Current Biology

Report

Net illumination reduces fisheries bycatch, maintains catch value, and increases operational efficiency

Highlights

- Illuminated gillnets reduce total discarded fisheries bycatch biomass
- This includes decreases in elasmobranch, Humboldt squid, and finfish bycatch
- Illuminated gillnets also reduce the time required to retrieve and disentangle nets
- Illuminated gillnets do not decrease target fish catch or value

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In brief

Senko et al. find that illuminating gillnets with green LED lights reduces total discarded fisheries bycatch biomass, which includes decreases in elasmobranch, Humboldt squid, and unwanted finfish, without compromising target fish catch or value. Illuminated gillnets also reduce the time it takes fishers to retrieve and disentangle nets.

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Net illumination reduces fisheries bycatch, maintains catch value, and increases operational efficiency

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SUMMARY

Small-scale fisheries are vital for food security, nutrition, and livelihoods in coastal areas throughout the world's oceans.[1–9] As intricately linked social-ecological systems, small-scale fisheries require management approaches that help ensure both ecological and socioeconomic sustainability.[7,10–14] Given their ease of use and lucrative nature, coastal gillnet fisheries are globally ubiquitous.[10,15] However, these fisheries often result in high discarded capture of non-target organisms (bycatch) that can lead to significant cascading effects throughout trophic chains[16–18] and costly fisheries restrictions that result in important revenue losses in coastal communities with scarce economic alternatives.[19,20] Despite these challenges, few solutions have been developed and broadly adopted to decrease bycatch in coastal gillnet fisheries, particularly in developing nations.[5,21] Here we used controlled experiments along Mexico's Baja California peninsula to show that illuminating gillnets with green LED lights—an emerging technology originally developed to mitigate sea turtle bycatch—significantly reduced mean rates of total discarded bycatch biomass by 63%, which included significant decreases in elasmobranch (95%), Humboldt squid (81%), and unwanted finfish (48%). Moreover, illuminated nets significantly reduced the mean time required to retrieve and disentangle nets by 57%. In contrast, there were no significant differences in target fish catch or value. These findings advance our understanding of how artificial illumination affects operational efficiency and changes in catch rates in coastal gillnet fisheries, while illustrating the value of assessing broad-scale ecological and socioeconomic effects of species-specific conservation strategies.

RESULTS AND DISCUSSION

Designing bycatch reduction technologies (BRTs) that leverage sensory capabilities (e.g., auditory, chemosensory, electrosensory, and visual systems) of target and non-target species is thought to have potential for bycatch species, such as sea turtles,[22] elasmobranchs,[23] seabirds,[24] and marine mammals.[25] Over the past decade, net illumination has emerged as a promising tool to reduce bycatch of sea turtles in coastal gillnet fisheries while maintaining target catch.[26–33] More recently, illuminated nets have been found to decrease bycatch of other marine megafauna without affecting target catch, including seabirds[34] and small cetaceans.[32] In theory, net illumination provides a visual cue within the appropriate sensitivity range that selectively deters or alerts non-target species to the presence of nets.[26]

Although testing of net illumination has expanded into multiple coastal gillnet fisheries worldwide, its potential effects on total bycatch biomass as well as fishery operations remain unknown and represent important knowledge gaps in this emerging field. Assessing these broader effects is fundamental to understanding the applicability and adoption potential of net illumination in similar coastal gillnet fisheries. Here, we use controlled experiments to investigate the effects of net illumination on total and diverse multi-taxa bycatch and target fish biomass as well as efficiency of gillnet operations off the Pacific coast of Baja California Sur, Mexico, a region with intense small-scale gillnet fisheries that overlap with a highly productive marine megafauna hotspot.[35–37] To accomplish this, we partnered with local expert gillnet fishers who deployed control-illuminated net pairs in prominent fishing grounds during the peak of the gillnet season using gear and practices identical to those employed by the local fleet under the guidance of Mexico's National Fisheries and Aquaculture Institute (Figure 1). This resulted in a robust sampling effort that included over

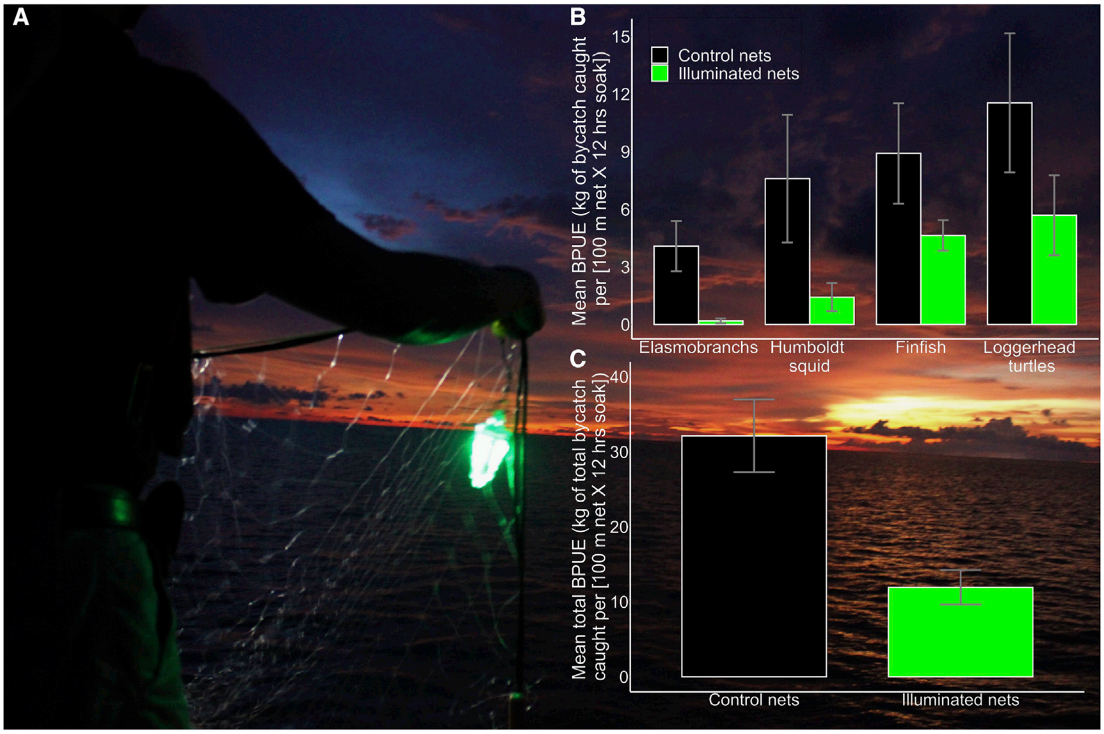

Figure 1. Bycatch between control and illuminated gillnets

(A) Illuminated gillnet with green LED light (photo © NOAA Fisheries) as well as comparison of mean biomass bycatch per unit effort (BPUE) of all bycatch taxonomic groups (B) and total bycatch (C) between control versus illuminated nets. Elasmobranch bycatch consisted of gray smooth-hound shark (*Mustelus californicus*), Mexican horn shark (*Heterodontus mexicanus*), Munk's devil ray (*Mobula munkiana*), Pacific cownose ray (*Rhinoptera steindachneri*), bat ray (*Myliobatis californica*), California butterfly ray (*Gymnura marmorata*), diamond stingray (*Hypanus dipterurus*), California skate (*Beringraja inornata*), rasptail skate (*Raja velezi*), shovelnose guitarfish (*Rhinobatos productus*), and banded guitarfish (*Zapteryx exasperata*), while finfish bycatch consisted of non-market-sized California halibut (*Paralichthys californicus*), non-market-sized Pacific bearded brotula (*Brotula clarkae*), non-market-sized inshore sand perch (*Diplectrum pacificum*), non-market-sized yellowfin croaker (*Umbrina roncador*), Pacific barracuda (*Sphyraenidae argentea*), popeye catalufa (*Pristigenys serrula*), whitesnout searobin (*Prionotus albirostris*), golden mojarra (*Deckertichthys aureolus*), Pacific hake (*Merluccius productus*), Chilhuil sea catfish (*Bagre panamensis*), California lizardfish (*Synodus lucioceps*), California scorpionfish (*Scorpaena guttata*), Pacific stargazer (*Astroscopus zephyreus*), and California moray eel (*Gymnothorax mordax*). Illuminated nets significantly reduced mean elasmobranch biomass of BPUE by 95% (n = 28 paired sets, p = 0.003), mean Humboldt squid (*Dosidicus gigas*) biomass of BPUE by 81% (n = 28 paired sets, p = 0.030), and mean finfish biomass of BPUE by 48% (n = 28 paired sets, p < 0.001), while reducing total biomass of BPUE by 63% (n = 28 paired sets, p < 0.001). By contrast, there was a non-statistically significant 51% reduction in mean loggerhead turtle (*Caretta caretta*) biomass of BPUE (n = 28 paired sets, p = 0.187). Bars represent SE.

10,000 m of control and illuminated gillnets (control = 4,995 m, mean ± SD = 178 ± 16 per net; illuminated = 5,022 m, mean ± SD = 179 ± 15 m per net) that soaked for nearly 700 h (control = 344 h, mean = 12.3 ± 1.6 h per net; illuminated = 351 h, mean = 12.5 ± 1.4 h per net) and captured 39 species that collectively weighed over 2.5 metric tons (Table 1).

The results of our experiment reveal that illuminated gillnets can significantly reduce total discarded bycatch biomass, maintain target fish catch and value, and decrease the time it takes fishers to retrieve and disentangle nets. Moreover, our findings establish net illumination as the first known potential bycatch reduction solution for three diverse taxonomic groups—elasmobranchs, cephalopods, and unwanted finfish—in coastal gillnet fisheries. Taken together, these results move beyond a single species assessment to advance our understanding of how artificial illumination affects efficiency of fishery operations and changes in catch rates, while highlighting the broader potential of net illumination to mitigate discarded biomass in similar coastal gillnet fisheries throughout the world's oceans.

Bycatch and target catch species composition

Discarded bycatch consisted of 27 bycatch species that comprised four taxonomic groups, which included loggerhead turtles (*Caretta caretta*), Humboldt squid (*Dosidicus gigas*), finfish, and elasmobranchs (Figure 1; Table S1). By contrast, 14 target fish species were retained for commercial sale, which included three primary target species and 11 secondary target species (Figure 2; Table S1).

Bycatch and target catch biomass composition

Bycatch biomass in control nets consisted of loggerhead turtles (35%), finfish (28%), Humboldt squid (23%), and elasmobranchs (14%) (Table 1). In illuminated nets, bycatch biomass was comprised of loggerhead turtles (48%), finfish (39%), Humboldt squid (12%), and elasmobranchs (1%) (Table 1). In both control (72%) and illuminated (61%) nets, non-finfish species (i.e., loggerhead turtles, Humboldt squid, and elasmobranchs) accounted for most bycatch biomass (Table 1). The majority of target fish biomass in control

Table 1. Bycatch, target fish catch and value, and haulback time between control and illuminated gillnets

	Control nets		Illuminated nets		% change[a]	p[b]
Bycatch discards	kg biomass (% of total bycatch biomass)	mean ± SE BPUE	kg biomass (% of total bycatch biomass)	mean ± SE BPUE		
Elasmobranch biomass	229.5 (14%)	4.09 ± 1.31	10.0 (1%)	0.19 ± 0.13	–95%	0.003*
Humboldt squid biomass	388.0 (23%)	7.59 ± 3.32	75.0 (12%)	1.43 ± 0.73	–81%	0.030*
Finfish biomass	457.0 (28%)	8.91 ± 2.61	243.0 (39%)	4.64 ± 0.79	–48%	<0.001*
Loggerhead turtle biomass	570.0 (35%)	11.54 ± 3.63	301.3 (48%)	5.69 ± 2.08	–51%	0.187
Number of loggerhead turtles[c]	17 turtles	0.34 ± 0.11 turtles	9 turtles	0.17 ± 0.06 turtles	–50%	0.187
Non-finfish bycatch biomass	1,187.5 (72%)	23.22 ± 4.70	386.3 (61%)	7.31 ± 2.32	–69%	0.003*
Total bycatch biomass	1,644.5 kg	32.13 ± 4.85	629.3 kg	11.95 ± 2.29	–63%	<0.001*
Primary target fish catch	kg biomass (% of total target fish biomass)	mean ± SE CPUE	kg biomass (% of total target fish biomass)	mean ± SE CPUE		
California halibut biomass	68.5 (52%)	1.34 ± 0.58	83.5 (58%)	1.56 ± 0.68	+16%	0.636
Grouper biomass	17.0 (13%)	0.34 ± 0.18	15.5 (11%)	0.28 ± 0.14	–18%	0.800
Total primary target fish biomass	85.5 (64%)	1.69 ± 0.67	99.0 (69%)	1.85 ± 0.74	+9%	0.944
Secondary target fish catch	kg biomass (% of total target fish biomass)	mean ± SE CPUE	kg biomass (% of total target fish biomass)	mean ± SE CPUE		
Total secondary target fish biomass	47.5 (36%)	0.87 ± 0.51	45.5 (31%)	0.85 ± 0.36	–2%	1.000
Total target fish catch	kg biomass	mean ± SE CPUE	kg biomass	mean ± SE CPUE		
Total (primary and secondary) target fish biomass	133.0	2.55 ± 1.07	144.5	2.70 ± 0.84	+6%	0.896
Market value	total catch value	mean ± SE MVPUE	total catch value	mean ± SE MVPUE		
Total (primary and secondary) target fish value	334.43 USD	6.52 ± 2.52	370.60 USD	6.91 ± 2.49	+6%	0.862
Haulback time	total time	mean ± SE	total time	mean ± SE		
Retrieval-sorting time per 100 m gillnet	635 min	12.86 ± 1.64	279 min	5.58 ± 0.63	–57%	<0.001*

Comparison of mean rates of BPUE, CPUE, MVPUE, and haulback time between control versus illuminated nets.
BPUE = kg of bycatch group/([net length/100 m] × [net soak time/12 h]); CPUE = kg of target fish catch/([net length/100 m] × [net soak time/12 h]); MVPUE = market value ($US) of target fish/([net length/100 m] × [net soak time/12 h]). Non-finfish bycatch biomass consisted of loggerhead turtles, Humboldt squid, and elasmobranchs. Total bycatch biomass comprised all bycatch taxonomic groups (i.e., loggerhead turtles, finfish, Humboldt squid, and elasmobranchs). Haulback time = the time (min) required to retrieve and disentangle all captured animal biomass (all bycatch and target fish catch) per 100 m of gillnet. See Table S1 for a complete list of species captured as target catch and bycatch as well as their corresponding regulations and general patterns of utilization.
[a]Percent change represents the differences in mean BPUE, CPUE, MVPUE, and haulback time from control to illuminated nets
[b]p values represent the differences in BPUE, CPUE, MVPUE, and haulback time between control and illuminated nets using a Wilcoxon signed-rank test paired by net, with significant differences indicated with an asterisk
[c]BPUE = number of loggerhead turtles caught/([net length/100 m] × [net soak time/12 h])

(64%) and illuminated (69%) nets consisted of primary target species (Table 1).

Effects of net illumination on total and multi-taxa bycatch

In 28 controlled sets of net pairs, the mean biomass of total bycatch per unit effort (12 h soak × 100 m net; BPUE) significantly decreased between control and illuminated nets by 63% (Figure 1; Table 1). In illuminated nets, mean elasmobranch BPUE was significantly reduced by 95%, mean Humboldt squid BPUE was significantly reduced by 81%, and mean finfish BPUE was significantly reduced by 48% (Figure 1; Table 1). Net illumination also significantly reduced mean non-finfish (i.e., loggerhead turtle, Humboldt squid, and elasmobranch) BPUE by 69% (Table 1). There were no significant differences in rates of loggerhead turtle biomass and number of turtles captured between control and illuminated nets (Figure 1; Table 1).

Effects of net illumination on target fish catch, market value, and fishery operations

There were no significant differences in biomass of total target fish catch per unit effort (12 h soak × 100 m net; CPUE), primary

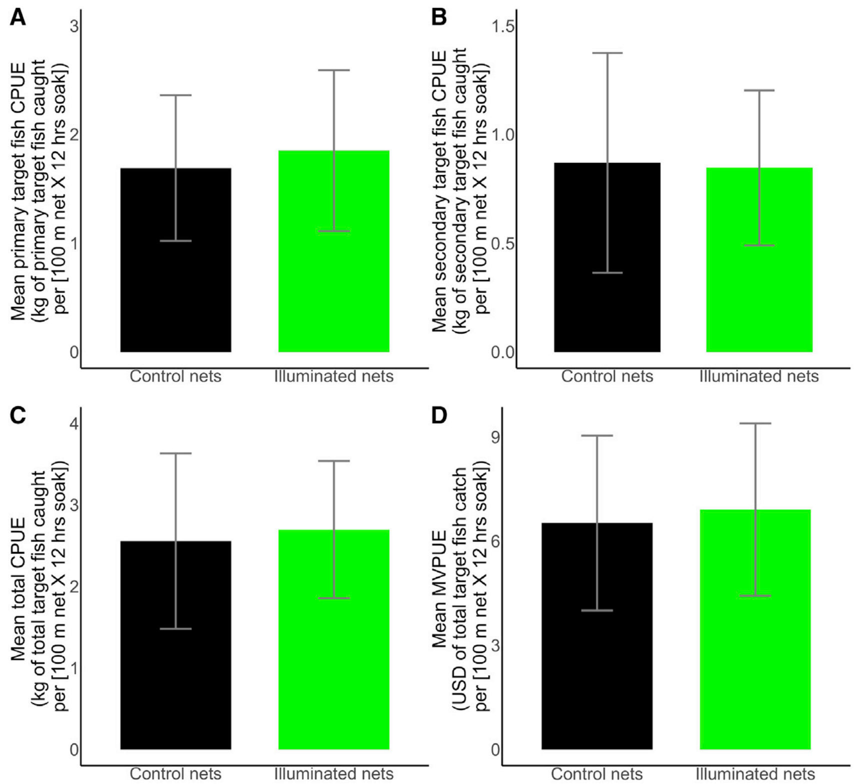

Figure 2. Target fish catch and value between control and illuminated gillnets

Comparison of mean primary target fish biomass catch per unit effort (CPUE) (A), mean secondary target fish biomass catch per unit effort (CPUE) (B), mean total target fish biomass catch per unit effort (CPUE) (C), and mean total target fish market value per unit effort (MVPUE) (D) between control versus illuminated nets. Primary target fish catch consisted of California halibut (*Paralichthys californicus*), star-studded grouper (*Hyporthodus niphobles*), and gulf coney/rooster hind (*Hyporthodus acanthistius*), while secondary target fish catch consisted of Pacific bearded brotula (*Brotula clarkae*), California sheepshead (*Semicossyphus pulcher*), ocean whitefish (*Caulolatilus princeps*), finescale triggerfish (*Balistes polylepis*), shortfin corvina (*Cynoscion parvipinnis*), Pacific porgy (*Calamus brachsomus*), Mexican rockfish (*Sebastes macdonaldi*), barred sand bass (*Paralabrax nebulifer*), Pacific goldeneye tilefish (*Caulolatilus affinis*), burrito grunt (*Anisotremus interruptus*), and splittail bass (*Hemanthias peruanus*). There was no significant difference in primary target fish CPUE (n = 28 paired sets, p = 0.944), secondary target fish CPUE (n = 28 paired sets, p = 1.000), total target fish CPUE (n = 28 paired sets, p = 0.896), and target fish MVPUE (n = 28 paired sets, p = 0.862) between control and illuminated nets. Bars represent SE.

target fish CPUE, secondary target fish CPUE, target California halibut CPUE, and target grouper (*Hyporthodus sp.*) CPUE between control and illuminated nets (Figure 2; Table 1). Similarly, the total (primary and secondary) target fish market value per unit effort (12 h soak × 100 m net; MVPUE) was not significantly different between net treatments (Figure 2; Table 1). Illuminated nets significantly reduced the mean haulback time (minutes required to retrieve and disentangle all bycatch and target catch per 100 m gillnet) by 57% (Figure 3; Table 1).

Effects and implications of net illumination on total and multi-taxa bycatch

The significant reduction in total discarded biomass was driven predominantly by decreases in large (i.e., non-finfish) bycatch species (Figure 1; Table 1), which follows a pattern of previously published studies whereby net illumination decreased bycatch of marine megafauna species while maintaining catch rates of target fish in different fisheries and ocean basins worldwide.[26–34] Trophic downgrading through removals of consumers occupying high trophic levels can have profound effects on the structure, function, and resilience of marine ecosystems.[16–18] Reductions in bycatch of large consumers, such as those observed in this study, may have important ecological benefits through ameliorating the potential impacts that bycatch might have on coastal ecosystems. Given the global extent and magnitude of coastal gillnet fisheries, future research is needed to better understand community and ecosystem-scale effects of net illumination and other BRTs.

Net illumination substantially reduced bycatch of elasmobranchs (Figure 1; Table 1), a taxonomic group of global conservation concern.[38] Over the past half century, elasmobranch populations have declined worldwide due to overfishing and bycatch,[39,40] and their removal can have important effects on the structure and function of coastal ecosystems.[17,38,40,41] Indeed, in the nearby Gulf of California, coastal food webs have been rapidly "fished down" through reductions in elasmobranchs, resulting in ecosystem-wide shifts from species belonging to high trophic levels to species from lower trophic levels.[17] Historically, bottom-set gillnet fishers in the region retained certain elasmobranch species if they fished under a permit for both finfish and elasmobranchs.[15,42] However, since 2012 Mexico has prohibited the catch and sale of all elasmobranchs during the summer;[19] thus, elasmobranchs have transitioned from a secondary target catch to discarded bycatch. While some solutions are being developed to decrease elasmobranch bycatch in longline fisheries (e.g., modified leaders, hooks, and bait[43,44]), this study establishes net illumination as the first known potential elasmobranch BRT for gillnet fisheries. As a taxonomic group with highly developed visual systems,[23,45] it is unclear if elasmobranchs are perturbed by and avoid illuminated nets, or if illumination provides a visual cue that serves as a deterrent to entanglement. The mechanisms behind these behavioral responses are important and require better understanding.

Illuminated nets markedly reduced bycatch of Humboldt squid, which to our knowledge establishes net illumination as the first known potential BRT for cephalopods, a taxonomic group that is typically targeted in specialist fisheries. Like other large mid-water squids, Humboldts have enlarged eyes that exceed the largest known fish eyes,[46] a common adaptation of

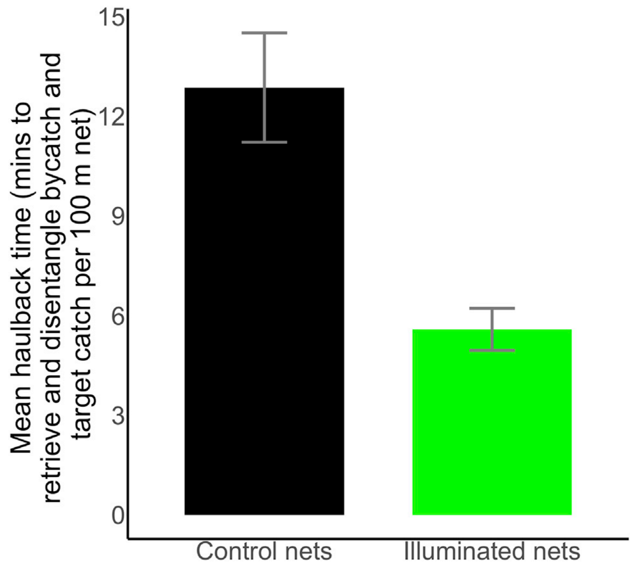

Figure 3. Haulback time between control and illuminated gillnets
Comparison of mean haulback time between control versus illuminated nets. Illuminated nets significantly reduced the mean time required to retrieve and disentangle nets by 57% ($n = 28$ paired sets, $p < 0.001$). Bars represent SE.

deep-sea visual predators,[47] which may have facilitated their recognition and avoidance of the illuminated nets. Alternatively, Humboldts may have avoided the high irradiance generated by the LED lights. Japanese flying squid (*Todarodes pacificus*) have been shown to avoid the high irradiance zone in the near-field area in lighted jig fisheries, while being attracted in the far-field region.[48] In Mexico, Humboldt squid are also targeted in lighted jig fisheries, where they are captured alive and in good condition. However, they are not retained in Mexican gillnet fisheries because (1) a specific permit is required to take them, which gillnet fishers do not typically possess; (2) they are usually dead and in poor condition from soaking overnight in gillnets; (3) the monofilament netting of gillnets can cut their skin, further degrading their quality; (4) when captured alive, they can be difficult to remove from gillnets and can ink fishers and the boat, resulting in additional maintenance time; and (5) even when captured alive and in good condition, their short shelf life requires that they be iced and processed immediately, which gillnet fishers are not equipped to do due to a lack space and capital to process their catch at sea.

In addition to elasmobranchs and Humboldt squid, illuminated nets significantly reduced finfish bycatch, which primarily consisted of small-bodied bycatch species that garnered no commercial value or target species that were too small (juveniles) to be sold (Table S1). Vision and visual capacity of fish can vary across species and ontogeny,[49] which may explain why net illumination reduced finfish bycatch, but not target finfish catch. In juvenile fish, visual systems are used to perform simple tasks such as vertical migrations to avoid predators, whereas older lifestages have more developed visual systems that are used for complex tasks such as predation, spatial vision, navigation, reproduction, and communication.[50] Predator avoidance, or predation itself, may have also played a role in the reduced bycatch rates observed in illuminated nets. For example, large target finfish may have been attracted to the illuminated nets as a means to aid or enhance predation, resulting in smaller finfish bycatch avoiding the illuminated nets or even being preyed upon. Consequently, behavioral avoidance or predation in the area adjacent to the illuminated nets may have contributed to the higher finfish bycatch rates observed in control nets.

Finfish bycatch that cannot be sold commercially can sometimes have important non-monetary or additive value, such as consumption by the crew, subsistence consumption in local communities, or use as bait in other fisheries. However, eight of the 14 finfish bycatch species captured during this study (i.e., whitesnout searobin, Pacific hake, Chilhuil sea catfish, California lizard fish, golden mojarra, California scorpionfish, Pacific stargazer, and California moray eel; Table S1) are rarely retained for any purpose because either their small body size and/or spines limit their usefulness or they must be fully processed at sea due to their short shelf-life, thus rendering them as bycatch (Table S1). Additionally, some of these species can be difficult to remove from gillnets due to their numerous and sometimes venomous spines (Table S1). With the exception of Pacific barracuda and popeye catalufa, which are sometimes consumed locally, albeit seldom captured, the remaining four finfish species classified as bycatch consisted of primary or secondary target fish species that were too small (juveniles) to retain and sell. As such, reducing their bycatch may increase catch value in subsequent years if/when they reach market size.

Unlike previous studies,[26–33] we did not find a significant decrease in sea turtle bycatch associated with net illumination. Nonetheless, reductions in mean rates of biomass and number of loggerhead turtles in illuminated nets were high (51% and 50%, respectively; Table 1), indicating a potential trend for reduced bycatch that warrants further investigation. Regardless, the multi-taxa and total bycatch reductions observed in this study would likely mitigate broader impacts of gillnet bycatch in the study area.

Effects and implications of net illumination on fishery operations

Illuminated nets reduced the time it took fishers to retrieve and sort gillnets following their overnight soak, representing the first time operational efficiency of net illumination has been assessed. Increased efficiency likely resulted from fishers needing to remove fewer entangled bycatch and, to a lesser extent, reduced hydrodynamic drag stemming from less biomass in the net. Given that gillnet fishers in Pacific Mexico generally fish with 800–1,000 m of net, the reduced haulback time would be expected to save fishers an average of 55.5 to 70.6 min per trip. In addition to the intrinsic benefits associated with time saved, small-scale fisheries generally lack adequate space and capital to ice their catch upon capture, which can quickly degrade its quality and necessitates offloading fish products as soon as possible. Thus, assuming fishers fish with the same effort, the time saved from increased operational efficiency could help reduce catch wastage and improve catch quality by allowing it to be offloaded and iced sooner.

Retrieval of nets by hand is a common practice in many small-scale gillnet fisheries. The benefits of net illumination go beyond reduction of haulback time, as the physical exertion and nuisance associated with untangling massive quantities of bycaught animals from nets are also reduced. In particular, reducing finfish bycatch helps fishers with the very tangible, cumbersome, time-consuming, and potentially costly process of cleaning, untangling, and repairing nets. Similarly, removing non-finfish bycatch species, such as sea turtles or sharks, requires dangerous handling of large animals that can injure fishers and damage nets, resulting in additional expense, maintenance time, and opportunity cost. In Mediterranean gillnet fisheries, marine megafauna bycatch interactions have resulted in considerable costs and downtime to fishers who need to repair nets.[51]

Adoption potential, study limitations, and future directions

Although most BRTs have historically been developed for specific bycatch taxa,[24,25,52,53] solutions that reduce total bycatch discards could mitigate implementation costs and ease broader adoption in fisheries that interact with multiple bycatch species.[32,34] The significant reduction in total bycatch is important when considering the likelihood of fisher adoption, as bycatch events of protected species tend to be rare, which can make the impetus for uptake of new technologies or compliance with regulations more abstract to fishers. In most cases, reductions in total bycatch discards will be more apparent to fishers than reductions of rare bycatch species. Nevertheless, the reduction in bycatch of protected and vulnerable species is also important as it has the potential to mitigate revenue losses by curtailing costly and inefficient government interventions. Bycatch of protected marine megafauna has led to fisheries regulations (e.g., closures, gear switches, and buyouts) that have incurred substantial socioeconomic costs on coastal communities.[19,20,54] In this particular gillnet fishery, high bycatch of loggerhead turtles resulted in a fishery closure that eliminated the seasonal income of thousands of fishers.[19]

Given the large volume of organisms and diversity of species captured in this study, coupled with constraints on time and effort, we used biomass to assess the effects of net illumination on catch and bycatch rates. Biomass is a commonly used metric in fisheries management, especially in high-volume capture fisheries where individual animals cannot always be sorted efficiently.[55] However, biomass may bias results based on the capture of a few large or several small individuals if they exhibit different behaviors, which may have important implications for understanding behavioral responses of certain species, size classes, and lifestages to illuminated nets. Thus, in addition to biomass, future studies should strive to collect length measurements and counts of individuals to better understand the finer-scale effects of net illumination on species, lifestages, and individuals.

Ease of use and cost are important to consider when developing gear modifications. LEDs were relatively easy to clip on the float line and remained illuminated throughout the trials. Given that illuminated nets are essentially fished identically to control nets, no training is required for adoption. At their current price point (~7–9 USD/light), the LED lights we tested remain costly, especially in developing nations. Other less expensive LED fishing lights (~1.5 USD/light) are available, but their efficacy in reducing bycatch and durability in gillnet fisheries have yet to be investigated. Moreover, the batteries in existing LED lights necessitate recurring operational costs for fishers. To address these challenges, we have developed solar-powered LED lights that can remain operational for several years without the need to change batteries.[56] Regardless, the increased operational efficiency and reduction in total bycatch could justify the costs to fishers that convert to illuminated nets. In cases of high biodiversity and conservation importance, governments and NGOs could subsidize their adoption. In other gillnet fisheries, net illumination has been estimated to cost as little as 16 to 34 USD to prevent a sea turtle bycatch event.[28,31] We encourage conservation practitioners, fishery managers, and other stakeholders to work with industry to develop new technologies, domestically manufacture LED lights, and seek new methods to increase efficiency and availability.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2021.12.050.

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AUTHOR CONTRIBUTIONS

J.F.S., J.H.W., and S.H.P. designed the study. D.A.-R. and S.H.P. provided critical logistic and field support. J.F.S. collected and collated data. J.F.S. and J.H.W. analyzed the data and wrote the manuscript. All authors edited the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
All data and code	This paper	Open Science Framework (https://osf.io/FMXBY/)
Software and algorithms		
R version 4.0.5	The R Project for Statistical Computing	https://www.r-project.org/

RESOURCE AVAILABILITY

Lead contact

Further information and requests should be directed to and will be fulfilled by the lead contact, Jesse Senko (jesse.senko@asu.edu).

Materials availability

This study did not generate new unique reagents.

Data and code availability

Data files have been deposited at the Open Science Framework and are publicly available as of the date of publication. Accession numbers are listed in the key resources table. This paper does not report original code. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Ethics statement

The animal use protocol for this research was reviewed and approved by the Institutional Animal Care and Use Committee at Arizona State University (IACUC protocol #12-1256R). All research activities were performed under the supervision of the National Fisheries and Aquaculture Institute of Mexico and authorized by the Mexican government through SEMARNAT permit SGPA/DGVS/05137/12.

METHOD DETAILS

Fishing trials and experimental design

Controlled experiments were conducted in partnership with Mexico's National Fisheries and Aquaculture Institute (INAPESCA) and local expert gillnet fishers in the Gulf of Ulloa, Baja California Sur, Mexico (see Peckham et al.,[35] Wingfield et al.,[36] and Seminoff et al.[37] for maps of study area). Bottom-set gillnet vessels working in the region pursue California halibut (*Paralichthys californicus*) and large grouper (*Hyporthodus sp.*) as their primary target fish catch, while retaining secondary target fish species of lesser commercial value (Table S1). We tested the effects of net illumination on bycatch and target fish biomass by pairing illuminated bottom-set gillnets with control (conventional) bottom-set gillnets in prominent fishing grounds in the Gulf of Ulloa. Specifically, we compared bycatch rates, target fish catch rates, market value rates, and haulback time between treatment (i.e., illuminated) and control (i.e., conventional) nets. To ensure that all nets fished similarly, we contracted local fishers to build nets by hand with materials and specifications identical to those used by the local fleet. Nets had a stretched diagonal single thread monofilament mesh size of 20 cm and ranged in length from 153 to 199 m, all with a net height of 20 meshes (approximately 6.1 m). All nets were fished with 1.5 m tie downs or "suspenders" that connected the float line to the sink line, thus resulting in loose bags of monofilament net material that increased entanglement.[35] Tie downs were placed every 2 m along the gillnets and helped ensure each net was the same height.

In the summer of 2012, we deployed 28 sets of paired bottom-set gillnets at sunset and soaked them overnight for 8-14 h. Nets were deployed, retrieved, and sorted by the same fishing crew throughout the duration of the study. Illuminated nets were attached to control nets of the same diagonal mesh size and approximate length using 200 m rope to form the paired nets. Treatment nets were illuminated by clipping AA battery-powered waterproof fishing lights that contained green light emitting diodes (LEDs) of wavelength 500 nm in a hard plastic casing (Centro Power Light CFL-D3, Centro) at 10 m intervals along the float line, while control nets received inactive LED lights of the same model at 10 m intervals. When attached to the float line, the LED lights pointed downward such that the monofilament net material was illuminated. Nets were set over rock ledges and sandbars at depths ranging from 10.9 m to 43.9 m in well-known halibut and grouper fishing grounds.[15,35] We used four replicates of each net pair and fished each replicate in prominent locations of the Gulf of Ulloa gillnet fishery to control for site effects. The direction of control-illuminated net pairs relative to depth contours was switched after each soak. Thus, each net type (illuminated and control) from each pair was soaked at the same depth and over the same substrate of each fishing location. All animal (i.e., bycatch and target fish catch) biomass captured during the study was recorded by species, sorted, and weighed by taxonomic group.

Bycatch

Species were classified as bycatch if they were not retained in this fishery or if their retention and sale were prohibited (see Table S1 for a complete list of species and their corresponding regulations). All bycatch was recorded by species, sorted, and weighed by taxonomic group (i.e., loggerhead turtles, Humboldt squid, finfish, and elasmobranchs; Table 1). Due to their endangered status, loggerhead turtles were also counted. We determined bycatch rates (bycatch per unit effort; BPUE) of each taxonomic group for each net as: BPUE = kg of bycatch group/([net length/100 m] × [net soak time/12 h]).

Target fish catch, market value, and fishery operations

All target fish species were recorded and collectively weighed based on their designation as primary or secondary target fish catch. Primary target fish catch consisted of California halibut and large grouper (*Hyporthodus sp*.), while secondary target fish catch included all other finfish species that are retained and sold commercially. The time at which the crew began retrieval and completed sorting (disentangling all animal biomass) of each net was also recorded. Market value of all target fish species was determined by a local master fisher from the Gulf of Ulloa with over 30 years fishing experience using the 2012 market prices.

We determined target fish catch rates (catch per unit effort; CPUE) for each net as: CPUE = kg of target fish catch/([net length/100 m] × [net soak time/12 h]). We determined market value rates (market value per unit effort; MVPUE) for each net as: MVPUE = market value ($US) of target fish/([net length/100 m] × [net soak time/12 h]). We determined haulback time for each net by calculating the time (mins) it took the same fishing crew to retrieve and disentangle all animal biomass (all catch and bycatch) per 100 m of gillnet.

QUANTIFICATION AND STATISTICAL ANALYSIS

Data analysis

We compared: 1) rates of bycatch biomass (BPUE) for total discarded bycatch, elasmobranch bycatch, finfish bycatch, Humboldt squid bycatch, loggerhead turtle bycatch, and non-finfish (i.e., loggerhead turtle, Humboldt squid, and elasmobranch) bycatch; 2) rates of target fish catch biomass (CPUE) for total target fish catch, primary target fish catch (halibut and grouper), secondary target fish catch, target halibut catch, and target grouper catch; 3) rates of market value (MVPUE) for total target fish catch; and 4) haulback time between control and illuminated nets. Total discarded bycatch included all bycatch taxonomic groups (i.e., elasmobranchs, finfish, Humboldt squid, and loggerhead turtles), while total target fish catch comprised all target fish (i.e., primary and secondary target fish) species. Differences between each metric were compared using a Wilcoxon matched-pairs signed-rank test paired by net, with statistical significance inferred at a probability of 0.05 or less. All analyses were performed in R 4.0.5.