed during the study of the commercial gear	Wang *et al.* (2009)

Table 3 Continued.

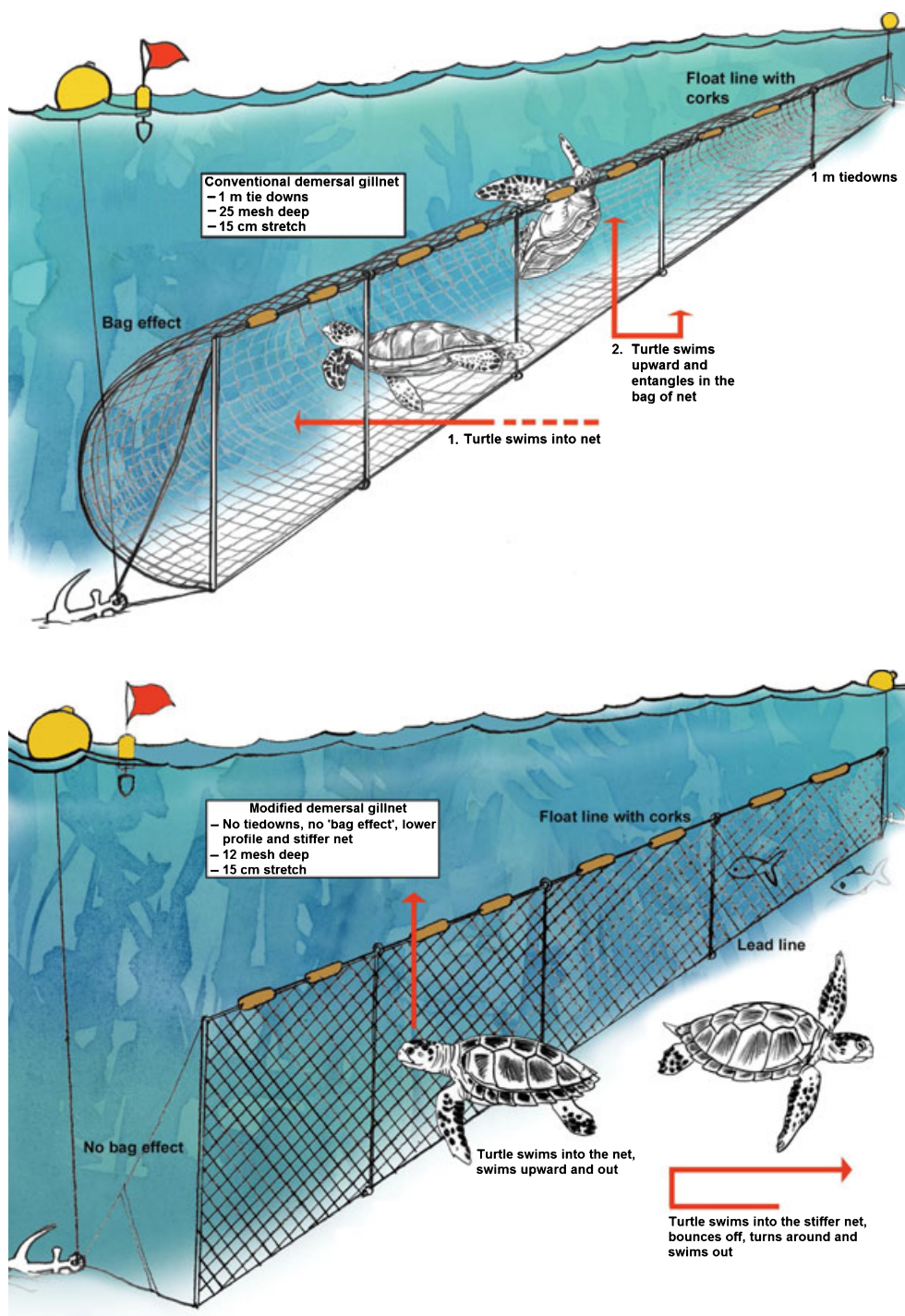| Fishery	Experimental Design	Findings	Citation
Puerto López Mateos Baja California Sur, Mexico halibut and grouper demersal gillnet fisheries	Three controlled experiments were conducted in 2004 and 2005 from Puerto López Mateos: (i) In 2004 a controlled experiment was conducted to compare the difference in fish and sea turtle catch rates of a control vs. low-profile (half the panel height) and 44% shorter tiedown length experimental net. From July to August 2004, 117 sets were made, where in each set two control sections of net, 1.8 m (2 fathoms)/20 meshes deep with 1.8 m long tiedowns, were alternated with experimental treatment sections of net of 0.9 m (1 fathom)/10 meshes deep with 1 m long tiedowns. Each section was 60 m long, such that each set was a total of 240 m horizontal length (ii) From June to July 2005, a controlled experiment was conducted to compare the fish and sea turtle catch in 129 sets with four alternating sections of a control net with the same design as in 2004, and an experimental design with a 1 m long tiedown (both the control and experimental treatments were 1.8 m/20 meshes deep). Each section was 100 m long, such that each set was a total of 400 m horizontal length	(i) In 2004, the control net caught significantly more fish by weight than the experimental net. Only one green sea turtle was caught during the experiment, in a control treatment section of net (ii) More fish by number and weight were caught in the experimental net (896 fish weighing 2398 kg vs. 1309 fish weighing 3330 kg in the control vs. experimental nets respectively). There was no significant difference in sea turtle catch rates between the control and experimental treatment nets, however, there was a small sample size of only 16 turtle caught in total, with 9 in the experimental treatment, 7 in the control treatment (iii) At all three depths, experimental treatment nets caught a slightly larger number of fish. There was no significant difference in sea turtle catch rates between the control and experimental treatment nets. There was a positive correlation between the depth that nets were set at and the turtle by-catch rate, and positive correlation between depth and proportion of caught turtles that drown. A total of thirteen sea turtles were captured (1 green, 1 olive ridley and 11 loggerhead turtles). Four turtles were caught in shallow nets (all alive), 1 in the medium-depth nets (alive) and 11 in the deep-depth nets (8 dead, 3 alive) (iv) (a) At depths >32 m, there was no significant difference in sea turtle capture rates. 47% fewer turtles were caught in experimental nets (9 turtles, 0.3 ± 0.5 turtles set^{-1}) vs. in control nets (19 turtles, 0.5 ± 1.3 turtles set^{-1}). There was also no significant difference in target fish catch rates. (b) At depths <32 m, there was no significant difference in sea turtle catch rates (only one turtle captured) and there was no significant difference in target fish catch rates. The mean target fish catch rate in the experimental net (4.8 ± 8.5 kg set^{-1}) was larger than in the control net (1.8 ± 3.4 kg set^{-1})	Maldonado *et al.* (2006); Peckham *et al.* (2009)

Table 3 Continued.

Fishery	Experimental Design	Findings	Citation
	(iii) In July 2005, 146 sets were made to compare the fish and turtle catch rates of nets set at three different depths: <9, 18–29 and >31 m depth, employing the same design of alternated control and experimental treatment nets as in the second experiment (half with conventional length tiedowns, half with tiedowns at half the length) (iv) In 2007 and 2008 a controlled experiment was conducted to compare fish and sea turtle catch between an experimental buoyless net (without buoys on float line) compared to a control net. As a result of the difference in the soaking characteristics of bouyless nets, experimental nets were set adjacent to control nets as opposed to tied together as in previous experiments. 35 sets were observed at depths >32 m, and 30 at depths <32 m		
Pound net			
Chesapeake Bay, Virginia, USA pound net fishery	Four pound nets were monitored twice daily using side scan sonar and visual inspections to identify sea turtle entanglement in pound net leaders. From 15 May to 28 June 2004 a controlled experiment was conducted with an experimental design pound net containing a modified leader, where the top two-thirds of the traditional mesh panel leader was replaced with vertical ropes made of polypropylene rope (0.95 cm) and spaced every 61 cm. A 5 May to 29 June 2005 controlled experiment was conducted with an experimental design pound net where the vertical polypropylene ropes were replaced with a hard lay Polysteel rope (0.79 cm). Ten paired control and experimental treatments were used to compare catch rates for five target finfish species	Combined data from the two experiments (lumping the two different experimental treatments) identified a significantly lower sea turtle by-catch rate in the experimental treatment. In 2004, six turtles interacted with the control treatment, one with the experimental treatment. In 2005, 15 turtles interacted with the control treatment, and no turtles were observed interacting with the experimental treatment. There was no significant difference in target species catch rates by weight for four species [Atlantic croaker (*Micropogonias undulatus*], weakfish (*Cynoscion regalis*), harvestfish (*Peprilus alepidotus*), and Atlantic thread herring (*Opisthonema oglinum*)], while the experimental leader resulted in a significantly higher butterfish (*Peprilus triacanthus*) catch rate	DeAlteris and Silva (2008)

Table 3 Continued.

Fishery	Experimental Design	Findings	Citation
Japan large-scale pound net (*teichi-ami*) fishery	Different degrees of angles of the top of large traps were assessed for their effect on the efficacy of directing turtles towards the portion of the trap where a releasing device could be located. Three experimental trap designs, each with a base of 8 m x 8 m, were used: (i) a box-shaped trap with a height of 1 m and a top that was parallel to the bottom; (ii) a box-shaped trap with a top angled at 10° towards the centre of the trap; and (iii) a rectangular-pyramid-shaped trap with the top angled at 20° towards the apex. Five loggerhead turtles raised in captivity were used in the experiment. For each trial, one turtle was placed in each trap, and its movements were recorded using a video recorder located above the trap and a depth meter attached to the turtle's carapace	In all three traps, approximately five minutes after initiating the experiment, all turtles consistently moved their heads upward, with their bodies upright, and poked at the top of the trap. As time progressed, the motion increased in frequency. In the trap with a flat top, and the trap with a 10° angled-top, directional movement associated with the poking motion was minimal. However, in the trap with a 20° angled top, the turtles were observed to make large movements upward while making the poking motion, and all turtles reached the apex of the trap and continued the poking motion. These observations suggest that it is possible to direct turtles towards a releasing device by placing an approximately 20° angle on the top of the trap	Takahashi *et al.* (2008); Abe and Shiode (2009)
Japan small-scale southern pound net fishery	Observed the proportion of captured turtles and fish that escape from a trap equipped with a releasing device. The trap in this fishery is cone shaped, 10 m long, 1.3 m wide. A 40 cm × 50 cm hole was made in the upper portion of the cone in the trap and a hinged flap was installed over the hole (Fig. 7). The releasing device was designed to automatically close after a turtle pushes through the flap by making use of the tension in the net. 16 green sea turtles of ≤56 cm straight carapace length were observed. Only turtles of <100 cm carapace circumference (straight carapace length of about 56 cm) can enter the trap because of the size of the funnel net in the bays. 128 tropical coral fish and squid of 37 species were observed in the trap overnight	81% of green turtles and 4% of fish and squid escaped through the releasing device	Abe and Shiode (2009)

Figure 1 Conventional demersal gillnet with tiedowns (top) and modified net without tiedowns. Reducing the length or eliminating the use of tiedowns and the amount of webbing in demersal gillnets reduces or eliminates the bag of slack webbing, which has been found to reduce the incidence of sea turtle entanglement in the North Carolina flounder demersal gillnet fishery (Price and Van Salisbury 2007; original drawing by Jeff Gearhart, re-designed by Manuela D'Antoni, Food and Agriculture Organization of the United Nations).

identify an effective turtle by-catch reduction measure, counter to lessons learned previously in the North Carolina studies (Price and Van Salisbury 2007). As a result of a small sample size, no significant difference in turtle catch rates was observed, with nine turtles caught in the nets with shorter tiedowns, and seven in nets with longer tiedowns (Maldonado *et al.* 2006), generally consistent with the North Carolina findings (Price and Van Salisbury 2007). Similarly, in a 2004 study, Maldonado *et al.* (2006) employed an experimental treatment with two factors of 44% shorter tiedowns and half the net profile. There was no significant difference in turtle catch rates, with only one turtle observed to be caught, but the experimental treatment resulted in a significantly lower target species catch rate (Maldonado *et al.* 2006), perhaps because the negative effect on target species catch rate from the reduced net profile outweighed the positive effect from shorter tiedowns. This highlights the need for improved coordination and communication between the small number of professionals involved in this relatively new research area.

Results from research in a Mexico demersal gillnet fishery suggest that illuminating nets with green lightsticks attached to the net can reduce green sea turtle by-catch rates without adversely affecting the catch rate of target species when compared to control nets without illumination (Table 3, Fig. 2; Wang *et al.* 2009). Additionally, incorporating a shark shape (Fig. 3) was also found to result in a significant reduction in sea turtle catch rates; however, this resulted in a large and significant reduction in the target species catch rate (Table 3; Wang *et al.* 2009).

Using float lines without buoys has been trialled in a controlled experiment in a Baja California Sur demersal gillnet fishery. Results found no significant differences in sea turtle and target species catch rates, likely because of a small sample size, with 47% fewer turtles caught in the experimental gear (Peckham *et al.* 2009).

As in demersal gillnet fisheries, the low profile technique has also proved effective at reducing turtle by-catch rates in surface gillnet fisheries (Fig. 4; Gearhart and Eckert 2007; Eckert *et al.* 2008). Research conducted in 2007 in the Trinidad surface drift gillnet fishery for mackerel (Scombridae) demonstrated a significant 32% reduction in leatherback by-catch rates through the use of lower profile nets, while catch rates of target species increased but the difference was not significant (Table 3, Fig. 4; Eckert *et al.* 2008). A previous experiment in 2006 in this fishery found that setting mid-water gillnets 4.6 m (15 feet) deeper than conventional surface nets caused a significant decrease in target catch (Table 3; Gearhart and Eckert 2007).

There is evidence that larger mesh sizes increase sea turtle catch rates (e.g. Price and Van Salisbury 2007). Gillnet fisheries that target sea turtles use a mesh size of between 20 and 60 cm, presumably based on experience that these mesh sizes maximize turtle catch rates. Therefore, for some fisheries, regulations which specify maximum mesh size have been promulgated in an effort to minimize turtle capture (Price and Van Salisbury 2007; Yeo *et al.* 2007). However, consideration should also be presented to a minimum mesh size threshold, below which the catch of undersized, juvenile fish becomes problematic.

Gearhart *et al.* (2009) found no significant differences in target and turtle catch rates between long wavelength red vs. broader spectrum white marker lights in the Trinidad mackerel surface drift gillnet fishery, where for each set, two marker lights were attached at the ends of the net above the water
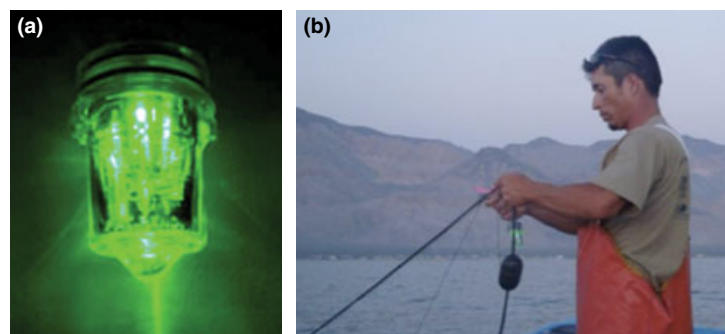
Figure 2 (a) Green battery-powered Light-emitting diodes (LED) light stick assessed for affect on sea turtle and (b) target species catch rates in a Mexico demersal gillnet fishery (Wang *et al.* 2009).
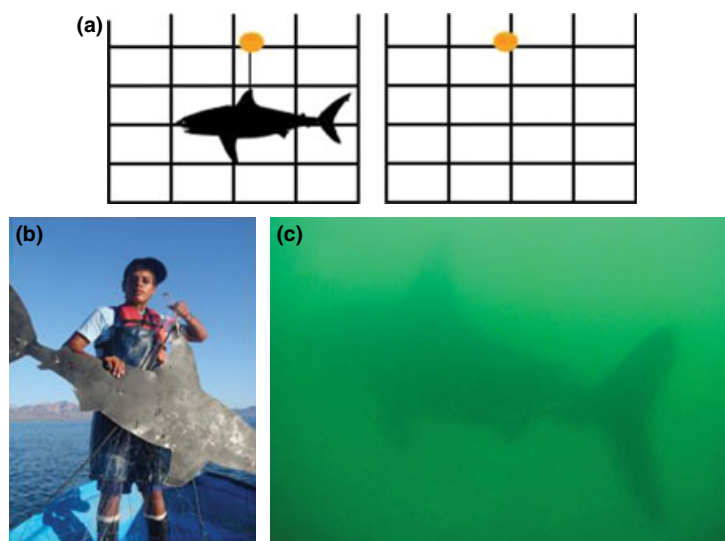
Figure 3 (a) Line drawing of an experimental gillnet with a shark shape attached every 10 m along the net, suspended from a float 60 cm below the surface (left), and a control net without the shape, used in daytime studies in a Mexico demersal gillnet fishery (Table 3; Wang *et al.* 2009). (b) Shark shape made of polyvinyl chloride, painted black, and weighted with a 1.3 kg lead plate. (c) View of shark shape when deployed underwater.
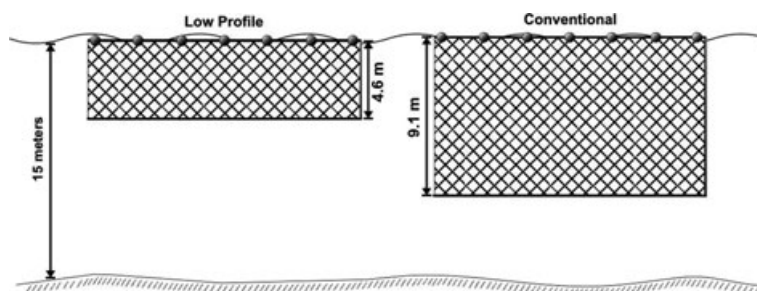
Figure 4 Low profile and conventional surface drift gillnet configurations employed to reduce leatherback sea turtle by-catch in Trinidad's artisanal mackerel gillnet fishery (Eckert *et al.* 2008; by Jeff Gearhart, U.S. National Marine Fisheries Service, Southeast Fisheries Science Center).

surface. The findings suggest that the penetration of the light from both the red and white marker lights might have only nominally illuminated the underwater net, and that the spectral frequencies, temporal frequencies, and/or brightness of the two lights were equally detectable by the interacting species of turtles and fish (Crognale *et al.*, 2008; Wang *et al.*, 2009). However, investigators observed that using red headlamps in place of white made it easier to disentangle leatherback turtles from gear because leatherbacks did not become as frightened when landed on vessels employing the red lights.

In summary, the following are gear-technology approaches that have been shown to significantly reduce sea turtle catch rates in individual gillnet fisheries:

- Reducing net profile (vertical height; Price and Van Salisbury 2007; Eckert *et al.* 2008).
- Increasing tiedown length, or eliminating tiedowns (Price and Van Salisbury 2007).
- Placing shark-shaped silhouettes adjacent to the net (Wang *et al.* 2009); and
- Illuminating portions of the net using green lightsticks (Wang *et al.* 2009).

Of these techniques, only net illumination was found to not cause a significant decrease in target species catch rates (Wang *et al.* 2009).

Pound net fisheries

Figure 5 illustrates the three main components of two designs of pound nets: the leader (hedging), bays (heart, turn backs or playing ground) and the trap (pound, head, capture chamber or fish bag; Bellmund *et al.* 1987; DeAlteris and Silva 2008). Sea turtles have been observed to be captured within pound net traps (Ishihara 2007; Takahashi *et al.* 2008) and entangled within pound net leaders (Mansfield *et al.* 2001, 2002; DeAlteris and Silva 2008). Similar passive net trap gear, which employ large nets that are anchored or fixed on stakes, includes fyke and stow nets, pots, weirs, corrals, barriers, fences and aerial traps (Nedelec and Prado 1990).

Observations reported by Ishihara (2007) support the contention that pound nets with an open-roofed trap result in substantially lower sea turtle mortality levels than those with a closed subsurface trap (Table 2). Research conducted on Japanese large pound nets by Takahashi *et al.* (2008) and Abe and Shiode (2009) found that use of a rectangular, pyramid-shaped subsurface trap with a top angled at 20° towards the apex may be effective at consistently directing turtles towards a location where a releasing device could be installed (Table 3, Fig. 6). In Japanese small pound nets, inclusion of a turtle releasing device into the trap was observed to effectively allow turtles to escape with nominal escapement of fish (Table 3, Fig. 7; Abe and Shiode 2009). Abe and Shiode (2009) also describe the design of a turtle releasing device suitable for use in the box-shaped traps used in the Japanese large-scale pound net fishery, which might prove effective when the top of the trap is designed in a pyramid-shape.

Research on a modified leader by the U.S. National Marine Fisheries Service (DeAlteris and Silva 2008) resulted in a significant reduction of turtle catch rates in the leader section of pound nets in Chesapeake Bay, Virginia. The modified leader replaced the upper two-thirds of the traditional mesh panel leader with vertical ropes made of either polypropylene rope (0.95 cm) or a hard lay polysteel rope (0.79 cm) and spaced every 61 cm (Table 3).

In summary, empirical evidence of sea turtle by-catch mitigation in pound nets from three studies found that:

- Replacing mesh with ropes in the upper portion of leaders caused a significant reduction in the turtle capture rate with an increase in catch rate of one target species and no significant difference in catch rates of four other target species.
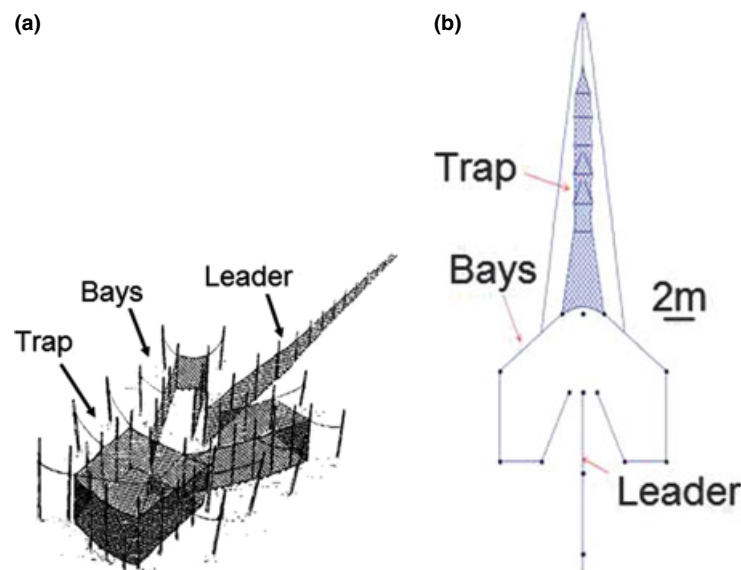
Figure 5 Leader, bays and trap used in the Chesapeake Bay, USA pound net fishery, which uses a box-shaped trap (left; DeAlteris and Silva 2008) and in the small pound net fishery of Okinawa, Japan, which uses a cone-shaped trap (right).
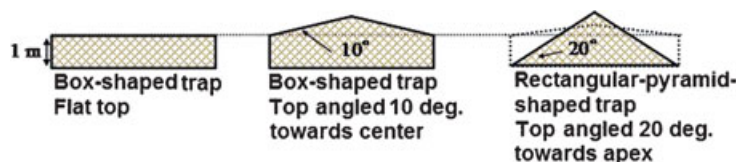
Figure 6 A rectangular-pyramid-shaped trap with the top angled at 20° towards the apex (right) was found to direct turtles towards the apex, suggesting that this design could effectively direct turtles towards a releasing device. The other two designs of trap did not effectively direct turtles' movement in a consistent direction (adapted from Takahashi *et al.* 2008).

Figure 7 Turtle releasing device tested in the small-scale Japanese pound net fishery. The fishery employs cone-shaped traps, which are relatively small, have a circular cross section and have relatively stable net tension. The high tension causes the device's flap to automatically close, where turtles can open it but not fish (Abe and Shiode 2009).

- Incorporating a prototype turtle releasing device into the roof of the cone-shaped trap in the small-scale southern Japan subsurface pound net fishery resulted in high escapement of green sea turtles with nominal target species escapement.
- Modifying the roof of the trap in the Japanese large-scale pound net fishery to a rectangular-pyramid-shaped trap with the top angled at 20° towards the apex effectively directed turtles towards the apex of the subsurface trap's roof, where an escapement device could be installed.
- Pound nets with open vs. closed traps have higher survival rates of captured turtles.

Discussion and conclusions

Assessments and risk categorizations

Risk assessments
The knowledge of the relative risks of the full suite of mortality sources on the long-term health of

individual sea turtle populations is generally poor (Chaloupka 2007). As a result, despite growing attention to the threat to sea turtles from coastal net fisheries (FAO, 2004, 2005, 2007, in press), there is uncertainty regarding the relative magnitude of threat from these fisheries and from other anthropogenic activities. Three reasons for this limited understanding of the relative risk of coastal net fisheries are:

- The lack of standard definitions of coastal net fishing effort (FAO, 2007).
- Inadequate by-catch data because of limited or non-existent observer coverage of the fisheries, especially in densely populated archipelagic regions (FAO 2007).
- Inadequate analytical approaches for dealing with temporal and spatial effects for relatively rare by-catch events (Gilman *et al.* 2007a).

A cost-benefit type risk framework is needed to compare the relative degree of risk that individual mortality sources pose to individual sea turtle populations, and to identify the associated costs of mitigating each threat. A probability-based approach can be used to evaluate the relative risks of threats to sea turtles in data-poor and knowledge-vague settings (Chaloupka 2007).

There are numerous anthropogenic sources of sea turtle mortality in addition to fisheries interactions. Of the myriad anthropogenic factors adversely affect sea turtles, there is a long history of efforts to mitigate threats to sea turtles from chronic predation by humans of eggs and adult females at nesting beaches (e.g. Pritchard and Trebbau 1984; Chan and Liew 1996; Márquez *et al.* 1998; Eckert and Lien 1999; Limpus *et al.* 2003; Hitipeuw and Pet-Soede 2004; Alfaro-Shigueto *et al.* 2005, 2007; Marcovaldi and Chaloupka 2007; SIRAN, 2007; Chaloupka *et al.* 2008; Peckham *et al.* 2008). There is likewise a relatively long history of mitigating the predation of eggs, hatchlings and nesting females by

feral pigs, dogs and other species (Pritchard 1979; Spring 1982a,b; Quinn *et al.* 1983; Hirth *et al.* 1993; Kinch 2006; Wurlianty and Hitipeuw 2006; Hitipeuw *et al.* 2007; Tapilatu and Tiwari 2007). Beach erosion, including from relative sea-level rise, is an additional threat to incubating sea turtle nests (Pritchard 1971; Quinn *et al.* 1983; Dutton *et al.* 2005; Hitipeuw *et al.* 2007; Tapilatu and Tiwari 2007). Certain land uses threaten turtle nesting habitat (Sharma 2000; Hitipeuw and Pet-Soede 2004). Sand temperatures at some sea turtle nesting beaches may be exceeding the thermal tolerance of embryos, causing high embryo mortality (Yntema and Mrosovsky 1982; Mrosovsky 1994; Ackerman 1997). Anthropogenic causes of increased sand temperatures include alterations to beach vegetation as well as climate change. Rising sea surface temperature could also adversely affect sea turtle breeding (Chaloupka 2001; Limpus *et al.* 2003). The input of marine debris, including derelict fishing gear, plastics and petroleum byproducts, into the oceans, causes injury and mortality of sea turtles when they ingest or become entangled in debris (Carr 1987). Contaminants from plastic pollution are another possible mortality source: phthalates, derived from plastics, have been found in leatherback egg yolks (Juárez-Cerón 1998). Persistent organic pollutants, including polychlorinated biphenyls and pesticides, such as dichlorodiphenyltrichloroethane, have negatively affected reptiles and other wildlife populations; for instance, low levels of organochlorine pesticides were found in nine post-yearling green, loggerhead and olive ridley sea turtles (Gardner *et al.* 2003).

Fishery assessment method considerations
As a result of the methods employed, there is substantial uncertainty in turtle catch rates, fleet-wide catch levels, temporal and spatial patterns of turtle by-catch, and trends in turtle by-catch rates in most of the coastal net fisheries summarized in Table 2. There are various pros and cons with alternative fishery assessment methods, including: social surveys; onboard and dockside observers; logbooks; satellite imagery (to observe number of participating vessels); and electronic vessel monitoring systems. Fisher surveys provide a critically important first-order qualitative understanding of whether or not problematic sea turtle capture levels are occurring and an initial understanding of the magnitude of the problem where previously little or no information was available (Table 2; Frazier and

Brito 1990; Eckert and Lien 1999; Lee Lum 2006; Alfaro-Shigueto *et al.* 2007; Gearhart and Eckert 2007; Ishihara 2007; Pilcher *et al.* 2007; Yeo *et al.* 2007). While at-sea data collected by onboard observers are optimal to understand catch characteristics and rates, including for sea turtle by-catch, the cost can be prohibitive and can be impractical in small-scale fisheries. Limited observer coverage can provide an index of the fleet as a cost-effective preliminary assessment and a low-cost method to validate information collected via fisher interviews. However, even monitoring data collected by onboard observers need to be considered with caution, as vessels that take on an observer may deviate from conventional fishing methods in an attempt to avoid turtle captures (e.g. select fishing grounds where turtle by-catch is known to be relatively infrequent), or crew may conceal interactions with sensitive species from observers (e.g. Gilman *et al.* 2005). Long-term data series may be needed to account for high inter-annual variability in gear used, gear designs, fishing grounds, turtle interaction rates and other fishery characteristics.

Four general categories of information are required to understand the degree of risk a fishery poses to sea turtles and to identify mitigation opportunities (FAO, 2008b; Gilman 2009):

- Magnitude of the problem, both in terms of: (i) effect on sea turtle populations (conservation status of affected turtle populations, age classes affected, status and trends in levels of turtle mortality from fishery interactions, and ultimately are population-level effects being caused by net fishery by-catch) and (ii) Effect on the fishery (gear damage and loss from interactions, time to remove turtles from the gear and repair or replace gear, lost catch, effects of any relevant regulatory measures).
- Fishery characterization, including size of the fishery, gear types used, characteristics of each gear type, fishing operations and catch characteristics. Hall *et al.* 2009 provides two draft forms designed for use in fishery assessments to collect information on coastal gillnet, trammel net, pound net and fyke net gear characteristics and fishing methods hypothesized to have a significant effect on turtle and target species catch and mortality rates. For example, for gillnets and trammel nets, information recommended for collection includes: is gear set at the sea surface, mid-water or at seafloor; mesh size; twine

material; line diameter; line colour; float and float line characteristics; distance between floats; is bait used in nets, and if yes, what species; angle of the net in relation to the coastline; and fishing depths (Hall *et al.* 2009).

- Management framework (self-management, co-management or no management), including monitoring, control and surveillance, and the capacity to institute alternative mitigation approaches.
- The socioeconomic context, i.e. how will alternative by-catch reduction strategies affect fishers' social and economic welfare.

The observation of retention of by-caught sea turtles for human consumption in some locations (Frazier and Brito 1990; Cheng and Chen 1997; Eckert and Lien 1999; Alfaro-Shigueto *et al.* 2007; SIRAN, 2007; Peckham *et al.* 2008) highlights the need to understand and account for the socioeconomic and cultural context of these fishing communities and markets for sea turtle products if efforts to reduce this anthropogenic mortality source are to be successful. Conversely, in some fisheries, sea turtle entanglement is perceived as detrimental to the fisheries' viability, and turtles are typically discarded. For example, in Trinidad gillnet fisheries, fishers report frequent entanglement of leatherbacks during the nesting season, resulting in costly damage to gear and down time for repairs, where fishers kill caught turtles to avoid additional gear damage, and dismember caught turtles to facilitate their removal from nets (Eckert and Lien 1999; Eckert and Eckert 2005; Lee Lum 2006; Gearhart and Eckert 2007). In these cases, fishing industry uptake of effective and commercially viable by-catch reduction approaches can be expected to be relatively high.

Fishery assessments have not accounted for indirect adverse effects on sea turtles, which are difficult to observe and quantify. For instance, some fishing gear can cause "ghost" fishing, where the lost or discarded passive gear continually catches and kills fish and other marine life, including sea turtles. Derelict fishing gear may also damage habitat important to sea turtles. Gear may also be located in areas where it poses an obstacle for turtles to access critical habitat, including for foraging and nesting, and migration routes. Coastal net fisheries may provide an unnatural source of food for sea turtles because turtles may depredate species caught in coastal passive net fisheries that are not typical components of their diet. Coastal net fisheries may reduce predator population sizes, possibly representing a positive indirect effect for sea turtles, but causing complex changes in coastal ecosystem functioning and structure, with concomitant indirect adverse effects on sea turtles. Individual turtles may be repeatedly captured and released in a coastal net fishery, causing adverse effects from chronic stress. These indirect threats require consideration in risk characterizations of net fisheries.

Assessments also should attempt to collect information needed to provide accurate estimates of unobserved sea turtle mortality, such as from removal by scavengers, currents or other mechanical action during the gear soak and haul (Alverson *et al.*, 1994; Gilman *et al.* 2005). This is a potential important factor in gillnets and trammel nets, and leaders of trap gear. Delayed mortality of released turtles and concealment by crew of caught turtles from onboard observers are additional potentially important contributions to unobserved mortality in all gear types (Swimmer *et al.* 2002; Chaloupka *et al.* 2004; Gilman *et al.* 2005).

It would be beneficial to standardize units for the reporting of sea turtle catch-per-unit-of-effort (CPUE) in gillnet and trammel net fisheries to enable more meaningful comparisons between experiments and fisheries. Alternative turtle CPUE units for passive net fisheries identified in Gilman (2009) were the number of caught turtles per: (i) trip, (ii) set, (iii) unit length of net, (iv) unit area of net, (v) unit area per soak time and (vi) the weight of the net. For example, reporting turtle catch per horizontal length of a net can be a misleading measure of turtle CPUE for comparisons of different net designs if the net heights are dissimilar, and if turtles are not caught in the same vertical portion of the net. Fishing effort is not characterized suitably by identifying the number of vessels in a fleet or number of fishers participating in a fishery. It is potentially misleading to compare effort between coastal net fishery gear types.

Considering potential socioeconomic effects of alternative sea turtle by-catch mitigation practices is critical for success. This includes considering all potential effects of implementing the by-catch mitigation method on the commercial viability of a fishery, including economic viability, practicality and crew safety. Many coastal artisanal fishers select their profession because it is the only available source of income, and/or because of family tradition. For many, alternative employment may not be available (e.g. Yeo *et al.* 2007). Presenting this socioeconomic

context, it is critical to consider potential effects of by-catch reduction strategies on fishers' social and economic welfare, in particular, for artisanal fisheries (Panayotou 1982; McGoodwin 2001; Yeo *et al.* 2007). The FAO conducted a review of initiatives by Intergovernmental Organizations (IGO), including Regional Fisheries Management Organizations and other Regional Fishery Bodies, to address sea turtle interactions in marine capture fisheries (Gilman *et al.* 2007a). FAO found that, at that time of the study in 2007, there were no IGO that had put in place legally binding measures that require fishing vessels to implement sea turtle avoidance methods. Presenting this state of fisheries management frameworks, including limited resources for monitoring, control and surveillance, particularly with economically marginal fisheries, approaches at reducing by-catch that have been demonstrated to be effective 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. Identifying commercially viable by-catch solutions, where commercial viability refers to both the effect on income and practicality of employment, including crew safety concerns, will maximize the likelihood of fishery uptake.

Direct participation of artisanal fishers is critical for successful fishery assessment and by-catch mitigation activities (Gilman *et al.* 2005; Peckham *et al.* 2007, 2009; FAO, 2008b). Fishers have a large repository of knowledge, which can be tapped to contribute to finding effective and commercially viable solutions to problematic by-catch that will ultimately be acceptable to the artisanal fishing community (Gilman *et al.* 2005). Several by-catch reduction methods were developed by fishers, including the bird-scaring tori line for longlining, technical methods to reduce dolphin mortality for eastern Pacific purse seining (Hall *et al.* 2000), and fisher-selected and enforced turtle protected areas (Peckham *et al.* 2007, 2009). Furthermore, participation of fishers can result in industry developing a sense of ownership for by-catch reduction practices (Gilman *et al.* 2005).

Lessons learned from the few small-scale coastal net fisheries where progress has been made in assessing (Table 2) and mitigating (Table 3) sea turtle by-catch should be examined to guide the development of a generic decision tree/process tool. Such a decision tree could be used as a starting point for interventions in other fisheries (Gilman 2009).

Mitigation opportunities

Empirical evidence of the fishery-specific efficacy and commercial viability of gear-technology approaches at mitigating sea turtle capture in coastal passive net fisheries is available from only a small number of fisheries and studies (Table 3). At this incipient stage, it is unclear whether or not gear-technology approaches can be an effective and commercially viable solution to sea turtle by-catch in coastal passive net fisheries, such as in fisheries that overlap with relatively high densities of sea turtles (Peckham *et al.* 2007). It is possible that gear-technology approaches, employed in concert with other turtle by-catch mitigation approaches (Table 1), will provide fishery-specific solutions.

Solutions to by-catch problems are likely to be fishery-specific (Gilman *et al.* 2005; Gilman 2009). For instance, differences in gear designs and materials, turtle species and sizes, turtle abundance at fishing grounds, and other differences between fisheries, may cause sea turtle by-catch reduction approaches to differ in efficacy. Different turtle species and age classes might exhibit different behaviour when foraging (e.g. depth in the water column, time of day, attraction to caught fish and bait in gear), and behaviour in response to being caught in fishing gear. Differences in target species and sizes, the local socioeconomic context and management framework will determine commercial viability and social acceptability of by-catch mitigation methods, including industry acceptability of any reductions in catch rates of commercially important species. Consequently, broad assessments in individual fisheries must precede advocacy for uptake of specific turtle by-catch reduction methods.

Lessons learned in addressing by-catch of other species groups in net fisheries (Melvin *et al.* 2001; Werner *et al.* 2006) and proven methods to mitigate by-catch in other gear types (e.g. Hall *et al.* 2000; Gilman *et al.* 2005, 2006a; Watson *et al.* 2005; Werner *et al.* 2006; Eayrs 2007; FAO, in press) may facilitate identifying additional promising approaches for reducing turtle by-catch in passive net fisheries. Several promising gear-technology approaches warrant additional or new investigation:

- Fishing at sufficiently shallow depths, and increasing net liftability by adjusting the weighting design and/or anchoring system can allow captured turtles to reach the surface and breathe during the gear soak, increasing the proportion

of caught turtles that survive the gear interaction (Gearhart 2003; Maldonado *et al.* 2006).

- Minimizing soak time or increasing patrols of the gear to reduce the time incidentally caught turtles remain in the net might increase the proportion of caught turtles that survive the gear interaction (Gearhart 2003; Watson *et al.* 2005; Gilman *et al.* 2006a).
- Modifying the time of day of fishing operations might reduce the rate of turtle captures (Watson *et al.* 2005; Gilman *et al.* 2006a).
- Using alternative net materials and illumination mechanisms can reduce turtle capture rates. Making the upper portion of nets more visible, but leaving the lower portion of the net profile relatively undetectable, as conducted in a drift gillnet salmon fishery to reduce seabird by-catch without compromising target catches (Melvin *et al.* 2001), may also hold promise to reduce turtle catch rates. Similarly, using a clear, UV-absorbent plastic material for netting could reduce turtle by-catch without compromising fish catch rates. Using coarse multifilament line in place of monofilament (Eckert and Lien 1999; Lee Lum 2006), replacing webbing with stiff lines in the upper portion of a pound net leader (DeAlteris and Silva 2008), and embedding luminescent materials into netting material (Werner *et al.* 2006), a similar intent as incorporating light-sticks (Wang *et al.* 2009) have been suggested as additional strategies to reduce turtle capture rates without compromising catch of target species. In addition, further research on the effects on turtle and target species catch rates from alternative spectral frequencies, brightness, as well as temporal frequencies (i.e., the flickering rate of a light source) for net illumination are needed, including increased understanding of differences in visual capacities between turtle species (Crognale *et al.*, 2008; Wang *et al.*, 2009).

- Increasing the net hanging ratio (ratio of net height to net width) might reduce turtle entanglement risk.
- Using buoyless floatlines (Price and Van Salisbury 2007; Peckham *et al.* 2009), modifying float characteristics, and/or reducing the number of floats and vertical float lines might reduce turtle attraction and incidence of entanglement.
- Developing and conducting trials of devices to avoid and minimize turtle entrance into traps of

pound nets and fyke nets, such as use of a deflector grid, can reduce turtle capture rates.
- Modifying baiting techniques, where baiting is used, can reduce turtle capture rates.
- Setting gear perpendicular to the shore, instead of parallel to the shore, may reduce the amount of gear that poses an obstacle for turtles accessing nesting habitat (Eckert and Eckert 2005), and exploring effects of other gear orientations to and distance from the coastline might allow for reduced turtle capture rates.
- Incorporating a shark-shaped silhouette constructed from clear UV-absorbent plastics might retain turtle deterrent efficacy but reduce the loss of targeted species observed in trials by Wang *et al.* (2009), where polyvinyl chloride and plywood were used to construct a shark silhouette. Using other deterrents, including sonic "pingers," lights or chemical olfactory repellents (Eckert and Eckert 2005) might effectively reduce turtle capture rates with acceptable effect on target catch levels.
- Using alternative net materials (appropriate twine diameter and material) to produce a breaking strength that allows turtles to break free of the gear and escape might reduce turtle capture rates with acceptable effect on target catch levels.
- Investing in research, development and testing of equipment to disentangle turtles caught in nets. For instance, developing and using purpose-made line cutters, and selecting a headlamp light colour to reduce turtle stress during handling (using headlamps with red instead of white light were observed to cause less leatherback stress in Trinidad [Gilman 2009]) warrant investigation.

In addition to these research needs, to identify improved techniques for effective and commercially viable sea turtle by-catch solutions, continuing research initiated by Gearhart and Price (2003), Brown and Price (2005), Price and Van Salisbury (2007), Eckert *et al.* (2008) and Gearhart *et al.* (2009) on reduced net profile and increased length or elimination of tiedowns; by Abe and Shiode (2009) on turtle releasing devices for use in different types of pound net and fyke net gear; by Takahashi *et al.* (2008) and Abe and Shiode (2009) on trap shapes with the aim of consistently directing turtles towards a location where a releasing device could be incorporated is a priority.

The understanding of why different species and age classes of turtles interact with coastal net fisheries (e.g. are turtles brought into gear by

currents, attracted to floats or net lines, and/or fish in the gear) and the mechanics of how gear captures both target and by-catch species (gilling, entangling, enmeshing and enclosing in a trap) is limited. Aspects of gear design, materials and methods that affect turtle survivorship after interaction with gear is also limited. This information is fundamental to guiding further research and development of gear-technology approaches to by-catch mitigation, and is a research priority. However, this limited understanding does not necessitate or warrant delaying action to mitigate problematic turtle by-catch (Gilman 2009).

Studies will have stronger ability to infer the effect of single factors on turtle and target catch rates and turtle survivorship when a modelling approach explicitly accounts for as many covariates and factors that are known to significantly affect catch rates (e.g. Gilman *et al.* 2007a). To this end, there is a need for improved understanding of which factors of fishing gear and methods, and other factors, justifies lumping vs. splitting them for designing controlled and comparative experiments and for statistical purposes (Hall 2009). Various factors, including variability in fishing gear designs and methods, and environmental variables, may affect sea turtle entanglement and mortality rates in coastal passive net fisheries. Findings may be misleading if a factor that has a significant effect on turtle catch rates is not accounted for in statistical modelling exercises. Additional consideration of the potential significance of the myriad of factors in their affect on catch rates, and approaches to deal with the sources of variation, is needed (see Gilman 2009, Chapter 6).

It is important to identify any conflicts as well as benefits of by-catch reduction strategies for one species on all other vulnerable non-target species (Gilman and Lundin 2009). Experiments assessing changes in fishing gear and methods to reduce turtle capture rates should be designed to also collect information on changes in capture rates of other sensitive species groups, including marine mammals, seabirds and sharks.

Acknowledgements

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