Reducing green sea turtle bycatch in small-scale fisheries using illuminated gillnets: The Cost of Reducing Sea Turtle Bycatch

by

Natalia Ortiz[1], Jeffrey C. Mangel[1,2,*], John Wang[3], Joanna Alfaro-Shigueto[1,2], Sergio Pingo[1], Astrid Jimenez[1], Tania Suarez[1], Yonat Swimmer[3], Felipe Carvalho[3,4], Brendan J. Godley[2]

1. ProDelphinus, Octavio Bernal 572-5, Lima 11, Peru

2. Centre for Ecology and Conservation, University of Exeter,

Penryn, Cornwall, TR10 9EZ, UK

3. NOAA – Pacific Islands Fisheries Science Center, Honolulu, HI, USA

4. University of Hawaii, Joint Institute for Marine and Atmospheric

Research. Honolulu, HI, USA

* Email: J.Mangel@exeter.ac.uk

Keywords: LEDs; green sea turtles; CPUE; small-scale fishery; gillnets; bycatch; Peru.

Running page head: Net illumination reduces sea turtle bycatch in Peruvian gillnet fisheries

Abstract

Gillnet fisheries exist throughout the oceans and have been implicated in high bycatch rates of sea turtles. In this study, we examined the effectiveness of illuminating nets with light-emitting diodes (LEDs), placed on floatlines in order to reduce the sea turtle bycatch in a small-scale bottom-set gillnet fishery. In Sechura Bay, Northern Peru, 114 pairs of control and experimental nets were deployed. The predicted mean Catch Per Unit of Effort (CPUE) of target species, standardized for environmental variables using generalized additive model analysis, was similar for both control and experimental nets. In contrast, the predicted mean CPUE of green sea turtles (*Chelonia mydas*) was reduced by 63.9% in experimental nets. One hundred twenty-five green sea turtles were caught in control nets while 62 were caught in experimental nets illuminated by LEDs. This statistically significant ($p<0.05$) reduction in sea turtle bycatch suggests that net illumination could be an effective conservation tool. Challenges to implementing the use of LEDs include equipment costs, increased net handling times, and limited awareness among fishermen regarding the effectiveness of this technology. Cost estimates for preventing a single sea turtle catch range from $32 to $196 USD with a tendency to decrease over time, while the costs to outfit the fishery in Sechura Bay range from $19.3K to $33.4K USD. Understanding these cost challenges emphasizes the need for institutional support from National ministries and international non-governmental organizations in order to more broadly implement net illumination as a sea turtle bycatch reduction strategy.

I. Introduction

The unintentional take of species, or bycatch (Hall *et al*., 2000), in industrial and small-scale fisheries is a major threat to many marine taxa such as seabirds, sea turtles, and marine mammals (Peckham *et al*., 2007; Soykan *et al*., 2008; Gilman *et al*., 2010; Mangel *et al*., 2010; Anderson *et al*., 2011). Previous studies implicate high-seas industrial fisheries, such as driftnets and longlines, in the dramatic population declines of several species (Lewison *et al*., 2004; Camhi *et al*., 2009). More recent work also shows that small-scale fisheries pose a significant threat to endangered marine species due to a range of factors. Despite being defined by their minor use of mechanization and their smaller size and tonnage capacity (Chuenpagdee *et al*., 2006; Jacquet & Pauly, 2008), small-scale fisheries have large fleet sizes, high relative density of fishing capacity occurring in highly productive coastal oceans where many threatened species co-occur, and limited control and enforcement measures (Peckham *et al*., 2007; Soykan *et al*., 2008; Alfaro-Shigueto *et al*., 2010, 2011; Moore *et al*., 2010; Stewart *et al*., 2010).

To help limit the negative impacts of fisheries, bycatch reduction technologies (BRTs) have been developed for a limited number of fisheries (Cox *et al*., 2007). For sea turtles, most efforts have focused on the use of circle hooks in longline fisheries (Gilman *et al*., 2006; Serafy *et al*., 2012) and the use of Turtle Excluder Devices (TEDs) in shrimp trawl fisheries (Crowder *et al*., 1994, 1995; Watson *et al*., 2005; Lewison & Crowder, 2006; Read, 2007; Jenkins, 2011). In contrast, the development of bycatch mitigation measures for gillnets, one of the most ubiquitous gear types, has been relatively slow (Melvin *et al*., 1999; Gilman *et al*., 2006).

Peru's gillnet fleet comprises the largest component of the nation's small-scale fleet and is conservatively estimated to set 100,000 km of net per year (Alfaro-Shigueto *et al*., 2010). Recent studies clearly show that gillnet fisheries in Peru have high interaction rates with sea turtles and exert significant pressure on sea turtle populations throughout the Pacific (Wallace *et al*., 2010; Alfaro-Shigueto *et al*., 2011; Lewison *et al*., 2014). Multiple populations of sea turtle species use Peruvian coastal waters as foraging grounds (Hays-Brown & Brown, 1982; Shillinger *et al*. 2008; Boyle *et al.*, 2009; Dutton *et al*., 2010; Gaos *et al*., 2010; Velez-Zuazo & Kelez, 2010; Alfaro-Shigueto *et al*., 2011). This includes green sea turtles (*Chelonia mydas*), olive ridley (*Lepidochelys olivacea*) and hawksbill (*Eretmochelys imbricata*) sea turtles that occur throughout the eastern Pacific region, and loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) sea turtles from both the eastern and western Pacific (Hays-Brown & Brown, 1982; Eckert & Sarti, 1997; Alfaro-Shigueto *et al*., 2004; Seminoff *et al*., 2008; Boyle *et al*., 2009; Velez-Zuazo & Kelez, 2010). Studies also indicate that the green sea turtle is the sea turtle species most frequently caught in Peruvian net fisheries, varying between 84.9% and 98.5% according to the fishing port (Alfaro-Shigueto *et al*., 2010, 2011). In Constante, Peru, Alfaro-Shigueto *et al*. (2011) estimated that 321 green sea turtles were caught annually in the bottom set gillnet fishery.

Reducing bycatch, particularly in gillnets, could help with management and eventual recovery of these populations. However, there are few bycatch mitigation measures in place to reduce sea turtle interactions with coastal gillnet fisheries (Cox *et al*., 2007; Gilman *et al*., 2010; Wang *et al*., 2010, 2013). One strategy for developing effective mitigation measures includes the consideration of the ecology, physiology, and behaviours of bycatch species (Southwood & Avens 2010; Jordan *et al*., 2013). Sea turtles such as loggerheads, leatherbacks, and green sea turtles have been shown to rely extensively on visual cues (Constantino & Salmon, 2003; Wang *et al*., 2007; Young *et al*., 2012), particularly when foraging (Swimmer *et al*., 2005; Southwood *et al*., 2008; Wang *et al*., 2010). Recent bycatch mitigation studies exploiting this reliance on visual cues suggest that net illumination may be an effective visual alert in the reduction of sea turtle interactions with gillnets (Wang *et al*., 2010, 2013). These studies used either light-emitting diode (LED) lightsticks or chemical lightsticks to illuminate portions of nets and were shown to reduce sea turtle catch rates, while maintaining the overall target catch rates and catch values (Wang *et al*., 2010, 2013). In this study, we sought to 1) assess the effectiveness of net illumination with LEDs to reduce the bycatch of green sea turtles in a bottom-set gillnet fishery in Peru, 2) assess the effect of LED lights on target species catch rates and 3) calculate the cost to reduce the bycatch of a sea turtle.

II. Materials and Methods

Net trials were conducted from January 2011 to July 2013 in Sechura Bay, along the north coast of Peru (05°40'S, 80°95'W) (Fig. 1). Trials were undertaken using typical fishing practices and as part of regular fishing trips, on eleven different fishing vessels that departed from the port of Constante, Peru. Fishing vessels ranged in length from 6 to 10m and each trip consisted of setting a pair of bottom set gillnetswhich were already in use by fishermen in the Constante small-scale fishery. Bottom gillnets were made of multifilament rope and were composed of multiple net panes that measured 56.4 meters long by 2.8 meters high, with a stretched mesh of approximately 24 cm. The number of gillnet panes set each evening varied slightly, depending on the fishing crew, but averaged 11 panes (Table 1). Nets were typically deployed in the late afternoon, soaked overnight, and retrieved the following morning. For each pair, there was a control and an experimental net. The experimental net had green LED lights (Centro Power Light Model CM-1, Centro Co., Ltd., Korea) placed every 10 m along the float line. Pairs of nets in each set were separated by a minimum of 200 m to avoid illumination of control nets.

Observers monitored control and experimental nets for each sampling day. As described in Alfaro-Shigueto *et al.* (2008), observers were trained in collection of data specific to the fishery operation, including methods of identifying, handling and collecting data on target and bycatch species. Observers recorded information on gear characteristics (e.g., net size and number of panes) and information for each set (e.g., location, time of set and haul, sea surface temperature, water depth, and water visibility) using GPS, watches, thermometers, and secchi disks. They also recorded sea turtle bycatch and curved carapace length (CCL; notch to tip (cm)) of all sea turtles. Live sea turtles were released in accordance with internationally recognized guidelines (Epperly *et al*., 2004). Finally, observers also recorded target species catch number. The primary target species in this fishery were flounder species (*Paralichtys* spp) and guitarfish (*Rhinobatos planiceps*). In addition, other ray species from Rajidae, Urotrygonidae, Dasyatidae and Rhinopteridae families were also captured and pooled in the analysis of target species.

The effect of net illumination on green sea turtles and target species catch rates was estimated with generalized additive models (GAMs) using the statistical modelling program R 2.15.1 (R Development Core Team 2011). GAMs were used to predict relative abundance of green sea turtles and target species between control and experimental nets based on estimates of catch rates and regional environmental covariates at fishing locations. GAMs have the possibility of fitting nonlinear relationships between the response variable and independent covariates. In this study, preliminary exploratory scatter plots indicated non-linear relationships between the dependent variable and covariates. Two GAMs were fit separately to green sea turtles and target species catch rates by net type (illuminated versus control) with an offset to account for variations in effort. Due to the large number of zero observations for the green sea turtles group, a GAM was developed using a negative binomial distribution, while in the GAM for the target species group a Poisson distribution was applied. In order to find the most parsimonious GAM, we used standard selection criteria (Akaike Information Criteria, AIC; and Bayesian Information Criteria, BIC) to determine which covariates best explained the variability in the data. We started building the model with net type and each of the other covariates separately (Stage I). We selected the best model using AIC and BIC, and moved to the next stage. Stages II to IV built on the initial model, with each additional predictor considered one at a time. The dependent variable in the models was catch rate and included the following covariates: sea surface temperature (SST), lunar index of the illuminated percentage of lunar light calculated from an astronomical algorithm (Meeus, 1991), depth at the fishing location, water visibility, and net type. Both models were fit using the ‘mgcv’ package in the R version 3.1.0 environment.

Additionally, two-sample t-tests were used to analyse differences in body size for sea turtles and guitarfish between control and experimental nets.

III. Results

Fishing effort

A total of 114-paired nets were deployed. The total number of panes used in each net varied slightly among boats and within trips as some panes were added to increase target species catch or were removed for repair. Therefore, net length varied; control nets averaged 0.62 ± 0.03 standard error (SE) km, while illuminated nets averaged 0.59 ± 0.02 (SE) km (Table 1). Soak time for control nets averaged 17.06 ± 0.39 (SE) h, while experimental nets averaged 17.38 ± 0.39 (SE) h (Table 1). The fishing effort for each net deployment was calculated by combining net length and soak time (km*24 h soak). The mean fishing effort averaged 0.43 ± 0.02 (SE) (km*24 h) for control nets, while illuminated nets averaged 0.42 ± 0.01 (SE) (km*24 h) (Table 1).

Target species catch

Of the 2,387 target species fish caught, 1,211 (51%) were caught in control nets and 1,176 (49%) were caught in illuminated nets (Table 2). Flounders, guitarfish, and various ray species comprised 8%, 30%, and 63% of the target catch by quantity. The final model explained 44.3% of the deviance (Table 3). All of the covariates in the final model were found to be significant ($p < 0.05$) and were included in the final model (Table 3). The predicted mean CPUE of target species was not significantly affected by the presence of LEDs (Table 4, Fig. 2). Target species catch rates were similar between paired nets with a predicted mean CPUE of 10.62 (± 0.71 SE) for target species $(\text{km}*24\ \text{h})^{-1}$ in control nets and a predicted mean CPUE of 10.35 (± 0.86 SE) for target species $(\text{km}*24\ \text{h})^{-1}$ in experimental nets (Table 4 and Fig. 2).

Sea turtle bycatch

A total of 194 sea turtles were caught during the study period. 125 green sea turtles (Table 2), 3 hawksbills and 1 olive ridley were caught in the control nets. The illuminated nets caught 62 green sea turtles (Table 2) and 3 hawksbills. The GAM analysis was only conducted for green sea turtles since they comprised the majority of sea turtles caught. The final model explained 52% of the deviance (Table 3). All of the covariates in the final model were found to be significant ($p < 0.05$) and were included in the final model (Table 3). The catch rate of green sea turtles was significantly ($p < 0.05$) affected by the presence or absence of LEDs (Table 4, Fig. 2). Analysis with GAMs indicated that the predicted mean CPUE of 1.40 (± 0.16 SE) green sea turtles $(\text{km}*24\ \text{h})^{-1}$ in control nets was significantly ($p = 0.04$) reduced by 63.9% in illuminated nets to a predicted mean CPUE of 0.50 (± 0.06 SE) green sea turtles $(\text{km}*24\ \text{h})^{-1}$ (Table 4 and Fig. 2).

CCL for green sea turtles in control nets averaged 55.5 ± 7.9 (SE) cm and 57.4 ± 9.8 (SE) cm in illuminated nets (Table 6). CCL was not significantly influenced by the presence or absence of LEDs (Two-sample t-test, $t_{182} = 1.42$, $p = 0.16$).

Costs to save a sea turtle

LEDs are the most economically viable option available for illuminating nets as they have a robust design and multi-year functional life (Wang et al., 2010, 2013). Additionally, given the maturation of LED manufacturing, the cost of a single LED lightstick has fallen to between $2 and $10 USD. A typical boat in this fishery utilizes 2200 m of net and would require at least 221 lights, and will, therefore, have an initial cost of implementation ranging between $2,420 and $4,180 USD.

Using Alfaro-Shigueto et al.'s (2011) annual estimate of green sea turtle bycatch for this gillnet fishery based in Constante, the observed reduction in bycatch reported here (ca. 63%), and the projected costs involved in equipping the Constante fleet with LED lights ($2,420-$4,180 per vessel), we estimate the cost of preventing a single sea turtle interaction to range from $96 to $197 in the first year (Table 5). Since these LED lights can last multiple fishing seasons, this initial cost could be amortized over multiple years and over a three-year lifespan of the LED lights, reducing costs to save a sea turtle from $31.95 to $65.50 (Table 5).

IV. Discussion

Small-scale fishing activity in Peru represents a major source of income for more than 500,000 people in coastal communities with few economic resources other than those related to fishing (Alvarez, 2003). Any changes to target species catch rates can affect their livelihoods. Our study shows that using green LEDs to illuminate nets as a bycatch mitigation measure in the small-scale bottom set gillnet fishery in Sechura Bay, Peru could substantially reduce green sea turtle bycatch without affecting target species catch rates, and could, therefore, serve as an effective sea turtle BRT for this type of fishery.

Managing the bycatch of sea turtles in gillnets would promote the long-term stability of both sea turtle populations and local fisheries. This will require particular attention if international obligations and agreements are to be fulfilled by Peru, as well as other nations throughout the region that possess similar small-scale fisheries (Alvarez, 2003; Salas *et al.,* 2007). There are thousands of small-scale net vessels operating in Peru catching many thousands of sea turtles per annum (Alfaro-Shigueto *et al*., 2011).If the use of lights could be deemed effective and implemented more broadly, the potential positive impacts to sea turtle populations in the region are sizeable.

Coastal gillnets interact with sea turtles globally (Wallace *et al*., 2010). For example, net fisheries along the eastern seaboard of the United States (Gearhart, 2003), along the Pacific coast of Mexico (Peckham *et al*., 2007), within the Mediterranean (Echwikhi *et al.*, 2010; Casale, 2011; Snape *et al*., 2013) and in the Caribbean (Lum, 2006), have been shown to have high rates of interactions with sea turtles. It will be important to replicate this study in multiple locations and fisheries to assess the effectiveness of net illumination in a variety of gear designs, environmental conditions, and potential catch compositions (Southwood *et al*., 2008; Gilman *et al*., 2010). In order to effectively implement net illumination or other mitigation methods, any future studies need to consider costs and implications for fishermen, their target species catch, and the effect on other bycatch species (Cox *et al*., 2007). Trials of this BRT in small-scale fisheries could serve as an important step in the global conservation of sea turtles.

Understanding the costs associated with this BRT helps provide a better awareness of the necessary challenges for its broader implementation. Even with the lowest priced LEDs spread across multiple years, the cost still represents an untenable amount in comparison to the incomes of Peruvian small-scale fishers. In Constante, for example, Alfaro-Shigueto *et al.* (2011) estimated the per trip net profit at only $82 USD. This indicates that efforts are needed at the National ministerial or international non-governmental levels to leverage financial support from such institutions if this BRT is to be broadly implemented. In addition, by having an approximate cost to prevent a single sea turtle interaction ($32 to $196 USD) as well as the costs to outfit the fisheries ($19.3K to $33.4K USD), economic analyses could be better refined when considering other potential conservation measures such as fisheries closures, time area closures and development of marine reserves (Balmford *et al*., 2004; McClanahan *et al*., 2006).

Despite the challenges to the implementation of net illumination in small-scale fisheries (e.g. cost, light stick design, fisher awareness), our results emphasize the effectiveness of controlled fisheries experiments for the testing of bycatch reduction measures in small-scale gillnet fisheries. This work also highlights the value of using an understanding of the sensory physiology of bycatch animals as a foundation for the development of bycatch reduction technologies (Southwood *et al.*, 2008; Jordan *et al.*, 2013; Martin & Crawford, 2015) and suggests that similar technologies could be developed for other bycatch taxa. Future studies with net illumination should examine its potential usefulness as a multi-taxa BRT for elasmobranchs, seabirds, and marine mammals as these animals also rely heavily on visual cues (Jordan *et al.*, 2013; Martin & Crawford 2015, Schakner & Blumstein, 2013). In addition, continued development of LED lights could improve their efficiency and should include assessments of the light's batteries to ensure optimal performance. Solar powered LEDs could also be developed in order to reduce the cost and waste associated with batteries and would have the added benefit of helping ensure continuous charge. Fishermen involved with the trials were primarily positive and provided essential feedback, which included encouragement to develop LED light sticks designed specifically for net fisheries. Such continued collaborations with fishermen and their fishing communities will be critically important in the continued development and testing of net illumination as well as other bycatch strategies for small-scale fisheries.

V. Acknowledgements

We thank the following field assistants who participated in data collection: E. Alfaro, N. Balducci, E. Campbell, T. Clay, P. Doherty, A. Luna, H. Parra, A. Pasara, and A. Ugolini. We also thank the fishermen and their families at Constante, Piura, Peru for their support on every fishing trip. This work and study was supported by ProDelphinus, the Darwin Initiative, the National Marine Fisheries Service of the National Oceanic and Atmospheric Administration, and the University of Hawaii Joint Institute for Marine and Atmospheric Research.

VI. References

Alfaro-Shigueto, J., Dutton, P.H., Mangel, J. & Vega, D. (2004). First confirmed occurrence of loggerhead turtles in Peru. *Marine Turtle Newsletter* **103**, 7-11.

Alfaro-Shigueto, J., Mangel, J., Seminoff, J.A. & Duton, P.H. (2008). Demography of loggerhead turtles *Caretta caretta* in the southeastern Pacific Ocean: fisheries based observations and implications for management. *Endang. Species Res.* **5**, 129-135.

Alfaro-Shigueto, J., Mangel, J., Pajuelo, M., Dutton, P.H., Seminoff, J.A. & Godley B.J. (2010). Where small can have a large impact: Structure and characterization of small-scale fisheries in Peru. *Fish. Res.* **106**, 8-17.

Alfaro-Shigueto, J., Mangel, J., Bernedo, F., Dutton, P.H., Seminoff, J.A. & Godley B.J. (2011). Small scale fisheries of Peru: a major sink for marine turtles in the Pacific. *J. Appl. Ecol.* **48**, 1432-1440.

Alvarez, J. (2003). Estudio sobre el impacto socioeconomico de la pesca artesanal en los Estados Miembros de la Comisión Permanente del Pacífico Sur. Reporte preparado para la Secretaria General-Dirección de Asuntos Económicos de la CPPS, 27 p.

Anderson, O.R.J., Small, C.J., Croxall, J.P., Dunn, E.K., Sullivan, B.J., Yates, O. & Blach, A. (2011). Global seabird bycatch in longline fisheries. *Endang. Species Res.* **14**, 91-106.

Balmford, A., Gravestock, P., Hockley, N., McClean, C.J. & Roberts, C.M. (2004). The worldwide costs of marine protected areas. *Proc. Natl. Acad. Sci.U.S.A.* **101**, 9694-9697.

Boyle, M.C., Fitz-Simmons, N.N., Limpus, C.J., Kelez, S., Velez-Zuazo, X. & Waycott, M. (2009). Evidence for transoceanic migrations by loggerhead sea turtles in the southern Pacific Ocean. *Proc. R. Soc B* **276**, 1993-1999.

Camhi, M.D., Valenti, S.V., Fordham , S.V., Fowler, S.L. & Gibson, C. (2009). The conservation status of pelagic sharks and rays: Report of the IUCN Shark Specialist Group Pelagic Shark Red List Workshop. IUCN Species Survival Commission Shark Specialist Group. Newbury, UK, 78 p.

Casale, P. (2011). Sea turtle by-catch in the Mediterranean. *Fish . Fish.* **12**, 299-316.

Chuenpagdee, R., Liguori, L., Palomares, M.L.D. & Pauly, D. (2006). Bottom –up, global estimates of small-scale fisheries catches. *Fisheries Center Research Report* **14**, 110.

Constantino, M.A. & Salmon, M. (2003). Role of chemical and visual cues in food recognition by leatherback posthatchlings (*Dermochelys coriacea* L). *Zoology* **106**, 173-181.

Cox, T.M., Lewison, R.L., Zydelis, R., Crowder, L.B., Safina, C. & Read, A.J. (2007). Comparing effectiveness of experimental and implemented bycatch reduction measures: the ideal and the real. *Conserv. Biol.* **21**, 1155-1164.

Crowder, L.B., Crouse, D.T., Heppell, S.S. & Martin, T.H. (1994). Predicting the impact of Turtle Excluder Devices on loggerhead sea turtle populations. *Ecol. Appl.* **4**, 437-445.

Crowder, L.B., Hopkins-Murray, S.R. & Royle, J.A. (1995). Effects of Turtle Excluder Devices (TEDs) on loggerhead sea turtle strandings with implications for conservation. *Copeia* **4**, 773-779.

Dutton, P.H., LaCasella, E.L., Alfaro-Shigueto, J. & Donoso, M. (2010). Stock origin of leatherback (*Dermochelys coriacea*) foraging in the southeastern Pacific. In: Blumenthal, J., Panagopoulou A. & Rees, A.F. (eds) Proceedings of the 30 Annual Symposium on sea turtle biology and conservation. NOAA Technical Memorandum NMFS-SEFSC-640, 91.

Echwikhi, K., Jribi, I., Bradail, M.J. & Bouain, A. (2010). Gillnet fishery – loggerhead turtle interactions in the Gulf of Gabes, Tunisia. *Herpetol. J.* **20**, 25-30.

Eckert, S.A. & Sarti, L. (1997). Distant fisheries implicated in the loss of the world's largest leatherback population. *Marine Turtle Newsletter* **78**, 2-7.

Epperly, S., Stokes., L. & Dick, S. (2004). Careful release protocols for sea turtle release with minimal injury. NOAA Technical Memorandum NMFS-SEFSC-524, 42.

Gaos, A.R., Abreu-Grobois, F.A., Alfaro-Shigueto, J., Amorocho, D., Arauz, R., Baquero, A., Briseño, R., Chacón, D., Dueñas, C., Hasbún, C., Liles, M., Mariona, G., Muccio, C., Muñoz, J.P., Nichols, W.J., Peña, M., Seminoff, J.A., Vásquez, M., Urteaga, J., Wallace, B., Yañez, I.L. & Zárate, P. (2010). Signs of hope in the eastern Pacific: international collaboration reveals encouraging status for the severely depleted population of hawksbill turtles *Eretmochelys imbricata*. *Oryx* **44**, 595-601.

Gearhart, J. (2003). Sea turtle bycatch monitoring of the 2002 fall flounder gillnet fishery of southeastern Pamlico Sound, North Carolina. Completion report for ITP 1398. North Carolina Department of Environment and Natural Resource, Division of Marine Fisheries. 39 p.

Gilman, E., Zolett, E., Beverly, S., Nakano, H., Davis, K., Shiode, D., Dalzell, P. & Kinan, I. (2006). Reducing sea turtle by-catch in pelagic longline fisheries. *Fish Fish.* **7**, 2-23.

Gilman, E., Gearhart, J., Price, B., Eckert, S., Milliken, H., Wang, J., Swimmer, Y., Shiode, D., Abe, O., Peckham, S..H., Chaloupka, M., Hall, M., Mangel, J., Alfaro-Shigueto, J., Dalzell, P. & Ishizaki, A. (2010). Mitigating sea turtle by-catch in coastal passive net fisheries. *Fish Fish.* **11**, 57-88.

Hall, M.A., Alverson, D.L. & Metuzals, K.I. (2000). Bycatch: problems and solutions. *Mar. Pollut. Bull.* **41**, 204-219.

Hays-Brown, C. & Brown, W. (1982). Status of sea turtles in the Southeastern Pacific: Emphasis on Peru. In: Bjorndal, K.A. (eds) *Biology and Conservation of Sea Turtles*. Smithsonian Institution Press, Washington, DC, 235-240.

Jacquet, J. & Pauly, D. (2008). Funding priorities: big barriers to small-scale fisheries. *Conserv. Biol.* **22**, 832-835.

Jenkins, L. (2011). Reducing sea turtle bycatch in trawl nets: A history of NMFS turtle excluder device (TED) research. *Marine Fisheries Review* **74**, 26-44.

Jordan, L.K., Mandelmann, J.W., McComb, D.M., Fordham, S.V., Carlson, J.K. & Werner, T.B. (2013). Linking sensory biology and fisheries bycatch reduction in elasmobranch fishes: a review with new directions for research. Conservation Physiology 1. (doi: 10.1093/conphys/cot002).

Lewison, R.L., Crowder, L.B., Read, A.J. & Freeman, S. (2004). Understanding impacts of fisheries on marine megafauna. *Trends Ecol. Evol.* **19**, 598–604.

Lewison, R.L. & Crowder, L.B. (2006). Putting longline bycatch of sea turtles into perspective. *Conserv. Biol.* **21**, 79-86.

Lewison, R.L., Crowder, L.B., Wallace, B.P., Moore, J.E., Cox, T.M., Zydelis, R., McDonald, S., DiMatteo, A., Dunn, D.C., Kot, C., Bjorkland, R.H., Kelez, S., Soykan, S., Stewart, K.R., Sims, M., Boustany, A., Read, A.J., Halpin, P.N., Nichols, W.J. & Safina, C. (2014). Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 5271-5276.

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

Mangel, J.C., Alfaro-Shigueto, J., Van Waerebeek, K., Caceres, C., Bearhop, S., Witt, M.J. & Godley, B.J. (2010). Small cetacean captures in Peruvian artisanal fisheries: High despite protective legislation. *Biol. Conserv.* **143**, 136-143.

Martin, G.R. & Crawford, R. (2015). Reducing bycatch in gillnets: A sensory ecology perspective. *Global Ecology and Conservation* **3**, 28-50.

McClanahan, T.R., Marnane, M.J., Cinner, J.E. & Kiene, W.E. (2006). A comparison of marine protected areas and alternate approaches to coral-reef management. *Current Biology* **16**, 1408-1413.

Meeus, J. (1991). Astronomical Algorithms. Richmond, Virginia: Willmann-Bell, 29 p.

Melvin, E.F., Parrish, J.K. & Conquest, L.L. (1999). Novel tools to reduce seabird bycatch in coastal gillnet fisheries. *Conserv. Biol.* **13**, 1386-1397.

Moore, J.E., Cox, T.M., Lewison, R.L., Read, A.J., Bjorkland, R., McDonald, S.L., Crowder, L.B., Aruna, E., Ayissi, I., Espeut, P., Joynson-Hicks, C., Pilcher, N., Poonian, C.N.S., Solarin, B. & Kiszka, J. (2010). An interview-based approach to assess marine mammal and sea turtle captures in artisanal fisheries. *Biol. Conserv.* **143**, 795–805.

Peckham, S.H., Diaz, D.M., Walli, A., Ruiz, G., Crowder, L.B. & Wallace, J.N. (2007). Small-scale fisheries bycatch jeopardizes endangered pacific loggerhead turtles. *PLoS ONE* **2**, 1-6.

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

Salas, S., Chuenpagdee, R., Seijo, J.C. & Charles, A. (2007). Challenges in the assessment and management of small-scale fisheries in Latin America and the Caribbean. *Fish. Res.* **87**, 5-16.

Schakner, Z.A., Blumstein, D.T. (2013). Behavioral biology of marine mammal deterrents: A review and prospectus. *Biol. Conserv.*. **167**, 380-389.

Seminoff, J.A., Zárate, P., Coyne, M., Foley, D.G., Parker, D., Lyon, B.N. & Dutton, P.H. (2008). Post-nesting migrations of Galápagos green turtles *Chelonia mydas* in relation to oceanographic conditions: integrating satellite telemetry with remotely sensed ocean data. *Endang. Species Res.* **4**, 57-72.

Serafy. J.E., Cooke, S.J., Diaz, G.A., Graves, J.E., Hall, M., Shivji, M. & Swimmer, Y. (2012) Circle hooks in commercial, recreational, and artisanal fisheries: research status and needs for improved conservation and management. *Bull. Mar. Sci.* **88**, 371-391.

Shillinger, G.L., Palacios, D.M., Bailey, H., Bograd, S.J., Swithenbank, A.M., Gaspar, P., Wallace, B.P., Spotila, J.R., Paladino, F.V., Piedra, R., Eckert, S.A. & Block, B.A. (2008). Persistent leatherback turtle migrations present opportunities for conservation. *PloS Biol.* **6**, 1408-1416.

Snape, R.T.E., Damla, B., Broderick, A.C., Cicek, A.B., Fuller, W.J., Ozden, O. & Godley, B.J. (2013). Strand monitoring and anthropological surveys provide insight into marine turtle bycatch in small-scale fisheries of the eastern Mediterranean. *Chelonian Conserv. Biol.* **12**, 44-55.

Southwood, A., Fritsches, 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.

Southwood, A. & Avens, L. (2010). Physiological, behavioral, and ecological aspects of migration in reptiles. *J. Comp. Physiol. [B.]* **180**, 1-23.

Soykan, C.U., Moore, J.E., Zydelis, R., Crowder, L.B., Safina, C. & Lewison, R.L. (2008). Why study bycatch? An introduction to the theme section on fisheries bycatch. *Endang. Species Res.* **5**, 91102 .

Stewart, K.R., Lewison, R.L., Dunn, D.C., Bjorkland, R.H., Kelez, S., Halpin, P.N. & Crowder, L.B. (2010). Characterizing Fishing Effort and Spatial Extent of Coastal Fisheries. *PLoS ONE* **5**. (doi:10.1371/journal.pone.0014451).

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.

Velez-Zuazo, X.. & Kelez, S. (2010). Multiyear analysis of sea turtle bycatch by Peruvian longline fisheries: A genetic perspective. Proceedings of the 30th Annual Symposium on sea turtle biology and conservation, Goa, India.

Wallace, B.P., Lewison, R.L., McDonald, S.L., McDonald, R.K., Kot, C.Y., Kelez, S., Bjorkland, R., Finkbeiner, E.M., Helmbrecht, S. & Crowder, L.B. (2010). Global patterns of marine turtle bycatch. *Conserv. Lett.* **10**, 131-142.

Wang, J.H., Boles, L.C., Higgins, B. & Lohmann, K.J. (2007). Behavioral responses of sea turtles to lightsticks used in longline fisheries. *Anim. Conserv.* **10**, 176-182.

Wang, J.H., Fisler, S. & Swimmer, Y. (2010). Developing visual deterrents to reduce sea turtle bycatch in gill net fisheries. *Mar. Ecol. Prog. Ser.* **408**, 241-250.

Wang, J.H., Barkan, J., Fisler, S., Godinez-Reyes, C. & Swimmer, Y. (2013). Developing ultraviolet illumination of gillnets as a method to reduce sea turtle bycatch. *Biol. Letters* 5, no. 5.

Watson, J.W., Epperly, S.P., Shah, A.K. & Foster, D.G. (2005). Fishing methods to reduce sea turtle mortality associated with pelagic longlines. *Can. J. Fish. Aquat. Sci.* **62**, 965-981.

Young, M., Salmon, M. & Forward, R. (2012). Visual wavelength discrimination by the loggerhead turtle, *Caretta caretta*. *The Biological Bulletin* **222**, 46-55.

Tables and Figures

Table 1. Summary measures of fishing effort by net type (Control = without LED illumination, Experimental = with LED illumination) for paired gillnet sets in Sechura Bay, Peru.

		Set duration (h)		Net length (km)		Fishing effort (km*24 h)	
Net type	**Sets**	**Mean ± se**	**Range**	**Mean ± se**	**Range**	**Mean ± se**	**Range**
Control	114	17.06 ± 0.39	2.83 to 24.07	0.62 ± 0.03	0.32 to 1.28	0.43 ± 0.02	0.07 to 1.10
Experimental	114	17.38 ± 0.39	3.75 to 24.33	0.59 ± 0.02	0.32 to 1.15	0.42 ± 0.01	0.09 to 0.75

Table 2. Summary of target species (guitar, rays, and flounders) and green sea turtles (number caught) by net type (Control = without LED illumination, Experimental = with LED illumination) for paired gillenet sets in Sechura Bay, Peru.

Net type	Sets	Total Effort (km*24 h)	Target species caught	Green sea turtles caught
Control	114	48.96	1211	129
Experimental	114	47.71	1176	65

Table 3. Results from the generalized additive model (GAM) for the catch rate of target species (guitarfish, rays, and flounders) and green sea turtles using five covariates (sea surface temperature (SST), calculated lunar light (Meeus, 1991), depth at the fishing location, water visibility, and net type). The best-fit model is highlighted in grey. DE denotes Deviance explained.

	Model (Target species catch)	**DE (%)**	**AIC**	**BIC**
Stage I	1) Net type + SST	9.6	3,444.52	3,511.04
	2) Net type + Lunar light	8.4	3,475.44	3,531.54
	3) Net type + Visibility	15.3	3,277.09	3,344.36
	4) Net type + Depth	17.1	3,224.54	3,291.88
Stage II	6) Net type + Depth + Lunar light	24.9	3,026.58	3,147.69
	7) Net type + Depth + Visibility	27.5	2,950.15	3,073.05
	8) Net type + Depth + SST	29	2,911.09	3,038.90
Stage III	10) Net type + Depth + SST + Visibility	36.6	2,719.66	2,907.90
	11) Net type + Depth + SST + Lunar light	37.2	2,702.65	2,888.25
Stage IV	13) Net type + Depth + SST + Lunar light + Visibility	44.3	2,527.57	2,772.03

	Model (Green sea turtles catch)	**DE (%)**	**AIC**	**BIC**
Stage I	1) Net type + SST	14.1	790.05	829.10
	2) Net type + Lunar light	17.9	767.27	811.62
	3) Net type + Visibility	28.8	704.29	764.86
	4) Net type + Depth	26.2	713.90	769.39
Stage II	6) Net type + Visibility + SST	38.8	658.20	756.93
	7) Net type + Visibility + Depth	38.1	659.57	769.43
	8) Net type + Visibility + Lunar light	39.1	652.42	751.67
Stage III	10) Net type + Visibility + Lunar light + Depth	48.8	619.50	773.87
	11) Net type + Visibility + Lunar light + SST	52	593.81	741.18
Stage IV	13) Net type + Visibility + Lunar light + SST + Depth	57.1	599.31	753.38

Table 4. Final GAM outputs and predicted mean Catch Per Unit of Effort (CPUE – #/km*24 h) for the catch rate of target species (guitarfish, rays, and flounders) and green sea turtles using five covariates (sea surface temperature (SST), calculated lunar light (Meeus, 1991), depth at the fishing location, water visibility, and net type (Control is without LED illumination and Experimental is with LED illumination)).

		Predicted mean CPUE (km*24 h)			
Response variable	**Model fit/deviance explained**	**Control net**	**Experimental net**	**% Difference**	**p-value**
Target species	44.3%	10.62 ±0.71 se	10.35 ±0.86 se	-2.5%	0.78
Green sea turtles	52.0%	1.40 ±0.16 se	0.50 ±0.06 se	-63.9%	0.04

Table 5. Cost calculations to reduce bycatch of sea turtles in Sechura Bay, Peru gillnet fishery. The left column is the most inexpensive LED currently available. The right column is based upon the cost of the LED used in this experiment. Estimates are based on an eight boat fishery with an average total net length of 17,200 m which would require 1,760 lights placed every 10 m, and a 63% (202 individuals) reduction in sea turtle catch rate per year if LED illuminated nets were adopted into the fishery.

	LED cost (USD)	
	$2	$10
Annual cost of LED + batteries	$11	$19
Total annual cost per vessel	$2,420	$4,180
Total annual cost for fishery	$19,360	$33,440
Cost to reduce catch of one sea turtle		
Over 1 year	$95	$196
Over 2 years	$47	$98
Over 3 years	$31	$65

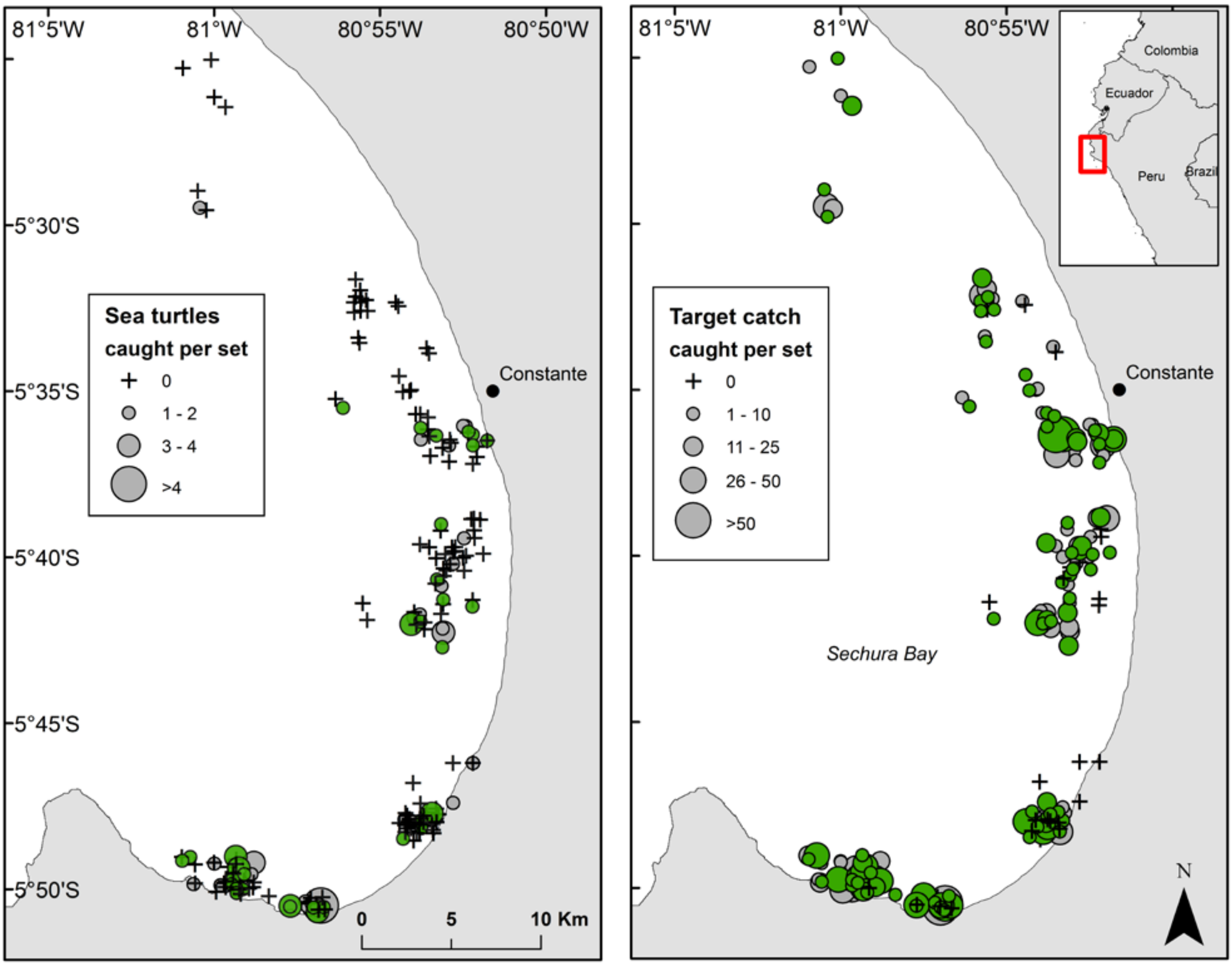

Figure 1. Location and catch (number caught) per set of sea turtles (A) and total target catch (B) by net type (Control (green) = without LED illumination, Experimental (grey) = with LED illumination) for paired gillnet sets in Sechura Bay, Peru.

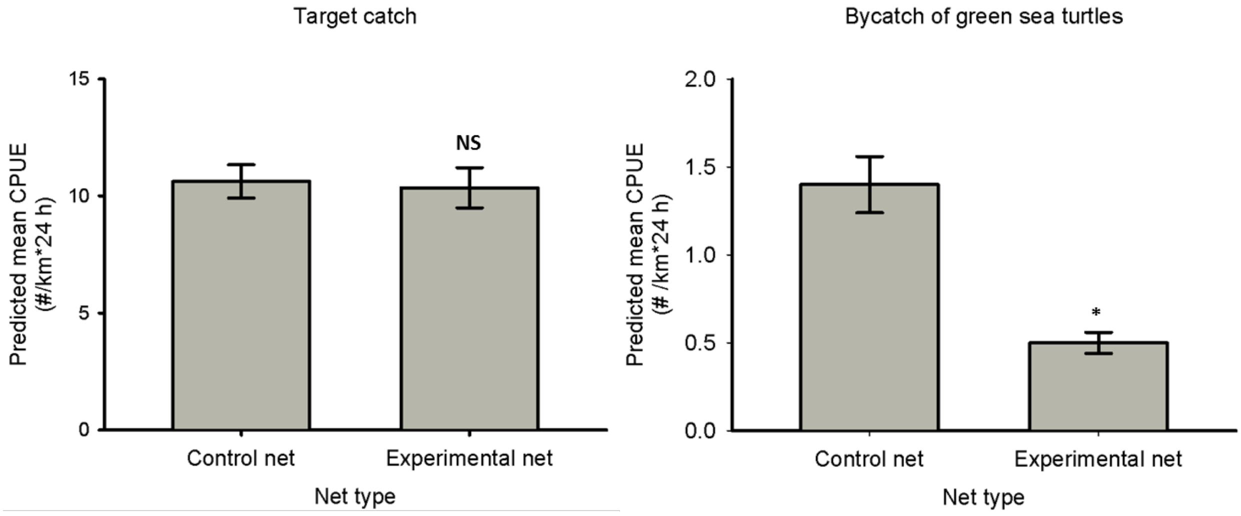

Figure 2. A) Comparison of the predicted mean Catch Per Unit of Effort (CPUE – #/km*24 h) of target species between control (without LED illumination) and experimental (with LED illumination) nets showing no significant difference. B) Comparison of the predicted mean CPUE of green sea turtles between control and experimental nets showing a significant 63.9% decrease in experimental nets. (NS: not significant, *: p-value <0.05).