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An illuminating idea to reduce bycatch in the Peruvian small-scale gillnet fishery

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ABSTRACT

Found in the coastal waters of all continents, gillnets are the largest component of small-scale fisheries for many countries. Numerous studies show that these fisheries often have high bycatch rates of threatened marine species such as sea turtles, small cetaceans and seabirds, resulting in possible population declines of these non-target groups. However, few solutions to reduce gillnet bycatch have been developed. Recent bycatch reduction technologies (BRTs) use sensory cues to alert non-target species to the presence of fishing gear. In this study we deployed light emitting diodes (LEDs) - a visual cue - on the floatlines of paired gillnets (control vs illuminated net) during 864 fishing sets on small-scale vessels departing from three Peruvian ports between 2015 and 2018. Bycatch probability per set for sea turtles, cetaceans and seabirds as well as catch per unit effort (CPUE) of target species were analysed for illuminated and control nets using a generalised linear mixed-effects model (GLMM). For illuminated nets, bycatch probability per set was reduced by up to 74.4 % for sea turtles and 70.8 % for small cetaceans in comparison to non-illuminated, control nets. For seabirds, nominal BPUEs decreased by 84.0 % in the presence of LEDs. Target species CPUE was not negatively affected by the presence of LEDs. This study highlights the efficacy of net illumination as a multi-taxa BRT for small-scale gillnet fisheries in Peru. These results are promising given the global ubiquity of small-scale net fisheries, the relatively low cost of LEDs and the current lack of alternate solutions to bycatch.

1. Introduction

Gillnet fisheries are found in the coastal waters of all continents (Gilman et al., 2010; Waugh et al., 2011) and for many countries, gillnet fisheries comprise the largest component of their small-scale fishing fleets (Alfaro-Shigueto et al., 2010; Žydelis et al., 2013). Incidental catch, or 'bycatch', in gillnets is a major threat to many marine taxa and contributes to the population decline of numerous threatened marine species (Alfaro-Shigueto et al., 2011; Read et al., 2006). Gillnet fisheries are regarded as some of the largest sources of mortality for sea turtles (Lewison et al., 2014; Peckham et al., 2007), cetaceans (Dawson and Slooten, 2005; Lowry et al., 2018; Read et al., 2006; Reeves et al., 2013) and seabirds (Crawford et al., 2017; Žydelis et al., 2013). However, solutions to the problem of bycatch in net fisheries, have been difficult to identify and implement (Martin and Crawford, 2015; Žydelis et al., 2013).

In Peru, the total length of gillnets set is estimated to exceed 100,000 km per year (Alfaro-Shigueto et al., 2010). This fleet also has frequent interactions with threatened taxa such as marine mammals, seabirds and sea turtles (Alfaro-Shigueto et al., 2010; Majluf et al., 2002; Mangel et al., 2010). Mangel et al. (2010), reported that bycatch of small cetaceans in Peru was likely in excess of 10,000–20,000 animals per year. Two of the most common small cetacean bycatch species caught - the dusky dolphin (*Lagenorhynchus obscurus*) and the Burmeister's porpoise (*Phocoena spinipinnis*) - are considered conservation priorities by the IUCN Cetacean Specialist Group (Reeves et al., 2003). The Burmeister's porpoise is also listed as Near Threatened by the IUCN Red List of Threatened Species (IUCN, 2018). Coastal gillnets in Peru are also thought to be a population sink for multiple protected sea turtle species (Alfaro-Shigueto 2011), including leatherback (*Dermochelys coriacea*), hawksbill (*Eretmochelys imbricata*), loggerhead (*Caretta caretta*), green (*Chelonia mydas*) and olive ridley (*Lepidochelys olivacea*).

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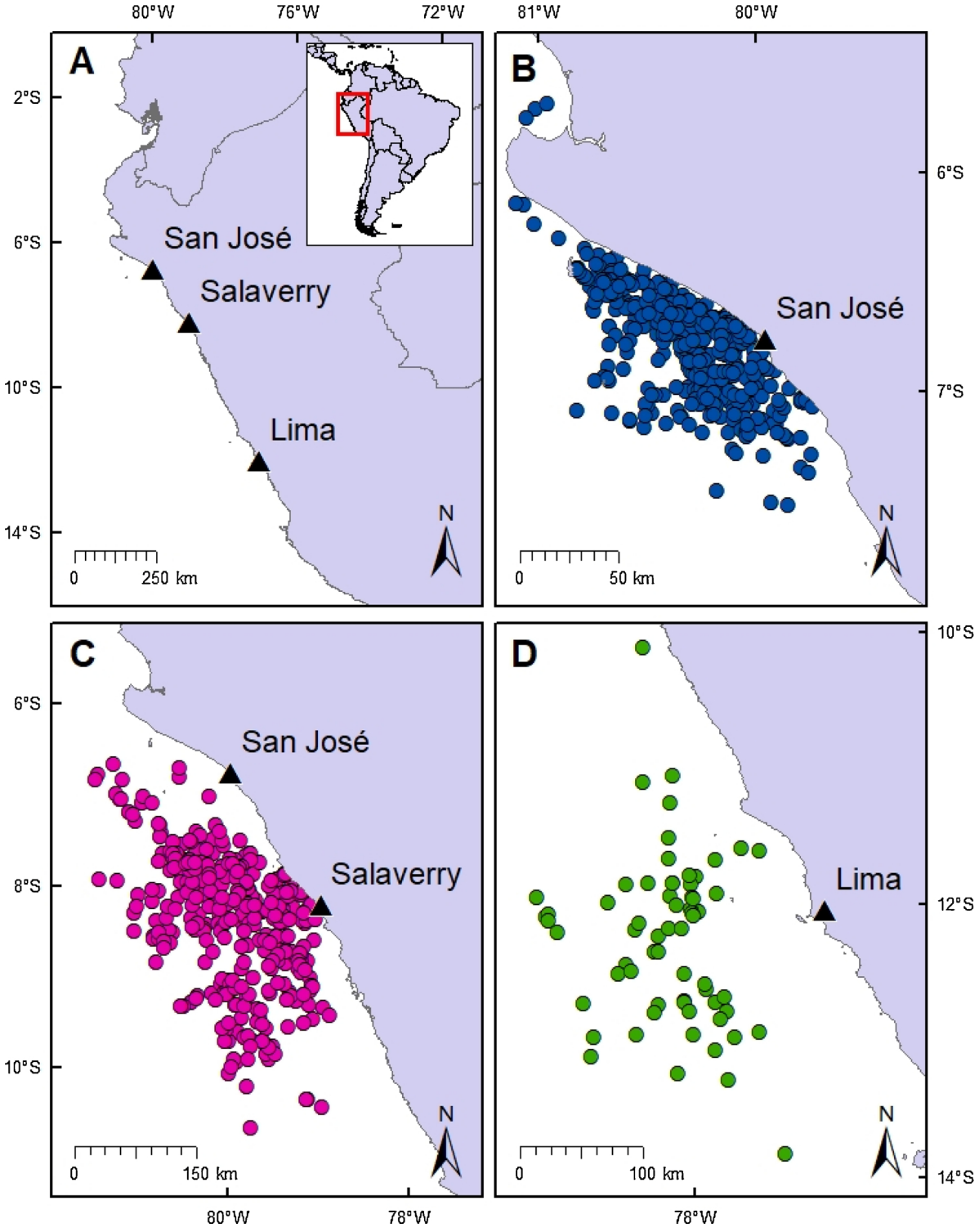

Fig. 1. Location of the three ports (A) and fishing set pairs in San José (B), Salaverry (C) and Ancon (D). Each dot represents one pair of nets.

While seabird bycatch rates have not been as thoroughly documented in Peru's small-scale fisheries (SSF), the Peruvian coast hosts more than 90 species of pelagic birds (Spear and Ainley, 2008), including species of conservation concern like the waved albatross (*Phoebastria irrorata*), pink-footed shearwater (*Ardenna creatopus*), white-chinned petrel (*Procellaria aequinoctalis*) and Humboldt penguin (*Spheniscus humboldti*), all of which are documented to interact with Peruvian SSF (Awkerman et al., 2006; Jahncke et al., 2001; Majluf et al., 2002).

Strategies to reduce this bycatch have included examining methods to utilize the sensory capabilities of these animals to alter their behavior around fishing gear (Jordan et al., 2013; Southwood et al., 2008). For example, as cetaceans primarily employ echolocation for many aspects of their ecology (Wartzok and Ketten, 1999), acoustic deterrent devices have been tested as a method to reduce cetacean bycatch or depredation (Schakner and Blumstein, 2013). A recent study by Mangel et al. (2013) showed that acoustic alarms, or 'pingers', had the potential to reduce small cetacean bycatch in the gillnet fisheries based in Salaverry, Peru.

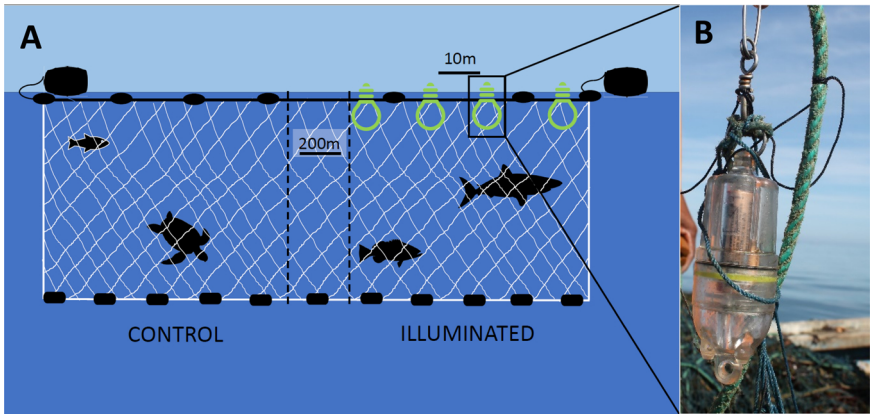

Fig. 2. Experimental design (not to scale): paired nets (A) and an example of LED used in the experiment (B).

The use of visual cues has also been suggested as a potential method to reduce bycatch in fisheries (Southwood et al., 2008; Wang et al., 2007). Visual cues play important roles in the behavioral ecology of many marine vertebrates. Sea turtles rely primarily upon visual information to help guide their foraging behaviour (Constantino and Salmon, 2003; Southwood et al., 2008; Swimmer et al., 2005) and orientation (Wang et al., 2007; Witherington and Bjorndal, 1991). Many species of seabirds use a combination of visual and olfactory cues to find their food (Martin and Crawford, 2015; Silverman et al., 2004; White et al., 2007). In addition, marine mammals not only rely on acoustic cues, but also on vision for important biological functions such as feeding, orientation and individual recognition (Griebel and Peichl, 2003; Wartzok and Ketten, 1999). A potential (and until now elusive) benefit here is that, if effective, a bycatch reduction technology (BRT) based upon visual cues may work across taxa. BRTs have typically been designed to address interactions with one particular taxon (e.g. acoustic pingers for dolphins, circle hooks for turtles (Read, 2007), hookpods for seabirds (Sullivan et al., 2018). A multi-taxa BRT could derive multiple benefits such as effectiveness across a range of fisheries, reduced cost and eased implementation in fisheries with bycatch of multiple taxa.

Net illumination (a type of visual cue) has recently been tested as a bycatch reduction technology on sea turtles (Ortiz et al., 2016; Wang et al., 2013, 2010, 2007) and seabirds (Mangel et al., 2018) and showed significant reductions in bycatch interactions for both taxa when fishing nets were illuminated. Ortiz et al. (2016) reported that green LEDs placed on the floatlines of a demersal set gillnet fishery in Peru reduced the incidental catch rate of green sea turtles (*C. mydas*) by 63.9 % without any significant reduction in target catch per unit effort (CPUE) or catch value. Mangel et al. (2018), in a companion study of this same fishery reported an 85.1 % decline in the catch rate of guanay cormorants (*Phalacrocorax bougainvillii*) in the illuminated nets compared with the non-illuminated control nets.

Given the high levels of bycatch reported in coastal gillnet fisheries and their massive annual fishing effort both in Peru and globally, bycatch mitigation solutions are urgently needed. Building upon the success of previous net illumination trials, this study aimed to test the efficacy of LEDs as a multi-taxa BRT in Peru's small-scale coastal gillnet fisheries. More specifically, the present analysis investigated the effect of gillnet illumination on (i) the probability of catching sea turtles, seabirds and cetaceans and (ii) catch per unit effort of target species.

2. Materials and methods

2.1. The fishery

This study was conducted under true fishing conditions aboard six small-scale gillnet fishing vessels departing from the ports of San José (6° 46′S, 79° 58′W), Salaverry (8° 12′S, 78° 58′W), and Ancon (12° 02′S, 77° 01′W; Fig. 1). Small-scale vessels have a maximal storage capacity of 32.6 m^3, maximum length of 15 m and rely on manual work during fishing operations (Reglamento de la ley general de pesca, 2001).

Gear characteristics varied somewhat between sets and ports. Surface driftnets were used aboard all vessels, while in San José both bottom set nets and surface driftnets were sometimes used in the same fishing trip (but only one net type was used within a set) and data are skewed towards bottom set net sets. Considering all ports combined, data are skewed towards driftnet sets. Participating vessels used net panels of stretched mesh sizes ranging from 20.3 cm to 45.7 cm. Nets were typically set in the late afternoon, soaked overnight and retrieved the following morning.

Target species were primarily elasmobranchs including smooth hammerhead sharks (*Sphyrna zygaena*), smooth hounds (*Mustelus spp.*), bronze whalers (*Carcharhinus brachyurus*), blue sharks *Prionace glauca* and eagle rays (*Myliobatis spp.*) However, the fishery is highly opportunistic and also catches other species such as tuna (*Thunnus spp.*), dolphinfish (*Coryphaena hippurus*) and other Osteichthyes.

2.2. Experimental design

Gillnets were equipped with green visible spectrum light emitting diodes (LEDs) of wavelength 500 nm (Centro Power Light, Model SW-1, CENTRO; Fig. 2) inside a waterproof hard plastic casing with two AA batteries. For each fishing set, paired experimental (illuminated) and control nets (non-illuminated), were deployed. Only one net type (bottom set net or surface driftnet) was used in each pair. LEDs were placed every 10 m along the floatline of the illuminated net. Control and illuminated nets were separated by approximately 200 m to avoid any effect of LEDs on control nets (Fig. 2). The length of illuminated nets was shorter than the length of control nets because of the limited numbers of LEDs available. The difference in effort was accounted for during the analysis.

2.3. Data collection

The experiment was replicated in 864 fishing sets (140 trips) between January 2015 and April 2018 (Table S1). Onboard observers were trained in deployment of LEDs, species identification and data collection. Data recorded included information about the gear, the number of LEDs used and their position along the net. In addition, GPS locations and net soak time were recorded for each set. The species, quantity, and size of target catch and bycatch (i.e. sea turtle, seabird, small cetacean) were recorded for both control and illuminated nets. Bycatch of pinnipeds was not systematically recorded over the course of the study so was not included in the analysis.

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Table 1
Top model sets of generalised linear mixed-effect models (GLMM) for bycatch and target groups. Within the top model sets, models used for predictions (the best-fit models) are highlighted in grey. Group: species group whose data were analysed with the model. Family: error distribution used for the model. Response: the dependent variable; for bycatch, estimated bycatch probability is per set; for target catch, effort was included as an offset term to estimate the response as catch per unit effort (CPUE). Fixed effects: the explanatory variables included in the model. AIC: Akaike's Information Criterion. ΔAIC: difference in AIC relative to the model with the lowest AIC. Weight: Akaike's weight.Adj: adjusted weights calculated after excluding nested models. R^2_m : marginal R^2, amount of variance explained by the model including fixed effects only; R^2_c : amount of variance explained by the model including fixed and random effects.

Group	Family	Response	Fixed effects	AIC	ΔAIC	Weight	Adj. weight	R^2_m (%)	R^2_c (%)
Sea turtles	Binomial	Bycatch probability	~ Effort + Treatment + Net type	659.25	0.00	1	NA	0.29	0.48
Small cetaceans	Binomial	Bycatch probability	~ Effort + Treatment + Net type	369.45	0.00	0.94	0.95	0.30	0.42
			~ Effort + Net type	374.89	5.44	0.06	0.06		
Sharks	Negative binomial	CPUE	~ Net type + offset(log(Effort))	8652.6	0.00	0.72	1.00	0.02	0.83
			~ Treatment + Net type + offset(log(Effort))	8654.5	1.90	0.28	NA		
Bony fish	Negative binomial	CPUE	~ Net type + offset(log(Effort))	3118.3	0.00	0.60	1.00	0.23	0.89
			~ Treatment + Net type + offset(log(Effort))	3119.1	0.77	0.40	NA		
Rays	Negative binomial	CPUE	~ Treatment + Net type + offset(log(Effort))	4091.4	0.00	0.60	0.60	0.003	0.96
			~ Treatment + offset(log(Effort))	4092.2	0.81	0.40	0.40		

Table 2
List of predictor (independent) variables included in the generalised linear mixed-effects models.

Predictor Variable	Fixed/Random Effect	Type	Description
Treatment	Fixed	Categorical	Control net (i.e. no LEDs applied) or or illuminated net (i.e. LEDs applied).
Effort	Fixed	Continuous	Fishing effort, calculated for each fishing set as (net length/1000 m)*(soak time/24 h), for control and illuminated net separately.
Net type	Fixed	Categorial	Surface driftnet or bottom set net. Bottom sets only used in San Jose.
TripID	Random	Categorical	Unique code given to each fishing trip.
Year	Random	Discrete	The year the fishing set was conducted (i.e. 2015 to 2018).
Season	Random	Categorical	The season the fishing set was conducted (i.e. win, spr, sum, fal).
PortID	Random	Categorical	The name of the vessel departure port (i.e. San José, Salaverry or Ancon).
Vessel	Random	Categorical	The name of the vessel on which the experiment was conducted.

2.4. Data analysis

2.4.1. Generalised linear mixed-effect models

To analyse i) bycatch probability per set for bycatch taxa (i.e. sea turtles, small cetaceans, seabirds) and ii) catch per unit effort (CPUE) for target species in control and illuminated nets, we fitted separate Generalized Linear Mixed-Effects Models (GLMM) in the statistical modelling programme R 3.5.3. (R Core Team, 2019). The models were fitted using the 'glmer' function in the 'lme4' package (Bates et al., 2015b). Expected bycatch probability per set and expected CPUE from the GLMM models were determined using the 'predict' function in the 'stats' package.

We performed information theoretic (IT) model selection based on Akaike's information criterion (AIC; Akaike, 1998) and Akaike weights (Burnham and Anderson, 2002) using the 'MuMIn' package (Barton, 2018) where a top model set, listing the most parsimonious models (i.e. with lowest AIC), was created by using a cut-off of ΔAIC ≤ 6(Richards, 2005; Richards et al., 2011). The top model sets are listed in Table 1. To avoid selecting overly complex models we selected a model only if it had a Δ-AIC less than the Δ-AIC of all of its simpler nested models (Richards, 2007). After this adjustment, the model with the highest adjusted Akaike weight was considered the best-fit model used for the analysis (Burnham and Anderson, 2002).

Models were checked for overdispersion (Zuur et al., 2009) and for singularity. If a singularity issue was detected, the random effect structure was simplified by removing the random effect with the lowest variance (Bates et al., 2015a). The amount of variance explained (R^2) by the best-fit model was calculated with the method described in (Nakagawa and Schielzeth, 2013).

2.4.2. Bycatch

We built separate models for sea turtles, small cetaceans, and seabirds described by Eq. (1). Specifically, given a dependent variable y and a set of x independent covariates, the relationship between them is established by:

$$y = X\beta + Zu + \varepsilon \quad (1)$$

The dependent term (y) in our models was binomial set data (0 = no bycatch on a set; 1 = one or more turtles/cetaceans/seabirds caught per set) and was modelled with a GLMM with binomial distribution and a logit link function (Table 1). X is a matrix of the independent covariates or predictor variables; β is a vector of the fixed-effects regression coefficients; Z is the matrix for the random effects (the random complement to the fixed X); u is a vector of the random effects (the random complement to the fixed β); and ε is a vector of the residuals, that part of y that is not explained by the model.

Full models included the following predictor variables as fixed effects (Table 2): Treatment (control or illuminated), Net Type (surface driftnet or bottom set net) and Effort. Effort was included in all models during the model selection and was calculated as *(net length/1000 m)*(soak time/24 h)* in a fishing set, for control and illuminated nets separately. The variables 'Season', 'TripID', 'Set Year', and 'Port ID' were included as random effects to account for the changing environmental parameters among seasons, weeks, years and fishing area; the random effect 'Vessel', indicating the name of the vessel, accounted for the different fishing methods used on different vessels (Table 2). Results are presented for bottom set (demersal) nets and for driftnets (surface) as expected mean bycatch probability per set. For seabirds, we did not estimate bycatch probability as the model did not converge, instead we provide the mean nominal bycatch per unit effort (BPUE) calculated as number of individuals incidentally captured divided by Effort.

2.4.3. Target catch

To account for differences in target species catches between ports we built separate models for three species groups: sharks (Selachimorpha), rays (Batoidea) and bony fish (Osteichthyes),

described by Eq. (1). The dependent term (y) was count data (number of individuals captured in one set) and was modelled using a GLMM with a negative binomial distribution and log link function to account for overdispersion (Table 1). The other terms of Eq. (1) remained consistent with those explained in section 2.4.2.

Full models for the three groups included Treatment and Net type as fixed effects. The natural logarithm of Effort (i.e. log(Effort)) was included in all models as an offset term (Table 2) to account for differences in fishing effort between control and illuminated net and to standardise catch data. Random effects remained consistent between models (section 2.4.3.). In the results we present mean expected CPUE, i.e. expected number of individuals captured when fishing effort = 1, if the model includes Treatment as a predictor.

3. Results

3.1. Bycatch

3.1.1. Descriptive summary

During the experiment 131 sea turtles were captured incidentally of which 86.2 % were green turtles. Loggerhead and olive ridley turtles were captured in smaller numbers. Of the 53 small cetaceans captured, 47.2 % were long beaked common dolphins, 26.4 % were dusky dolphins and 24.5 % were Burmeister's porpoises. Of the 46 seabirds captured during the experiment 71.7 % were white-chinned petrels and 17.4 % Humboldt penguins, with pink-footed shearwaters also captured in smaller numbers (Table S2). Raw nominal bycatch per unit effort are also provided (Table S3).

3.1.2. Bycatch probabilities

The top model sets are summarized in Table 1. The best-fit models selected to estimate bycatch probabilities for (a) sea turtles and (b) small cetaceans were:

(a) ~ Treatment + Effort + NetType + (1|SetYear/TripID) + (1|Observer) + (1|Season) + (1|PortID)
(b) ~ Treatment + Effort + NetType + (1|SetYear) + (1|TripID) + (1|Observer) + (1|Season) + (1|PortID)

A summary of the fixed effect estimates and of the random effect variance components is presented in Table S4.

The GLMM identified that for sea turtles, the expected bycatch probability per set is lower in illuminated nets (Fig. 3). For bottom set nets, the expected bycatch probability per set is 0.010 in control nets as compared to 0.003 in illuminated nets; for surface driftnets, the expected bycatch probability per set is 0.086 in control nets as compared to 0.022 in illuminated nets (Table 3). These results indicate that sea turtle bycatch probability per set was reduced by 70.0 % and 74.4 % in the presence of LEDs, for bottom set nets and surface driftnets, respectively.

Table 3
Expected bycatch probabilities per set (for sea turtles and cetaceans) and CPUEs (for rays) from GLMM models that included Treatment as a predictor. Negative % change values indicate bycatch probability was lower in illuminated nets than in control nets; positive values indicate CPUE was higher in illuminated nets than in control nets.

	Surface driftnet			Bottom set net		
	Probability		CPUE	Probability		CPUE
Treatment	Sea turtles	Cetaceans	Rays	Sea turtles	Cetaceans	Rays
Control	0.086	0.048	0.034	0.010	0.006	0.021
Illuminated	0.022	0.014	0.052	0.003	0.002	0.033
% change	−74.4	−70.8	+34.6	−70.0	−66.7	+36.4

Likewise, the GLMM identified that for small cetaceans, the expected bycatch probability per set is lower in illuminated nets (Fig. 3). For bottom set nets, the expected bycatch probability per set is 0.006 in control nets as compared to 0.002 in illuminated nets; for surface driftnets, the expected bycatch probability per set is 0.048 in control nets as compared to 0.014 in illuminated nets (Table 3). These results indicate that small cetacean bycatch probability per set was reduced by 66.7 % and 70.8 % in the presence of LEDs, for bottom set nets and surface driftnets, respectively.

For seabirds, 60.9 % of bycatch events occurred in 3 sets and 99 % of sets had zero seabirds recorded. As a result, the model did not converge. Hence it was only possible to calculate a nominal bycatch per unit effort (BPUE) for each set instead of determining bycatch probabilities from the model. Seabirds were only captured in surface driftnets. Forty-four seabirds were captured in control nets and two in illuminated nets. Mean nominal BPUE was 0.088 in control nets and 0.014 in illuminated nets, indicating that BPUE was reduced by 84.0 % in the presence of LEDs.

3.2. Target catch per unit effort

The total target catch consisted of 17 596 sharks, 5087 rays and 3677 bony fishes. The top model sets are summarized in Table 1. The marginal R^2 values of the best-fit models for rays and sharks were 0.003

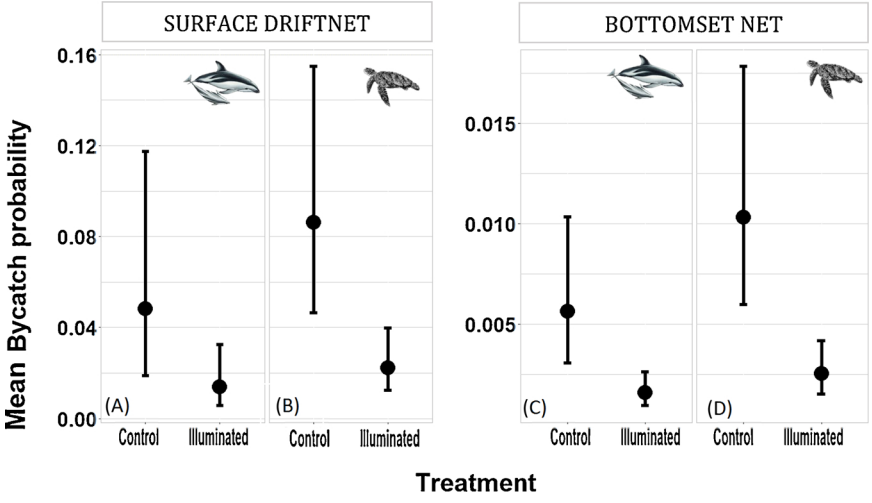

Fig. 3. Expected mean bycatch probability per set for cetaceans (A, C) and sea turtles (B, D) in control and illuminated nets. A and B show expected values for surface driftnets, C and D for bottom set nets. Error bars are SE.

and 0.02 respectively, indicating that the deviance explained by the models is low.

The only factor found to influence the capture of (a) sharks and (b) bony fish is Net Type, implying that Treatment is not a predictor for shark and bony fish CPUE. For rays (c), the factors found to influence their capture are Net Type and Treatment (Table 1 and S4).

(a) ~ offset(log(Effort)) + NetType + (1|SetYear) + (1|TripID) + (1|Observer) + (1|Season) + (1|PortID)
(b) ~ offset(log(Effort)) + NetType + (1|SetYear/TripID) + (1|Observer) + (1|Season) + (1|PortID)
(c) ~ offset(log(Effort)) + Treatment + NetType + (1|TripID) + (1|Observer)

The GLMM identified that the expected CPUE for rays is higher in illuminated nets compared to control nets (Table 3). For bottom set nets, the expected CPUE is 0.021 in control nets compared to 0.033 in illuminated nets; for surface driftnets, the expected bycatch probability per set is 0.034 in control nets compared to 0.052 in illuminated nets. These results indicate that for rays, CPUE increased by 36.4 % and 34.6 % in the presence of LEDs, for bottom set nets and surface driftnets, respectively.

4. Discussion

In this study, fishing nets illuminated by LEDs achieved reductions in sea turtle bycatch probability without negatively affecting target species catch rates. The expected sea turtle bycatch probability per set was reduced by 70.0 % and 74.4 % in bottom set nets and surface driftnets, respectively. This corroborates the findings of Ortiz et al. (2016) which reported that net illumination reduced sea turtle BPUE by 63.9 % in bottom set nets from the Constante, Peru landing site. The use of net illumination as a sensory cue has now been shown to be effective at reducing sea turtle bycatch in multiple studies (Ortiz et al., 2016; Virgili et al., 2018; Wang et al., 2013, 2010). Apart from BRTs focusing on visual cues, several modifications to fishing net design have also shown some potential to reduce sea turtle bycatch including buoyless bottom set nets (Peckham et al. 2015), lower profile nets, increased tie-down lengths, and mid-water driftnets (Gilman et al., 2010; Peckham et al., 2016). Additional testing of these methods and comparisons of their effectiveness at reducing sea turtle bycatch while maintaining target catch will assist managers, fishers and other stakeholders to identify the appropriate solution in the context of their fisheries.

In line with the findings of Alfaro-Shigueto et al. (2011), green turtles were the predominant species of sea turtle captured in this study, accounting for 86.2 % of the total sea turtle bycatch. Whether net illumination has a consistent effect on all sea turtle species is still unclear since existing studies have occurred in areas where captures of one species predominated. Recent testing in bottom set nets in Peru (Ortiz et al., 2016) and Mexico (Wang et al., 2013, 2010) showed declines in green turtle interactions, and Virgili et al. (2018), in a study of a bottom set net fishery in the central Mediterranean Sea, reported the elimination of loggerhead turtle interactions when nets were illuminated. All sea turtle species are, however, known to locate food visually (Constantino and Salmon, 2003) and there is evidence that loggerhead and leatherback turtles can detect green light (Horch et al., 2008; Wang et al., 2007; Young et al., 2012). Additional studies are recommended to further explore the effectiveness of net illumination on specific sea turtle species.

Bycatch is the primary anthropogenic threat to small cetaceans (Read et al., 2006) and gillnets are one of the largest sources of mortality in the world (Lewison et al., 2014). In our study, the expected bycatch probability per set for small cetaceans declined by 66.7 % in the illuminated bottom set nets and 70.8 % in illuminated surface driftnets. To our knowledge this is the first test of a visual deterrent to reduce small cetacean bycatch interactions (Northridge et al., 2017; Schakner and Blumstein, 2013). Small cetacean bycatch included dusky dolphins and Burmeister's porpoises which, due to their genetically and morphologically distinct and small populations in Peru (Clay et al., 2018; Rosa et al., 2005; Van Waerebeek, 1994), may be severely affected by the high levels of mortality reported in Peru's small-scale gillnet fisheries. Acoustic alarms (pingers) have for the past several decades been the most commonly used BRT to reduce small cetacean interactions (Schakner and Blumstein, 2013) and have been tested and implemented to a limited extent in Peru (Mangel et al., 2013). However, despite being highly auditory animals, cetaceans rely also on vision for many important biological functions (Griebel and Peichl, 2003) and some species, such as the bottlenose dolphin, have visual systems sensitive to green wavelengths (Griebel and Schmid, 2002) used in several net illumination studies (Mangel et al., 2018; Ortiz et al., 2016; Wang et al., 2010). This supports the idea that BRTs based on visual cues could be effective for small cetaceans as well. Mangel et al. (2013) showed that pingers reduced cetacean BPUE by 37 % in surface driftnets deployed from the port of Salaverry, while the current study indicates that net illumination reduced small cetacean bycatch probability by up to 70.8 % (Fig. 3). Because of the different metrics used (i.e. catch numbers vs probability), it is impossible to directly compare the results of the two studies; however, it is clear that pingers and LEDs are both successful at reducing bycatch.

The availability of a new BRT option for small cetaceans in the form of net illumination may be particularly timely. Recent developments under the United States Marine Mammal Protection Act (effective 1 January 2017; National Oceanic and Atmospheric Administration, 2016) highlight the need for fisheries exporting their products to the United States to meet certain bycatch mitigation standards (Williams et al., 2016). This recent attention to marine mammal bycatch issues may hopefully instigate further testing of net illumination as a potential marine mammal BRT. In addition, future studies could examine the potential for synergistic effects when both BRTs (pingers and LEDs) are utilized or to compare their effectiveness as stand-alone measures (in terms of their ability to reduce bycatch and their implementation costs). Given the success shown here of net illumination in mitigating small cetacean bycatch, we encourage additional trials in other gillnet fisheries and with bycatch of other marine mammal species, including pinnipeds.

In this study, entanglements of seabirds were rare and, as a result, we could not draw any conclusions from the model about the extent of the reduction in seabird bycatch by LED illumination. However, mean nominal BPUEs suggest a 84.0 % decline in bycatch in the presence of LEDs, which is in line with the recent study carried out in Constante, Peru, showing that illuminated bottom set gillnets reduced the bycatch of guanay cormorants by 85 % (Mangel et al., 2018). Furthermore, the majority of gillnet-susceptible birds are likely to be visually guided foragers (Martin and Crawford, 2015), suggesting that visual deterrents like LEDs are potential means to reduce seabird bycatch (Mangel et al., 2018; Melvin et al., 1999). Another variant of a visual cue to reduce bycatch in driftnets has also been proposed by Martin and Crawford (2015) in the form of high internal contrast 'stimulus panels' applied to net panes, however, to our knowledge, this is still being tested. Finally, it is worth noting that Mangel et al. (2018) tested LEDs on bottom set nets, while our results on seabird bycatch refer exclusively to driftnets, since no seabird interaction with bottom set nets was recorded during the trials (Table S3). Further testing of LEDs in surface gillnet fisheries could yield interesting results on the adaptability of this BRT to different fishing methods.

Although gillnet fisheries often interact with multiple bycatch taxa, previous studies of BRTs have tended to focus on reducing bycatch for one taxon at a time (Gazo et al., 2008; Mangel et al., 2018, 2013; Ortiz et al., 2016; Virgili et al., 2018; Wang et al., 2013). In contrast, our results show that net illumination has the potential to reduce bycatch for at least two taxa simultaneously – and under true fishing conditions in a SSF setting. This reinforces the findings of Ortiz et al. (2016) and

Mangel et al. (2018) that net illumination was effective at reducing both green turtle and guanay cormorant bycatch in a bottom set net fishery. Moreover, net illumination has now been shown to be similarly effective in both surface driftnets and bottom set nets. Having one technology that can reduce bycatch of two or possibly three taxa could simplify recommendations to fishers and reduce costs of implementation. Also, as noted by Ortiz et al. (2016), the relatively low cost of LEDs (about USD10 per LED as tested) may make them an affordable and accessible tool, even for SSF. For example, to initially equip a 2 km length gillnet would require an investment of about USD 2000 for LEDs (10 m spaced as tested) compared to approximately USD 2600 for pingers (spaced 100 m as recommended, at USD 130 per pinger). Despite the similar initial costs, LED ability to reduce bycatch of sea turtles and small cetaceans may make them a potentially preferable BRT for some fisheries, especially if we consider that LED implementation costs could be lower in fisheries where the optimal spacing between lights is higher (e.g. 15 m in Virgili et al., 2018).

Moreover, our results showed that catch rates of the main target species were not negatively affected by net illumination. The fact that there was no negative impact on target catch suggests a reduced potential economic burden for fishers. This could further ease assimilation into normal fishing practices and benefit fishers by avoiding time consuming entanglements and damage to fishing gear (Panagopoulou et al., 2017). The increase we observed in catch rates for rays (one of these fisheries primary target species) in the illuminated nets could be an added incentive for fishers but is also a topic worthy of additional monitoring given the growing concern for the conservation status for certain species of elasmobranchs. However, the deviance explained by the models for rays and sharks was low, therefore our results should be treated with caution.

Our findings highlight that net illumination using LEDs is a potential multi-taxa BRT for small-scale gillnet fisheries. LEDs were shown to be adaptable and effective for different fishing methods, target species and locations. Given the global ubiquity of gillnet fisheries and their bycatch interaction with multiple taxa, we encourage continued testing, especially by those in SSF, to assess net illumination's potential as a robust and economically viable bycatch reduction technology.

Declaration of Competing Interest

We confirm that this manuscript is original research and that all the listed co-authors have agreed to their inclusion and have approved the submitted version of the manuscript. The manuscript is in its original form and has not been submitted elsewhere. All funding sources have been acknowledged and the authors have no direct financial benefit from publication. All research not carried out by the authors has been acknowledged in full. All necessary permits were obtained to conduct the research.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.biocon.2019.108277.

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