Effects of Day-night Net Illumination on Bycatch, Target Catch, and Market Value in Coastal Gillnet Fisheries

by

Kyli Elizabeth Elise Denton

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved April 2021 by the
Graduate Supervisory Committee:

Jesse Senko, Co-Chair
Susanne Neuer, Co-Chair
Stephen Pratt

ARIZONA STATE UNIVERSITY

May 2021

ABSTRACT

One of the most pronounced issues affecting the management of fisheries today is bycatch, or the unintentional capture of non-target species of marine life. Bycatch has proven to be detrimental for many species, including marine megafauna and pelagic fishes. One method of reducing bycatch is illuminated gillnets, which involves utilizing the differences in biological visual capabilities and behaviors between species of bycatch and target fish catch. To date, all studies conducted on the effects of net illumination on bycatch and target fish catch have been conducted at night. In this study, the effects of net illumination on bycatch, target fish catch, and market value during both night and day periods at Baja California Sur, Mexico were compared. It was found that i) net illumination is effective ($p < 0.05$) at reducing bycatch of finfish during the day and at night, ii) net illumination at night is more effective ($p < 0.05$) at reducing bycatch for elasmobranchs, Humboldt squid, and aggregate bycatch than during the day, iii) time of day did not have an effect ($p > 0.05$) on sea turtle bycatch, and iv) net illumination did not significantly ($p > 0.05$) affect target catch or market value at night or during the day. These results suggest that net illumination may be an effective strategy for reducing finfish bycatch in fisheries that operate during the day or across 24 h periods, and is especially effective for reducing elasmobranch, Humboldt squid, and total bycatch biomass at night.

DEDICATION

This thesis is dedicated to myself. Throughout a global pandemic, and many troublesome times within my family, I made it here. There were countless nights where I debated whether or not I should move forward with the process of pursuing my degree; many times where I thought I was not capable of handling everything on my plate. Despite all of these doubts that replayed in my mind, I never gave up. In my heart, I knew I wanted to achieve this goal I had set for myself. I kept pushing forward day by day, and this document serves as a reminder to myself that I am capable of overcoming hard things. I am capable of doing whatever it is that I set my mind to.

ACKNOWLEDGMENTS

I would like to acknowledge my committee members for all of the help they have provided me along this journey. Firstly, I would like to thank Dr. Neuer for all of her expertise in oceanography. This information really helped to add a nice element to my project and has allowed me a more well-rounded view of the underlying processes that drove the findings of my research. Secondly, I would like to thank Dr. Pratt for all of the time he dedicated each week to answering all of my questions and ensuring that I was on the right track with my analyses. He has taught me quite literally everything I know about statistics today. I still would not consider myself a statistician by any means, but I am a lot closer to becoming one thanks to him. Last, but certainly not least, I would like to thank Dr. Senko. His work has been inspiring me for many years now, and he has really shaped who I am as a scientist and where I would like to go in my career. I would like to thank him for entrusting me with this data and for always believing in me. I truly could not have completed my project if it were not for the help of each of these wonderful individuals.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Fisheries play a critical role in trade, sustaining human livelihoods through increased food security and employment, and ocean health on a global scale. Both the magnitude and efficiency of global marine fishing fleets have changed drastically over time. Over the course of 65 years, the global fishing fleet had expanded from 1.7 million vessels in 1950 to 3.7 million vessels in 2015 (Rousseau et al., 2019). This was largely made possible due to the dramatic 68% increase in motorization of the global fleet by the year 2015 (Rousseau et al., 2019). With this increase in efficiency followed an increase in exploitation of fished resources. During this same period of time from 1950 to 2015, catch per unit effort (CPUE) decreased by a substantial 80% for many of the world's nations (Rousseau et al., 2019).

One of the most pronounced issues affecting the management of fisheries today due to the massive rise in global fishing effort is bycatch, or the unintended capture of non-target species. Bycatch accounts for over 40% of total catch in fisheries on a global scale and affects a wide range of marine fauna (Davies et al., 2009). In 1994, there was estimated to be an average of 27 million tons of fish discarded as bycatch globally each year in commercial fisheries (Crowder & Murawski, 1998). Numbers of this magnitude undoubtedly have important population level effects for the affected species and can, also, lead to major changes in food webs (Crowder & Murawski, 1998). Although still detrimental to many species of fish, bycatch is especially detrimental to many species of marine megafauna due to certain life history characteristics such as longer lifespans, late maturity, and low reproductive output (Liles et al., 2017; Senko et al., 2014). In fact, bycatch is one of the leading causes of population decline for many taxa of marine megafauna including sea turtles, seabirds, and marine mammals which also leads to major disruptions in species biodiversity and ecosystem functioning (Hall et al., 2000; Lewison et al., 2014; Senko et al., 2014). The distribution of bycatch is widespread across the globe; however, bycatch intensity differs by region and by gear type. The gear type with the highest bycatch intensity amongst sea turtles, seabirds, and marine mammals is currently the gillnet (Lewison et al., 2014). Bycatch intensity for finfish in gillnets is also very high for certain fisheries, including particular ones located in Baja California (Shester & Micheli, 2011).

Bycatch was largely ignored by scientists conducting stock assessments for a long period of time; however, this is now an integral factor in the managing of many fisheries. There have been many different strategies implemented in attempt to mitigate the bycatch of marine fauna. Bycatch limits, time-area closures, buy-outs, and modifications made to fishing gear are just some of these strategies that have been tested. Gear modifications have been identified as having the most potential out of all four strategies when it comes to effectively reducing the bycatch of sea turtles, seabirds, and marine mammals (Senko et al., 2014). Not only are gear modifications generally more successful at reducing bycatch, but they are also useful because they do not redistribute the effects of bycatch elsewhere and are the preferred method by many fishermen (Senko et al., 2014). There are over 50 unique gear modifications that have been developed and tested including acoustic pingers/alarms, electromagnetic deterrents, excluder devices, and the illumination of nets (Werner et al., 2006).

The use of illuminated nets, specifically, as a bycatch reduction strategy is useful as it involves utilizing the differences in biological visual capabilities and behaviors of certain taxa of bycatch and target fish catch. In one review of various studies conducted in order to assess the visual cues of pelagic fishes and sea turtles, it was found that the two taxa differ in spectral sensitivity and in capabilities to sense UV light (Southwood et al., 2008). Sea turtles are better able to differentiate between colors and, unlike many pelagic fishes, are able to detect light in the UV spectrum (Southwood et al., 2008). Drawing from this knowledge, there have been multiple studies conducted on the effects of ultraviolet illumination of gillnets on sea turtle bycatch (Virgili et al., 2018; Wang et al., 2013). This strategy was also utilized to test the effects of illuminated gillnets on the bycatch of other taxa such as elasmobranchs and seabirds, as well (Jordan et al., 2013; Mangel et al., 2018). In each of these studies, the results concluded that the illuminated nets decreased the bycatch of marine megafauna while maintaining current levels of target fish catch (Jordan et al., 2013; Mangel et al., 2018; Virgili et al., 2018; Wang et al., 2013).

This paper introduces a study involving the use of green light-emitting diode (LED) illuminated gillnets in reducing bycatch of multiple taxa of marine fauna in Baja California Sur, Mexico. This particular study differs from other similar studies in one major way. To date, all studies done on the effects of any variation of net illumination on bycatch of marine fauna have been conducted only during the night. Thus, this is the first study that has aimed to compare the effects of net illumination on bycatch during the night and during the day. Specifically, the purpose of this study was to assess the effectiveness of net illumination on bycatch, target catch, and market value between periods of day and night.

CHAPTER 2

METHODOLOGY

Study Site

This study was conducted in the Gulf of Ulloa, along the Pacific coast of Baja California Sur, Mexico. The location was chosen as it is home to a tightly knit community of fishers and is also a global hotspot for many taxa of marine megafauna and pelagic fishes. The California Current System, located within the Pacific Ocean off the Baja California Peninsula, is a known hotspot for economically and ecologically important species such as whales, sea birds, sharks, and sea turtles (Wingfield et al., 2011). What makes this location so favorable to these higher trophic levels is the unique combination of geomorphological and physical oceanographic features that are present. The merging of frontal structures created by warm water converging with newly upwelled cold water along with positive wind-stress curl promotes dense populations of red crabs, thereby promoting high prey abundances in the region (Gómez-Gutiérrez et al., 2000; Wingfield et al., 2011).

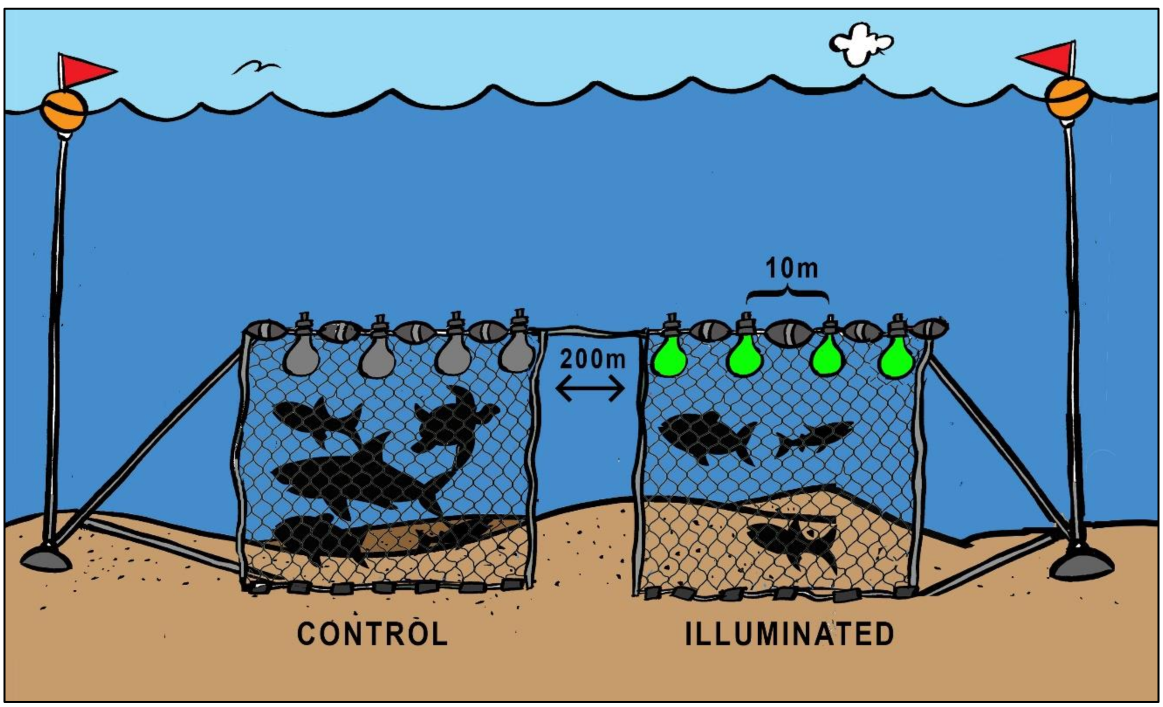
Study Design and Data Collection

Local fishers were contracted to hand-build nets with a height of 6.1 m, a mesh size ranging from 18 to 22 cm, and a length ranging from 153 to 199 m. These specifications, and the materials used, were chosen in order to match those of the local gillnet fleet. During the summer of 2012, a total of 32 net pairs were deployed during the day beginning at sunrise, and 28 net pairs were deployed during the night beginning at sunset. Each net pair consisted of an illuminated net being connected to a control net of similar size with a 200 m rope (Fig. 1). After soaking for

8 to 12 h per deployment from sunrise to sunset (daytime) and sunset to sunrise (nighttime), each net pair was retrieved. Green light-emitting diodes (LEDs) powered by AA batteries were clipped to the treatment nets at every 10 m along the float line. The control nets were given the same treatment but with inactive LEDs. Each net pair was set in highly productive halibut and rockfish fishing grounds at a depth ranging from 10.9 m to 43.9 m. In order to control for site effects, each net pair was fished in a different location.

Figure 1

Schematic of Experimental Design



Note. Experimental design showing pairing between control and illuminated nets used in this study. Drawings are not to scale.

For the purposes of this study, bycatch was defined as any species that were either not retained in these fisheries or their take was prohibited during the period of study. All bycatch and target catch were binned in their respective species groups where they were then recorded and weighed. The taxa of bycatch captured in this study included loggerhead turtles (*Caretta caretta*), elasmobranchs (i.e. sharks, rays, and skates), Humboldt squid (*Dosidicus gigas*), and finfish (i.e. bony fish). The taxa of target catch captured in this study included California halibut (*Paralichthys californicus*), various grouper species, and other finfish (finfish other than halibut and grouper). Other variables that were also included were aggregate BPUE (every taxonomic bycatch group combined), marine megafauna BPUE (i.e. turtles, elasmobranchs, and squid), number of sea turtles BPUE, and aggregate CPUE (all taxonomic catch groups combined). Sea turtles were the only group in which the number of individuals captured was recorded in addition to them being weighed.

Bycatch rates, or bycatch per unit effort (BPUE), were determined for each taxon and each net via the following formula: BPUE = kg of bycatch group/ ([net length/100 m] x [net soak time/12 h]). Similarly, target catch rates, or catch per unit effort (CPUE), were determined for each taxon and each net via the following formula: CPUE = kg of target catch group/ ([net length/100 m] x [net soak time/12 h]). Market value was included as a variable in this study as well in order to determine the effect of the illuminated nets on catch value of target fish. Market value rates, or market value per unit effort (MVPUE), was determined for total target catch rates of each net via the following formula: MVPUE = USD of target fish caught/ ([net length/100 m] x [net soak time/12 h]).

Data Analysis

Rates between control and illuminated nets during the day and at night were compared separately using a Wilcoxon matched-pairs signed-rank test for each variable (each species or taxonomic group of bycatch and target catch, or market value) using the 'wilcox.test' function from the 'stats' package (R Core Team, 2020). All statistical analyses were conducted using a significance level of 0.05.

CHAPTER 3

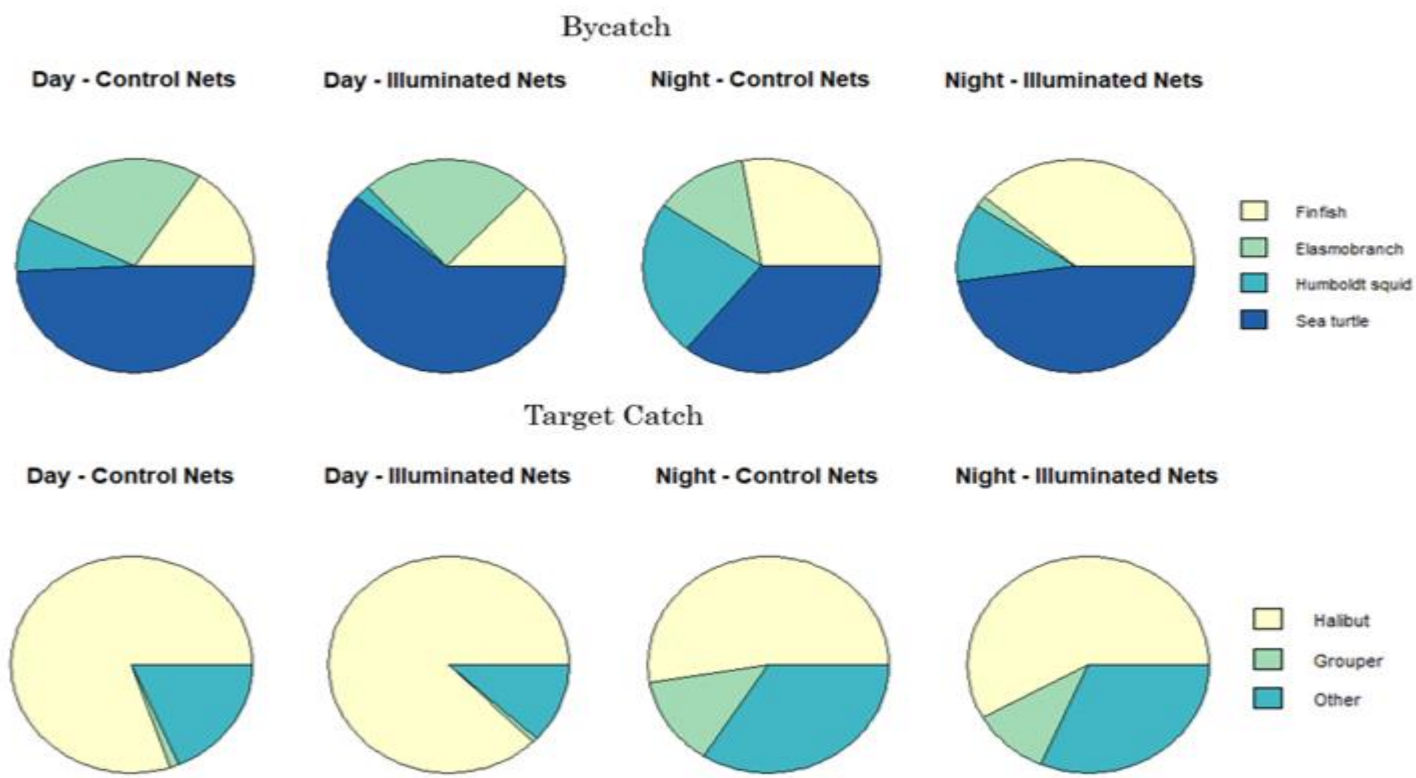
RESULTS

Descriptive Summary

Throughout the duration of the experiment, aggregate BPUE totaled 4,034 kg. The total bycatch biomass per taxonomic group was 830, 789, 401, and 2,015 kg for elasmobranchs, finfish, Humboldt squid, and sea turtles, respectively. The 2,015 kg of sea turtles accounted for 90 individuals, all of which were loggerheads. Aggregate CPUE totaled 383 kg throughout the study. The total biomass per taxonomic group was 279, 20, and 83 kg for halibut, grouper, and finfish other than halibut and grouper, respectively. Market value MVPUE of aggregate target fish totaled 1,026 USD. Species composition for each taxonomic group per net type and time of day are also provided (Figure 2).

Figure 2

Species Composition Charts



Note. Pie charts demonstrating species composition for bycatch and target fish catch for each combination of time of day and net type.

Bycatch Rates

For aggregate bycatch, there was a 15% decrease in BPUE in illuminated nets (mean BPUE = 40.2 ± 10.5 s.e.) during the day (n = 32 paired sets) as compared to the control nets (mean BPUE = 47.3 ± 11.6 s.e.) during the day (n = 32 paired sets, $P = 0.6645$; Fig. 3, Table 1). At night (n = 28 paired sets), aggregate BPUE was significantly lower in the illuminated nets (mean BPUE = 11.9 ± 2.29 s.e.) as compared to control nets (mean BPUE = 32.1 ± 4.85 s.e.) at night (n = 28 paired sets, $P = 0.0003814$; Fig. 3, Table 1), representing a 63% decrease in the aggregate bycatch rate.

For marine megafauna BPUE, there was a 12% decrease in BPUE in illuminated nets (mean BPUE = 34.9 ± 10.0 s.e.) during the day (n = 32 paired sets) as compared to the control nets (mean BPUE = 39.8 ± 11.4 s.e.) during the day (n = 32 paired sets, $P = 0.7605$; Fig. 3, Table 1). At night (n = 28 paired sets), megafauna BPUE was significantly lower in the illuminated nets (mean BPUE = 7.31 ± 2.32 s.e.) as compared to control nets (mean BPUE = 23.2 ± 4.70 s.e.) at night (n = 28 paired sets, $P = 0.003479$; Fig. 3), representing a 68% decrease in the marine megafauna bycatch rate.

There was a 26% decrease in elasmobranch BPUE in illuminated nets (mean BPUE = 9.43 ± 7.78 s.e.) during the day (n = 32 paired sets) as compared to the control nets (mean BPUE = 12.8 ± 8.34 s.e.) during the day (n = 32 paired sets, $P = 0.155$; Fig. 3, Table 1). Elasmobranch BPUE was significantly lower in the illuminated nets (mean BPUE = 0.19 ± 0.13 s.e.) at night (n = 28 paired sets) as compared to the control nets (mean BPUE = 4.09 ± 1.31 s.e.) at night (n = 28 paired sets, $P = 0.003483$; Fig. 3, Table 1), representing a 95% decrease in the elasmobranch bycatch rate.

For finfish, BPUE was significantly lower in the illuminated nets (mean BPUE = 5.27 ± 1.65 s.e.) during the day (n = 32 paired sets) as compared to control nets (mean BPUE = 7.53 ± 2.19 s.e.) during the day (n = 32 paired sets, $P = 0.02613$; Fig. 3, Table 1), representing a decrease of 30% in the finfish bycatch rate. Finfish BPUE was also significantly lower in illuminated nets (mean BPUE = 4.64 ± 0.79 s.e.) at night (n = 28 paired sets) as compared to control nets (mean BPUE = 8.91 ± 2.61 s.e.) at night (n = 28 paired sets, $P = 0.0009657$; Fig. 3, Table 1), representing a decrease of 48% in the finfish bycatch rate.

There was a 77% decrease in Humboldt squid BPUE in the illuminated nets (mean BPUE = 0.87 ± 0.46 s.e.) during the day (n = 32 paired sets) compared to the control nets (mean BPUE = 3.75 ± 2.72 s.e.) during the day (n = 32 paired sets, $P = 0.1775$; Fig. 3, Table 1). At night (n = 28 paired sets), Humboldt squid BPUE was significantly lower in illuminated nets (mean BPUE = 1.43 ± 0.73 s.e.) compared to control nets (mean BPUE = 7.59 ± 3.32 s.e.) during the night (n = 28 paired sets, $P = 0.02997$; Fig. 3, Table 1), representing an 81% decrease in the Humboldt squid bycatch rate.

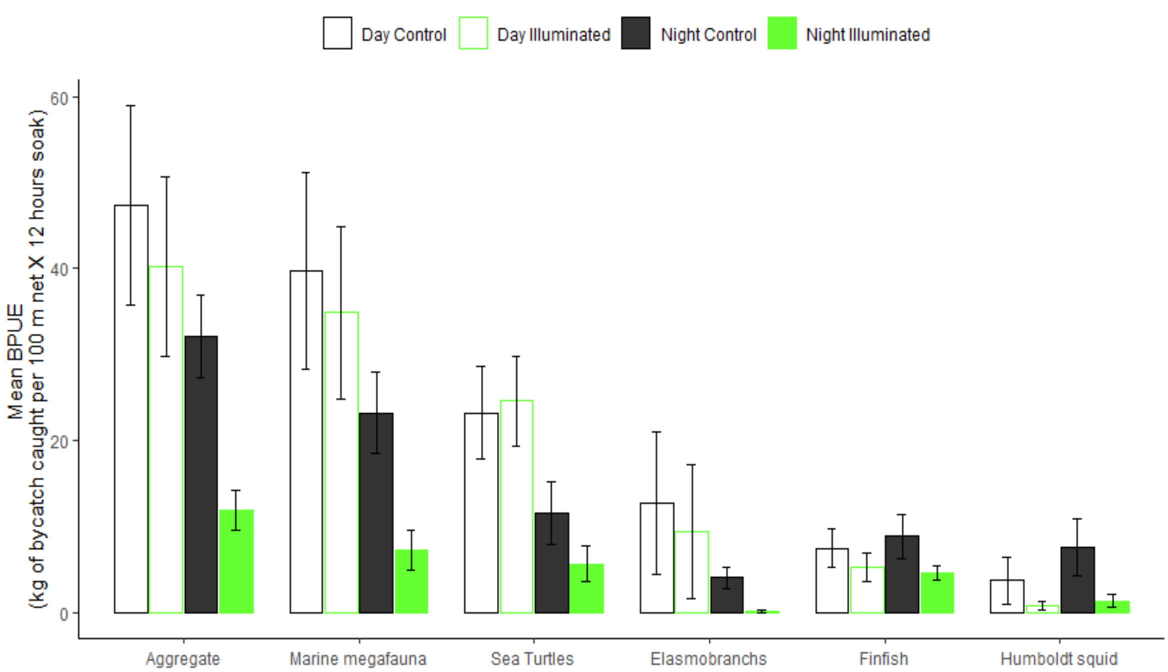
For loggerhead turtle BPUE (biomass), there was a 6% increase in the illuminated nets (mean BPUE = 24.6 ± 5.25 s.e.) during the day (n = 32 paired sets) compared to control nets (mean BPUE = 23.2 ± 5.31 s.e.) during the day (n = 32 paired sets, $P = 0.7544$; Fig. 3, Table 1). At night (n = 28 paired sets), there was a 51% decrease in loggerhead BPUE (biomass) in illuminated nets (mean BPUE = 5.69

± 2.08 s.e.) compared to the control nets (mean BPUE = 11.5 ± 3.63 s.e.) at night (n = 28 paired sets, $P = 0.1874$; Fig. 3, Table 1).

Similarly, for the number of loggerhead turtles there was an 8% increase in BPUE in illuminated nets (mean BPUE = 0.74 ± 0.15 s.e.) during the day (n = 32 paired sets) as compared to control nets (mean BPUE = 0.68 ± 0.16 s.e.) during the day (n = 32 paired sets, $P = 0.7282$; Table 1). At night (n = 28 paired sets), there was a 50% decrease in BPUE for number of loggerheads in illuminated nets (mean BPUE = 0.17 ± 0.06 s.e.) as compared to control nets (mean BPUE = 0.34 ± 0.11 s.e.) at night (n = 28 paired sets, $P = 0.1874$; Table 1).

Figure 3

Mean BPUE per Category of Bycatch



Note. Mean values for bycatch, BPUE, for each combination of time of day and net type ± standard error.

Target Fish Catch & Market Value Rates

For aggregate CPUE, there was a 19% increase in illuminated nets (mean CPUE = 4.06 ± 2.11 s.e.) during the day (n = 32 paired sets) as compared to control nets (mean CPUE = 3.30 ± 1.46 s.e.) during the day (n = 32 paired sets, P = 0.7282; Fig. 4, Table 1). At night (n = 28 paired sets), there was a 6% increase in aggregate CPUE in illuminated nets (mean CPUE = 2.70 ± 0.84 s.e.) as compared to the control nets (mean CPUE = 2.55 ± 1.07 s.e.) at night (n = 28 paired sets, P = 0.8961; Fig. 4, Table 1).

For halibut CPUE, there was a 25% increase in illuminated nets (mean CPUE = 3.54 ± 2.10 s.e.) during the day (n = 32 paired sets) compared to the control nets (mean CPUE = 2.64 ± 1.34 s.e.) during the day (n =32 paired sets, P = 0.2635; Fig. 4, Table 1). Halibut CPUE was 14% higher in illuminated nets (mean CPUE = 1.56 ± 0.68 s.e.) at night (n = 28 paired sets) compared to control nets (mean CPUE = 1.34 ± 0.58 s.e.) at night (n = 28 paired sets, P = 0.6356; Fig. 4; Table 1).

There was a decrease of 25% in grouper CPUE in illuminated nets (mean CPUE = 0.03 ± 0.03 s.e.) during the day (n = 32 paired sets) as compared to the control nets (mean CPUE = 0.04 ± 0.03 s.e.) during the day (n = 32 paired sets, P = 1.00; Fig. 4, Table 1). At night (n = 28 paired sets), there was a decrease of 18% for grouper CPUE in illuminated nets (mean CPUE = 0.28 ± 0.14 s.e.) as compared to control nets (mean CPUE = 0.34 ± 0.18 s.e.) at night (n = 28 paired sets, P = 0.7998; Fig. 4, Table 1).

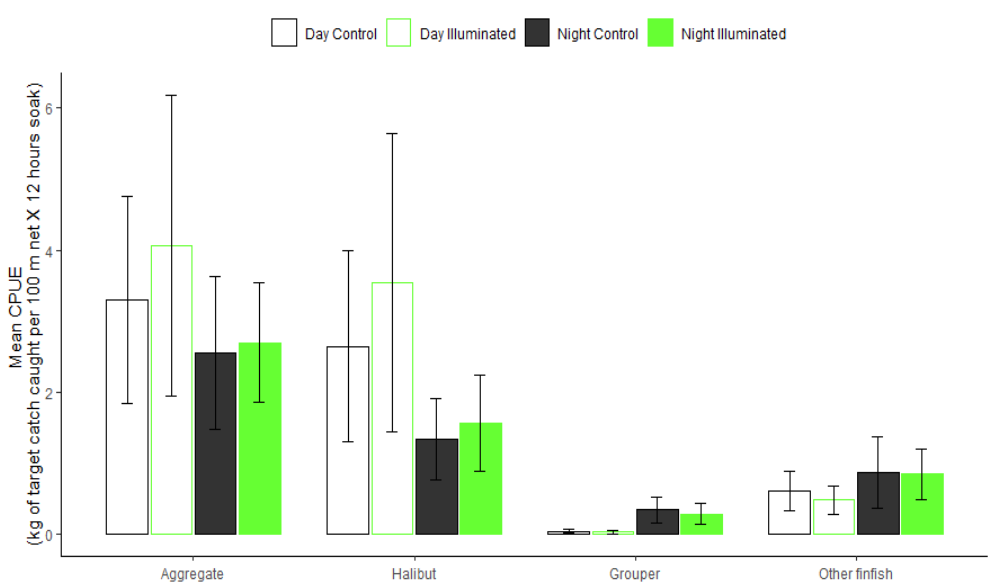
There was a 20% decrease in other finfish CPUE in the illuminated nets (mean CPUE = 0.49 ± 0.20 s.e.) during the day (n = 32 paired sets) compared to the control nets (mean CPUE = 0.61 ± 0.28 s.e.) during the day (n = 32 paired sets, P =

0.9499; Fig. 4, Table 1). Other finfish CPUE experienced a 2% decrease in the illuminated nets (mean CPUE = 0.85 ± 0.36 s.e.) at night (n = 28 paired sets) compared to the control nets (mean CPUE = 0.87 ± 0.51 s.e.) at night (n = 28 paired sets, $P = 1.00$; Fig. 4, Table 1).

For market value MVPUE, there was a 31% increase in illuminated nets (mean MVPUE = 12.0 ± 6.30 s.e.) during the day (n = 32 paired sets) as compared to control nets (mean MVPUE = 8.29 ± 4.10 s.e.) during the day (n = 32 paired sets, $P = 0.1541$; Fig. 5, Table 1). Market value MVPUE experienced a 6% increase in illuminated nets (mean MVPUE = 6.91 ± 2.49 s.e.) during the night (n = 28 paired sets) as compared to control nets (mean MVPUE = 6.52 ± 2.52 s.e.) during the night (n = 28 paired sets, $P = 0.8617$; Fig. 5, Table 1).

Figure 4

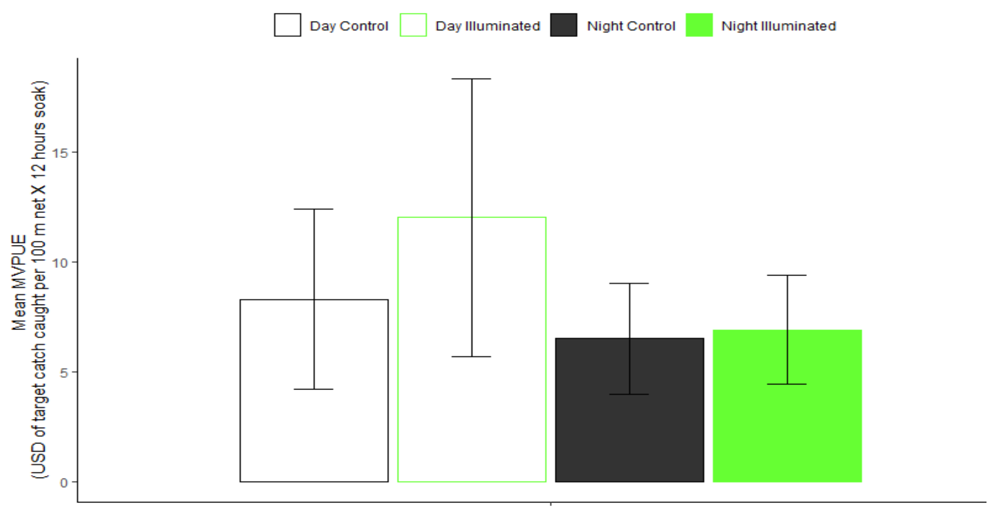
Mean CPUE per Category of Target Fish Catch



Note. Mean values for target catch, CPUE, for each combination of time of day and net type ± standard error.

Figure 5

Mean MVPUE of Aggregate Target Fish Catch



Note. Mean values for market value, MVPUE, of target catch for each combination of time of day and net type ± standard error.

Table 3

Comparison of Control and Illuminated Nets per Time of Day

			Day				Night			
Category	Response	Unit	Control	Illuminated	% Change	P-value	Control	Illuminated	% Change	P-value
Aggregate	BPUE	kg per 100 m X 12 hrs	47.3 ± 11.6	40.2 ± 10.5	-15	0.6645	32.1 ± 4.85	11.9 ± 2.29	-63	**0.0003814**
Marine Megafauna	BPUE	kg per 100 m X 12 hrs	39.8 ± 11.4	34.9 ± 10.0	-12	0.7605	23.2 ± 4.70	7.31 ± 2.32	-68	**0.003479**
Elasmobranchs	BPUE	kg per 100 m X 12 hrs	12.8 ± 8.34	9.43 ± 7.78	-26	0.155	4.09 ± 1.31	0.19 ± 0.13	-95	**0.003483**
Finfish	BPUE	kg per 100 m X 12 hrs	7.53 ± 2.19	5.27 ± 1.65	-30	**0.02613**	8.91 ± 2.61	4.64 ± 0.79	-48	**0.0009657**
Humboldt squid	BPUE	kg per 100 m X 12 hrs	3.75 ± 2.72	0.87 ± 0.46	-77	0.1775	7.59 ± 3.32	1.43 ± 0.73	-81	**0.02997**
Sea turtles (biomass)	BPUE	kg per 100 m X 12 hrs	23.3 ± 5.31	24.6 ± 5.25	5	0.7544	11.5 ± 3.63	5.69 ± 2.08	-51	0.1874
Sea turtles (# turtles)	BPUE	kg per 100 m X 12 hrs	0.68 ± 0.16	0.74 ± 0.15	8	0.7282	0.34 ± 0.11	0.17 ± 0.06	-50	0.1874
Aggregate	CPUE	kg per 100 m X 12 hrs	3.30 ± 1.46	4.06 ± 2.11	19	0.7544	2.55 ± 1.07	2.70 ± 0.84	6	0.8961
Halibut	CPUE	kg per 100 m X 12 hrs	2.64 ± 1.34	3.54 ± 2.10	25	0.2635	1.34 ± 0.58	1.56 ± 0.68	14	0.6356
Grouper	CPUE	kg per 100 m X 12 hrs	0.04 ± 0.03	0.03 ± 0.03	-25	1.00	0.34 ± 0.18	0.28 ± 0.14	-18	0.7998
Other finfish	CPUE	kg per 100 m X 12 hrs	0.61 ± 0.28	0.49 ± 0.20	-20	0.9499	0.87 ± 0.51	0.85 ± 0.36	-2	1.00
Market value	MVPUE	USD per 100 m X 12 hrs	8.29 ± 4.10	12.0 ± 6.30	31	0.1541	6.52 ± 2.52	6.91 ± 2.49	6	0.8617

Note. Mean BPUE, CPUE, and MVPUE ± standard error in control vs. illuminated nets during the day and at night. Negative percent change values indicate that the mean value was lower in the illuminated nets as compared to the control nets. P-values signify whether or not there was a significant difference between corresponding mean values for control vs illuminated during the day and at night. Significant values are indicated in bold.

CHAPTER 4

DISCUSSION

Significant decreases in bycatch in illuminated nets at night were found for aggregate BPUE, marine megafauna BPUE, finfish BPUE, elasmobranch BPUE, and Humboldt squid BPUE with 63%, 68%, 48%, 95% and 81% reductions, respectively. Significant decreases in bycatch in illuminated nets during the day were found for finfish with a 30% reduction. There were no significant differences for target catch or market value during the day or at night. Although reductions differed between taxonomic groups, the overall aggregate BPUE was reduced by 15% in illuminated nets during the day and by 63% in illuminated nets at night, as mentioned. Aggregate CPUE was increased by 19% in illuminated nets during the day and by 6% in illuminated nets at night. Market value MVPUE increased by 31% in illuminated nets during the day and by 6% in illuminated nets at night.

There have been studies identifying illuminated nets set at night as an effective bycatch reduction strategy for multiple taxa of marine life, such as sea turtles and sea birds, while maintaining target catch (Bielli et al., 2020; Mangel et al., 2018; Ortiz et al., 2016; Wang et al., 2010). The study presented here confirms these findings as it, also, concluded that gillnets illuminated by LEDs achieved significant reductions in bycatch for multiple taxa during the night without significantly affecting the rates of target catch species or their market value. There have not, however, previously been any studies to demonstrate the effectiveness of the illuminated nets on bycatch, target catch, and market value during the day as this is the first study of its kind.

There are many factors, both biological and environmental, that play a role in the visual capabilities of different marine organisms. As depth increases in aquatic environments, available light is restricted to wavelengths in the range of blue to green and yellow depending upon water turbidity (Horch et al., 2008; Sverdrup & Kudela, 2019). Because of the exponential attenuation of light in water, the percentage of solar energy reaching depths of 20 meters can be as low as 20 percent even in the clearest of marine waters (Sverdrup & Kudela, 2019). In coastal habitats where the water is often much less clear, the transmission of light varies not only with depth, but also with fluctuations in dissolved organic matter and concentrations of particulates (Horch et al., 2008). Here, in turbid coastal waters, the percentage of solar energy transmitted to depths of 20 meters can be as low as only 1 percent (Sverdrup & Kudela, 2019). Even without the array of environmental factors that may impact an organism's vision, biological visual capabilities already vary greatly from species to species (Marshall, 2017; Nguyen & Winger, 2019).

Studies have indicated that sea turtles rely primarily on visual cues in searching for food, and these capabilities likely have an effect on interactions between sea turtles and different types of fishing gear (Southwood et al., 2008; Swimmer et al., 2005; Wang et al., 2007, 2010). Loggerhead turtles, the only species caught in this particular study, are one species of sea turtle that is known to possess the capability of detecting green light (Horch et al., 2008; Wang et al., 2007). Although it has been demonstrated that certain age classes of loggerheads are attracted to wavelengths of green light as in Wang et al. (2007), it is thought that the LEDs are still better able to alert the turtles to the presence of the nets, therefore, decreasing the likelihood of entanglement within them (Wang et al., 2010). The study presented here found there to be no significant difference in loggerhead BPUE between control and illuminated nets at night, however, other studies have found evidence to suggest otherwise, indicating that the results here could be due to chance or possibly certain environmental factors that were not measured in this study. The lack of a significant difference between control and illuminated nets at night could also be due to the number of turtles that interacted with the nets at night. It is possible that the number of turtles interacting with the nets was too low to draw an accurate conclusion from, with 17 in the control nets and 9 in the illuminated nets, as was the case in Gilman et al. (2010).

This study also concluded that loggerhead BPUE did not differ between control and illuminated nets during the day. In fact, loggerhead BPUE was actually slightly higher in the illuminated nets during the day. Loggerheads primarily forage for food during the daytime near the ocean surface where they often encounter a broad spectrum of wavelengths of light (Horch, 2008). Because of this wide range of wavelengths present during the day, it is possible that the LED lights were not intense enough for the eyes of the loggerheads to sense, as was hypothesized by Wang et al. (2007). Studies testing out different intensities of LED lights would provide further information on the visual capabilities of loggerhead sea turtles under photopic conditions and the effects of these lights on the ability of the turtles to avoid interactions with the nets. Additionally, these studies should also be carried out in fisheries where there are known to be interactions between fishing gear and species of sea turtles other than loggerheads to test for differences in visual capabilities amongst different species.

Elasmobranch BPUE was significantly lower in the illuminated nets compared to the control nets at night. Elasmobranch BPUE did not experience a significant difference between the illuminated and control nets during the day, however. Elasmobranchs use electrical, chemical, mechanical, and visual cues to locate both predators and prey (Jordan et al., 2013). Many species of elasmobranchs have retinas containing rhodopsins, which are sensitive to light within blue to green wavelengths (Gardiner et al., 2012). The rod-dominated retinas of elasmobranchs imply that their vision may be better adapted to conditions of low light (Gardiner et al., 2012). Other studies have argued that the occlusible tapetum lucidum, a layer of tissue in the eye, present in many elasmobranchs allows for visual adaptation to a wide range of light levels (Collin, 2012; Hueter et al., 2004). More research on the visual acuity of elasmobranchs in both photopic and scotopic conditions is needed, however, there are studies to suggest that ultraviolet or near-ultraviolet LED lights can reduce the bycatch of elasmobranchs by serving as a warning to the net and, therefore, helping to prevent interactions with it (Jordan et al., 2013).

Humboldt squid BPUE experienced a significant reduction in the illuminated nets compared to the control nets at night. There was not, however, a significant reduction between control and illuminated nets during the day. Nonetheless, reductions in bycatch during day and night were nearly identical (Table 1). It was recently proposed that cephalopods, including Humboldt squid, are able to differentiate between colors using their off-axis pupil shape by way of a method known as chromatic aberration, or the focusing of different wavelengths of light at different distances behind a lens in the eye (Stubbs & Stubbs, 2016). This information, along with the fact that squid are attracted to light (Nguyen & Winger, 2019), suggests that Humboldt squid may be able to detect the green LEDs placed on the gillnets and, therefore, avoid encounters with them.

Although spectral discrimination is preserved across a wide range of ambient light in cephalopods, this method of chromatic aberration works best in environments with considerable spectral contrast (Stubbs & Stubbs, 2016). This could potentially explain why there was no significant difference in Humboldt squid BPUE between illuminated and control nets during the day. This, and the fact that Humboldt squid spend most of their time during the day in deep waters so there is already less chance for a potential interaction (Trueblood et al., 2015). In this study, 23.2% of nets caught squid at night and only 12.5% of nets caught squid during the day, indicating that the sample size during the day may have been too small to draw an accurate conclusion from.

Finfish bycatch was the only taxonomic group that experienced a significant reduction during the day and at night in illuminated nets as compared to the control nets. On the other hand, neither halibut, grouper, nor other types of finfish target catch experienced any significant differences between control and illuminated nets during the day or at night. Many species of fish, such as pointhead flounder and red halibut, are capable of recognizing colors, including the wavelengths corresponding to green light (Matsuda et al., 2009; Nguyen & Winger, 2019). People have been using artificial forms of light to attract fish for thousands of years, however, the reasonings behind this attraction are still largely unknown (Nguyen & Winger, 2019). One potential possibility that could describe why the illuminated nets affected the target fish and fish caught as bycatch differently is due to the differences in life stages between the groups. Much of the finfish caught as bycatch in this study were juveniles. Vision in juvenile fish often differ greatly from that of adult fish of the same species as they are not required to perform as elaborate of functions as they do in older life stages, such as prey recognition and capture, mate selection and communication, and the use of spatial vision (Nguyen & Winger, 2019).

This significant reduction in bycatch for finfish is a noteworthy finding as finfish bycatch is a very common problem in many gillnet fisheries (Davies et al., 2009), even more so than turtle bycatch, for example. Although the location in which this study was conducted is considered to be a hotspot for sea turtles, interactions between individual sea turtles and fishing gear in most parts of the world are considered to be rare events, statistically (McCracken, 2004). In this study alone, 93% of the nets caught finfish as bycatch whereas only 39% of the nets caught turtles. These findings are consistent with those from another study conducted by Silvani et al. (1999) in which it was discovered that *M. mola*, the world's largest bony fish, constituted roughly 70 to 93% of the total fish catch amongst all Spanish drift gillnet fisheries between the years of 1992 and 1994 in the Mediterranean. In addition, they found that loggerhead turtle bycatch comprised only 0.32% to 0.92% during this same period of time (Silvani et al., 1999).

CHAPTER 5

CONCLUSION

This study has demonstrated the differences in effectiveness of using illuminated nets as a bycatch reduction strategy for multiple taxa of marine life while maintaining target catch and market value at night and during the day. This study has shown that i) net illumination is effective at reducing bycatch of finfish during the day and night, ii) net illumination at night is more effective at reducing bycatch for elasmobranchs, Humboldt squid, and overall aggregate bycatch than during the day, iii) time of day did not have an effect on loggerhead turtle bycatch, and iv) net illumination did not significantly affect target catch or their market values at night or during the day.

Although the illuminated nets in this study did help to reduce bycatch of elasmobranchs, Humboldt squid, and aggregate bycatch during the daytime, the results were not significant. Additionally, loggerhead turtle bycatch was actually higher in the illuminated nets during the day as compared to the control nets. For these reasons, more testing on the effectiveness of the illuminated nets during the day will need to be conducted before they can be considered for implementation. Testing the effects of different intensities of green LEDs is recommended to see which, if any, will have the desired impact of significantly reducing bycatch during the day for all taxa represented in this study, while still maintaining target fish catch and market value. Additionally, more testing on how different LED flicker rates impact behaviors of bycatch and target fish catch could also provide useful information (Jordan et al., 2013).

Most gillnet fisheries along the Baja coast operate mainly at night, however, there are still some gillnet fisheries, including a commercial bottom-set gillnet fishery located in Bahia de los Angeles, that operate for periods of 24 hours at a time (Wang et al., 2010, 2013). There are gillnet fisheries that operate for 24-hour periods in other parts of the world, as well, such as one specific grouper/catfish/flounder fishery known as 'malhão' off the coast of Brazil (Fiedler et al., 2020). Because of fisheries like these, finding a way to reduce bycatch both at night and during the day is crucial for the conservation of many species of marine life. Not only is a reduction in bycatch necessary for marine life, but it is also beneficial to fishermen, as well. Less bycatch results in less damage to fishing gear, thereby mitigating the amount of time and money spent for reparations on behalf of the fishermen (Jordan et al., 2013). A reduction of finfish bycatch during both day and night would be a great incentive for the fisherman to adopt this technology into their fleets. Once it has been determined how the illuminated nets can be used to significantly decrease bycatch at night and during the day, the illuminated nets have the potential to serve as a comprehensive solution to reducing bycatch of multiple taxa while maintaining target catch and their market value within the local fleets of this Baja California Sur hotspot.

REFERENCES

Bielli, A., Alfaro-Shigueto, J., Doherty, P. D., Godley, B. J., Ortiz, C., Pasara, A., … Mangel, J. C. (2020). An illuminating idea to reduce bycatch in the Peruvian small-scale gillnet fishery. *Biological Conservation*, *241*(December 2019), 108277. https://doi.org/10.1016/j.biocon.2019.108277

Collin, S. P. (2012). The neuroecology of cartilaginous fishes: Sensory strategies for survival. *Brain, Behavior and Evolution*, *80*(2), 80–96. https://doi.org/10.1159/000339870

Crowder, L. B., & Murawski, S. A. (1998). Fisheries Bycatch: Implications for Management. *Fisheries*, *23*(6), 8–17. https://doi.org/10.1577/1548-8446(1998)023<0008:fbifm>2.0.co;2

Davies, R. W. D., Cripps, S. J., Nickson, A., & Porter, G. (2009). Defining and estimating global marine fisheries bycatch. *Marine Policy*, *33*(4), 661–672. https://doi.org/10.1016/j.marpol.2009.01.003

Fiedler, F. N., Pazeto, D. M., & Valle de Lacerda, L. L. (2020). High mortality rates of Chelonia mydas in a small-scale bottom gillnet fishery in the south-west Atlantic Ocean. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *30*(10), 1902–1909. https://doi.org/10.1002/aqc.3370

Fletcher, D., MacKenzie, D., & Villouta, E. (2005). Modelling skewed data with many zeros: A simple approach combining ordinary and logistic regression. *Environmental and Ecological Statistics*, *12*(1), 45–54. https://doi.org/10.1007/s10651-005-6817-1

Gardiner, J. M., Maruska, K. P., Sisneros, J., & Casper, B. (2012). Energetics, Metabolism, and Endothermy in Sharks and Rays. *Biology of Sharks and Their Relatives*, (April), 227–254. https://doi.org/10.1201/b11867-15

Gilman, E., Gearhart, J., Price, B., Eckert, S., Milliken, H., Wang, J., … Ishizaki, A. (2010). Mitigating sea turtle by-catch in coastal passive net fisheries. *Fish and Fisheries*, *11*(1), 57–88. https://doi.org/10.1111/j.1467-2979.2009.00342.x

Gómez-Gutiérrez, J., Domínguez-Hernández, E., Robinson, C. J., & Arenas, V. (2000). Hydroacoustical evidence of autumn inshore residence of the pelagic red crab pleuroncodes planipes at Punta Eugenia, Baja California, Mexico. *Marine Ecology Progress Series*, *208*(December), 283–291. https://doi.org/10.3354/meps208283

Hall, M. A., Alverson, D. L., & Metuzals, K. I. (2000). By-catch: Problems and solutions. Marine Pollution, *41*(00). Retrieved from http://ac.els-cdn.com/S0025326X00001119/1-s2.0-S0025326X00001119-

main.pdf?_tid=0247eace-e446-11e4-93a8-00000aacb35e&acdnat=1429195186_c4313f6b424985573188e90a537cade8

Horch, K. W., Gocke, J. P., Salmon, M., & Forward, R. B. (2008). Visual spectral sensitivity of hatchling loggerhead (Caretta L.) and leatherback (Dermochelys coriacea L.) sea turtles, as determined by single-flash electroretinography . *Marine and Freshwater Behaviour and Physiology*, *41*(2), 107–119. https://doi.org/10.1080/10236240802106556

Hueter, R. E., Mann, D. A., Maruska, K. P., Sisneros, J. A., & Demski, L. S. (2004). Sensory biology of elasmobranchs. *Biology of Sharks and Their Relatives*, 325–368. https://doi.org/10.1201/9780203491317.ch12

Jordan, L. K., Mandelman, J. W., McComb, D. M., Fordham, S. V., Carlson, J. K., & Werner, T. B. (2013). Linking sensory biology and fisheries bycatch reduction in elasmobranch fishes: A review with new directions for research. *Conservation Physiology*, *1*(1), 1–20. https://doi.org/10.1093/conphys/cot002

Lewison, R. L., Crowder, L. B., Wallace, B. P., Moore, J. E., Cox, T., Zydelis, R., … Safina, C. (2014). Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(14), 5271–5276. https://doi.org/10.1073/pnas.1318960111

Liles, M. J., Gaos, A. R., Bolaños, A. D., Lopez, W. A., Arauz, R., Gadea, V., … Peterson, M. J. (2017). Survival on the rocks: High bycatch in lobster gillnet fisheries threatens hawksbill turtles on rocky reefs along the Eastern Pacific coast of Central America. *Latin American Journal of Aquatic Research*, *45*(3), 521–539. https://doi.org/10.3856/vol45-issue3-fulltext-3

Mangel, J. C., Alfaro-Shigueto, J., Witt, M. J., Hodgson, D. J., & Godley, B. J. (2013). Using pingers to reduce bycatch of small cetaceans in Peru's small-scale driftnet fishery. *Oryx*, *47*(4), 595–606. https://doi.org/10.1017/S0030605312000658

Mangel, J. C., Wang, J., Alfaro-Shigueto, J., Pingo, S., Jimenez, A., Carvalho, F., … Godley, B. J. (2018). Illuminating gillnets to save seabirds and the potential for multi-taxa bycatch mitigation. *Royal Society Open Science*, *5*(7), 4–7. https://doi.org/10.1098/rsos.180254

Marshall, J. (2017). Vision and lack of vision in the ocean. *Current Biology*, *27*(11), R494–R502. https://doi.org/10.1016/j.cub.2017.03.012

Matsuda, K., Torisawa, S., Hiraishi, T., & Yamamoto, K. (2009). Comparison of the color vision and spectral sensitivity of three flatfish species of different ecotypes, and application to selective fishing methods. *Fisheries Science*, *75*(1), 35–42. https://doi.org/10.1007/s12562-008-0008-6

McCracken, M. L. (2004). Modeling a very rare event to estimate sea turtle bycatch: lessons learned. *Fisheries Science*, (November), 30pp. Retrieved from http://www.pifsc.noaa.gov/tech/NOAA_Tech_Memo_PIFSC_3.pdf

Nguyen, K. Q., & Winger, P. D. (2019). Artificial Light in Commercial Industrialized Fishing Applications: A Review. *Reviews in Fisheries Science and Aquaculture*, *27*(1), 106–126. https://doi.org/10.1080/23308249.2018.1496065

Ortiz, N., Mangel, J. C., Wang, J., Alfaro-Shigueto, J., Pingo, S., Jimenez, A., … Godley, B. J. (2016). Reducing green turtle bycatch in small-scale fisheries using illuminated gillnets: The cost of saving a sea turtle. *Marine Ecology Progress Series*, *545*(May), 251–259. https://doi.org/10.3354/meps11610

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rothery, P. (1988). A cautionary note on data transformation: Bias in back-transformed means. *Bird Study*, *35*(3), 219–222. https://doi.org/10.1080/00063658809476992

Rousseau, Y., Watson, R. A., Blanchard, J. L., & Fulton, E. A. (2019). Evolution of global marine fishing fleets and the response of fished resources. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(25), 12238–12243. https://doi.org/10.1073/pnas.1820344116

Senko, J., White, E. R., Heppell, S. S., & Gerber, L. R. (2014). Comparing bycatch mitigation strategies for vulnerable marine megafauna. *Animal Conservation*, *17*(1), 5–18. https://doi.org/10.1111/acv.12051

Shester, G. G., & Micheli, F. (2011). Conservation challenges for small-scale fisheries: Bycatch and habitat impacts of traps and gillnets. *Biological Conservation*, *144*(5), 1673–1681. https://doi.org/10.1016/j.biocon.2011.02.023

Silvani, L., Gazo, M., & Aguilar, A. (1999). Spanish driftnet fishing and incidental catches in the western Mediterranean. *Biological Conservation*, *90*(1), 79–85. https://doi.org/10.1016/S0006-3207(98)00079-2

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. *Endangered Species Research*, *5*(2–3), 225–238. https://doi.org/10.3354/esr00097

Stubbs, A. L., & Stubbs, C. W. (2016). Spectral discrimination in color blind animals via chromatic aberration and pupil shape. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(29), 8206–8211. https://doi.org/10.1073/pnas.1524578113

Sverdrup, K. A., & Kudela, R. (2019). *Investigating Oceanography*. McGraw-Hill Education.

Swimmer, Y., Arauz, R., Higgins, B., McNaughton, L., McCracken, M., Ballestero, J., & Brill, R. (2005). Food color and marine turtle feeding behavior: Can blue bait reduce turtle bycatch in commercial fisheries? *Marine Ecology Progress Series*, *295*(June), 273–278. https://doi.org/10.3354/meps295273

Trueblood, L. A., Zylinski, S., Robison, B. H., & Seibel, B. A. (2015). An ethogram of the Humboldt squid. *Behaviour*, *152*(14), 1911–1932. https://doi.org/10.1163/1568539X-00003324

Virgili, M., Vasapollo, C., & Lucchetti, A. (2018). Can ultraviolet illumination reduce sea turtle bycatch in Mediterranean set net fisheries? *Fisheries Research*, *199*(May 2017), 1–7. https://doi.org/10.1016/j.fishres.2017.11.012

Wang, J. H., Boles, L. C., Higgins, B., & Lohmann, K. J. (2007). Behavioral responses of sea turtles to lightsticks used in longline fisheries. *Animal Conservation*, *10*(2), 176–182. https://doi.org/10.1111/j.1469-1795.2006.00085.x

Wang, J. H., Fisler, S., & Swimmer, Y. (2010). Developing Visual deterrents to reduce sea turtle bycatch in gill net fisheries. *Marine Ecology Progress Series*, *408*(June 2010), 241–250. https://doi.org/10.3354/meps08577

Wang, J., Barkan, J., Fisler, S., Godinez-Reyes, C., & Swimmer, Y. (2013). Developing ultraviolet illumination of gillnets as a method to reduce sea turtle bycatch. *Biology Letters*, *9*(5), 1–6. https://doi.org/10.1098/rsbl.2013.0383

Werner, T., Kraus, S., Read, A., & Zollett, E. (2006). Fishing techniques to reduce the bycatch of threatened marine animals. *Marine Technology Society Journal*, *40*(3), 50–68. https://doi.org/10.4031/002533206787353204

Wingfield, D. K., Peckham, S. H., Foley, D. G., Palacios, D. M., Lavaniegos, B. E., Durazo, R., … Bograd, S. J. (2011). The making of a productivity hotspot in the Coastal ocean. *PLoS ONE*, *6*(11), 2–7. https://doi.org/10.1371/journal.pone.002787