Developing Visual deterrents to reduce sea turtle bycatch in gill net fisheries

Article *in* Marine Ecology Progress Series · June 2010

DOI: 10.3354/meps08577

John Wang
University of Hawaiʻi at Mānoa
30 PUBLICATIONS **846** CITATIONS

Yonat Swimmer
National Oceanic and Atmospheric Administration
63 PUBLICATIONS **1,497** CITATIONS

Vol. 408: 241–250, 2010
doi: 10.3354/meps08577

MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser

Published June 3

Developing visual deterrents to reduce sea turtle bycatch in gill net fisheries

John H. Wang[1,*], Shara Fisler[2], Yonat Swimmer[3]

[1]Joint Institute for Marine and Atmospheric Research, University of Hawaii at Manoa, 1125B Ala Moana Blvd., Honolulu, Hawaii 96814, USA
[2]Ocean Discovery Institute, 2211 Pacific Beach Drive, Suite A, San Diego, California 92109, USA
[3]NOAA Fisheries, Pacific Islands Fisheries Science Center, 501 W. Ocean Blvd., Suite 4200, Long Beach, California 90802, USA

ABSTRACT: Visual cues play important roles in sea turtle foraging behavior and likely influence their interactions with fishing gear. Altering these cues may be a useful strategy to reduce the incidental catch of sea turtles in various fisheries. We examined the potential effectiveness of 3 visual cues — shark shapes placed along the length of the gill net, illumination of nets by LED lights, and nets illuminated with chemical lightsticks — in reducing bycatch of green sea turtles *Chelonia mydas* in gill nets. We then adapted these potential deterrents into commercial bottom gill net fishery to quantify their effects on target fish catch rates and the catch value. Our results indicate that the presence of shark shapes significantly reduced the mean catch rates of green turtles by 54% but also reduced target catch by 45% and, correspondingly, catch value by 47%. In contrast, nets illuminated by LED lights significantly reduced mean sea turtle catch rates by 40% while having negligible impacts on target catch and catch value. Similarly, nets illuminated by chemical lightsticks also significantly reduced mean sea turtle catch rates by 60% while having no significant impact on target catch and catch value. These results illustrate the potential for modifying fishing gear with visual deterrents to effectively reduce sea turtle catch rates.

KEY WORDS: Bycatch · Sea turtles · Gill net · Longlines

INTRODUCTION

Bycatch in fisheries has been implicated as a significant source of mortality and subsequent population declines for numerous sea turtle species (Chan et al. 1988, Chan & Liew 1996, Lewison et al. 2004, Lum 2006, Lewison & Crowder 2007, Peckham et al. 2007). The incidental capture and mortality of sea turtles in pelagic longline fisheries has generated international research efforts, aimed at reducing these interactions by modifying fishing gear, which have had varying degrees of success (Gilman et al. 2006, Lewison & Crowder 2007, Read 2007). Concerns have also been raised over the high rates of incidental capture and mortality of sea turtles in gill net fisheries (Chan et al. 1988, Chan & Liew 1996, Lum 2006, Lewison & Crowder 2007, Peckham et al. 2007, 2008, Gilman et al. 2009). Recent studies suggest that mortality of the loggerhead sea turtle *Caretta caretta* attributed to gill net fisheries located along the Pacific coast of Baja California Sur, Mexico, may be comparable to that of industrial-scale pelagic longline fisheries (Peckham et al. 2007, 2008). Gill net fisheries occur throughout the world and are often poorly regulated, which makes quantifying their total fishing effort and impact on bycatch species nearly impossible (Northridge 1991).

In pelagic longline fisheries, strategies to reduce sea turtle bycatch and mortality include seasonal and fishery closures, development of better sea turtle handling procedures, and changes in fishing gear (Watson et al. 2005, Gilman et al. 2006, Read 2007). In shallow-set (<100 m) pelagic longline fisheries, the mandatory adoption of relatively large (e.g. 18/0) circle hooks and fish bait in lieu of squid by US-based Atlantic and

---

*Email: john.wang@noaa.gov

Pacific swordfish fisheries has resulted in significant reductions in sea turtle bycatch with minimal impacts to the economic viability of the industry (Watson et al. 2005, Gilman et al. 2007). While use of circle hooks may not be effective in reducing sea turtle bycatch in all pelagic longline fisheries (Read 2007), their use causes less tissue damage than traditional J- or tuna-style hooks, and most likely increases the survivorship of released sea turtles (Watson et al. 2005, Gilman et al. 2007).

In contrast, few strategies to reduce sea turtle interactions with coastal gill nets exist, though several methods are being explored (Gilman et al. 2009). One approach to reducing sea turtle interactions with gill nets includes examining their sensory and behavioral ecology (Swimmer & Brill 2006, Southwood et al. 2008). Identifying cues that may act as deterrents and determining how they influence turtle behaviors are important steps in the development of bycatch reduction strategies. Subsequently, adapting these strategies to a specific fishery and testing their effectiveness with regards to both sea turtle and target species catch rates are required prior to implementation. Ultimately, such efforts should provide fisheries managers with a suite of effective bycatch reduction measures that best fit the needs of each individual fishery.

Behavioral and physiological studies have shown that visual cues are likely to play an important role during sea turtle foraging behavior (Moein-Bartol et al. 2002, Constantino & Salmon 2003, Moein-Bartol & Musick 2003, Swimmer et al. 2005, Southwood et al. 2008). Recent laboratory experiments indicate that lightsticks used on pelagic longlines influence loggerhead sea turtle orientation and swimming behaviors (Wang et al. 2007). It has been suggested that modifying the illumination from lightsticks may lead to reductions in turtle catch rates (Lohmann & Wang 2007). Exploiting this reliance on visual cues could be one method to modify turtle behaviors in relation to gill nets as well as other fishing gear (Swimmer et al. 2005, Swimmer & Brill 2006, Wang et al. 2007, Southwood et al. 2008).

In the present study, we tested the effects of 3 different visual cues on sea turtle catch rates and subsequently examined their effects on target catch and catch value in a commercial bottom-set gill net fishery. Shark shapes placed along the length of the gill net were tested as one visual cue. Sharks are a major predator of sea turtles, and previous observations of captive reared loggerhead turtles indicate that shark shapes trigger an escape response, suggesting that shark shapes could be useful as a sea turtle deterrent (Higgins 2006). We also tested sea turtles' responses to visually modified gill nets with illumination from either battery-powered LED lights or chemical lightsticks. This study aimed to determine promising visual cues that could be developed into strategies useful for reducing sea turtle bycatch in coastal net fisheries without negatively impacting target catch and ultimately catch value.

MATERIALS AND METHODS

The effect of shark shapes was tested during the day, while the effect of net illumination was tested at night. Experiments examining sea turtle catch rates were conducted along the Pacific coast, near Punta Abreojos, Baja California Sur, Mexico (26° 48′ N, 113° 27′ W) (Fig. 1a) in conjunction with ongoing sea turtle population surveys (López-Castro et al. 2010). Effects on fish catch and catch market value were tested in a commercial bottom-set gill net fishery located along the Gulf of California coast, near Bahía de los Angeles (BLA), Baja California, Mexico (28° 57′ N, 113° 33′ W) (Fig. 1a). Experiments were conducted in July 2006, and May to September 2007 to 2009.

Testing effects on sea turtle catch rates. To determine the effects of either shark shapes or net illumination on sea turtles, a pair of nets consisting of a control net and a modified experimental net was deployed. Experimental nets had either shark shapes, LED lights, or lightsticks placed along the net. In our initial trials, carried out in June 2006, we used 2 nets measuring 80 and 60 m. During subsequent trials in 2007 to 2009, we used 2 identical 95 m nets. These nets were surface-set and used by local fishers to conduct green sea turtle population surveys (López-Castro et al. 2010). Nets were made of monofilament and had a stretched diagonal mesh of 40 cm. Both nets were placed in the same region of the lagoon such that the distance between nets was less than 1 km. The location of the control net and experimental net was switched during each consecutive deployment. Nets were deployed during the 4 d centered on the neap tide when tidal flux was minimal.

Nets were monitored every 90 min for sea turtles to minimize stress to the animals as well as to limit disturbances caused by our presence. Turtles were removed from the nets and were transferred to a floating dock where they were tagged with Inconel metal tags, measured, and released. The tagging and morphometric data were incorporated in the Grupo Tortugero long-term monitoring database (López-Castro et al. 2010). The catch-per-unit-effort (CPUE) for each net was determined as: CPUE = no. of turtles captured/(net length/100 m) × (soak time of net/12 h). Sea turtle CPUE for the experimental net was compared to the control net using a Wilcoxon matched-pairs signed-rank test (InStat, GraphPad).

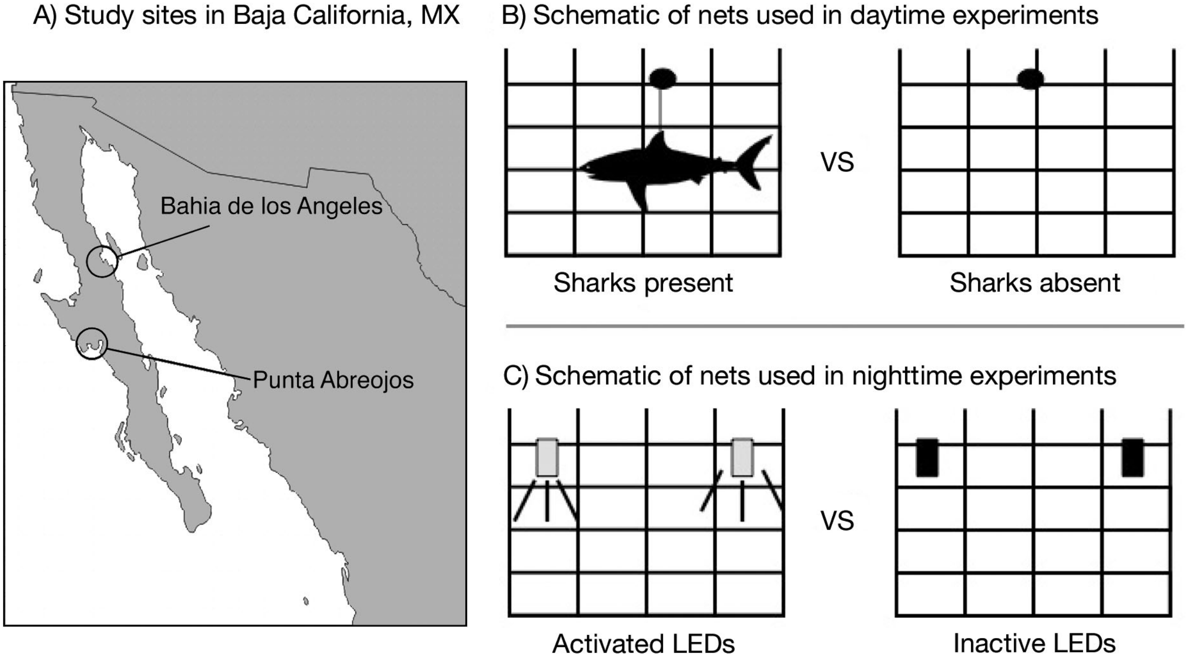

Fig. 1. (A) Study sites along the coast of Mexico's Baja California peninsula. Experiments examining sea turtle catch rates were conducted in Punta Abreojos, while experiments examining target catch and catch values were conducted in a commercial bottom-set gill net fishery in Bahia de los Angeles (BLA), Mexico. (B) Schematic of experimental nets with shark shapes suspended next to the nets from floats and control nets with only floats used in daytime studies. (C) Schematic of experimental nets with activated LED lights or lightsticks and control nets with inactive LED lights or lightsticks used in nighttime studies

Testing effects on target fish catch rates and catch value. In a commercial bottom-set gill net fishery, we examined the effects of either shark shapes or net illumination by deploying pairs of nets consisting of a control net and an experimental net. Gill nets deployed were typical monofilament nets used by local fishers. Nets were standardized so that they were all the same length during a fishing season (200 m in 2008 and 400 m in 2009), 1.5 m deep, and had stretched diagonal mesh from 16.5 to 20 cm. Each pair of nets (experimental vs. control) was deployed simultaneously, approximately 200 m apart, with similar depth and bottom topography. Fishing depth ranged from 10 to 30 m depending on the exact fishing site.

Fishermen primarily targeted species from the families Bothidae (flatfish) and Pleuronectidae (flatfish), as well as several species of Elasmobranchii (sharks, guitarfish, rays, skates). In addition, they caught and brought to the market a variety of other fish from the families Serranidae (e.g. sea bass, grouper), Scorpaenidae (e.g. scorpion fish), Scaridae (e.g. parrotfish), Haemulidae (e.g. grunts), and Balistidae (e.g. triggerfish). Catch from each of the nets was identified and categorized into 3 groups: target species (fish kept to be sold), bycatch (fish that were discarded), and other (catch kept by fishermen for consumption or retained for bait in other unrelated fisheries). The target species CPUE for each net was determined as: CPUE = no. of target species of fish/(net length/200 m) × (soak time of net/12 h). For each experiment, the target species CPUE for the experimental net was compared to the control net using the Wilcoxon matched-pairs signed-rank test.

We then followed the catch to the local fish buyer where it was separated into marketable species (e.g. shark, rays, guitarfish, flatfish), weighed, and assigned a purchase value. The total value of the catch allowed us to compare the market value from experimental nets to the market value from control nets using the Wilcoxon matched-pairs signed-rank test.

Experiments testing shark shapes. Shark shape experiments utilized simple shark cut-outs placed at 10 m intervals along the experimental net. Shark shapes were cut out from a PVC sheet, painted black, and weighted with a 1.3 kg lead plate to make the shapes negatively buoyant. Experiments conducted in July 2006 used shark shapes cut out of 1.9 cm thick plywood and painted dark gray. All shark shapes had a fork length of 150 cm.

In the sea turtle catch rate trials, the experimental net had shark shapes suspended 60 cm below a 30 cm orange bullet float. The floats were then attached to the surface-set net by 1.5 m of line. This allowed the shark shapes to float near the net without becoming entangled. On the control net, only orange bullet floats were attached along the net at 10 m intervals (Fig. 1b). Paired control and experimental nets were deployed only during daylight hours (approx. 07:00 to 19:00 h).

In the bottom-set gill net fishery the same shark shapes were used. We, however, adapted the shark shape attachment to a bottom-set gill net. We did this by not suspending the shapes from floats, but by directly attaching them to the gill nets' float line at intervals of 10 m. Control nets used in this experiment did not have a shark shape attached. Paired control and experimental nets were deployed during the day (approx. 07:00 to 19:00 h).

Experiments testing gill nets illuminated by LEDs or lightsticks. During the 2006 to 2008 sea turtle catch experiments, we illuminated the experimental net by placing green LED lights (Lindgren-Pittman Electralumes) at 10 m intervals along the net's float line. The control net had inactive LED lights placed at 10 m intervals. In 2009, we illuminated the experimental net by placing activated 15.25 cm chemiluminescent green lightsticks (Blackrock) at 5 m intervals along the net's float line. The control net had inactive 15.25 cm lightsticks placed at 5 m intervals. Net illumination experiments were conducted at night (19:00 to 07:00 h) by deploying a paired experimental and control net.

For experiments conducted in the commercial bottom-set gill net fishery, the same green LED lights (Lindgren-Pittman Electralumes), were placed at 10 m intervals along the experimental bottom-set gill net's float line. Inactive LED lights were placed along the control net's float line. During the 2009 season, we illuminated the experimental gillnets using 15.25 cm chemiluminescent green lightsticks place at 5 m intervals along the experimental net's float line and inactive lightsticks along the control net's float line. All experiments were conducted at night (19:00 to 07:00 h).

RESULTS

Shark shape experiments

A total of 14 trials were conducted to examine the effects of shark shapes on sea turtle catch rates. In total, 133 green sea turtles were captured. Control nets caught 85 turtles, while experimental nets caught 48. Control nets had a mean CPUE of 12.1 ± 3.1 (SE) (turtles/[12 h × 100 m]), compared to experimental nets, which had a mean CPUE of 5.6 ±1.1 (SE) (Fig. 2a). This represented a 53.9% reduction in CPUE. Of the 14 trials, 10 resulted in having lower sea turtle CPUE in the experimental net, which was statistically different (n = 14, p = 0.023) between nets.

The mean straight carapace length (SCL) for green sea turtles was 59.0 ± 0.7 (SE) cm (range: 42.2 to 100.6 cm). The mean SCL of turtles captured in control nets was 57.8 ± 1.3 (SE) cm and was 56.1 ± 1.7 (SE) cm in experimental nets.

To examine the effects on fish catch and catch value in a commercial fishery due to shark shapes, a total of 22 pairs of nets were deployed in BLA. During the experiments, no sea turtles interacted with either net. For target fish species, control nets had a mean CPUE of 10.6 ± 1.8 (SE) (fish/[12 h × 200 m]), while experimental nets showed a mean CPUE of 5.8 ± 0.8 (SE), which represented a 45.0% reduction (Fig. 2b), which was statistically significant (n = 22, p = 0.014). Control nets had a mean catch value of US$7.70 ± 1.7 (SE), while experimental nets reduced mean catch values by 47.4% to US$4.10 ± 0.9 (SE) (Fig. 2c), indicating a statistically significant difference in market value (n = 22, p = 0.001) between treatments.

Using LED lights to illuminate nets

To examine the effects of illuminating nets with LED lights on sea turtle catch rates, 15 trials were con-

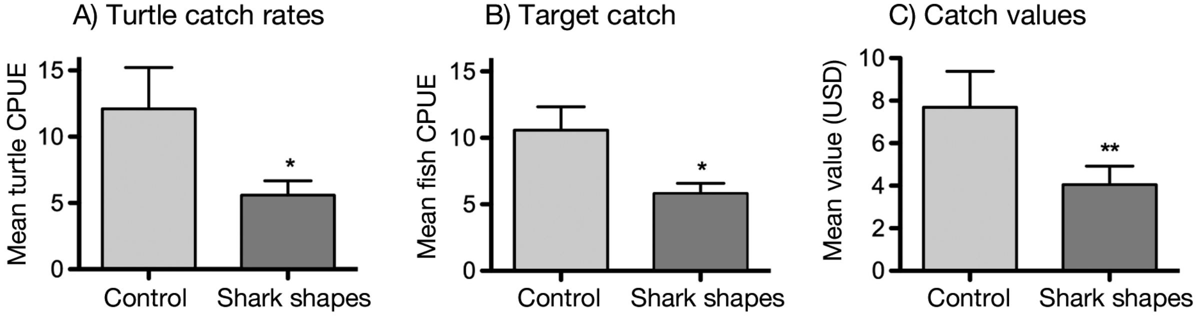

Fig. 2. Effects of deploying shark shapes on green sea turtle catch rates, target fish catch, and catch value using control nets versus experimental nets (with shark shapes). (A) Shark shapes resulted in a 53.9% reduction in the mean CPUE (turtles/[12 h × 100 m]) from the control nets. (B) Mean CPUE of target fish (fish/[12 h × 200 m]) was decreased by 45.0%. (C) Mean catch value (US$) decreased by 47.4%. Analysis with the Wilcoxon matched-pairs signed-rank test; significance: *p < 0.05, **p < 0.01

ducted. Of the 187 green sea turtles caught, 117 turtles were caught in control nets while 70 were caught in illuminated nets. The mean CPUE of control nets was 12.4 ± 2.4 (SE) (turtles/[12 h × 100 m]) with the experimental nets showing a 40% reduction to a mean CPUE of 7.4 ± 1.6 (SE) (Fig. 3a). Of the 15 trials, 12 resulted in having lower sea turtle CPUE in the experimental net. Analysis of the results indicated a significant difference in CPUE (n = 15, p = 0.026).

SCL of turtles ranged from 42.2 to 100.6 cm with a mean SCL of 59.0 ± 0.7 (SE) cm. The mean SCL of turtles in control nets was 60.3 ± 1.2 (SE) cm, while the mean SCL of turtles in the experimental nets was 61.1 ± 1.7 (SE) cm.

A total of 23 pairs of nets were deployed to examine the effects of using LED lights to illuminate nets on fish catch and catch value in a commercial fishery. Control nets showed a mean target CPUE of 11.3 ± 1.9 (SE) (fish/[12 h × 200 m]), while experimental nets showed a statistically similar CPUE of 11.0 ± 1.5 (SE) (Fig. 3b; n = 23, p = 0.76). Control nets had a mean catch value of US$9.70 ± 2.5 (SE), while experimental nets had a mean catch value of US$11.20 ± 2.7 (SE) (Fig. 3c), which were statistically similar (n = 23, p = 0.40).

Using chemical lightsticks to illuminate nets

We tested the effect of using chemical lightsticks to illuminate nets on sea turtle catch rates during 6 trials. Of the 115 green sea turtles caught, control nets had 81 turtles, while experimental nets had 34 green sea turtles. The mean CPUE of control nets was 19.0 ± 3.7 (SE) (turtles/[12 h × 100 m]), compared to a 59% reduction in experimental nets, which had a CPUE of 7.8 ± 1.7 (SE) (Fig. 4a). All trials had lower sea turtle catches in the experimental net (n = 6, p = 0.016).

Sea turtles SCL ranged from 37.2 to 102.7 cm, with a mean SCL of 60.5 ± 1.0 (SE) cm. Mean SCL in control nets was 61.2 ± 1.2 (SE) cm, while the mean SCL of turtles caught in the experimental nets was 59.0 ± 1.8 (SE) cm.

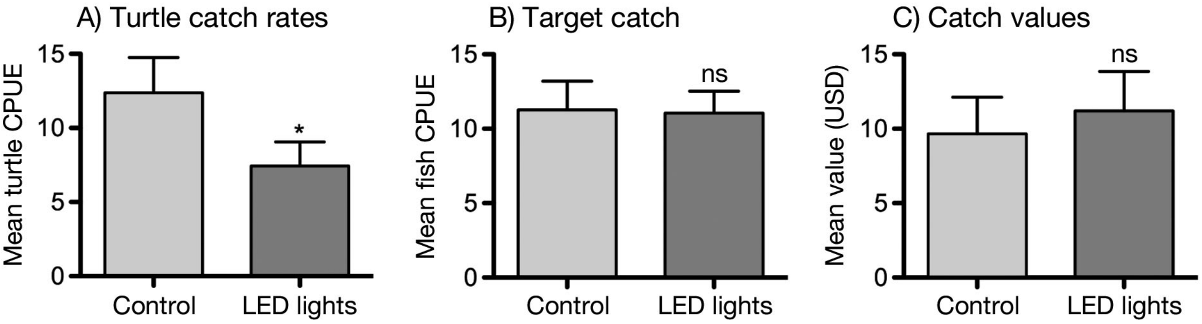

Fig. 3. Effects of LED light illumination on turtle catch rates, target fish catch, and catch value. LED lights were placed every 10 m along the net. (A) LED illumination resulted in a 40.0% reduction in the mean CPUE (turtles/[12 h × 100 m]) from the control nets. (B) Mean CPUE of target fish (fish/[12 h × 200 m]) was 2% lower in control nets. (C) Mean catch value (US$) increased by 15.9%. Analysis with the Wilcoxon matched-pairs signed-rank test; significance: *p < 0.05, ns: not significant

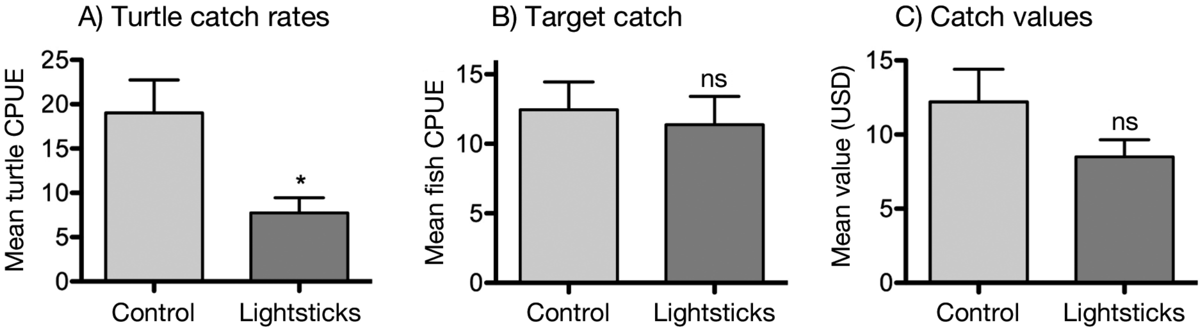

Fig. 4. Effects of chemical lightstick illumination on turtle catch, target fish catch, and catch value. Lightsticks were placed every 5 m along the net. (A) Lightstick illumination resulted in a 59.9% reduction in the mean CPUE (turtles/[12 h × 100 m]) from the control nets. (B) Mean CPUE of target fish (fish/[12 h × 200 m]) was 2% lower in control nets. (C) Mean catch value (US$) decreased by 30.3%. Analysis with the Wilcoxon matched-pairs signed-rank test; significance: *p < 0.05, ns: not significant

To examine effects on fish catch and market value, 17 pairs of nets were deployed in a commercial fishery. Control nets showed a mean CPUE of target fish of 12.8 ± 1.9 (SE) (fish/[12 h × 200 m]), while experimental nets showed a mean CPUE of 11.9 ± 2.0 (SE) (Fig. 4b), which was similar (n = 17, p = 0.61). Control nets had a mean market value of US$12.20 ± 2.2 (SE), which was statistically similar to the value of experimental nets, which was US$8.50 ± 1.2 (SE) (Fig. 4c; n = 17, p = 0.09).

DISCUSSION

Studies on the sensory capabilities of sea turtles indicate that visual cues play important roles in sea turtle foraging behavior (Moein-Bartol et al. 2002, Constantino & Salmon 2003, Moein-Bartol & Musick 2003) and most likely influence sea turtles' interaction with fishing gear (Swimmer et al. 2005, Swimmer & Brill 2006, Wang et al. 2007, Southwood et al. 2008). Altering the visual environment associated with fishing nets, traps, baits, or hooks may be an effective strategy to reduce the incidental capture of sea turtles in both pelagic and coastal fisheries (Lohmann & Wang 2007, Southwood et al. 2008).

One difficulty in developing and testing potential bycatch mitigation strategies is the need for sufficient interactions with sea turtles. Despite the relatively large cumulative numbers of sea turtles interacting with commercial fisheries (e.g. Lewison et al. 2004, Peckham et al. 2008), individual sea turtle interactions with fishing gear (e.g. pelagic longlines and coastal gill nets) are statistically considered 'rare events' (McCracken 2004). To obtain sufficient sea turtle interactions needed to quantify the effects of our proposed bycatch mitigation methods, we conducted our sea turtle catch rate experiments in Punta Abreojos, Baja California, Mexico, a region reported to have high rates of turtle capture in population monitoring studies (López-Castro et al. 2010).

In order to determine how these methods could affect target fish catch rates and ultimately the profitability of the fishing operation, we tested our turtle bycatch mitigation methods in a commercial bottom-set gill net fishery in BLA. Over the past 5 decades, green sea turtle populations in BLA have declined, initially as a result of directed fishing efforts (Cliffton et al. 1982) and more recently as a result of pressures from illegal fishing, incidental captures in local fisheries, and habitat degradation (Nichols 2003). The fishery in BLA uses common methods and targets similar fish species as other coastal gill net fisheries throughout the Baja California peninsula. Despite the low probability of interacting with sea turtles, the similarities with other coastal gill net fisheries in the Baja California peninsula make the BLA fishery an instructive site for developing sea turtle bycatch mitigation strategies.

Shark shape experiments

Sharks are a primary predator of sea turtles and have been shown to influence their feeding behaviors and habitat use (Heithaus et al. 2002, 2005, 2008, Higgins 2006). In addition, preliminary tank studies indicate that shark shapes trigger an innate flight response in captive-bred sea turtles that have not been exposed to sharks or other predators (Higgins 2006). In the present study, the decrease in turtles caught on nets with shark shapes (Fig. 2a) suggests that the turtles' behavioral (aversive) response to the visual cue results in turtles moving away from the nets. When shark shapes were placed on commercial bottom-set gill nets, catch rates of target species significantly decreased, as did corresponding market value (Fig. 2b,c). These findings suggest that target fish species showed a similar flight response, and/or the shapes increased net fouling, thereby reducing fish catch rates. While it is not known what features of a shark shape may be important in triggering such flight behaviors, the use of shark shapes is a potentially effective strategy for reducing sea turtle interactions with fishing gear.

Uses of predator models such as scarecrows, raptor models, or even cat silhouettes are common techniques used to deter unwanted bird species, often with variable success (Marsh et al. 1992). Successful implementation of such deterrent devices often entails extensive investigation and modification, such as adding motion or sound to enhance the lifelike characteristics. We aim to further modify the shark shapes used in the present study to identify a more effective deterrent that could be used in a multitude of situations. Regardless, modifications to the current shark shape design and to its attachment methods are needed to minimize effects on fish catch.

Exploiting differences between the sensory systems of sea turtles and fish species may help improve the selectivity of bycatch strategies (Swimmer & Brill 2006, Southwood et al. 2008). Several commercially important pelagic fish species, such as tunas, billfish, and dolphinfish (mahi mahi) have visual systems that filter ultraviolet (UV) light (<400 nm) (Fritches et al. 2000, Fritsches & Warrant 2006). In contrast, anatomical (Mathger et al. 2007), electrophysiological (Crognale & Eckert 2007, Salmon & Wyneken 2007), and behavioral evidence (Witherington & Bjorndal 1991, Fritsches & Warrant 2006, Wang & Swimmer 2007) indicate that sea turtles are able to see into the UV spectrum. This difference in visual physiology may allow us to selectively communicate with sea turtles if shapes are constructed with transparent, UV-absorbent plastics. Thus, shark shapes may appear as black silhouettes and trigger avoidance behaviors in sea turtles while remaining transparent and undetected by target fish species.

Shark shapes may also be useful in other settings where unwanted sea turtle interactions occur. For example, sea turtles are known to enter the seawater intakes for coastal power plants and desalination facilities (NRC 1990, Bresette et al 1998, Meakins & Al-Mohanna 2000). The St. Lucie power plant on Hutchinson Island, FL, draws in hundreds of sea turtles that result in a range of injuries (Norem 2005) as well as several mortalities each year (NRC 1990, Bresette et al. 1998). Overall mortality estimates due to power plants along the US Gulf and Atlantic coasts suggest that approximately 70 sea turtle deaths occur each year (NRC 1990). Additionally, sea turtles often interact with static fishing gear such as the coastal pound nets in Japan that can result in very high mortality rates (Ishihara 2007). Placing shark shapes near the openings of power plant intakes or along the leader nets that guide sea turtles into coastal pound nets may potentially reduce accidental interactions and lower mortality.

Net illumination experiments

In longline fisheries, lightsticks are placed near baited hooks and are thought to provide a visual cue that increases sea turtle interactions (Watson et al. 2005, Southwood et al. 2008). Results from behavioral experiments show that these light sources influence the orientation of hatchling and captive-reared juvenile loggerhead sea turtles (*Caretta caretta*) (Wang et al. 2007). Studies with post-frenzy-stage leatherback turtles, however, (Gless et al. 2008) indicate no orientation influence, which suggests potential interspecific and ontogenetic behavioral differences. Lightsticks, nonetheless, may attract some species and some age classes of sea turtles (Wang et al. 2007). In contrast, placing light sources on gill nets decreases green turtle catch rates (Figs. 3a & 4a). These findings indicate that, while turtle behaviors are altered, the illuminated nets provide the necessary visual cue to help turtles decrease their chances of becoming entangled.

The spacing of lights and the radiometric differences of light sources may be important factors in the reduction of sea turtle catch rates. Chemical lightsticks placed every 5 m resulted in a larger decrease (59%) in mean turtle catch rates than nets with LED lights placed every 10 m (40%). These results imply that either increasing the amount of lights reduces sea turtle interaction rates or that chemical lightsticks are better than LED lights at preventing turtle entanglement. LEDs and chemical lightsticks have a variety of radiometric differences. LED lights have narrower spectra and greater irradiance, while chemical lightsticks have broader spectra containing multiple peaks and less irradiance, which decays over time (Wang et al. 2007, Gless et al. 2008). Regardless, wavelengths emitted from the 2 light sources are well within the range of sea turtle visual sensitivities (Mathger et al. 2007, Fritsches & Warrant 2006), which suggests that increased lights on nets may be the more important factor. Nonetheless, further experimentation will be needed to maximize the efficiency of illuminated nets.

With regards to effects on target species, illuminating commercial bottom-set gill nets resulted in a negligible difference between the CPUE of target fish on illuminated nets and control nets (Figs. 3b & 4b). Consequently, the market value between nets was also statistically indistinguishable (Figs. 3c & 4c). These results suggest that net illumination could be amenable to fishermen if there are minimal added costs. Unfortunately, however, the cost of illumination is relatively high and will need to be reduced in order to make this strategy more adoptable.

The costs of illuminating nets vary greatly depending on the techniques and materials used to illuminate a net at night. Disposable chemical lightsticks range between US$0.10 to US$1.00 per lightstick (depending on the manufacturer) and the initial costs are substantially cheaper than battery-powered LED lights, which can range from US$10 to US$40 each. Chemical lightsticks, however, only produce light for up to 24 h, while the LED lights can remain continuously illuminated for over 1 mo. Chemical lightsticks offer an initially less expensive illumination method, though over an entire fishing season battery-powered LED lights may become more cost effective and will result in less plastic waste. In the case of our experiments, the costs of chemiluminenscent (US$30 per 200 m of net) and LED light (US$700 per 200 m of net) illumination methods are cost-prohibitive for a fishery that produces catches of relatively low value. As such, determining how best to maximize the effectiveness of the light sources while developing cheaper and more efficient methods of illuminating nets are important necessary steps.

An alternative to illuminating gill nets with lightsticks is to weave nets out of materials that glow in the dark. By adding luminescent materials such as strontium aluminate ($SrAl_2O_4$) to monofilament and nylon rope during the manufacturing process, the net material becomes photoluminescent. Nets made from these materials can be laid out in sunlight, allowed to absorb solar energy, and used at night as they glow. Depending on the fishing depth, turbidity of water, and other environmental factors, luminescent nets could be effective even during the daytime. Such luminescent nets are currently being designed and tested in fisheries that interact with marine mammals (Werner et al. 2006).

Another consideration is to make strategic portions of nets more selectively visible to sea turtles than to target species. For example, Melvin et al. (1999) significantly reduced the bycatch of seabirds by replacing the transparent nylon netting on either the upper 10 or 25 % of gill nets with a highly visible white nylon cord. The white cord created a visible deterrent on the shallow-most portions of the surface gill net, where seabird entanglement typically occurred. Since target fish catch occurred mostly in the deeper portions of the net, the transparent netting continued to catch target fish at the same rate. A similar approach could be adapted to reduce the bycatch of sea turtles in surface gill nets given that sea turtles spend the majority of their time at or near the surface (Polovina et al. 2002, Swimmer et al. 2006), whereas target fish species may approach from greater depths.

CONCLUSIONS

Results from net illumination experiments illustrate the potential for modifying current fishing gear with visual deterrents to effectively reduce sea turtle catch rates. This simple measure requires relatively minimal effort on the part of fishermen and, based on the findings presented here, should not substantially impact target species catch rates or catch value. The costs, however, are currently prohibitive, and solutions will require further development to render them more cost-effective and improve likelihood of adoption. While the shark shape predator model concept shows promise in reducing sea turtle interaction rates, the negative impact on target species catch rates and resulting loss of revenue suggests that they would not be readily adopted in their present form. Future goals include further modifying shark shapes to improve target species catch rates, developing more cost-effective net illumination methods, and testing net illumination in other commercial fisheries.

By working in these 2 locations in Baja California, Mexico, we have developed a model for initially testing sea turtle bycatch mitigation strategies that can be exported to improve the selectivity of coastal gill net fisheries. However, the efficacy of these strategies in actual fishery settings will be influenced by numerous factors, may vary depending on the species and age class of the sea turtles caught, and will require testing in those specific fisheries. As such, continued collaborations with fishing communities are vital in order to identify the best possible solutions for balancing sea turtle conservation goals while maintaining economic viability of fisheries.

Acknowledgements. We thank the following Ocean Discovery Institute students for their hard work and willingness to tackle diverse challenges: E. Alva, A. Alvarez, U. Barraza, C. Castro, C. Corado, L. Cueva, K. C. Dam, A. C. Figueroa, Y. Mehari, D. Mercado, N. Rangel, M. Rivera, A. Rodriguez, S. Sillas, S. Thang, T. Tran, and E. Trujillo. We also thank the fishers and communities of Punta Abreojos, Baja California, Mexico, in particular the members of Grupo Tortugero de las Californias, including I. Arce, R. Lopez Espinosa, A. Camacho Liera, I. Patrón de la Toba, J. Villavicencio, F. Valenzuela Zuniga and M. Valenzuela Zuniga; and the fishers and communities of Bahía de los Angeles, Baja California, Mexico, in particular H. Romero Arce, E. Paredes Arroyo, E. Ocaña Fuerte, R. Ocaña Fuerte, F. Verdugo Leree, H. Morales Romero, E. Cordero Rubio, B. Morales Valdez, and B. Navarro Verdugo. We thank E. Ezcurra and A. Resendiz for their support and expertise and also the Comisión Nacional de Áreas Naturales Protegidas (B. Bermudez, A. Zavala Gonzalez, and C. Godinez Reyes). In addition, we thank K. Dean, C. Fahy, S. Green, B. Higgins, T. T. Jones, E. Kane, D. Lawson, M. Lopez, C. Marshall, W. J. Nichols, J. Rodriguez, A. Salazar, J. Sandoval, and J. Seminoff. We also thank the staff of the Ocean Discovery Institute, including S. Akhtar, S. Blakeslee, A. Correia, E. Finkbeiner, L. Hall, C. Hooven, M. Kansteiner, M. Katigbak, K. C. Nguyen, M. Ortega, L. Peavey, C. Pisbe, E. Ruiz, V. Sandoval, and M. Simon. We thank L. Benaka for his continued support and K. Bigelow, C. Boggs, G. Balaz, M. Snover, and 3 anonymous reviewers for their comments and suggestions. This work was supported by NMFS-PIFSC, NMFS–SWFRO, NOAA-BREP, the Hawaii FDRP, and the following supporters of Ocean Discovery Institute: CONACYT, International Community Foundation, JiJi Foundation, J. W. Sefton Foundation, Marisla Foundation, Fund of the Orange County Community Foundation, PADI Foundation Project Aware. The Mexican government through the Comisión Nacional de Áreas Naturales Protegidas (CONANP) authorized this research. All animal handling procedures were in compliance with the IACUC protocols of the University of Hawaii, Manoa. The work described in this paper was sponsored by the Joint Institute for Marine and Atmospheric Research under Cooperative Agreement N-A17RJ1230 from NOAA.

LITERATURE CITED

Bresette M, Gorham J, Perry B (1998) Site fidelity and size frequencies of juvenile green turtles (*Chelonia mydas*) utilizing near shore reefs in St. Lucie County, Florida. Mar Turtle Newsl 82:5–7

Chan EH, Liew HC (1996) Decline of the leatherback population in Terengganu, Malaysia, 1956–1995. Chelonian Conserv Biol 2:196–203

➤ Chan EH, Liew HC, Mazlan AG (1988) The incidental capture of sea turtles in fishing gear in Terengganu, Malaysia. Biol Conserv 43:1–7

Cliffton K, Cornejo DO, Felger RS (1982) Sea turtles of the Pacific coast of Mexico. In: Bjorndal KA (ed) Biology and conservation of sea turtle. Smithsonian Institution Press, Washington, DC, p 199–209

Constantino MA, Salmon M (2003) Role of chemical and visual cues in food recognition by leatherback posthatchlings (*Dermochelys coriacea*). Zoology 106:173–181

Crognale M, Eckert S (2007) Spectral and temporal sensitivity of adult and hatchling leatherback sea turtles. In: Swimmer Y, Wang, JH (eds) 2006 sea turtle and pelagic fish sensory workshop, Sept 12–13, 2006. National Oceanic and Atmospheric Administration, Honolulu, HI. NOAA Tech Memo NMFS-PIFSC-12, p 9–12

Fritsches KA, Warrant E (2006) Differences in the visual capabilities of sea turtles and blue water fishes—implication for bycatch reduction. In: Swimmer Y, Brill R (eds) Sea turtle and pelagic fish sensory biology: developing techniques to reduce sea turtle bycatch in longline fisheries. National Oceanic and Atmospheric Administration, Honolulu, HI. NOAA Tech Memo NMFS-PIFSC-7, p 1–7

Fritsches KA, Partridge J, Pettigrew JD, Marshall NJ (2000) Colour vision in billfish. Philos Trans R Soc Lond B 355: 1253–1256

Gilman E, Zollet E, Beverly S, Nakano H and others (2006) Reducing sea turtle by-catch in pelagic longline fisheries. Fish Fish 7:2–23

Gilman E, Kobayashi D, Swenarton T, Brothers N, Dalzell P, Kinan-Kelly I (2007) Reducing sea turtle interactions in the Hawaii-based longline swordfish fishery. Biol Conserv 139:19–28

Gilman E, Gearhart J, Price B, Eckert S and others (2009) Mitigating sea turtle bycatch in coastal passive net fisheries. Fish Fish 11:57–88

Gless JM, Salmon M, Wyneken J (2008) Behavioral responses of juvenile leatherbacks *Dermochelys coriacea* to lights used in the longline fishery. Endang Species Res 5: 239–247

Heithaus MR, Frid A, Dill LM (2002) Shark-inflicted injury frequencies, escape ability, and habitat use of green and loggerhead turtles. Mar Biol 140:229–236

Heithaus MR, Frid A, Wirsing A, Bejder L, Dill LM (2005) Biology of sea turtles under risk from tiger sharks at a foraging ground. Mar Ecol Prog Ser 288:285–294

Heithaus MR, Wirsing AJ, Thomson JA, Burkholder DA (2008) A review of lethal and non-lethal effects of predators on adult marine turtles. J Exp Mar Biol Ecol 356:43–51

Higgins B (2006) Shark decoy experiments. In: Swimmer Y, Brill R (eds) Sea turtle and pelagic fish sensory biology: developing techniques to reduce sea turtle bycatch in longline fisheries. National Oceanic and Atmospheric Administration, Honolulu, HI. NOAA Tech Memo NMFS-PIFSC-7, p 77–86

Ishihara T (2007) Japan coastal bycatch investigations. In: North Pacific Loggerhead Sea Turtle Expert Workshop December 19–20, 2007. Western Pacific Regional Fishery Management Council and US National Marine Fisheries Service, Honolulu, HI, p 21–22

Lewison RL, Crowder LB (2007) Putting longline bycatch of sea turtles into perspective. Conserv Biol 21:79–86

Lewison RL, Freeman SA, Crowder LB (2004) Quantifying the effects of fisheries on threatened species: the impact of pelagic longlines on loggerhead and leatherback sea turtles. Ecol Lett 7:221–231

Lohmann KJ, Wang JH (2007) Behavioral responses of sea turtles to prototype experimental lightsticks. In: Swimmer Y, Wang JH (eds) 2006 Sea Turtle and Pelagic Fish Sensory Workshop, Sept 12–13, 2006. NOAA Tech Memo NMFS-PIFSC-12, p 15–17

López-Castro, MC, Koch V, Mariscal-Loza A, Nichols WJ (2010) Long term monitoring of black turtles (*Chelonia mydas*) at coastal foraging areas of the Baja California Peninsula, México. Endang Spec Res 11:35–45

Lum LL (2006) Assessment of incidental sea turtle catch in the artisanal gill net fishery in Trinidad and Tobago, West Indies. Appl Herpetol 3:357–368

Marsh RE, Erickson WA, Salmon TP (1992) Scarecrows and predator models for frightening birds from specific areas. In: Borrecco JE, Marsh RE (eds) Proc Fifteenth Vertebrate Pest Conf, March 3–5, 1992. University of California, Davis, CA, p 112–114

Mathger LM, Litherland L, Fritsches KA (2007) An anatomical study of the visual capabilities of the green turtle, *Chelonia mydas.* Copeia 2007(1):169–179

McCracken ML (2004) Modeling a very rare event to estimate sea turtle bycatch: lessons learned. National Oceanic and Atmospheric Administration, Honolulu, HI. NOAA Tech Memo NMFS-PIFSC-3

Meakins RH, Al-Mohanna SY (2000) Sea turtles in Kuwait after the Gulf War. Mar Turtle Newsl 88:7–8

Melvin E, Parrish J, Conquest L (1999) Novel tools to reduce seabird bycatch in coastal gill net fisheries. Conserv Biol 13:1386–1397

Moein Bartol S, Musick JA (2003) Sensory biology of sea turtles. In: Lutz PL, Musick JA, Wyneken J (eds) The biology of sea turtles, Vol 2. CRC Press, Boca Raton, FL, p 79–102

Moein Bartol S, Musick JA, Ochs AL (2002) Visual acuity thresholds of juvenile loggerhead sea turtles (*Caretta caretta*): an electrophysiological approach. J Comp Physiol A 187:953–960

NRC (National Research Council) (1990) Decline of the sea turtles: causes and prevention. National Academy Press, Washington, DC

Nichols WJ (2003) Biology and conservation of sea turtles in Baja California, Mexico. PhD dissertation, University of Arizona, Tucson, AZ

Norem AD (2005). Injury assessment of sea turtle utilizing the neritic zone of the southeast United States. MS thesis, University of Florida, Gainesville, FL

Northridge S (1991) Driftnet fisheries and their impacts on non-target species: a worldwide review. FAO Fish Tech Pap 320. FAO, Rome

Peckham SH, Maldonado Diaz D, Walli A, Ruiz G and others (2007) Small-scale fisheries bycatch jeopardizes endangered Pacific loggerhead turtles. PLoS ONE 2(10): e1041, doi: 10.1371/journal.pone.0001041

Peckham SH, Maldonado Diaz D, Volker K, Mancini A, Gaos A, Tinker MT, Nichols WJ (2008) High mortality of loggerhead turtles due to bycatch, human consumption and strandings at Baja California Sur, Mexico, 2003 to 2007. Endang Species Res 5:171–183

Polovina JJ, Howell E, Parker DM, Balazs GH (2002) Dive depth distribution of loggerhead (*Caretta caretta*) and olive ridley (*Lepidochelys olivacea*) sea turtles in the central North Pacific: Might deep longline sets catch fewer turtles? Fish Bull 101:189–193

Read AJ (2007) Do circle hooks reduce the mortality of sea turtles in pelagic longlines? A review of recent experiments. Biol Conserv 135:155–169

Salmon M, Wyneken J (2007) Visual physiology and orientation of juvenile leatherbacks and loggerheads. In: Swimmer Y, Wang JH (eds) 2006 Sea Turtle and Pelagic Fish Sensory Workshop, Sept 12–13, 2006. National Oceanic and Atmospheric Administration, Honolulu, HI. NOAA Tech Memo NMFS-PIFSC-12, p 5–8

Southwood AL, Fritches K, Brill R, Swimmer Y (2008) Sound, chemical, and light detection in sea turtles and pelagic fishes: sensory based approaches to bycatch reduction in longline fisheries. Endang Species Res 5:225–238

Swimmer Y, Brill R (2006) Sea turtle and pelagic fish sensory biology: developing techniques to reduce sea turtle bycatch in longline fisheries. National Oceanic and Atmospheric Administration, Honolulu, HI. NOAA Tech Memo, NMFS-PIFSC-7

Swimmer Y, Arauz R, Higgins B, McNaughton L, McCracken M, Ballestro J, Brill R (2005) Food color and marine turtle feeding behavior: Can blue bait reduce turtle bycatch in commercial fisheries? Mar Ecol Prog Ser 295:273–278

Swimmer Y, Arauz R, McCracken M, McNaughton L and others (2006) Diving behavior and delayed mortality of olive ridley sea turtles *Lepidochelys olivacea* after their release from longline fishing gear. Mar Ecol Prog Ser 323:253–261

Wang JH, Swimmer Y (2007) Preliminary field experiments in Baja California, Mexico with lightsticks and shark shapes. In: Swimmer Y, Wang JH (eds) 2006 Sea Turtle and Pelagic Fish Sensory Workshop, Sept 12–13, 2006. National Oceanic and Atmospheric Administration, Honolulu, HI. NOAA Tech Memo NMFS-PIFSC-12, p 18–19

Wang JH, Boles LC, Higgins B, Lohmann KJ (2007) Behavioral responses of sea turtles to lightsticks used in longline fisheries. Anim Conserv 10:176–182

Watson JW, Epperly SP, Shah AK, Foster DG (2005) Fishing methods to reduce sea turtle mortality associated with pelagic longlines. Can J Fish Aquat Sci 62:965–981

Werner T, Kraus S, Read A, Zollett E (2006) Fishing techniques to reduce the bycatch of threatened marine animals. Mar Technol Soc J 40:50–68

Witherington BE, Bjorndal KA (1991) Influences of wavelength and intensity on hatchling sea turtle phototaxis: implications for sea-finding behavior. Copeia 1991: 1060–1069

Editorial responsibility: Konstantinos Stergiou,
Thessaloniki, Greece

Submitted: September 3, 2009; Accepted: March 9, 2010
Proofs received from author(s): May 14, 2010