Ortiz, N., J.C. Mangel, J. Wang, J. Alfaro-Shigueto, S. Pingo, A. Jimenez, T. Suarez, Y. Swimmer, F. Carvalho & B.J. Godley. In press. Reducing green sea turtle bycatch in small-scale fisheries using illuminated gillnets: the cost of saving a sea turtle. Marine Ecology Progress Series. DOI 10.3354/meps11610.

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

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 turtles; CPUE; small-scale fishery; 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 sea turtle bycatch in a small-scale bottom-set gillnet fishery. In Sechura Bay, Northern Peru, 114 pairs of control and illuminated 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 illuminated nets. In contrast, the predicted mean CPUE of green turtles (*Chelonia mydas*) was reduced by 63.9% in illuminated nets. One hundred twenty-five green turtles were caught in control nets while 62 were caught in illuminated nets. This statistically significant reduction (GAM analysis, $p<0.05$) 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 are as low as $34 USD, while the costs to outfit the entire gillnet fishery in Sechura Bay can be as low as $9200 USD. Understanding these cost challenges emphasizes the need for institutional support from national ministries, international non-governmental organizations and the broader fisheries industry to make possible widespread implementation of net illumination as a sea turtle bycatch reduction strategy.

1. 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, including green (*Chelonia mydas*), olive ridley (*Lepidochelys olivacea*) and hawksbill (*Eretmochelys imbricata*) turtles that originate from the eastern Pacific region and loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) turtles from both the eastern and western Pacific (Hays-Brown & Brown 1982, Eckert & Sarti 1997, Alfaro-Shigueto et al. 2004, Seminoff et al. 2008, 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). Studies also indicate that the green 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 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 to date, 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 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 to reduce 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 the present study, we sought to 1) assess the effectiveness of net illumination with LEDs to reduce the bycatch of green turtles in a bottom-set gillnet fishery in Peru, 2) assess the effect of LEDs on target species catch rates and 3) calculate the cost to reduce the bycatch of a sea turtle.

2. 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 10 m and each trip consisted of setting a pair of bottom set gillnets. Nets used were gillnets already in use by fishermen in the Constante small-scale fishery. Bottom gillnets were made of multifilament twine and were composed of multiple net panes that measured 56.4 m long by 2.8 m 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 illuminated net. The illuminated net had green LEDs (Centro Power Light Model CM-1, Centro Co., Ltd., Korea, Fig. 2) 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. Over the course of the experiment approximately 5 lights had to be replaced due to damage (e.g. corrosion) or loss.

Observers monitored fishing operations for each sampling period. As described in Alfaro-Shigueto et al. (2008), observers were trained in collection of data specific to the fishery operation, including how to identify, handle and collect 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 National Oceanic and Atmospheric Administration (NOAA) guidelines (Epperly et al. 2004). Finally, observers also recorded target species catch number. The primary target in this fishery were flounder species (*Paralichtys* spp), guitarfish (*Rhinobatos planiceps*), and rays (Batoidea).

The effect of net illumination on green turtles and target species catch rates was estimated with generalized additive models (GAMs) using the "mgcv" library in the statistical modelling program R 2.15.1 (R Development Core Team 2011). GAMs were used to predict relative abundance of green turtles and target species between control and illuminated 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 the present study, an extensive exploration of the data was performed to deal with basic GAM assumptions (e.g. collinearity and outliers). Possible correlations between predictors were investigated in order to avoid including correlated variables in the same model. Spearman's rank correlation coefficient was assessed for all pairwise combinations of continuous predictors using the *cor.test* function in the "STATS" library in R. Results from these analyses showed no problematic correlations between the variables, thus all variables were considered in the models. Two GAMs were fit separately to green 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 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).

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. At each step in the model selection procedure, the factor that resulted in the greatest reduction in AIC and BIC from the model in the previous step was added to the model. The contributions of each covariate to the explanation of deviance from the null model were also provided to determine importance of each covariate.

Although the choice of the final covariates in the model is not the primary aim of this study, the covariates affect the fitted CPUE rates, and likewise, any significant difference between them. To ensure that the overall forward selection procedure resulted in the best model, and that the estimated rates are not sensitive to the model selection technique, we tested the use of different selection criteria (e.g. forward/backward, and backward). Test results obtained using different selection criteria (not included here) were consistent with those from the forward selection.

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. The natural cubic spline smoother was chosen as appropriate for the explanatory variables. The degree of smoothing was also chosen based on the observed data and the Generalized Cross

Validation method suggested by Wood (2006) and incorporated in the "mgcv". In order to detect statistical differences between the control and illuminated nets catch rates, the mean CPUE values for both were computed from the fitted values of the GAMs and compared using a *t*-test.

Additionally, two-sample t-tests were used to analyse differences in body size for sea turtles and guitarfish between control and illuminated nets. Maps were prepared using ArcMap v. 10.3 (ESRI, Redlands, USA).

We also developed estimates of the cost to implement net illumination in this fishery and the cost associated with preventing individual green turtle interactions. These estimates were calculated using the Alfaro-Shigueto et al. (2011) annual estimate of green turtle bycatch in this fishery, the observed reduction in bycatch reported here, and the projected costs involved in equipping with LEDs and batteries the eight vessels that comprise the Constante fishing fleet.

3. Results

3.1. Fishing effort

A total of 114-paired nets were deployed. The total number of panes used in each net varied slightly between 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). Set duration for control nets averaged 17.06 ± 0.39 (SE) h, while for illuminated nets averaged 17.38 ± 0.39 (SE) h (Table 1). The fishing effort for each net deployment was calculated by combining net length and set duration (km*24 h). 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).

3.2. Target species catch

Of the 2387 target fish species caught, 1211 (51%) were caught in control nets and 1176 (49%) were caught in illuminated nets (Table 2). 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. 3). Target species catch rates were similar between paired nets with a predicted mean CPUE of 10.62 ± 0.71 (SE) for target species $(km*24\ h)^{-1}$ in control nets and a predicted mean CPUE of 10.35 ± 0.86 (SE) for target species $(km*24\ h)^{-1}$ in illuminated nets (Table 4, Fig. 3).

3.3. Sea turtle bycatch

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

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

3.4. Costs to save a sea turtle

LEDs are the most economically viable option available to illuminate nets as they have a robust design and multi-year functional life (Wang et al. 2010, 2013). Additionally, given the advances in LED technology, the cost of a single light has fallen to between $2 and $10 USD. A typical boat in this fishery utilizes 2200 m of net and, at a 10 m spacing, would require at least 221 lights. Although the LEDs were of robust design, a small number needed to be replaced due to damage or loss. We have calculated for an additional 10 lights per vessel per year, yielding an average of 231 lights per vessel. An additional $3 USD per year in battery costs per LED yields an initial cost of implementation ranging between $1155 and $3003 USD (Table 5). The eight vessel fleet as a whole sets an estimated 17 600 m of net and would require 1848 lights at a fleet cost of between $9240 and $24 024 USD (Table 5). Additional crew training in the use and attachment of LEDs would also be required but does not reflect a substantial time expenditure. Moreover, while the LEDs did cause increased tangles in the net at the beginning of the study, this was quickly minimized. Future designs of LEDs specifically for gillnets could further reduce tangles and LED replacements.

Given a 63% (202 individuals) reduction in sea turtle catch rate per year if LED illuminated nets were adopted into the fishery, we estimate the cost of preventing a single green turtle interaction to range from $45.74 to $118.93 in the first year (Table 5). Since these LEDs can last multiple fishing seasons, this initial cost could be amortized over multiple years and over a three-year lifespan of the LED, reducing costs to save a sea turtle from $34.07 to $60.58 USD (Table 5). As Constante is one of six ports that operate demersal set net vessels in Sechura Bay, the per turtle cost of LED implementation could potentially be reduced even further if this BRT was used in all of these fleets.

4. 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 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 and 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). Given that 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 shown 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 instance, 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. We approximate the cost to prevent a single sea turtle interaction to range from $34 to $119 USD and the costs to outfit the fishery to range from $9200 to

$24 000 USD. 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 from national ministries, international non-governmental organizations and the broader fisheries industry to make possible widespread implementation of net illumination as a sea turtle bycatch strategy. Such economic analyses to determine the costs per animal saved could also be useful for other BRTs (e.g. pingers, circle hooks), and could potentially serve as a common denominator of effectiveness of conservation dollars. Such 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 LEDs 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 the lights are always charged. Fishermen involved with the trials were primarily positive and provided essential feedback, which included encouragement to develop LEDs 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.

Ortiz, N., J.C. Mangel, J. Wang, J. Alfaro-Shigueto, S. Pingo, A. Jimenez, T. Suarez, Y. Swimmer, F. Carvalho & B.J. Godley. In press. Reducing green sea turtle bycatch in small-scale fisheries using illuminated gillnets: the cost of saving a sea turtle. Marine Ecology Progress Series. DOI 10.3354/meps11610.

5. 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.

Ortiz, N., J.C. Mangel, J. Wang, J. Alfaro-Shigueto, S. Pingo, A. Jimenez, T. Suarez, Y. Swimmer, F. Carvalho & B.J. Godley. In press. Reducing green sea turtle bycatch in small-scale fisheries using illuminated gillnets: the cost of saving a sea turtle. Marine Ecology Progress Series. DOI 10.3354/meps11610.

6. References

Alfaro-Shigueto J, Dutton PH, 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 JA, Duton PH (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 PH, Seminoff JA, Godley BJ (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 PH, Seminoff JA, Godley BJ (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, p 27

Anderson ORJ, Small CJ, Croxall JP, Dunn EK, Sullivan BJ, Yates O, Blach A (2011) Global seabird bycatch in longline fisheries. Endang Species Res 14: 91-106

Balmford A, Gravestock P, Hockley N, McClean CJ, Roberts CM (2004) The worldwide costs of marine protected areas. Proc Natl Acad Sci USA 101: 9694-9697

Boyle MC, Fitz-Simmons NN, Limpus CJ, 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 MD, Valenti SV, Fordham SV, Fowler SL, 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, p 78

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

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

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

Cox TM, Lewison RL, Zydelis R, Crowder LB, Safina C, Read AJ (2007) Comparing effectiveness of experimental and implemented bycatch reduction measures: the ideal and the real. Conserv Biol 21: 1155-1164

Ortiz, N., J.C. Mangel, J. Wang, J. Alfaro-Shigueto, S. Pingo, A. Jimenez, T. Suarez, Y. Swimmer, F. Carvalho & B.J. Godley. In press. Reducing green sea turtle bycatch in small-scale fisheries using illuminated gillnets: the cost of saving a sea turtle. Marine Ecology Progress Series. DOI 10.3354/meps11610.

Crowder LB, Crouse DT, Heppell SS, Martin TH (1994) Predicting the impact of Turtle Excluder Devices on loggerhead sea turtle populations. Ecol Appl 4: 437-445

Crowder LB, Hopkins-Murray SR, Royle JA (1995) Effects of Turtle Excluder Devices (TEDs) on loggerhead sea turtle strandings with implications for conservation. Copeia 4: 773-779

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

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

Eckert SA, 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, p 42

Gaos AR, Abreu-Grobois FA, Alfaro-Shigueto J, Amorocho D, Arauz R, Baquero A, Briseño R, Chacón D, Dueñas C, Hasbún C, Liles M, Mariona G, Muccio C, Muñoz JP, Nichols WJ, Peña M, Seminoff JA, Vásquez M, Urteaga J, Wallace B, Yañez IL, 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, p 39

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 SH, 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 MA, Alverson DL, Metuzals KI (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 KA (eds) Biology and Conservation of Sea Turtles. Smithsonian Institution Press, Washington, DC, p 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. Mar Fish Rev 74: 26-44

Jordan LK, Mandelmann JW, McComb DM, Fordham SV, Carlson JK, Werner TB (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 RL, Crowder LB, Read AJ, Freeman S (2004) Understanding impacts of fisheries on marine megafauna. Trends Ecol Evol 19: 598–604

Lewison RL, Crowder LB (2006) Putting longline bycatch of sea turtles into perspective. Conserv Biol 21: 79-86

Lewison RL, Crowder LB, Wallace BP, Moore JE, Cox TM, Zydelis R, McDonald S, DiMatteo A, Dunn DC, Kot C, Bjorkland RH, Kelez S, Soykan S, Stewart KR, Sims M, Boustany A, Read AJ, Halpin PN, Nichols WJ, Safina C (2014) Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. Proc Natl Acad Sci USA 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 JC, Alfaro-Shigueto J, Van Waerebeek K, Caceres C, Bearhop S, Witt MJ, Godley BJ (2010) Small cetacean captures in Peruvian artisanal fisheries: High despite protective legislation. Biol Conserv 143: 136-143

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

McClanahan TR, Marnane MJ, Cinner JE, Kiene WE (2006) A comparison of marine protected areas and alternate approaches to coral-reef management. Curr Biol 16: 1408-1413

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

Melvin EF, Parrish JK, Conquest LL (1999) Novel tools to reduce seabird bycatch in coastal gillnet fisheries. Conserv Biol 13: 1386-1397

Moore JE, Cox TM, Lewison RL, Read AJ, Bjorkland R, McDonald SL, Crowder LB, Aruna E, Ayissi I, Espeut P, Joynson-Hicks C, Pilcher N, Poonian CNS, 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 SH, Diaz DM, Walli A, Ruiz G, Crowder LB, Wallace JN (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 JC, 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 ZA, Blumstein DT (2013) Behavioral biology of marine mammal deterrents: A review and prospectus. Biol Conserv 167: 380-389

Seminoff JA, Zárate P, Coyne M, Foley DG, Parker D, Lyon BN, Dutton PH (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 JE, Cooke SJ, Diaz GA, Graves JE, 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 GL, Palacios DM, Bailey H, Bograd SJ, Swithenbank AM, Gaspar P, Wallace BP, Spotila JR, Paladino FV, Piedra R, Eckert SA, Block BA (2008) Persistent leatherback turtle migrations present opportunities for conservation. PloS Biol 6: 1408-1416

Snape RTE, Damla B, Broderick AC, Cicek AB, Fuller WJ, Ozden O, Godley BJ (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 CU, Moore JE, Zydelis R, Crowder LB, Safina C, Lewison RL (2008) Why study bycatch? An introduction to the theme section on fisheries bycatch. Endang Species Res 5: 91-102

Stewart KR, Lewison RL, Dunn DC, Bjorkland RH, Kelez S, Halpin PN, Crowder LB (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

Ortiz, N., J.C. Mangel, J. Wang, J. Alfaro-Shigueto, S. Pingo, A. Jimenez, T. Suarez, Y. Swimmer, F. Carvalho & B.J. Godley. In press. Reducing green sea turtle bycatch in small-scale fisheries using illuminated gillnets: the cost of saving a sea turtle. Marine Ecology Progress Series. DOI 10.3354/meps11610.

Wallace BP, Lewison RL, McDonald SL, McDonald RK, Kot CY, Kelez S, Bjorkland R, Finkbeiner EM, Helmbrecht S, Crowder LB (2010) Global patterns of marine turtle bycatch. Conserv Lett 10: 131-142

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

Wang JH, 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 JH, 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 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

Wood, SN (2006) Generalized Additive Models: An Introduction with R. Chapman and Hall/CRC.

Young M, Salmon M, Forward R (2012) Visual wavelength discrimination by the loggerhead turtle, *Caretta caretta*. Biol Bull 222: 46-55

Tables and Figures

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

Net type	Sets	Total Effort (km*24 h)	Target species caught	Green turtles caught
Control	114	48.96	1211	125
Illuminated	114	47.71	1176	62

Table 3. Results from the generalized additive model (GAM) for the catch rate of target species (guitarfish, rays, and flounders) and green 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	3444.52	3511.04
	2) Net type + Lunar light	8.4	3475.44	3531.54
	3) Net type + Visibility	15.3	3277.09	3344.36
	4) Net type + Depth	17.1	3224.54	3291.88
Stage II	6) Net type + Depth + Lunar light	24.9	3026.58	3147.69
	7) Net type + Depth + Visibility	27.5	2950.15	3073.05
	8) Net type + Depth + SST	29	2911.09	3038.90
Stage III	10) Net type + Depth + SST + Visibility	36.6	2719.66	2907.90
	11) Net type + Depth + SST + Lunar light	37.2	2702.65	2888.25
Stage IV	13) Net type + Depth + SST + Lunar light + Visibility	44.3	2527.57	2772.03

	Model (Green 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

	SST	Lunar light	Visibility	Depth
Model (Target species catch)				
Effective degrees of freedom	9.83	8.66	5.62	6.39
Reference degrees of freedom	9.59	9.06	5.95	6.19
Model (Green turtle catch)				
Effective degrees of freedom	8.51	6.18	7.55	5.15
Reference degrees of freedom	9.23	7.32	8.43	5.33

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 turtles using five covariates (sea surface temperature (SST), calculated lunar light (Meeus, 1991), depth at the fishing location, water visibility, and net type (Control = without LED illumination and Illuminated = with LED illumination)).

Response variable	Model fit/deviance explained	Predicted mean CPUE (km*24 h) Control net ± SE	Illuminated net ± SE	% Difference	p-value
Target species	44.3%	10.62 ±0.71	10.35 ±0.86	-2.5%	0.78
Green turtles	52.0%	1.40 ±0.16	0.50 ±0.06	-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 17 600 m which, at a 10 m spacing, would require 1848 lights, 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	$5	$13
Total annual cost per vessel	$1155	$3003
Total annual cost for fishery	$9240	$24 024
Cost to reduce bycatch of one sea turtle		
Over 1 year	$45.74	$118.93
Over 2 years	$36.99	$75.17
Over 3 years	$34.07	$60.58

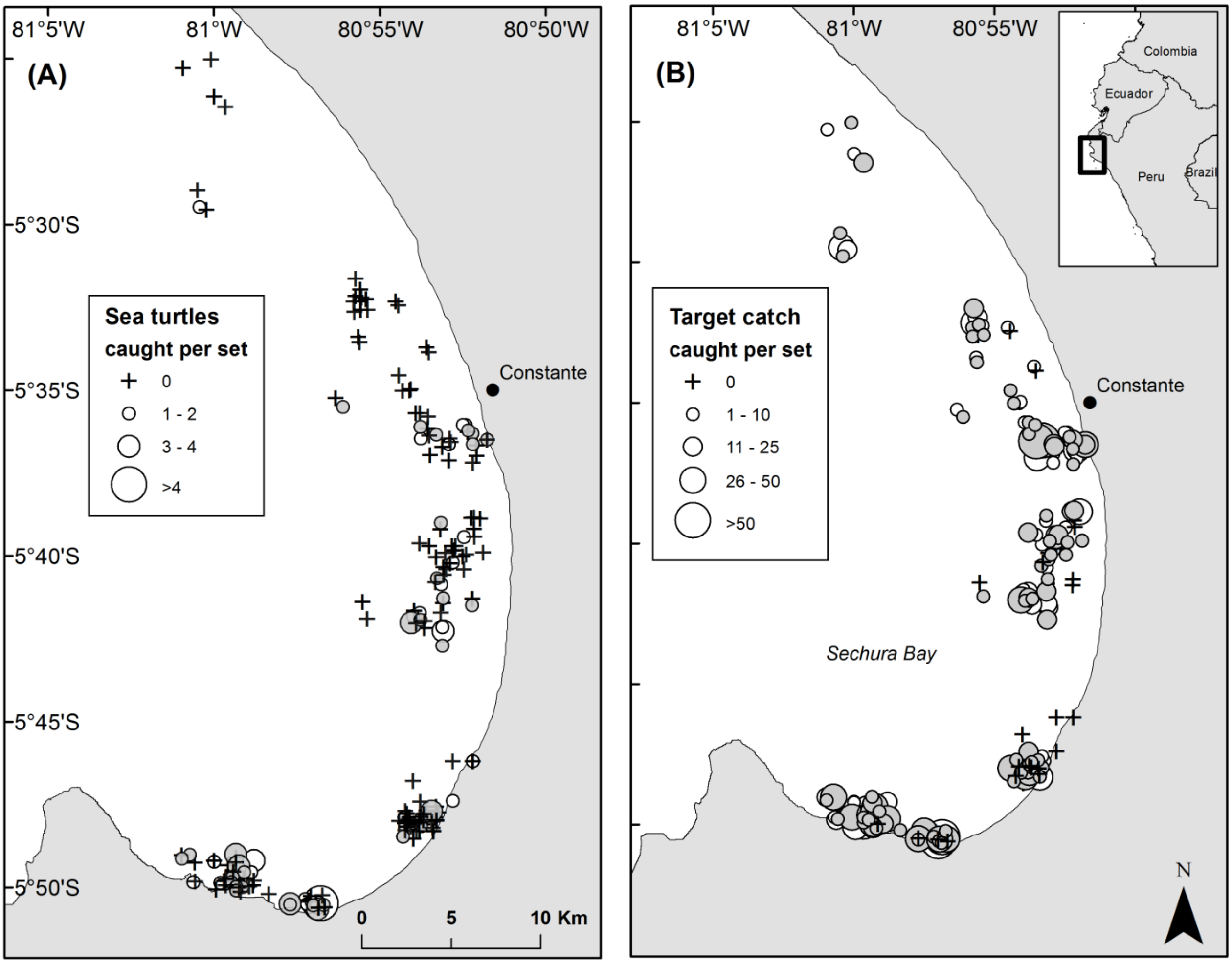

Figure 1. Location and catch (number caught) per set of sea turtles (A) and total target catch (B) by net type (Control (grey) = without LED illumination, Illuminated (white) = with LED illumination) for paired gillnet sets in Sechura Bay, Peru.

Ortiz, N., J.C. Mangel, J. Wang, J. Alfaro-Shigueto, S. Pingo, A. Jimenez, T. Suarez, Y. Swimmer, F. Carvalho & B.J. Godley. In press. Reducing green sea turtle bycatch in small-scale fisheries using illuminated gillnets: the cost of saving a sea turtle. Marine Ecology Progress Series. DOI 10.3354/meps11610.

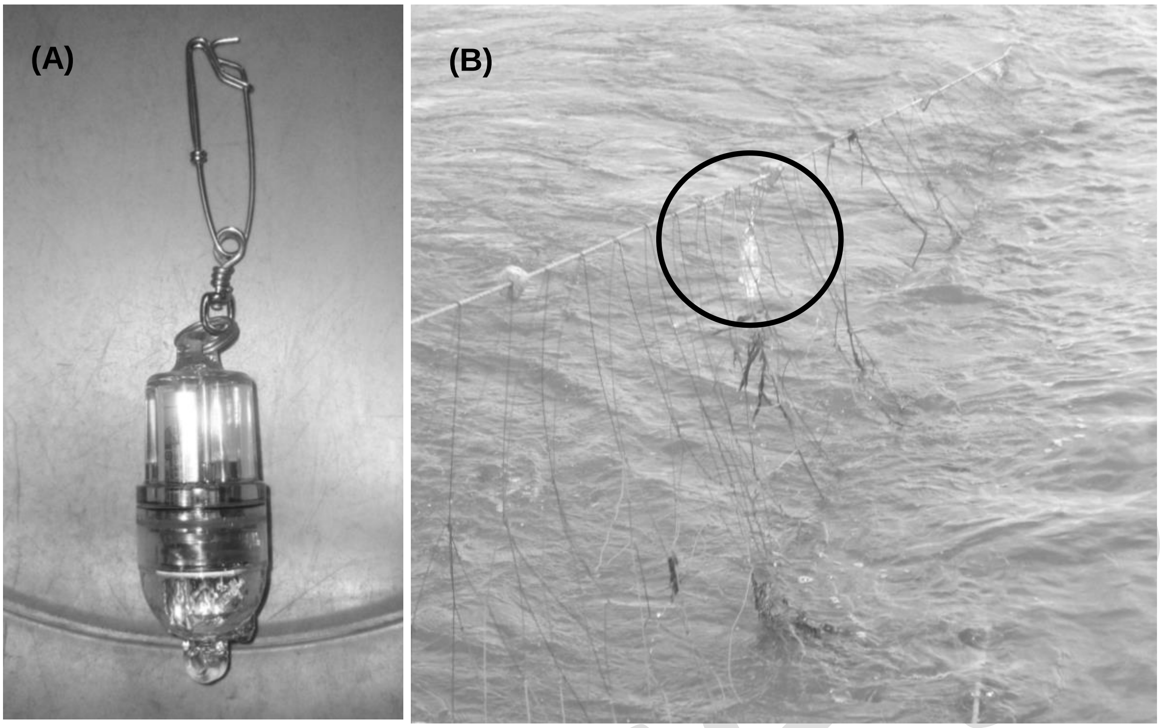

Figure 2. (A) Example of the LED used during the study. (B) LED (circled) fitted on a bottom-set gillnet in Peru.

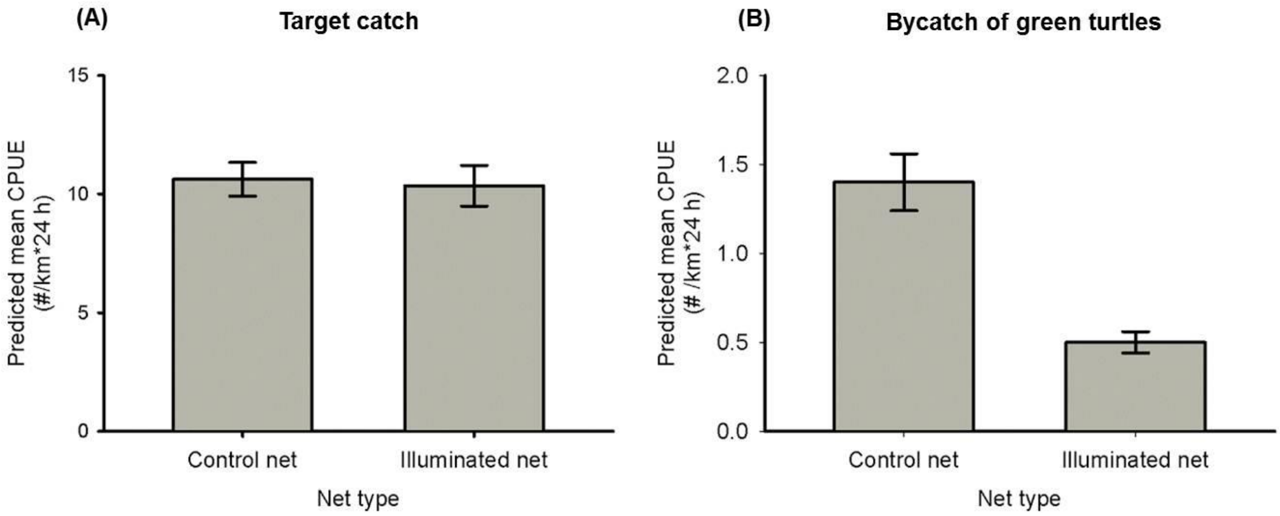

Figure 3. (A) Comparison of the predicted mean Catch Per Unit of Effort (CPUE – # / km*24 h) of target species between control (without LED illumination) and illuminated (with LED illumination) nets showing no significant difference. (B) Comparison of the predicted mean CPUE of green turtles between control and illuminated nets showing a significant 63.9% decrease in illuminated nets.