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Research Article

Trialing net illumination as a bycatch mitigation measure for sea turtles in a small-scale gillnet fishery in Ecuador

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ABSTRACT. In Ecuador, one of the main hazards for threatened marine species, such as sea turtles, is small-scale fisheries bycatch. At a global scale, currently, bycatch reduction technologies (BRTs) are being tested in many coastal nations to mitigate this issue. Despite some advances in Ecuadorian efforts for wildlife protection, BRTs to reduce bycatch have yet to be assessed. The purpose of this study was to test the BRT of net illumination using violet light-emitting diodes (LEDs) as a mitigation measure to reduce sea turtle interactions in the small-scale driftnet fishery operating from the ports of Santa Rosa, Puerto Lopez and Jaramijo. A total of 146 pairs of experimental sets (control and illuminated panes) were deployed in all ports. A generalized linear mixed-effect model (GLMM) was employed to analyze the bycatch per unit of effort (BPUE) for sea turtles, and the catch per unit of effort (CPUE) for target species; for both control and illuminated panes. Thirty-two sea turtles from three species were observed captured: olive ridley *Lepidochelys olivacea* (n=18), green *Chelonia mydas* (n=13) and leatherback turtles *Dermochelys coriacea* (n=1). Turtle species-specific modeling showed bycatch of green turtles declined by 93% in illuminated nets compared with control, non-illuminated nets, whereas no significant difference between control and illuminated nets was observed for olive ridley turtles. The catch per unit effort of the pelagic fish species including skipjack tuna, yellowfin tuna, mahi-mahi, thresher shark and smooth hammerhead shark was not affected by net illumination. Our results represent the first evaluation of the effects of net illumination using LEDs on reducing marine turtle bycatch in Ecuadorian small-scale driftnet fisheries. Despite its relatively small sample size, these results could be used by fisheries managers to support the implementation or further testing of this BRT in gillnet fisheries along the Ecuadorian coast.

Keywords: LEDs; sea turtles; small-scale fishery; bycatch; mitigation; Ecuador

INTRODUCTION

Ecuador possesses one of the largest small-scale fisheries (SSF) fleets of the countries of the Eastern Pacific Ocean (EPO) (Alava *et al*., 2015). Ecuadorian SSF is multispecies and employs mainly longlines and gillnets, with landings representing 19% of total annual national catch (Alava *et al*., 2015; Martínez-Ortiz *et al*., 2015). It is estimated that over 5% of the economically active population depends on this activity (Alava *et al*., 2019). During the 1990s, the Ecuadorian small-scale fishing fleet doubled in size from 7,000 to 15,500 vessels (Alava *et al*., 2019). Fishing activity has also increased and extended further offshore with the adoption of a "mother ship" fleet. These vessels, which tow up to 10 smaller fiberglass vessels, are capable of traveling far offshore (even to Galapagos Island [Alava *et al*., 2015]) and allow up to 25 days at sea before returning to the shore (Martínez-Ortiz *et al*., 2015). The 2013 Ecuador census recorded 21,798 operative artisa-

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nal vessels, of which 317 corresponded to “mother ships”. The expansion of the sector along the continental coastline and the Galapagos Archipelago could also increase the likelihood of overlapping with areas of marine megafauna occupancy such as marine mammals, sea turtles, seabirds and elasmobranchs.

The concern over fisheries bycatch arises from a combination of vulnerability due to ecological attributes of the species affected and of susceptibility to interactions driven by fishing characteristics (Lewison *et al*., 2014). For example, marine megafauna populations are vulnerable to relatively low level of bycatch due to life history characteristics (*e.g.*, slow growth, low reproductive rates) and also susceptible to excessive incidental mortality caused by fisheries (Heppell *et al*., 2000; Lewison *et al*., 2004); this has been highlighted in numerous studies focusing on seabirds, sea turtles, marine mammals, and elasmobranchs (Mangel *et al*., 2010; Anderson *et al*., 2011; Attwood *et al*., 2011). Despite bycatch being identified as a primary threat and driver of many marine megafauna population declines (Wallace *et al*., 2010; Lewison *et al*., 2014) and other non-target species difficult to assess (Kelleher, 2005), its cumulative effects are often underestimated by some fishers since they are caught sporadically and represent only a small part of the total bycatch biomass (Soykan *et al*., 2008).

In Ecuador, five species of sea turtles use coastal areas for nesting, migration and foraging (MAE, 2014). The Galapagos Islands holds one of the most important nesting sites of green turtles (*Chelonia mydas*) along the EPO, with more than 1309 nests identified from 2004 to 2007 (Zárate *et al*., 2013). Results from Chaves *et al.* (2017) also indicate genetic connectivity between the Galapagos population of green turtles with nesting sites at the Machalilla National Park on the Ecuador mainland (Peña-Mosquera *et al*., 2009). Ecuador rookeries of olive ridley turtles (*Lepidochelys olivacea*) and hawksbill turtles (*Eretmochelys imbricata*) have also been identified (Montero *et al*., 2016; Gaos *et al*., 2017). Two majors threats for sea turtles populations in the southeastern Pacific include plastic debris ingestion (Thiel *et al.* 2018) and fisheries interactions, with nets and longlines in particular (Wallace *et al*., 2010; Alfaro-Shigueto *et al*., 2011). An assessment conducted in Ecuador 2010 based on fisher surveys estimated that more than 13,000 sea turtles die annually as a consequence of bycatch events with small-scale gillnet fisheries in Ecuador (Alfaro-Shigueto *et al*., 2018).

Bycatch reduction technologies (BRT) have been developed not only to reduce bycatch but also to seek to maintain target catch revenues for fishers (Wang *et al*., 2013). For instance, the use of light-emitting diode (LED) lights on driftnets, as a visual stimulus, has been shown to be effective at reducing bycatch rates of sea turtles -with no impact on target species- in some countries of the EPO such as Mexico, USA, and Peru (Barkan, 2010; Wang *et al*., 2010; Ortiz *et al*., 2016). Building upon this research, the main objective of the present research was to assess the effectiveness of net illumination using violet-colored LED lights at reducing sea turtle bycatch in the Ecuadorian small-scale driftnet fishery. This information could be of relevance for the implementation of the Ecuadorian national strategy to reduce sea turtle bycatch and to support regional efforts for sea turtle populations of conservation concern.

MATERIALS AND METHODS

Observer onboard program

An observer monitoring program was implemented from January 2015 to December 2018 on small-scale driftnet fisheries from the fishing ports of Santa Rosa, Puerto Lopez, and Jaramijo (Fig. 1). Observers were trained in biological and fisheries data collection. The information recorded included i) vessel and gear information (*e.g.*, fishing boat, fishing gear, net length, mesh size, numbers of panes and storage capacity), ii) fishing activity information (*e.g.*, set and haul date, set and haul time, geographical position), and iii) target and bycatch data (*e.g.*, species identification, number of individuals captured, and morphometrics).

Experimental design of net illumination trial

Net trials were conducted onboard 21 driftnet vessels using typical fishing practices. Driftnets ranged in length from 1,000 to 2,000 m, 11 to 17 m in height, and with a stretched mesh size typically of 4 to 5 inches. Nets comprised multiple panes (between 12 and 16), deployed during the late afternoon (18:00-19:00 h) soaked overnight, and retrieved early the following morning (05:00-07:30 h). The experimental design consisted of pairs of control and illuminated nets deployed per fishing set in which illuminated nets comprised violet-colored LED lights (Centro Power light Model CM-6) attached to the driftnet float line at an interval of 12 to 14 m (Fig. 2). LED lights were housed in a waterproof plastic case and powered by two AA alkaline batteries.

Data collection

Observers recorded the composition of captures (target and bycatch species) per set. For the statistical analysis, fish species were grouped into two categories: 'bony fishers' and 'sharks'. The number of target and bycatch

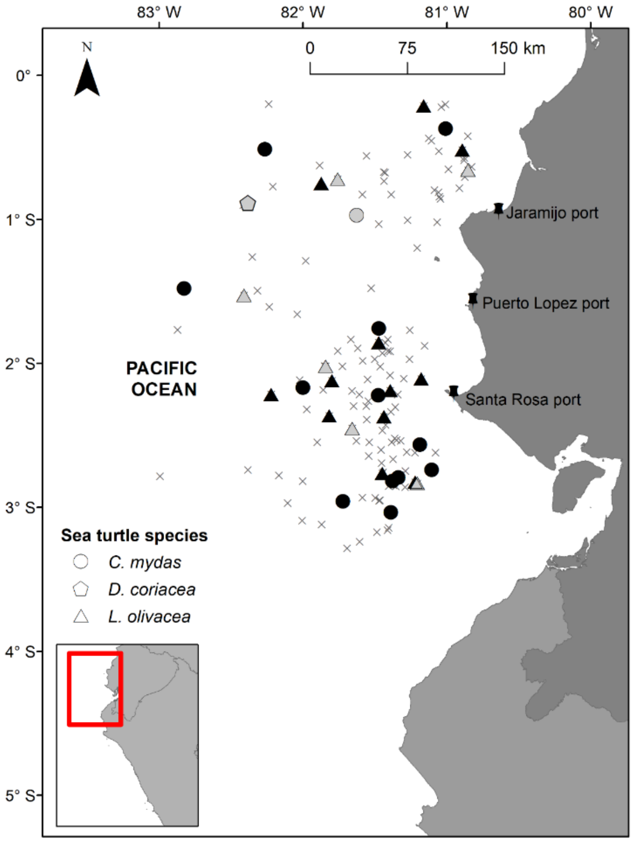

Figure 1. Location of gillnets sets in Ecuador represented by x. Black and grey figures represent sea turtles (*Lepidochelys olivacea*, *Chelonia mydas*, *Dermochelys coriacea*) incidentally captured in control and illuminated nets, respectively.

Figure 2. LEDs being recovered during the haul (left), and a LED light attached and activated on the net before the set (right).

specimens captured were used to estimate catch per unit effort (CPUE) and bycatch per unit effort (BPUE) on control and illuminated nets.

Sea turtles captured in illuminated and control net panes were recorded to estimate BPUE. Additionally, entangled turtles were brought onboard for species identification, curved carapace length (CCL) measurements, and were tagged in the front flippers using Inconel tags (Style 681IC, National Band and Tag Company). Based on CCL minimum sizes available in the literature, we inferred size class and classified animals as juveniles or adults. Green turtles (*Chelonia* *mydas*) with a CCL under 69 cm (Zarate *et al*., 2013) and olive ridley turtles (*Lepidochelys olivacea*) with a CCL under 69.9 cm (Arias *et al*., 2015) were considered as putative juveniles. For leatherbacks (*Dermochelys coriacea*), the CCL for adults was 144 cm, based on measurements of nesting females (Reina *et al*., 2002). We also recorded the capture position and fate of each captured turtle (release alive or discarded dead). No hawksbill (*Eretmochelys imbricata*) or loggerhead turtles (*Caretta caretta*) were reported captured during the study.

Data analysis

Fishing effort per set was calculated as (net length/1000 m) × (soak time/24 h). Then, to analyze i) BPUE for sea turtles and ii) CPUE for target species in control and illuminated nets, we fitted separate Generalized Linear Mixed-Effects Models (GLMM) in the statistical modeling program R 3.3.3. (R Core Team, 2017). The models were fitted using the 'glmer' function in the 'lme4' package (Bates *et al*., 2015) and the optimizer bobyqa.

For sea turtles, we built a model for all species grouped, as well as separate species-specific models (*i.e.*, olive ridley and green turtles; we did not run a separate model for leatherback since only one individual was captured). For fish species, we built separate models for two species groups: sharks (Selachimorpha) and bony fishes (Osteichthyes). Specifically, given a dependent variable y and a set of x independent covariates, the relationship between them is established by:

$$y = X\beta + Zu + \varepsilon$$

The dependent term (y) in our models is a count (number of individuals captured per set) and was modeled with a GLMM with Poisson distribution (or negative binomial, to account for overdispersion) and a log link function; X is a matrix of the independent covariates or predictor variables. β is a vector of the fixed-effects regression coefficient; 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 for (a) sea turtles and (b) target catch included the predictor variable 'treatment' (control or illuminated net) as a fixed effect and the natural logarithm of fishing effort (*i.e.*, log(Effort)) as an offset term (Table 1) to account for differences in fishing effort between control and illuminated nets and to standardize catch data.

BPUE ~ Treatment + (log(Effort)) + (1|Vessel/ TripID)
CPUE ~ Treatment + (log(Effort)) + (1|Vessel/ TripID)

The variable 'vessel', indicating the name of the vessel, was included as a random effect to account for different fishing practices used on different vessels; the random effect 'TripID' nested in 'vessel' was included as a random effect to account for the changing environmental parameters among seasons, weeks, years and fishing area (Table 1).

The best-fit models with the final terms are summarized in Table 2. The factor treatment was not included in the model for bony fish and sharks, implying that net illumination is not a predictor for the CPUE of these groups.

Models were checked for overdispersion (Zuur *et al*., 2009) and 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*., 2015) (Table 2).

After establishing the random terms to be included in the model, we performed the information-theoretic (IT) model selection for the fixed effect treatment. The model selection was based on Akaike's information criterion (AIC; Akaike, 1998) and Akaike weights (Burnham & Anderson, 2002) and used the 'MuMIn' package (Bartoń, 2013), to create a top model set by using a cut-off of ΔAIC ≤ 6, where ΔAIC is the difference between the AIC values of the focal model and the AIC best model (Richards, 2005; Richards *et al*., 2011).

To avoid selecting overly complex models, we selected a model only if it had a ΔAIC less than the ΔAIC of all of its simpler nested models (Richards, 2008). A model is said to be "nested" within another model if it contains a subset of parameters of the latter model but does not include other parameters (*e.g.*, model 'A+B' is nested within 'A+B+C' but not 'A+C+D'). After this adjustment, the model with the highest adjusted Akaike weight was considered the best-fit model used for the analysis (Burnham & Anderson, 2002). The amount of variance explained (R^2) by the best-fit model was calculated using the r.squared GLMM function in the 'MuMIn' package (Bartoń, 2013), and we present lognormal values, both marginal (variance explained by fixed effects only) and conditional (also random effects). The lognormal approximation was chosen because we used error distributions with a logarithmic link.

Expected BPUEs and CPUEs from the GLMM models were determined using the 'predict' function in the 'stats' package. In the results, we present expected

Table 1. List of predictors (independent variables) included in the generalized linear mixed-effects models.

Predictor variable	Fixed/random effect	Type	Description
Treatment	Fixed	Categorical	Control net (*i.e.*, no LEDs applied) or illuminated net (*i.e.*, LEDs applied)
Effort	Fixed	Continuous	Fishing effort for control and illuminated net separately
TripID	Random	Categorical	Unique code given to each fishing trip
Vessel	Random	Categorical	The name of the vessel on which the experiment was conducted

Table 2. Top model sets of generalized linear mixed-effect models (GLMM) for sea turtle 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 analyzed with the model. Family: error distribution used for the model. Response: the dependent variable, *i.e.*, estimated bycatch per unit effort (BPUE) for sea turtles and catch per unit effort (CPUE) for target catch. Fixed effects: the explanatory variables included in the model. Random effects: the random effects 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. weight: adjusted weights calculated after excluding nested models. R^2_m: marginal R^2, *i.e.*, amount of variance explained by the model including fixed effects only. R^2_c: conditional $R^{2,}$ *i.e.*, amount of variance explained by the model including fixed and random effects.

Group	Family	Response	Fixed effects	Random effects	AIC	ΔAIC	Weight	Adj. weight	R^2_m	R^2_c
All turtles	Poisson	BPUE	~ Treatment + offset(log(Effort))	(1|Vessel)	203.26	0.00	0.92	0.92	0.10	0.11
			~ offset(log(Effort))	(1|Vessel)	208.16	4.89	0.08	0.08	-	-
Green turtles	Poisson	BPUE	~ Treatment + offset(log(Effort))	(1|Vessel)	98.98	0.00	1.00	1.00	0.28	0.37
Olive ridley turtles	Poisson	BPUE	~ offset(log(Effort))	(1|TripID)	141.55	0.00	0.57	1.00	0.00	0.18
			~ Treatment + offset(log(Effort))	(1|TripID)	142.08	0.53	0.43	-	-	
Bony fish	Negative binomial	CPUE	~ offset(log(Effort))	(1|Vessel/TripID)	1958.68	0.00	0.63	1.00	0.00	0.72
			~ Treatment + offset(log(Effort))	(1|Vessel/TripID)	1959.76	1.08	0.37	-	-	-
Sharks	Poisson	CPUE	~ offset(log(Effort))	(1|Vessel/TripID)	315.74	0.00	0.73	1.00	0.00	0.70
			~ Treatment + offset(log(Effort))	(1|Vessel/TripID)	317.72	1.98	0.27	-	-	-

CPUEs and BPUEs, *i.e.*, the expected number of individuals captured when fishing effort = 1, if the model includes 'treatment' as a predictor.

RESULTS

Fishing effort

A total of 146 experimental sets (illuminated and control) were completed. As driftnets consisted of a single long net, we sought for each fishing set to have equivalent portions of the net illuminated as control (non-illuminated). Control nets length averaged 0.89 ± 0.15 km (mean ± standard error, SE), while illuminated nets averaged 0.81 ± 0.05 km. For set duration (soak time), control and illuminated nets averaged 11.74 ± 1.67 h. Fishing effort calculated for control nets averaged 0.44 ± 0.10 (km × 24 h), and for illuminated nets averaged 0.39 ± 0.06 (km × 24 h).

Sea turtle bycatch

During the experiment, 32 sea turtles were incidentally captured, of which 56.3% were olive ridley (*Lepidochelys olivacea*), 40.6% green (*Chelonia mydas*), and 3.1% (one individual) was a leatherback (*Dermochelys coriacea*) turtle (Table 3).

Mean CCL for olive ridley turtles was 57.7 ± 3.6 cm (mean ± SE) (range: 20 to 73 cm) and 44.4 ± 4.2 cm (mean ± SE) for green turtles (range: 43 to 77 cm). All green turtles and the leatherback incidentally captured were classified as juveniles; 72% of olive ridleys were

Table 3. The number of individuals captured in control and illuminated nets by species. Effort (km d^{-1}) is the total fishing effort. CM: *Chelonia mydas*; LO: *Lepidochelys olivacea*; DC: *Dermochelys coriacea*. BF: bony fish; SH: sharks.

Treatment	Effort	Sea turtles			Fish species	
	(km d^{-1})	CM	LO	DC	BF	SH
Control	63.6	12	12	0	2082	39
Illuminated	57.6	1	6	1	1937	35

Table 4. CCL measurements (cm) and fate by sea turtle species (olive ridley: *Lepidochelys olivacea*, green: *Chelonia mydas*, leatherback: *Dermochelys coriacea*) incidentally captured in control and illuminated nets. SE: standard error.

Treatment	Sea turtle species	CCL (cm) Mean ± SE	Fate % (n)	
			Released alive	Discarded dead
Control	Olive ridley	57.7 ± 3.6	100 (12)	0
	Green	44.4 ± 4.2	83 (10)	17 (2)
	Leatherback	-	0	0
Illuminated	Olive ridley	52.8 ± 7.1	67 (4)	33 (2)
	Green	56	100 (1)	0
	Leatherback	128	100 (1)	0

adults. Eighty-eight percent of the turtles captured were released alive (Table 4). Four turtles were recovered dead from the net, likely from drowning.

Regarding data analysis, the best-fit models with the final terms are summarized in Table 2. The factor 'treatment' was retained in the model for all turtle species combined and for green turtles individually. The GLMM indicates that the expected BPUE is lower in illuminated nets than in control nets for all sea turtle species and green turtles only, with reductions in BPUE of 62.2 and 93.3%, respectively (Fig. 3). For all turtle species, the expected bycatch BPUE is 0.37 km × 24 h in control nets compared to 0.14 km × 24 h in illuminated nets. For green turtles only, the expected BPUE is 0.15 km × 24 h in control nets as compared to 0.01 km × 24 h in illuminated nets (Fig. 3). For olive ridley turtles, 'treatment' was not included in the model, implying that the net illumination is not a predictor for the BPUE of this species.

Fish catch

A total of 4019 bony fishes and 74 sharks were recorded (Table 3). Among bony fishes captured, it was possible to identify species from the genus *Thunnus* and other species such as skipjack tuna *(Katsuwonus pelamis*) and mahi-mahi (*Coryphaena hippurus*). Shark species identified include thresher sharks (*Alopias* spp.), hammerhead sharks (*Sphyrna* spp.), and other species such as crocodile sharks (*Pseudocarcharias kamoharai*), blue sharks (*Prionace glauca*) and mako sharks (*Isurus oxyrinchus*).

The best-fit models with the final terms are summarized in Table 2. The factor Treatment was not included in the model for bony fish and sharks, implying that net illumination is not a predictor for the CPUE of these groups.

DISCUSSION

Effect on turtle bycatch

Our study shows that net illumination using violet-colored LEDs reduced sea turtle bycatch by small-scale driftnet vessels by 62.2%, which corroborates findings of similar studies in the EPO (Wang *et al*., 2013; Ortiz *et al*., 2016). Also, our results yielded novel, species-specific findings regarding the effects of net illumination on sea turtle bycatch. We assessed for species-level effects and found that net illumination reduced green turtle *Chelonia mydas* bycatch, a result similar to that of Wang *et al.* (2013). However, net illumination did not show the same effect on the bycatch of olive ridley turtles. This study is the first to assess the impact on olive ridley turtles *Lepidochelys olivacea* as other studies (using green LEDs) reported captures of only single individuals (Ortiz *et al*., 2016; Kakai, 2019).

The wavelength (100-400 nm) emitted by the LEDs used in this study is within the visual range of both the green and olive ridley turtle (Witherington, 1992). Nevertheless, as sea turtle response to wavelengths is associated with light intensity and varies among species (Cruz *et al*., 2018), a better understanding of the light intensity effect on wavelength sensitivity could help to

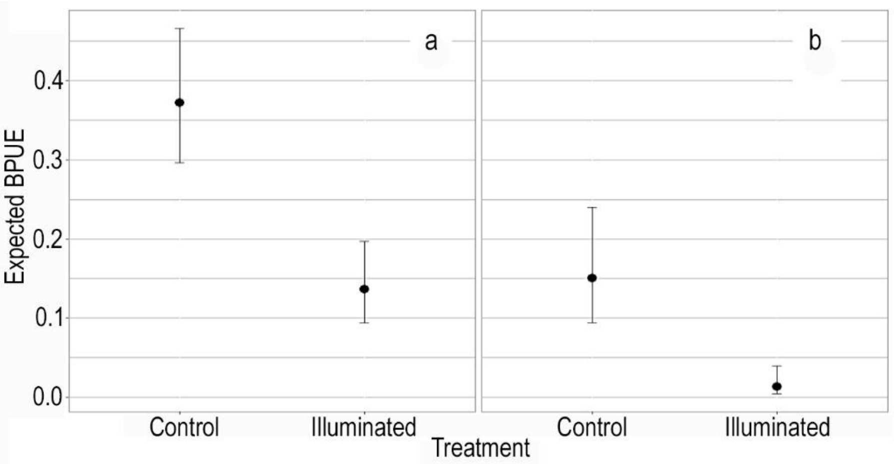

Figure 3. Expected BPUEs (individuals/km/day) in control and illuminated nets for a) all turtle species (*Lepidochelys olivacea*, *Chelonia mydas*, *Dermochelys coriacea*) and b) green turtles *C. mydas* only. Error bars are standard errors.

understand differences at a species level found by the model. In case sensitivity to light intensity is playing a crucial role in bycatch reduction effectiveness for individual species, an increase in the number of lights deployed per net panel could be an alternative for having a detectable effect of lights on olive ridley bycatch (Wang *et al*., 2010). In addition to light intensity, it is important to consider that environmental conditions (*i.e*., water visibility, sea surface temperature, lunar light) may be influencing net illumination efficiency as has been considered in previous studies (Ortiz *et al*., 2016; Virgili *et al*., 2018).

Previous studies suggest that sea turtles inhabiting southeastern Pacific waters belong to breeding areas such as Galapagos Islands, Mexico, Costa Rica, but also from the western Pacific (Velez-Zuazo & Kelez, 2010; Alfaro-Shigueto *et al*., 2011; Dutton *et al*., 2013; Alvarez-Varas *et al*., 2017). Our study shows that most turtle bycatch events were of putative juveniles, most likely individuals from the rookeries mentioned above that are using Ecuador's coastal waters as feeding grounds. Given the conservation status of some of these turtle populations (*e.g*., leatherbacks turtles *Dermochelys coriacea* of the EPO) and even though 88% of sea turtles in our study were released alive, these interactions may still represent a risk for these EPO populations due to the unknown levels of post-release mortality. Thus, even though net illumination with UV LEDs may represent a promising BRT, its implementation should be complemented with fisher training on sea turtle safe-handling and release techniques.

Effect on fish catch

Net illumination did not affect the capture efficiency of commercial species (bony fishes and sharks), a finding that is in line with other recent studies of net illumination (Ortiz *et al*., 2016; Virgili *et al*., 2018). It is important to consider, however, that we assessed target catch in terms of the number of individuals but did not assess the effect on specimen size or weight, which are also important metrics in terms of target catch economic value. Previous studies have shown that neither catch size, catch composition, or catch value is affected by net illumination (Wang *et al*., 2013; Virgili *et al*., 2018). However, future assessments should include the effect on target catch weight or size as any economic loss would be part of the cost associated with the implementation of net illumination.

It is also worth mentioning that apart from the violet LEDs tested here, a study conducted in Peru showed that green LEDs also reduced green turtle bycatch in commercial gillnet fisheries without affecting target catch rates (Ortiz *et al*., 2016). Bycatch in that study was exclusive to green turtles, however, making it clear that net illumination using green LED lights (as an alternative to violet LED lights) could also be tested in the Ecuadorian commercial gillnet fisheries.

It is encouraging that multiple studies have now shown that net illumination reduces turtle bycatch with no impact on target catch; however, local implementation may still be challenging due to the associated costs. We encourage the development of estimations of the costs associated with the implementation of net illumination as a BRT and how it may affect fishers' incomes. However, net illumination also has the potential to alleviate fishing gear damage associated with bycatch events (Panagopoulou *et al*., 2017). In this regard, it will be important to analyze the socio-economic factors that may affect the implementation of net illumination in Ecuador as each country may have particular issues and concerns.

Our study supports net illumination as a BRT for green turtles but provides evidence that its efficiency may vary between sea turtle species. Continuation of the testing of this BRT with different fishing gear types is recommended to more fully understand the efficacy of net illumination on bycatch reduction for different sea turtle species as well as on other taxa. Further testing will also provide the data necessary for more widespread implementation and its possible inclusion as part of a national strategy focusing on bycatch reduction.

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