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Gillnet illumination as an effective measure to reduce sea turtle bycatch

Phil Allman,[1] Andrews Agyekumhene,[2] and Leyna Stemle[3]

[1]Department of Biological Sciences, Florida Gulf Coast University, 10501 FGCU Boulevard South, Fort Myers, FL, 33965, U.S.A., email pallman@fgcu.edu
[2]Wildlife Division, Ghana Forestry Commission, PO Box 202 WB, Winneba, Ghana
[3]Department of Marine and Fisheries Science, University of Ghana, Legon, Ghana

Abstract: The growing demand for fish around the world is an immediate threat to marine megafauna that are unintentionally captured in commercial and artisanal fishery operations. Bycatch mitigation strategies, such as turtle excluder devices, circle hooks, and net illumination, have successfully reduced this risk in some fisheries. We explored the effectiveness of gillnet illumination to reduce sea turtle captures in 2 artisanal fisheries (Mankoadze and Winneba, Ghana) under normal fishing conditions. We first quantified sea turtle bycatch in Ghana's artisanal gillnet fishery from 15 boats for 12 months. We then quantified catch of targeted species and sea turtle bycatch from 20 boats for 15 months (7427 net sets). For 10 of these boats, we placed a Centro Economy green light (1 LED) at each 10-m interval on the net. We also quantified target catch and sea turtle bycatch from 30 boats for 8 months (2250 net sets). In 15 of these boats, a Centro Deluxe green light (3 LEDs) was installed at 15-m intervals. Boats with economy lights and those with deluxe lights both exhibited an 81% decrease in sea turtle captures ($W = 1$, $p < 0.001$, $n = 20$; $W = 215$, $p < 0.001$, $n = 30$, respectively) compared with control boats without lights. Illuminated nets resulted in fewer turtle catches for leatherback (Dermochelys coriacea), olive ridley (Lepidochelys olivacea), and green sea turtles (Chelonia mydas) ($p < 0.05$ for all species). Target catch (mass) ($W = 53$, $p = 0.853$ $n = 20$; $W = 76$, $p = 0.449$, $n = 23$) and value ($W = 50$, $p = 1$, $n = 20$; $W = 69$, $p = 0.728$, $= 23$) were not different across treatments. Our study affirms net illumination can reduce capture rates of 3 species of sea turtles, including the imperiled leatherback. Gear modification methods can successfully reduce bycatch if they are affordable and have broad applications for multiple species in different fisheries.

Keywords: fishery modification, Ghana, sea turtles

Iluminación de las Redes Agalleras como una Medida Efectiva para Reducir la Captura Incidental de Tortugas Marinas

Resumen: La creciente demanda de pescado en todo el mundo es una amenaza inmediata para la megafauna marina que es capturada accidentalmente durante las operaciones de pesca comercial y artesanal. Las estrategias de mitigación de la captura incidental como los dispositivos excluyentes de tortugas, los ganchos circulares y la iluminación de redes han reducido exitosamente este riesgo en algunas pesquerías. Exploramos la efectividad de la iluminación de las redes agalleras para reducir la captura de tortugas marinas en dos pesquerías artesanales (Mankoadze y Winneba, Ghana) bajo condiciones normales de pesca. Primero cuantificamos la captura incidental de tortugas marinas en la pesca artesanal con redes agalleras en Ghana a partir de 15 botes durante doce meses. Después cuantificamos la captura de especies focalizadas y la captura incidental de tortugas marinas a partir de 20 botes durante 15 meses (7,247 conjuntos de redes). En el caso de diez de estos botes, colocamos una luz verde Centro Economy (1 LED) en cada intervalo de 10 m en la red. También cuantificamos la captura focalizada y la captura incidental de tortugas marinas a partir de 30 botes durante 8 meses (2,250 conjuntos de redes). En 15 de estos botes se instaló una luz verde Centro Deluxe (3 LEDs) en cada intervalo de 15 metros. Los botes con las luces Economy y aquellos con las luces Deluxe exhibieron una disminución del 81% en la captura de tortugas marinas ($W = 1$, $p < 0.001$, $n = 20$; $W = 215$, $p < 0.001$, $n = 30$, respectivamente) en comparación con los botes control que no contaban con luces. Las redes iluminadas resultaron en una menor captura de tortugas laúd (*Dermochelys*

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coriacea), golfina (*Lepidochelys olivacea*) y verde (*Chelonia mydas*) ($p < 0.05$ para todas las especies). La captura focalizada (masa) ($W = 53$, $p = 0.853$ $n = 20$; $W = 76$, $p = 0.449$, $n = 23$) y el valor focalizado ($W = 50$, $p = 1$, $n = 20$; $W = 69$, $p = 0.728$, $n = 23$) no fueron diferentes entre los tratamientos. Nuestro estudio afirma que la iluminación de las redes puede reducir la tasa de captura de tres especies de tortuga marina, incluyendo a la tortuga laúd que se encuentra en grave peligro de extinción. Los métodos de modificación de equipamiento pueden reducir exitosamente la captura incidental si son asequibles y también tienen aplicaciones amplias para múltiples especies en diferentes industrias pesqueras.

Palabras Clave: Ghana, modificaciones a la industria pesquera, tortugas marinas

Introduction

The rising demand for fish as a source of protein creates a global challenge for sustaining fish stocks and conserving marine biodiversity. Global fish consumption increased 1.5% annually from 9.0 kg/person in 1961 to 20.5 kg/person in 2017; some island nations have reached 50 kg/person (FAO 2018). Fish consumption is expected to continue increasing at 1.6% annually for the next decade (FAO 2016). Nontarget bycatch can account for up to 40% of the total biomass from capture fisheries (Davies et al. 2009) and is considered the single greatest threat to some species of marine megafauna (sharks, sea turtles, seabirds, and marine mammals) (Wallace et al. 2011; Lewison et al. 2014; McCauley et al. 2015). Bycatch mitigation measures will be necessary to ensure ecosystem functions and increase sustainability of fisheries across the world as fishing efforts increase to meet a rising demand.

Marine fisheries affect coastal, deep sea, and open ocean ecosystems across multiple ecological scales and alter ecosystem functions, community dynamics, and species population levels (Ortuño Crespo & Dunn 2017). Mismanagement of fisheries has shifted trophic dynamics by changing the population structure and interactions across ecosystems (Hinke et al. 2004). The most direct effect of fisheries is the significant take of target and nontarget species that deplete fish stocks and increase the risk of extinction (Lazar et al. 2018). Multispecies fisheries, such as purse-seine and gillnet, may target more abundant fish stocks, but opportunistically capture depleted species that may have a higher value (Branch et al. 2013). These fisheries put additional pressure on depleted fish stocks as well as nontarget species threatened with extinction.

Large marine vertebrates have little commercial value in many countries and are generally not considered target species, but they are occasionally killed as bycatch in all major types of fisheries (Hall et al. 2000). Bycatch is now considered the primary risk for already depleted populations of sea turtles, marine mammals, and seabirds (Lewison et al. 2014; Taylor et al. 2017; Anderson et al. 2020). Further loss of marine predators not only threatens recovery efforts, but also reduces ecosystem functions as trophic dynamics continue to shift (Lewison et al. 2004; Worm et al. 2006; Pimiento et al. 2020). With small-scale gillnet fisheries having high rates of large vertebrate bycatch (Lewison et al. 2014), bycatch is alleged to have population-level effects on various species of megafauna (Moore et al. 2013).

Reducing the impact of fisheries across the globe will require ecosystem-based management strategies (Pikitch et al. 2004; Duffy et al. 2019). Developing effective bycatch mitigation strategies requires actions that maintain target catch and reduce nontarget captures. Recent bycatch mitigation strategies include spatial and temporal fishing restrictions (Lewison et al. 2004; Senko et al. 2014) and modified fishing gear (Werner et al. 2006), such as turtle-excluder devices for shrimp trawls (Crowder et al. 1995; Jenkins 2011) and circle hooks for longline fisheries (Watson et al. 2005; Serafy et al. 2012).

More recently, net illumination with green LED lights has been tested by pairing control and experimental vessels (Wang et al. 2010; Ortiz et al. 2016), but this design does not reflect actual conditions in artisanal fishing, where vessels typically fish independently of other vessels. Furthermore, net illumination has been shown to reduce capture rate of green sea turtles (*Chelonia mydas*) (Wang et al. 2010) but has yet to be tested on other chelonid turtles or the globally threatened leatherback (*Dermochelys coriacea*) in a natural setting (Ortiz et al. 2016). The efficiency of lights is influenced by local environmental factors (Wang et al. 2013), so it is important to test net illumination in multiple locations with different sea turtle species. These tests are especially vital for the leatherback turtle, which is critically endangered in the Pacific Ocean and primarily threatened by gillnet fisheries (Alfaro-Shigueto et al. 2018; Ortiz-Alvarez et al. 2020). This population requires immediate bycatch reduction to prevent extirpation (Laúd OPO Network 2020).

A sizable artisanal gillnet fishery occurs in Ghana, West Africa, where 5 of the world's 7 species of sea turtles coexist (in order of nesting abundance): olive ridley (*Lepidochelys olivacea*), leatherback, green, loggerhead (*Caretta caretta*), and hawksbill (*Eretmochelys imbricata*) (Agyekumhene et al. 2017). The artisanal fishery uses drift gillnets from large dug-out wooden canoes (boats) in shallow coastal areas to target pelagic fish (anchovy, sardine, and mackerel) (Atta-Mills et al. 2004;

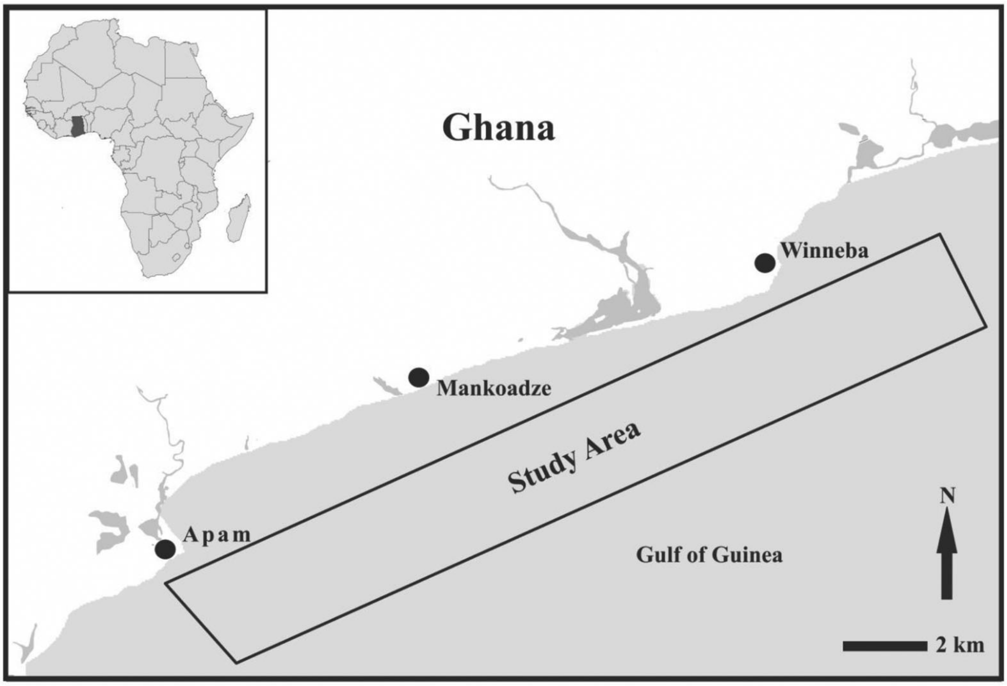

Figure 1. Study area within the Gulf of Guinea in the central region of Ghana, West Africa.

Lazar et al. 2018). In 2016, there were 11,600 registered boats and 292 landing sites along the 550-km Ghana's coastline (FAO 2016), but many unregistered vessels also operate. Prior research suggests that bycatch may represent a significant source of mortality for sea turtles in this region, especially during the nesting season (Alexander et al. 2017).

We examined the use of green gillnet illumination to simultaneously reduce sea turtle capture and maintain fish catch and market value, the first experiment of its kind in West Africa. The goals were to add to a growing body of knowledge on sea turtle mortality in gillnets and to test bycatch reduction technologies that work for both commercial and artisanal fisheries. Objective 1 was to quantify sea turtle bycatch rates in Ghana's artisanal fishery because there is a paucity of information on bycatch in the region. Objective 2 was to test whether net illumination reduces sea turtle bycatch in an artisanal fishery and whether lights alter target catch or market value. Objective 3 was to test the efficiency of a brighter light that may reduce the cost of implementing net illumination as a management tool.

Methods

Study Site

We studied sea turtle bycatch in 2 fishing communities in central Ghana: Winneba and Mankoadze (Gulf of Guinea). The fishing boats from these communities harvest the coastal waters of the Gomoa West District and Effutu Municipality, extending from 2 to 4 km offshore from Apam (5°17'10"N, 0°43'37"W) to Winneba (5°21'13"N, 0°35'46"W) (Fig. 1). This area (40 km^2) was ideal for our study because the main economic activity is fishing and fish mongering, the presence of sea turtle (olive ridley, leatherback, and green) nesting year round (primary nesting season September through February), and there is evidence of increasing interactions between fisheries and sea turtles (Ntiamoah-Baidu & Gordon 1991; Agyekumhene et al. 2017; Alexander et al. 2017). Furthermore, monthly mean sea surface temperature varies from 22.9 °C (August) to 30.1 °C (April) across seasons but does not vary within the study area (Freeman et al. 2017). The depth varies from 4 to 13 m (2–4 km from shore) (Freeman et al. 2017). We conducted our study in 3 phases from January 2015 through May 2019. The experiments were conducted with permission and in compliance of permits from and ethical standards of the Fishery Commission of Ghana, the Wildlife Division of the Forestry Commission (permit 01782821), and Florida Gulf Coast University (IACUC number 1011-08). We also received permission from the traditional chiefs and chief fishers of Mankoadze and Winneba.

Fishing occurs each day of the week, except for Tuesdays due to a taboo that forbids removing fish from the sea on this day (Alexander et al. 2017). Gillnetting and beach seining are the most common methods of fishing. There are approximately 818 motorized and 169 paddled fishing boats (1827 total) (FSSD 2016). The boats used in this study were 12–15 m and were registered motorboats. Crews consist of men from the same family or members of the community hired by a boat's owner (Alexander et al. 2017). Gillnet fishing occurs at night. Nets are in the water for approximately 2 h (soak time). We randomly provided GPS units (Garmin, Lenexa, Kansas) to boats throughout the study to confirm all boats stayed within the study area.

Experimental Design

To measure baseline sea turtle bycatch, trained observers in Mankoadze were randomly assigned to 15 boats during each fishing excursion in 2015 to record all turtle bycatch. Observers noted the species, curved carapace length (CCL), and curved carapace width. We used boats with nets 96–129 m long and 2.5 m deep with a 2.5-cm stretched mesh size. Observers were on the boat during each fishing trip (approximately 6 times/week) for 12 months from January through December.

We used 20 boats to assess the effect of Centro Economy (1 green LED, 6 lux) lights (Centro Company, Ilsangu Goyang-si, Gyeonggi-do) on turtle bycatch and fish catch from January 2016 to March 2017 in Mankoadze. We randomly assigned 10 boats to use nets with lights installed at 10-m intervals on the float line (11 lights/100 m) and 10 boats to use nets without lights (control). On average, gillnets were 114 m long (range 82–144 m) and 2.5 m deep with a 2.5-cm stretched mesh size. All boats remained within the defined study area, but changed daily positions based on normal fishing practices used to predict the most productive fishing locations. Observers were on boats during each fishing event to document turtle bycatch. We quantified fish catch market value by recording the total weight and market price from one net set for each boat for each month of the study period.

We used 30 boats to assess the effect of Centro Deluxe (3 green LEDs, 18 lux) lights on turtle bycatch and fish catch from September 2018 to May 2019 in Winneba. We randomly assigned 15 boats to use nets with lights installed at 15-m intervals on the float line and 15 boats to use nets without lights. The nets had fewer lights (8 lights/100 m) than the experiment in Mankoadze, but each light was brighter. On average, gillnets were 110 m long (range 50–190 m) and 2.5 m deep with 1.5-cm stretched mesh size. Observers were on the boats during each fishing event to document turtle bycatch. We quantified fish catch value by recording the total weight and market price from one net set for each boat for each month. Fishers occasionally used a secondary landing site, so not every boat could be sampled each month (Nunoo et al. 2009).

Statistical Analyses

Across all years, we standardized fishing effort for net length (per 100 m) and total soak time (per 24 h) for each net set. Sea turtle catch rate was calculated as the number of turtles (catch) per unit effort (CPUE) for each boat across each study period: number of turtles captured /[(net length/100 m) × (net soak time/24 h)] (Wang et al. 2010; Ortiz et al. 2016). We standardized the fish catch (kilograms) and market value (in U.S. dollars) for net length and total soak time by calculating CPUE (and value per unit effort [VPUE]) for each boat across the study period: total catch (kilograms)/[(net length/100 m) × (net soak time/24 h)]. We analyzed standardized turtle and fish catch data with a Mann–Whitney of the total CPUE (or VPUE) obtained across the sampling period for each boat, comparing between treatment and control boats (Virgili et al. 2018 or Wang et al. 2010). We used this to test the null hypotheses that turtle catch, fish catch, and fish market values do not vary between the control (no lights) and each of the 2 treatment (lights) groups separately. We conducted a post hoc power analysis (alpha = 0.05) to ensure the number of captures per species was sufficient for detecting a significant effect if present. All data were analyzed using JMP version 14 (SAS Institute, Cary, North Carolina) or R version 3.6.1.

Results

Fishers captured a total of 222 turtles during this study (Table 1). The 15 boats monitored in 2015 captured a total of 64 turtles during the 12-month study period (mean 4.3 turtles/boat/year). Across all years, olive ridleys were the most frequently captured (n = 152, 70% of total), but 38 (18%) leatherback and 27 (12%) green turtles were also entangled. One hundred sixty-three (75%) individuals were captured during the primary nesting season (September through February). All leatherbacks from 2015 to 2017 were captured during their nesting season of October through January. The average CCL was 66 cm (38–77 cm) for olive ridleys, 119 cm (80–181 cm) for leatherbacks, and 71 cm (30–101 cm) for green turtles. Six olive ridleys (4%), 18 leatherbacks (53%), and 21 greens (77%) were below the minimum size of nesting individuals observed in Ghana (Allman & Agyekumhene 2019). All adult-sized turtles (n = 167, 77%) were female based on tail length. Fishers caught turtles across age classes.

Effect of LED Lights on Sea Turtle Bycatch

Twenty nets were deployed in 2016–2017 (7427 net sets) and 30 nets in 2018–2019 (2334 net sets); half the boats served as control (no lights) and the other half had green lights attached to the float lines. Total fishing effort (100 m × 24 h) was 325.59 for control boats and 343.98 for treatment boats in 2016–2017 and 83.23 for control boats and 92.40 for treatment boats in 2018–2019 (Table 2).

Table 1. Sea turtle captures from each phase of the study on the efficacy of net illumination to avoid sea turtle bycatch in Mankoadze and Winneba, Ghana.

		Number of captured turtles						
		control (no lights)			*experimental (lights)*			
Year	*Number of boats (control, treatment)*	*olive ridley*	*leatherback*	*green*	*olive ridley*	*leatherback*	*green*	*total*
2015	15, 0	51	6	7	–	–	–	64
2016–2017	10, 10	52	7	7	16	1	0	83
2018–2019	15, 15	29	20	11	4	4	2	70*
Total		132	33	25	20	5	2	217*

**Five captures were released before they could be identified.*

Table 2. Summary values of fishing effort by net type for gillnet sets in Mankoadze (2016–2017) and Winneba (2018–2019), Ghana.

Year and group	*Net sets*	*Total effort (100 m × 24 h)*	*Mean soak time (minutes) (SE)*	*Mean net length (m) (SE)*	*Mean fishing effort (100 m × 24 h) (SE)*
2016–2017					
control	3729	325.59	113.75 (0.25)	110.5 (0.28)	0.087 (0.0003)
illuminated	3698	343.98	113.76 (0.26)	117.7 (0.11)	0.093 (0.0002)
2018–2019					
control	1269	83.23	91.65 (1.23)	102.99 (0.99)	0.066 (0.0011)
illuminated	1065	92.40	102.20 (1.41)	122.08 (0.70)	0.087 (0.0013)

Fishers in 2016–2017 captured 83 sea turtles during the study period: 66 captured in control nets (number of trials = 3729) and 17 captured in experimental nets (number of trials = 3698). Of the 83 captured in 2016–2017, 68 were olive ridleys, 8 were leatherbacks, and 7 were green turtles (Table 1). Sea turtle CPUE was significantly higher in the control nets (mean CPUE = 0.21 [SE 0.02]) than in the experimental nets (mean CPUE = 0.04 [0.01]) ($W = 1, p < 0.001$) (Table 3). This represented an 81% reduction in mean turtle catch rate for 2016–2017. The reduction in captured turtles between treatments varied from 78% for olive ridley ($W = 70$, $p<0.001$), to 89% for leatherback ($W = 80.5$, $p = 0.011$), to 100% for green ($W = 70, p = 0.035$) turtles (Table 3).

Seventy-five turtles were captured during the 2018–2019 study: 63 captured in the control nets (1269 net sets) and 12 in experimental nets (1065 net sets) (Table 1). The boats captured 33 olive ridley, 24 leatherback, and 13 green turtles across the 8 months (2018–2019) (Table 1). Sea turtle CPUE was significantly higher in the control nets (mean CPUE = 0.46 SE 0.07) than in the experimental nets (mean CPUE = 0.09 [SE 0.03]) ($W = 215, p < 0.001$) (Table 3). This represents an 81% reduction in mean turtle catch rate for 2018–2019. The reduction in captured turtles between treatments varied from 82% for olive ridleys ($W = 202$, $p<0.001$), to 74% for leatherbacks ($W = 171.5$, $= 0.011$), to 91% for greens ($W = 162$, $p = 0.012$) (Table 3).

The power analysis revealed high statistical power for olive ridleys (2016–2017, 0.99; 2018–2019, 0.99) and leatherbacks (2016–2017, 0.88; 2018–2019, 0.80). Statistical power was lower for green turtles (2016–2017, 0.54; 2018–2019, 0.56) because fewer individuals were captured.

Effect of LED Lights on the Target Fishery

Fishers caught a total of 36 fish species during the 2016–2017 experiment and a total of 9 fish species during the 2018–2019 study. Fish catches during both studies were primarily composed of species in the families Carangidae (bumper fish), Clupeidae (sardines), and Engraulidae (anchovies). No catches of birds, marine mammals, sharks, or rays were documented across all 3 studies in experimental or control nets.

In 2016–2017, control nets captured 31 fish species (1763 kg) and experimental nets captured 32 (1857 kg) (Tables 3 and 4). Total Fish CPUE by boat in 2016–2017 did not differ between treatments ($W = 53$, $p = 0.853$, $n = 20$), suggesting that lights did not affect the target fishery (VPUE, $W = 50, p = 1, n = 20$) (Tables 3 and 4). In 2018–2019, control nets captured 7 species (1036 kg)

Table 3. Standardized sea turtle (number of individuals) and target catch rates (kg, 100 m × 24 h) and market value for total gillnet sets with and without illumination in Mankoadze and Winneba, Ghana.

	2016–2017					2018–2019				
Catch variables	*net sets*	*control (SE)*	*illuminated (SE)*	*percent change*	p	*net sets*	*control (SE)*	*illuminated (SE)*	*percent change*	p
Sea turtle bycatch	7427	0.211 (0.03)	0.040 (0.01)	−81.0	<0.001*	2334	0.456 (0.07)	0.089 (0.03)	−80.5	<0.001*
Olive ridley		0.165 (0.03)	0.037 (0.01)	−77.6	<0.001*		0.245 (0.06)	0.045 (0.02)	−81.6	<0.001*
Leatherback		0.027 (0.01)	0.003 (0.003)	−88.9	0.011*		0.144 SE 0.03	0.037 SE 0.02	−74.3	0.011*
Green		0.019 (0.01)	0.000 (0.00)	−100.0	0.035*		0.067 −(0.02)	0.006 (0.01)	−91.0	0.012*
Target catch (kg)	201	91.1 (10.4)	91.9 (11.3)	+0.9	0.853	50	587 SE 176	544 SE 130	−7.3	0.449
Target catch value (US$)	201	57.8 (7.7)	57.6 (8.3)	+0.3	1	50	209 (64)	220 (53)	+5.3	0.728

Significant between treatments.

and experimental nets captured 9 (1315 kg) (Table 4). Fish CPUE did not differ between treatments ($W = 75$, $p = 0.449$, $n = 23$) and neither did VPUE ($W = 69$, $p = 0.728$ $n = 23$) (Table 3). Target fish CPUE was 0.9% greater in weight in 2016–2017 and 7.3% lower in weight in 2018–2019 than for control boats, whereas fish VPUE was 0.3% higher in 2016–2017 and 5.3% higher in 2018–2019 (Table 3) than for control boats.

Discussion

This study provides the first assessment of sea turtle bycatch in West Africa and the use of gear modification to reduce entanglement in an artisanal gillnet fishery. It is also the first study to test LED lights in a natural setting for threatened leatherback and the olive ridley sea turtles. Unlike prior studies in which paired control and experimental nets were deployed near each other based on researcher instructions, in our study, each fisher independently decided where to deploy nets based on standard fishing practices in the region. To our knowledge, the 9761 net sets is the largest study to date on net illumination in the gillnet fishery. The experimental design and robust data set provides additional confidence in the effectiveness of using lights to reduce sea turtle bycatch.

Observer data indicated––sea turtle bycatch was a considerable source of mortality for these species in the region and may disproportionately affect breeding females during nesting season. The placement of green LED lights on gill nets not only reduced sea turtle bycatch, but also maintained target catch and value. These results indicate that green LED lights can serve as an effective fisheries management tool, especially during sea turtle nesting season, to maintain target catch while simultaneously reducing capture of adult sea turtles. The efficiency of these lights has been demonstrated elsewhere to reduce sea turtle bycatch in paired-vessel experiments. In Mexico, the mean green sea turtle capture rate was 40% lower in gillnets illuminated with green LED lights than in nets without illumination (Wang et al. 2010; Bielli et al. 2020). Similar results have been observed for green turtles in Peru (Ortiz et al. 2016) and Kenya (Kakai 2019). Our results corroborate the reduction of green sea turtle captures and demonstrated the lights effectively reduced olive ridley and leatherback captures.

Studies conducted in the central Ghana suggest that sea turtle populations are much lower than they were in the past decade (Agyekumhene et al. 2014). The overwhelming majority of turtles captured in our study were adult females caught during the primary nesting season from September to February. However, nonbreeding-sized individuals were captured, including juvenile leatherbacks and greens. These animals may be using Ghana's coastal areas as temporary migration corridors or foraging grounds (Mettler et al. 2019), but

Table 4. Summary values of target catch and catch value for treatment (illumination) and control (no illumination) gillnet sets in Mankoadze (2016–2017) and Winneba (2018–2019), Ghana.

	2016–2017		*2018–2019*	
Catch variables	*control*	*illuminated*	*control*	*illuminated*
Net sets	100	101	24	26
Target catch (kg)	1763	1857	1036	1315
Market value (US$)	587.61	586.40	409.10	538.49

in-water studies are necessary to confirm this. The high bycatch risk to turtles in this area indicates that bycatch mitigation efforts should be a high conservation priority in the region. Furthermore, the size and sex of captured turtles indicates a strong potential for population-level effects that will create a barrier to population recovery until bycatch reduction can be implemented.

We found that green LED lights installed on gillnets reduced sea turtle bycatch for olive ridley, leatherback, and green turtles by an average of 81%. Ghanaian fishers do not intentionally capture turtles and report they create noise disturbances when observing a turtle in hopes of moving it away from their nets. Capturing a sea turtle creates a financial burden due to loss of target catch and damage to the net (Agyekumhene et al. 2014; Alexander et al. 2017). Replacing or repairing a damaged net is typically cost prohibitive for fishers because their annual income is well below the national average of $2100 (Smith et al. 2017). Fishers who had previous experience capturing leatherbacks reported the risk of their boats being turned over by the turtle struggling to free itself from the net. Furthermore, some communities in Ghana revere sea turtles so some fishers consider it taboo to harm or even touch one (Alexander et al. 2017). Fishers noted the use of LED lights may also prevent other fishing vessels from running into their nets and causing damage to the net and propeller. Fishers in both communities indicated they are eager to use lights because they recognize the safety benefits and the advantage of catching fewer turtles while maintaining target catch rates and market value.

The efficiency of the lights at reducing sea turtle capture likely varies across regions because water clarity, depth, and sea surface temperature have been shown to affect predicted CPUE in illuminated lights (Wang et al. 2010; Ortiz et al. 2016). Although we were unable to collect environmental data for each fishing location, the large number of net sets used in our small study area minimized variation in environmental conditions across boats and ensured any variation would have a minimal effect on the data structure. We, therefore, did not require fishing vessels to be paired but instead allowed the fishers to choose their location within the parameters of the study area based on their normal decision-making process. This ensured the study best mimicked the actual fishing conditions used, if lights are to be used as a recovery tool in Ghana. Allowing the fishers to make their own decision was important to earn the cooperation needed to acquire the desired number of boats and net sets. Furthermore, the short soak time used by artisanal fisheries may create unexpected interactions. For example, a sea turtle captured in one net may influence the likelihood of a sea turtle being captured in the paired net. The longevity of our study ensured that fishing vessels in all treatments were equally fishing across lunar cycles within a spatial scale that limited variation in surface temperature, water clarity, and depth. A sufficient number of green sea turtles was not captured to have high statistical power for this species, but results of other studies show illuminated nets can decrease green sea turtle captures (Ortiz et al. 2016; Kakai 2019; Bielli et al. 2020).

The nets with brighter lights ($13.50 a light in 2018, 2 AA batteries every 6 months) installed at 15-m intervals (2018–2019) appeared to perform as well as the nets with dimmer lights (2016–2017, $10 a light in 2016, 2 AA batteries every 4 months) (both 81% reduction). The cost of modifying a standard 100-m net with lights every 15 m would be $108. Whereas, illuminating a 100-m net with the dimmer lights every 10 m would be $110. With a minimum investment cost ($108) and operating expenses ($15 batteries), it would cost a fisher $130–165 to operate an illuminated net for 3 years. This cost is significantly lower than the cost of replacing a net ($225) that has been damaged by a turtle and therefore can serve as a cost-effective modification. Fishers report nets are typically replaced every 18 months, but individual panels or even the entire net must be replaced when a turtle is captured. Only 3 lights stopped working during the study, and most installed in 2016 are still being used. Assuming a $150 3-year operating cost and an 80% reduction in sea turtle capture, the cost of saving 1 sea turtle is $15.64 over 3 years. In a larger Peruvian fishery, Ortiz et al. (2016) indicate the cost of saving 1 sea turtle is $60.58.

Ghana's artisanal fishery employs over 250,000 individuals (FAO 2016). The industry is not well policed, reporting bycatch is not required, and there are no limits on the amount of fish taken (Kaczynski & Fluharty 2002). Securing the future of this trade will require the industry to fully support bycatch mitigation strategies that minimize bycatch while maintaining target catch. Both studies described here indicated that green LED lights can serve as an economical and functional modification to reduce the mortality of sea turtles in Ghana. The Gulf of Guinea likely serves as a migratory corridor for sea turtles, sharks, and marine mammals (Dutton et al. 2013; Segniagbeto et al. 2014; Coelho et al. 2016). Protecting marine megafauna in the region will, therefore, require nations across the region to implement bycatch reduction methods to maintain ecosystem function (Lewison et al. 2014).

Globally, it is imperative to develop new technologies and tools that will protect the world's marine diversity while sustaining fisheries that are capable of meeting increasing human demand for fish as a source of protein. Using bycatch mitigation strategies, such as gillnet illumination in coastal communities, around the world would likely result in a substantial reduction in the mortality of adult female sea turtles that are using the coastline as nesting habitat. These efforts may be especially important for reducing mortality of the critically endangered leatherback in the Pacific Ocean, where recent research indicates that bycatch mitigation efforts are immediately necessary to save this population (Laúd OPO Network 2020). Due to the extremely low population size, it is imperative that research from other locations informs effective conservation actions for recovering these populations.

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