Evaluating Current Knowledge and Future Directions of Visual Cues as Bycatch Reduction Technologies in Passive Net Fisheries

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Executive Summary

Fisheries bycatch is consistently identified as a leading cause of population decline for many species of sea turtles, seabirds, and marine mammals. Many of these species rely primarily, or in part, on visual cues to perceive their environment, and visual cues can affect behavior. Recent research suggests that utilizing visual cues on passive fishing gear, such as gillnets, can reduce incidental interactions and associated mortality. This review synthesizes studies on visual cue bycatch reduction technologies (BRTs), focusing on the use of colored nets and net illumination. It draws upon existing knowledge to discuss both potential benefits, including streamlining bycatch reduction of multiple species, and challenges, such as current cost and maintenance requirements, associated with visual cue BRT development and implementation. The success of visual cue BRTs in initial studies, primarily on gillnets, holds much promise for bycatch reduction of air-breathing megafauna in passive gear fisheries. However, this research is still in its early stages, and future studies must expand research to more passive gear types, identify and conduct local studies in applicable fisheries, consider their potential use with other stimuli as multi-sensory BRTs, and support the development of new light-emitting diode (LED) technologies that reduce cost and maintenance requirements.

As a case study, I present the preliminary findings from the first year of a multi-year study on the use of green LEDs as a sea turtle BRT on pound nets in the North Carolina flounder fishery. We compared the catch per unit effort (CPUE) of experimental green LEDs and control inactive LEDs on three pound nets in Core Sound (near Harker's Island, NC). Preliminary analyses suggest that green LEDs reduced sea turtle and elasmobranch bycatch rates but also reduced the target catch rate of flounder and other fish species. However, these results do not account for the potential influence of environmental conditions, and variables, including wind speed, reveal trends that may indicate influence on catch rates. These effects will need to be further considered after additional data collection. This research demonstrates one example of current, continued efforts to expand visual cue BRT research to multiple passive gear fisheries to increase their applicability.

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Introduction

Bycatch, or incidental capture of non-target species, is considered one of the most significant, immediate threats to ocean health and biodiversity (Davies et al. 2009). Long-lived animals with low population growth rates, such as sea turtles, marine mammals, and sea birds, are of particular concern due to their vulnerability to overexploitation (Heppell et al. 2005). Many of these species, collectively termed "air-breathing megafauna," are considered threatened, endangered, and/or protected in particular regions or across the globe (Gray and Kennelly 2018). However, a lack of consistent, reliable data, as is common in fisheries research, has made it difficult to calculate accurate estimates of bycatch; thus, our calculations remain conservative and likely underestimate the true interactions and mortality (Davies et al. 2009, Lewison et al. 2014).

Finkbeiner et al. (2011) conservatively estimated that even after instating bycatch mitigation measures, 137,000 sea turtle interactions resulting in 4,600 deaths occur annually in the United States alone. Read et al. (2006) calculated mean annual bycatch of marine mammals, estimating 6,215 individuals in the United States and 653,365 individuals globally per year from 1990 to 1999. Žydelis et al. (2013) estimated that at least 400,000 seabird mortalities occur each year in gillnets alone. Despite these numbers likely being underestimates, it is clear that air-breathing megafauna bycatch is a widespread, global conservation issue that requires immediate attention to reverse population declines. However, addressing the issue quickly becomes complex, as bycatch intensity varies within and across landscapes, regions, and gear types (Lewison et al. 2014).

To date, a majority of our knowledge pertaining to fisheries bycatch comes from the high seas and industrial fisheries, since most management and observer programs are focused on these fisheries (Reeves et al. 2013, Lewison et al. 2014). Critical knowledge gaps exist relating to coastal and small-scale fisheries, resulting in bycatch issues in these fisheries often being overlooked. Small-scale fisheries are those that require low capital investment and use low technology gear and vessels, and typically fish for subsistence for local or domestic markets (FAO/RAP/FIPL 2004). However, small-scale fisheries pose a comparable or greater threat than industrial fleets because the near-shore coastal areas in which they are located tend to overlap with or are near high-use migratory pathways, foraging grounds, and mating and nesting areas for many species of air-breathing megafauna (Peckham et al. 2007, Temple et al. 2018). For example, Peckham et al. (2007) determined that bycatch per unit effort (BPUE) and mortality of North Pacific loggerhead sea turtles (*Caretta caretta*) was higher in small-scale longline and gillnet fleets than industrial-scale fisheries. Similarly, Félix and Samaniego (1994) found high rates of small cetacean bycatch in Ecuadorian artisanal fisheries, potentially exhibiting higher mortality than in the neighboring directed dolphin fishery in Peru.

In recent years, small-scale fisheries utilizing passive gears have gained attention after causing the decline of several species of megafauna (Woodley and Lavigne 2001, Alfaro-Shigueto et al. 2011). Gaining the most notoriety, the seemingly inevitable extinction of the world's most endangered cetacean, the vaquita (*Phocoena sinus*), in the northern Gulf of California, Mexico is largely due to bycatch in artisanal large-mesh and small-mesh gillnets and illegal gillnets (D'Agrosa et al. 2000, Taylor et al. 2017). Passive fishing gear, such as a gillnet, is left in place for a period of time, allowing fish to swim into it, as opposed to active gear that is moved through the water to "chase" and capture fish (Bjordal 2009). Studies on passive gear often focus on gillnets, but can also include pound nets, trammel nets, fyke nets, and other types of traps. These passive gears are increasingly acknowledged as a leading cause of air-breathing megafauna bycatch and consequent mortality and population decline, as several reviews of fisheries bycatch calculated higher rates of bycatch in gillnets than in active gear, such as longlines or trawls (Read et al. 2006, Hatch 2018). Bycatch most often occurs due to an animal incidentally interacting with a net or being attracted by captured fish, consequently becoming entangled or trapped in the gear (Read et al. 2003, Martin and Crawford 2015, Uhlmann and Broadhurst 2015). For seabirds, this most commonly affects species using various diving foraging techniques (Melvin et al. 1999, Martin and Crawford 2015).

Despite the universality of bycatch, there is not and likely never will be a one-size-fits-all solution. Effective bycatch mitigation research and management requires region- and fishery-specific solutions that consider the relevant bycatch species, local commercial viability, and monitoring and enforcement mechanisms (Cox et al. 2007, Senko et al. 2014, NOAA 2016). Evaluating bycatch reduction technologies (BRTs) can also prove difficult; even though bycatch is significant to megafauna populations, interactions in individual fisheries are often rare, and it is difficult to obtain a large enough sample size in the duration of a study for robust statistical analyses (McCracken 2004). Several BRTs, primarily mechanical technologies such as turtle excluder devices (TEDs) and circle hooks, have been vigorously studied and implemented in fisheries to varying degrees (Watson et al. 2005, Jenkins 2012). A myriad of other BRTs, most of which focus on a specific bycatch species and gear type, are in a variety of research and development stages but have yet to be systematically implemented (Werner et al. 2006). Unlike TEDs and circle hooks, a large proportion of these BRTs aim to avoid contact with fishing gear, rather than facilitating the escape after capture (Werner et al. 2006). For example, researchers have tested passive acoustic devices that allow cetaceans to perceive the net via echolocation (Goodson and Mayo 1995) and artificial and dyed baits to reduce attraction and subsequent bycatch of seabirds (McNamara et al. 1999, Cocking et al. 2008). Both methods successfully reduced bycatch, but neither has been integrated into fisheries management thus far.

In recent years, researchers have investigated the role of sensory ecology in bycatch. Sensory ecology refers to the ability of an animal to perceive and respond to sensory cues—such as light, sound, and smell—in its environment (Lohmann et al. 2008). It has been suggested that high rates of incidental capture primarily arise from the physiological constraints on the vision of bycatch taxa, as well as the perceptual challenges that arise underwater (Martin and Crawford 2015). In essence, bycatch taxa simply cannot see the fishing gear in the water, and current knowledge indicates that altering the properties of passive gear to make it more detectable could decrease interactions. For example, lightsticks, often placed on longlines to attract tuna and other target species, have been found to attract sea turtles toward fishing gear (Wang et al. 2007). Although currently unproven, it seems likely that the light source makes bait visible to turtles, resulting in attraction to the gear. If this is the case, it is possible that the use of visual cues to increase the detection and subsequent avoidance of non-baited gear could be an effective multi-taxon, cost-effective technique for reducing bycatch (Read et al. 2003, Southwood et al. 2008, Martin and Crawford 2015). Similarly, manipulating visual cues, such as the color of bait, has been tested to reduce longline bycatch of seabirds by making bait more cryptic (McNamara et al. 1999, Cocking et al. 2008). A similar approach could be used to instead make passive nets more visible to the same species. Less is known about the response of marine mammals to visual cues. However, they are known to visually inspect their surroundings and spend more time looking at unfamiliar objects (Kremers et al. 2016). Sensory BRTs hold particular promise in coastal, passive net fisheries, in which collisions involve a mobile animal encountering a stationary net (rather than, for example, being encircled by an actively towed net), and a change in animal behavior (rather than a change in vessel behavior) could alter the likelihood of interactions (Gilman et al. 2010).

In an effort to use knowledge of sensory biology as a tool to develop successful BRTs, in recent years, researchers have tested a variety of visual cues as BRTs on passive gears to reduce marine mammal, seabird, and sea turtle bycatch. Thus far, studies have shown reasonable success, suggesting that visual BRTs hold promise and warrant further investigation. Since visual BRTs are still in developing stages, the purpose of this review is to synthesize existing literature pertaining to the study of sensory ecology and bycatch and experimentation of visual cues as BRTs, including colored nets and net illumination. From this synthesis, I identify current gaps in our knowledge and potential future directions for BRT research. Lastly, I present a current case study examining the effectiveness of green light-emitting diodes (LEDs) as a sea turtle BRT in the North Carolina pound net fishery.

Methods

To develop an understanding of how research and management have addressed visually based sensory BRTs with regard to sea turtle, marine mammal, and seabird bycatch, I reviewed relevant literature using a semi-structured literature search. I compiled articles through a combination of systematic literature searches in scholarly journals, soliciting relevant papers from field experts, and identifying gray literature from relevant organizations. I manually identified additional literature pertaining to specific topics, as necessary, through further literature searches. For the systematic literature searches, I queried search strings in Web of Science, Google Scholar, and JSTOR. Search strings included terms, such as "sea turtles" *and* "bycatch," "visual," "illumination," "net illumination," "sight," *or* "fisheries." I repeated each search string using "seabirds" or "marine mammals" in place of "sea turtles." For each relevant article within the first 50 results of each search, I read the text in full, summarizing and compiling information.

Vision of Air-Breathing Megafauna

To evaluate the rationale behind, and the potential effectiveness of, visual cues as BRTs, it is first necessary to understand the visual capabilities and dominant sensory modalities of the species in question. As such, the following provides a basic overview of sea turtle, seabird, and marine mammal vision as is necessary to provide such context. This summary by no means provides a complete picture of our physiological and behavioral understanding of the physiology and sensory biology of these air-breathing megafauna, as that is beyond the scope of this review. However, it does include sufficient information on visual capabilities and behavioral responses to understand and evaluate fishery-related visual cues.

Sea Turtles

Although there are seven extant species of sea turtles, most knowledge of vision thus far is limited to loggerhead, green (*Chelonia mydas*), and leatherback sea turtles (*Dermochelys coriacea*) (Fritsches and Warrant 2013). These sea turtles have well-developed visual systems that are adapted to their primary habitat, the well-lit surface layers of the ocean (Southwood et al. 2008). They have high sensitivity and resolving power in photopic conditions, while their perceptual abilities dramatically decrease in low-light environments (Levenson et al. 2004, Swimmer and Brill 2006). While this adaptation is fitting for the primarily diurnal loggerhead and green turtles, it seems less advantageous for leatherbacks, which are active both day and night and dive to great depths, although they may be foraging on bioluminescent organisms (Fritsches and Warrant 2013).

In regard to spectral sensitivity and color vision, loggerhead and green turtles are sensitive to similar wavelengths and can perceive colors on the electromagnetic spectrum from red to ultraviolet (~440-700nm) due to the presence of multiple photopigments and oil droplets (Bartol and Musick 2002, Levenson et al. 2004). Both species' peak sensitivity occurs in longer wavelengths associated with the color green (~580nm) (Levenson et al. 2004). Leatherbacks appear to have different sensitivity levels that peak in short wavelengths (~400nm), which matches their offshore habitat, although studies thus far have not been consistent in their quantification (Crognale et al. 2008, Horch et al. 2008). The presence of several visual pigments in leatherbacks suggests high spectral sensitivity and color vision (Crognale et al. 2008, Horch et al. 2008).

Behavioral studies indicate that sea turtle responses to light can vary by species. For some species, light is a presumed attractant. In a lab study, both juvenile loggerhead and green turtles oriented toward chemical lightsticks, regardless of their color (Wang et al. 2007). Alternatively, in a similar study, leatherbacks either ignored or oriented away from the light source (Gless et al. 2008). It is important to note, however, that both studies took place in laboratory settings and may not reflect conditions or responses that would occur in a natural setting. Moreover, recent hypotheses suggest that different populations of sea turtles, even those of the same species, may have different responses to visual stimuli (Fritsches 2012).

Visual cues are the primary mechanism by which sea turtles forage, as made evident by primarily foraging during the day (Narazaki et al. 2013) and their inability to locate prey using only olfactory cues (Southwood et al. 2008). Constantino and Salmon (2003) also found that while both visual and olfactory cues elicited prey capture responses, the responses to visual cues were stronger, and when both visual and olfactory cues were introduced, turtles oriented toward the visual cues. Electrophysiological and behavioral studies also indicate that they have high visual acuity, allowing them to identify small prey items, such as crabs (Bartol and Musick 2002). Loggerhead and green turtles have high densities of photoreceptors distributed in a dense horizontal band, allowing their acuity to be highest at a horizontal orientation, while leatherbacks have a small circular area of high density, better fit for a deep diving species (Fritsches and Warrant 2013).

Seabirds

Most seabirds rely primarily on vision for prey detection, yet have low spatial resolution and can only identify prey items from short distances (Martin and Crawford 2015). This may, in part, be due to the distribution of photoreceptors in their retinas. In some seabirds, high densities of photoreceptors—and thus their highest acuity vision—are located in a linear strip directed toward a horizontal point of view (Hayes and Brooke 1990). Such a distribution is logical for birds that live and forage in open environments, such as over the ocean, allowing them to scan a wide area of their environment (Hayes and Brooke 1990). However, this also leads to lower acuity vision in their forward field of view, resulting in shorter distance prey pursuits (Martin and Crawford 2015).

Regarding color vision, seabirds have complex eyes with rod receptors and four types of cone photopigments (as compared to a human's three), allowing them to detect fine differences in spectral wavelengths in bright light conditions (Martin and Osorio 2008). They can perceive wavelengths in the visible spectrum from red to violet (~400-650 nm), but their spectral and spatial discrimination abilities decrease in low light conditions (Martin and Crawford 2015). Most seabirds, with the exception of gulls, cannot see ultraviolet wavelengths (Martin and Crawford 2015).

It is important to note that few studies have been conducted on individual species, and our existing knowledge of the vision of seabirds primarily stems from studies on a few seabird and related species (Martin and Crawford 2015). Moreover, there is currently a lack of behavioral studies related to seabird sensory ecology, making it difficult to estimate their responses to cues they perceive. As such, generalizations and assumptions should be drawn from this knowledge with caution.

Marine Mammals

Relative to sea turtles and seabirds, marine mammals exhibit a significantly more multimodal sensory approach to perceiving their environment and locating prey, which is largely dependent upon the scale at which sensory detection is occurring (Kremers et al. 2016, Torres 2017). Odontocetes rely heavily on echolocation, particularly for detection at a distance or in dark or turbid environments, while vision is used in conjunction with echolocation for short distance communication and prey detection (Kremers et al. 2016, Torres 2017). Pinnipeds possess receptors in their vibrissae that are used for both direct touch and hydrodynamic perception, the ability to sense the movement of water from prey, predators, or other elements of their surroundings (Dehnhardt et al. 2001, Hanke et al. 2013). Dehnhardt et al. (2001) showed that they can detect the hydrodynamic trails of small prey species minutes after the prey swims away, indicating that hydrodynamic perception could be used for long distance pursuit.

Despite the importance of other sensory modalities, the vision of marine mammals is well-developed and important to sensory perception (Kremers et al. 2016). Cetaceans have strong brightness and contrast sensitivity, as well as motion detection, allowing them to detect and discriminate between prey (Kremers et al. 2016). They have significantly higher acuity at short distances underwater and in bright light environments, quickly diminishing further away or in low light (Herman et al. 1975). Pinnipeds are well adapted to their amphibious lifestyle with high resolution acuity, sensitivity, and a wide visual field (Hanke et al. 2009).

The existence of color vision in marine mammals, however, is still being studied and debated among researchers. Cetaceans and pinnipeds were originally believed to be monochromats, or essentially colorblind, because they do not possess short-wave-sensitive cones (blue to near-UV sensitive) like most species with color vision (Peichl et al. 2001, Hanke et al. 2009). Kraus et al. (2014) determined that North Atlantic right whales (*Eubalaena glacialis*) do not possess short-wave-sensitive or long-wave-sensitive cones, suggesting that they see the world as "black and white," only perceiving wavelengths in the blue-green region. However, a behavioral study found that bottlenose dolphins (*Tursiops truncates*) can perceive and discriminate between colors, contradicting these conclusions and suggesting that their rod photoreceptors may play a role and allow them to see color (Griebel and Schmid 2002). With this exception, most studies regarding marine mammal vision examine physiology, rather than behavior, which is a notable research gap.

Considering the Efficacy of Visual Cue Bycatch Reduction Technologies

The Appeal of Visual Cue BRTs

The development of visual cue BRTs seems promising since, as discussed above, many species of air-breathing megafauna caught as bycatch predominantly or partly rely on visual cues, particularly in close range (Southwood et al. 2008, Martin and Crawford 2015, Kremers et al. 2016). It is hypothesized that much bycatch occurs because the nets simply are not visible to relevant taxa, making it critical that an effective BRT alert them to the presence of the net (Martin and Crawford 2015). Since the principle is broadly applicable across bycatch species, one visual BRT may successfully reduce the incidental catch of multiple species or taxa. This is promising for both the purposes of research and implementation. In evaluations of bycatch, most studies focus only a single species or species group, despite the fact that bycatch and any implemented technology could have impacts on other species (Werner et al. 2006). When adopted, visual BRTs could reduce the need for multiple BRTs in a single fishery, reducing effort and costs of implementation (Mangel et al. 2018). Moreover, it could result in widely, possibly even globally, applicable BRTs generating large reductions in bycatch rates from a single technology (Mangel et al. 2018).

Design & Methodological Considerations

To create an effective BRT that relies on visual cues, not only should the species' visual capacity be considered, but the environment through which the cue is transmitted must be accounted for. Irradiance in water can take a much different path than through air, as water and suspended matter absorb and scatter light, resulting in significant attenuation (Martin and Crawford 2015). Moreover, spectral absorption and transmission vary with depth, allowing only shorter wavelengths to be perceived beyond around 200m (Jerlov 1968). This marine environment is complex in the clearest waters and varies significantly with concentrations of suspended matter. On a global scale, irradiance and spectral transmission significantly vary by location, depth, and oceanographic properties, making it important to consider these effects on a local scale.

Moreover, specifically for net illumination technologies, the properties of the BRT itself should be strategic. Different forms of illumination devices, such as LEDs and lightsticks, can have varying spectra and irradiance (Wang et al. 2007, Wang et al. 2010). The placement of these BRTs, such as the location on the net and distance between them, could also affect their visibility and the total irradiance (Wang et al. 2010, Virgili et al. 2018). Any of these factors have the potential to affect which species perceive and the subsequent response to these devices. Particularly in areas where multiple non-target species are present, these factors need to be considered regarding each species because light can elicit different responses in different forms and contexts. For example, light has been shown to attract loggerheads and green sea turtles in a captive environment (Wang et al. 2007), and some species of seabirds are also known to be attracted to and grounded by land-based artificial light (Rodríguez et al. 2017). As such, it is important to properly test net illumination devices in the local natural ecosystem before implementation to ensure they do not elicit such a response and increase bycatch or have other unintended consequences. Moreover, the time of day at which fishing occurs should be considered, as lights potentially could be less effective during daylight hours.

Current State of Visual Bycatch Reduction Technology Research

The Use of Colored Netting

It seems that many species caught as bycatch are captured because the nets, particularly those made of monofilament, are not visible to them (Martin and Crawford 2015). Therefore, it is theorized that increasing net visibility by changing its color may effectively reduce the bycatch of such species (Martin and Crawford 2015). Thus far, several studies have successfully tested this approach on several species of seabirds and marine mammals (Table 1).

Table 1. Summary of results of existing visual cue BRT studies using colored nets and ropes.

Visual Cue	**Study Location**	**Bycatch Species or Species Group**	**Bycatch Rate (%, if available)**	**Target Catch Rate**	**Target Catch Value**	**Citation**
White Upper Net (20 panels)	Puget Sound, WA	Common Murre	Decreased (45%)	No effect	No effect	Melvin et al. 1999
White Upper Net (50 panels)	Puget Sound, WA	Common Murre	Decreased (40%)	Decreased	Decreased	Melvin et al. 1999
White Upper Net (20 panels)	Puget Sound, WA	Rhinoceros Auklet	No effect	No effect	No effect	Melvin et al. 1999
White Upper Net (50 panels)	Puget Sound, WA	Rhinoceros Auklet	Decreased (42%)	Decreased	Decreased	Melvin et al. 1999
Orange Monofilament	In Captivity	Little Penguins	Decreased	Unknown	Unknown	Hanamseth et al. 2018
Orange and Red Rope	Cape Cod Bay	North Atlantic Right Whales	Decreased	Unknown	Unknown	Kraus et al. 2014
Glow Rope	Unknown	Cetaceans & Sea Turtles	Unknown	Unknown	Unknown	Werner et al. 2006

In a salmon gillnet fishery in Puget Sound, Washington, Melvin et al. (1999) attempted to increase the visibility of the upper net panels by making the top 20 or 50 meshes of the monofilament net white. The visual alerts decreased seabird bycatch by 45% and 40%, respectively, but only the 20-mesh panels maintained target catch levels, making it the only viable option. Such panels were briefly implemented in the fishery, but regulations applied only to non-treaty fishers, accounting for only a small minority of sockeye gillnet fleets, and were quickly removed due to controversy over inequity (Melvin et al. 1999). More recently, Hanamseth et al. (2018) tested colored monofilament on little penguins (*Eudyptula minor*) in a captive setting, exposing them to a gillnet mimic containing vertical rows of monofilament on a frame. Orange monofilament resulted in a much lower collision rate (5.5%) than green (30.8%) or clear (35.9%) monofilament. Orange monofilament allowed the net mimic to be detected from several meters away, as opposed to green and clear, in which penguins continued to try to swim into the net after colliding with it (Hanamseth et al. 2018).

Orange and red rope have also been tested as a method to reduce North Atlantic right whale bycatch, hypothesizing that if whales are monochromatic and perceive primarily blue-green wavelengths, the rope would appear black and be visible due to high contrast with the blue-green ocean water (Kraus et al. 2014). In Cape Cod Bay, Kraus et al. (2014) tested fake ropes of various colors and recorded subsequent whale behavior. Red and orange ropes were detected and resulted in avoidance behavior (turning away from the rope) at significantly further distances than black or green ropes, indicating that they have potential to decrease bycatch. Similarly, current research is testing the efficacy of “glow rope” consisting of polypropylene blended with a phosphor that brightly glows yellow-green underwater to reduce cetacean and turtle bycatch (Werner et al. 2006). This would allow the rope to be visible both during the day and night, unlike other colored ropes and nets.

Net Illumination BRTs

Several recent studies also test another emerging method to enhance net detectability for bycatch reduction, illuminating or lighting up the gear (Table 2). With an understanding of sea turtles' reliance on visual cues (Southwood et al. 2008, Narazaki et al. 2013) and following a study indicating that lightsticks used on pelagic longlines influence turtle behavior (Wang et al. 2007), researchers hypothesized that manipulating illumination as a visual cue could decrease bycatch rates in other fisheries (Lohmann and Wang 2007).

Table 2. Summary of results of existing visual cue BRT studies using net illumination.

Visual Cue (distance apart on net)	Study Location	Bycatch Species or Species Group	Bycatch Rate (%)	Target Catch Rate	Target Catch Value	Citation
Green lightsticks (5m)	Mexico	Sea Turtles	Decreased (60%)	No effect	No effect	Wang et al. 2010
Green LED (10m)	Mexico	Sea Turtles	Decreased (40%)	No effect	No effect	Wang et al. 2010
UV LED (5m)	Mexico	Sea Turtles	Decreased (100%)	No effect	No effect	Wang et al. 2013
Orange LEDs (5m)	Mexico	Sea Turtles	Decreased (50%)	No effect	No effect	Wang et al. 2014
Orange LEDs (5m)	Mexico	Finfish	Decreased (53%)	No effect	No effect	Wang et al. 2014
Orange LEDs (5m)	Mexico	Elasmobranchs	Decreased (50%)	No effect	No effect	Wang et al. 2014
Green LED (10m)	Peru	Sea Turtles	Decreased (63.9%)	No effect	No effect	Ortiz et al. 2016
Green LED (10m)	Peru	Seabirds	Decreased (74.0%)	No effect	No effect	Wang et al. 2018
UV LED (15m)	Mediterranean	Sea Turtles	Decreased (39.7%)	No effect	No effect	Virgili et al. 2018
Green LED (10m)	Peru	Guanay Cormorants	Decreased (85.1%)	Unknown	Unknown	Mangel et al. 2018

Exploring this possibility, Wang et al. (2010) tested green chemical lightsticks and green LEDs for green sea turtle bycatch reduction in a commercial bottom-set gillnet fishery in Baja California Sur, Mexico. Both BRTs significantly reduced bycatch rates, lightsticks by 60% and LEDs by 40%, without reducing target catch rate and value. Lightsticks were spaced closer together, which might account for the difference in bycatch reduction (Wang et al. 2010). Wang et al. (2010) noted that LEDs may be more economically viable, as they have a longer lifespan, resulting in less cost, maintenance, and waste (Wang et al. 2010). Following this study, green LEDs were tested in another bottom-set gillnet fishery in Peru and were again found to reduce sea turtle bycatch by 63.9%, as well as decreasing seabird bycatch by 74%, without affecting target catch (Ortiz et al. 2016, Wang et al. 2018). In Western Borneo, Indonesia, green LEDs tested in a coastal drift gillnet fishery reduced sea turtle bycatch by 61% with small increases in target catch rate and value (Wang et al. 2018).

With an understanding that the visual capacity of sea turtles extends into the UV and that of some commercially valuable fish species does not, researchers built upon their work in Baja California's coastal gillnet fishery to determine if it is possible to exploit this difference in visual capacities to develop an effective BRT (Wang et al. 2013). They examined the impact of UV LEDs on gillnets and found that they reduced green sea turtle catch rates by 39.7% while maintaining both target catch rate and value. Virgili et al. (2018) also tested UV LEDs in a Mediterranean gillnet fishery with similar success. No sea turtles were caught in illuminated nets (16 in control) while maintaining catch rates. In effort to maximize efficiency, they also tested various spacing patterns of LEDs on the float line and determined that ~15 m between LEDs maximizes gear performance and illumination (Virgili et al. 2018).

To test the effectiveness of longer wavelength light, Wang et al. (2014) evaluated orange LEDs in a coastal gillnet fishery in Baja California Sur, Mexico. Not only did they find that orange LEDs reduced sea turtle bycatch rates by 50% and maintained target catch, but they also found that they reduced finfish and elasmobranch bycatch rates by 53% and 50%, respectively (Wang et al. 2014).

Although most net illumination studies have focused on sea turtle bycatch, to build upon the one study that also found LEDs to reduce seabird bycatch, one recent study in a demersal, set gillnet fishery in Peru extended the trials to the reduction sea incidental seabird catch (Mangel et al. 2018). Green LEDs deployed on nets reduced seabird bycatch, primarily of guanay cormorants, by 85.1%. This suggests that a singular BRT could be useful for multitaxon bycatch reduction and warrants further research into the applicability to other species and foraging strategies.

Despite the success of these experiments and consequent promise of net illumination BRTs, the mechanism by which they work is still unknown. It seems possible that the studied species either avoid the illumination or are alerted by its presence (Wang et al. 2013).

Current Drawbacks and Knowledge Gaps

This review covers currently published studies, although many additional studies have been conducted. The ICES-FAO Working Group on Fishing Technology and Fish Behaviour is actively working to collect and synthesize the results of the unpublished work that is largely not publicly accessible in the form of a database and gray literature. However, this current gap in publicly accessible literature emphasizes the importance of publishing scientific studies to effectively synthesize, expand upon, and implement conclusions drawn from existing work. Moreover, it is important to note that thus far most visual BRT research in small-scale fisheries focuses on sea turtles, with less focus on seabirds and minimal data on marine mammals, leaving critical information gaps. Beyond these broad data gaps, several specific concerns that must be addressed are apparent and discussed below.

Cost, Maintenance, and Acceptance by Fishers

Regardless of the experimental success of any BRT, effective implementation requires the cooperation of the fishers involved. Many studies consider the impact of BRTs on target catch rates and catch value, knowing that fishers need to maintain a viable livelihood and will not willingly implement a technology that puts that at risk, regardless of its other benefits. Despite having been included as collaborators in research trials and seeing firsthand that the lights had no impact, some fishers have expressed concerns both about the potential for adverse effects on catch value and the implementation costs (Wang et al. 2013). This concern will have to be addressed by increasing the volume of evidence, continued inclusion of fishers in the research and development process, and education campaigns throughout associated fisheries.

As noted by the fishers' concerns, BRT research will also have to consider factors beyond catch, such as the cost of implementation and effort required to maintain the devices. Currently, net illumination BRTs are likely too expensive for individual fishers, particularly those in small-scale operations (Wang et al. 2010, Ortiz et al. 2016, Virgili et al. 2018). Chemical lightsticks cost \$0.10-\$1.00 per lightstick, but last only 24 hours, while LEDs range from \$10-\$40 and can last for years, but require batteries that have an approximately one-month lifespan (Wang et al. 2010). In recent years, these costs have declined and have the potential to continue declining in the future. However, at the moment, such a cost could result in a total investment of thousands of dollars for a single vessel. A strategy must be developed to decrease the burden of these costs on individual fishers. Options may include collaborative efforts with governments, NGOs, and other organizations and/or allowing for a gradual transition to BRTs by combining implementation with the use of other measures, such as time-area closures (Melvin et al. 1999, Ortiz et al. 2016).

Any instituted BRT must also be relatively easy to operate and maintain, and some studies are currently taking measures to account for that. For example, as part of a study testing colored ropes as a BRT, Kraus et al. (2014) partnered with local lobstermen to test the rope in normal fishing operations to compare fouling and handling characteristics to their normal equipment. Considerations such as these are easily overlooked but crucial to ensuring the successful implementation and long-term efficacy of any required devices or technologies.

Many of these efficacy concerns are currently being addressed by developing LED technologies. Primarily, solar-powered LEDs, currently being developed and tested by Dr. Jesse Senko and his team at Arizona State University, have the potential to significantly decrease purchasing cost, eliminate the cost and maintenance of batteries, and increase the lifespan of illuminating nets (pers. comm. Jesse Senko, Arizona State University). These solar-powered LEDs are designed to sit on the upper portions of a net with potential to act as a buoy, if desired (pers. comm. Jesse Senko, Arizona State University). Other technologies, including wave-powered LEDs or LEDs that could be incorporated into a net, have potential for future development (pers. comm. Jesse Senko, Arizona State University). New technologies such as these could make the use of LEDs more appealing to both fishers and managers and increase the potential for their implementation.

Potential for Unintended Negative Consequences

When developing a BRT intended to reduce the capture and mortality of megafauna, it is also an obvious priority to ensure that the technology does not have unintended negative consequences for the bycatch species or other taxa. Martin and Crawford (2015) expressed concern that BRTs involving light sources could affect the ability of the retina of a variety of marine species to adapt to ambient light levels at night. This claim does not appear to have been studied. However, it is an important consideration that should be assessed to ensure that a mechanism intended to reduce one impact on bycatch species does not cause a different problem.

Moreover, the use of artificial lights in coastal fisheries has the potential to threaten the survivorship of other marine species that utilize visual cues by affecting behaviors and interactions, such as orientation, reproduction, and predation (Davies et al. 2014). Having evolved under conditions with only natural light, many species utilize visual cues such as irradiance, spectra, and periodicity to understand their surroundings (Davies et al. 2014). For example, zooplankton use light as a cue for navigating vertical migrations on a daily cycle for foraging and predator avoidance (Cohen and Forward 2009). Moreover, artificial lights could create a source of unnatural regulation of fish assemblages, since many fish species aggregate near light sources (Becker et al. 2013). Marine plankton are attracted to light, which in turn aggregates small prey fish and creates unnaturally optimized feeding conditions for large, piscivorous fish (Becker et al. 2013). Impacts such as these will need to be considered on a local scale to account for spatial differences in species and ecosystem dynamics.

Future Directions

Identify High-Priority Fisheries

Given that most BRT implementation and management occur at a fishery-specific level, research should test the efficacy of visual BRTs in areas with high bycatch rates and in which they could realistically be adopted. Due to regional and fishery differences, such as oceanographic conditions, bycatch and target catch species, gear configurations, and management frameworks, the best and most applicable conclusions can be drawn from research that occurs directly in the waters where the BRT would be utilized. As such, potential fisheries and locations for future studies should be selected with intention from existing knowledge of bycatch species and interaction rates.

In the United States, this information could be drawn from sources such as the National Marine Fisheries Service (NMFS) List of Fisheries (83 FR 5349), in which individual fisheries are classified based on their interactions with marine mammals, as required by the Marine Mammal Protection Act. Fisheries classified as Category I, those with the highest impact on marine mammal stocks, should be prioritized for assessment. Based on these criteria, the Mid-Atlantic gillnet and Northeast sink gillnet fishery should be prioritized for BRT studies and implementation. Sea Turtle Recovery Plans, drafted by NMFS and US Fish and Wildlife Service (USFWS), also rate and prioritize threats to specific sea turtle populations, creating the opportunity to identify and prioritize fisheries for visual cue BRT implementation. For example, for the northwest Atlantic population of loggerhead sea turtles, large mesh gillnets have been identified as a threat, and gear modifications, as well as other measures like integrating range data and developing an observer program, were suggested as population recovery methods (NMFS and USFWS 2008).

Not only should the bycatch rates and potential reductions be considered, but also the feasibility of implementing BRTs based on existing regulations, management structures, and the fishers involved. Considering high adoption costs will likely require some form of government assistance (Ortiz et al. 2016), political viability will be an important factor and should be considered when directing research efforts. Fishers and local fisheries management will have to be involved, informed, and receptive to the concept of implementing visual BRTs as well, to create an environment for effective implementation and enforcement. Collaboration among agencies, organizations, and relevant stakeholders could be fostered through group efforts to discuss and develop strategies. For example, in 2015, the American Bird Conservancy and BirdLife International organized a workshop at which leaders across North America came together and identified bycatch reduction methods for gillnets that could be effective across taxa and planned research accordingly (Wiedenfeld et al. 2015).

Develop Multi-Sensory BRTs

To increase the effectiveness of BRTs and/or to reduce the bycatch of more than one species, the combined use of multiple sensory BRTs should be considered with future technological developments. This could be particularly effective for species groups, including many marine mammals, that use a multi-sensory approach to perceive their environment (Kremers et al. 2016, Torres 2017). Using multiple sensory cues could increase the likelihood that individuals perceive and react to one of the cues and avoid capture. A multi-sensory approach could potentially extend the use of BRTs to species beyond air-breathing megafauna. Jordan et al. (2013) believe that visual BRTs might be effective and warrant testing on elasmobranchs, as well, but that a multi-sensory approach could be best for these species, which rely heavily on their electrosensory system.

Multi-sensory BRTs could also make a single BRT effective for a greater number of species. For example, Read et al. (2003) suggested increasing gillnet detectability for bottlenose dolphins using an acoustic device, such as an alarm or a modified net that is detectable through echolocation. While this is a promising solution for dolphins and other cetaceans, they are often not the only species incidentally caught in gillnets. Therefore, using an auditory approach in tandem with a visual BRT might allow for the reduction of other species that do not rely on echolocation or acoustics as well. Determining the combination of cues that would be necessary to make an effective multi-sensory, multi-species BRT would likely require location and fishery-specific testing. However, having a suite of available gear-technology solutions to utilize in combination with each other and/or other bycatch reduction approaches would make it possible for individual fisheries to assess the options and develop viable solutions (Gilman et al. 2010).

Extend Research to Other Gear Types

As is made clear by this review, thus far, visual cue BRT research has focused primarily on gillnet fisheries. Gillnet fisheries and associated bycatch are a global occurrence (Wallace et al. 2010), but they are by no means the only relevant passive gear in which visual cue BRTs could be effective. In other passive fisheries, in which gear is similarly situated and static in the water column, visual cue BRTs could be used to alert nearby individuals to their presence. These could include, but are not limited to, pound nets, fyke nets, pots, and traps. Future studies should extend inquiry of the effectiveness of colored netting and net illumination techniques to these gears to determine if these BRTs could be useful in other fisheries. Such knowledge could establish visual cue BRTs as a flexible, widely applicable option and inspire interest in their application.

Case Study: Evaluating Green LED Bycatch Reduction Technologies in the North Carolina Pound Net Fishery

Background

The Atlantic Ocean has been classified as a high threat area for sea turtles due to a variety of anthropogenic threats, including bycatch (Wallace et al. 2011). As one example, Atlantic loggerhead sea turtles interact with more fisheries than any other species, resulting in at least 1,400 deaths annually (Finkbeiner et al. 2011). The North Atlantic Loggerhead Recovery Plan cites fisheries as the most important threat to their populations (NMFS and USFWS 2008).

In North Carolina, mature sea turtles tend to follow a pattern of inshore-offshore movement, migrating to inshore estuaries in the spring and emigrating south toward warmer ocean waters in the fall (Epperly et al. 1995, Hawkes et al. 2011). Immature loggerhead, green, and Kemp's ridley (*Lepidochelys kempii*) turtles, however, can be found in estuarine waters year-round, with some of these individuals using the waters of North Carolina as winter habitat (Epperly et al. 1995, Mansfield et al. 2009).

Small-scale passive net fisheries pose a significant threat due to their prominence in the same estuarine and coastal waters that these turtles inhabit. Pound nets, specifically, are used in major finfish fisheries with strong heritage in North Carolina, valued at nearly $3.5 million in 2018 (NCDMF 2018). Pound nets consist of several key parts. They contain a lead, which is a vertical wall of netting placed perpendicular to the coastline to intercept fish swimming nearshore and direct them offshore and into the net (Epperly et al. 2007). Connected to the lead, the heart is a maze of vertical netting that funnels fish into the tunnel, which in turn, guides fish into the pound, the enclosed end of the net in which fish are trapped (Epperly et al. 2007). They are primarily used in the flounder fishery, targeting southern (*Paralichthys lethostigma*), summer (*Paralichthys dentatus*), and gulf (*Paralichthys albiguttata*) flounder. The North Carolina flounder fishery begins setting nets in September with a peak fishing effort in November, declining by December (Epperly et al. 2007). The November peak also overlaps with the emigration of migratory species, including sea turtles, increasing the likelihood of interactions (Epperly et al. 2007).

In this study, we examine the impact of green LEDs as a BRT in the North Carolina pound net fall flounder fishery, which interacts with loggerhead, green, and Kemp's ridley sea turtles. We tested this method and the impacts of LED presence on pound nets on sea turtle bycatch rate and the catch rate of commercially valuable species. We also opportunistically included an examination of elasmobranch bycatch rates, after encountering many elasmobranchs during trials. The preliminary results presented represent the first-year of a multi-year study, thus are generated from a small sample size and should be interpreted with caution. Rather than to present definitive conclusions, this case study is included as an example of current research that is extending visual BRT development and experimentation to other gear types and multiple bycatch species.

Methods

Study Area

The study was conducted near Harker's Island (Back Sound and Core Sound), North Carolina (NC), and was the first year of a multi-year study conducted in partnership with the NMFS Southeast Fisheries Science Center (SEFSC) in Beaufort, NC and local Harker's Island inshore pound net fishermen (see Figure 1). Three pound nets were leased from and set by a local fisherman for two and a half weeks in October 2018. The nets were oriented in a staggered row perpendicular to the coastline with approximately 25 meters between each net. Each pound net contained several six-inch escape panels to allow small, non-target species to swim out the net.

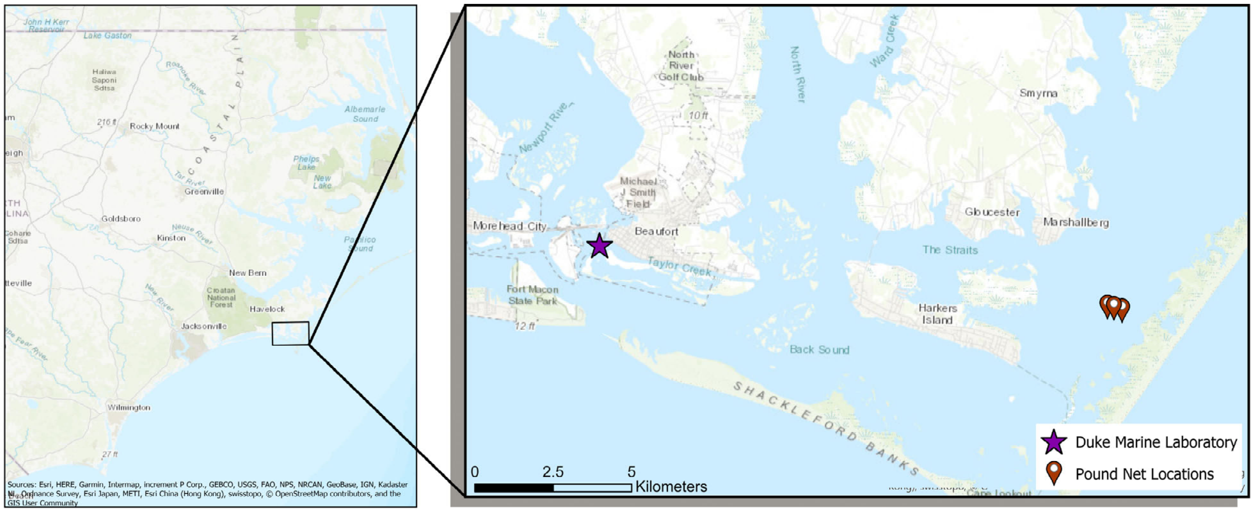

Figure 1. Study area and pound net location for LED trials from October 4–19, 2018. Three pound nets were placed off the coast of Harker's Island (Core Sound and Back Sound), and nets alternated between control (n=24) and experimental (n=18) trials by day. The location of the Duke University Marine Laboratory in Beaufort, NC is included for reference.

The study area is an estuary site and a sound, sheltered from the open ocean but indicative of high tidal flow. This study occurred shortly after Hurricane Florence made landfall in Wrightsville Beach, North Carolina, less than 100 miles from the study site, on September 14, 2018. As such, some environmental conditions, such as salinity, were still recovering and inconsistent with normal conditions.

Field Trials

For experimental trials, we placed active green LEDs (CENTRO Power Light CFL-D3) every 5 yards along the lead and outside of the heart and pound of each net. For control trials, we followed the same procedure with inactive LEDs, which contained dead batteries to ensure they were of the same weight and hung on the net similarly to active LEDs. Since the catch of each pound net was influenced by location and temporally variable environmental conditions, we alternated experimental and control trials each day, with all three nets receiving the same treatment on a given day. Each pound net was considered an individual trial, resulting in three trials per day.

Approximately every 24 hours, we checked and fished each net, and we recorded and processed all catch. We measured and recorded the length of all fish captured, and we collected and recorded morphometric data (curved carapace length, width, and weight) for each captured turtle. The turtles were flipper tagged with two Iconel tags, and a microchip (Passive Integrated Transponder/PIT) tag was inserted prior to release to ensure identification of re-encountered individuals. At the end of catch retrieval, we changed LEDs between experimental (active lights) and control (inactive lights), and a new set of trials began.

For each net, we collected environmental condition data (depth, temperature, salinity, wind speed and direction, and water visibility), the time at the start of each trial, and the time at the start of catch retrieval. Moon phase, predominant wind direction, and average wind speed on the previous day (wind data obtained from the NOAA National Data Buoy Center Cape Lookout Station CLKN7) were also recorded. This work was conducted under NMFS Institutional Animal Care and Use Committee (IACUC) permit 21233, Duke University IACUC permit A107-18-05, and NMFS ESA permit 16733.

Analysis

We calculated catch per unit effort (CPUE) of each net for each trial by calculating the number of individuals of each species group (turtles, elasmobranchs, flounder, other fish) caught per 24 hours of soak time. The average CPUE was then calculated for control and experimental trials. Despite a small sample size, we used generalized linear models (GLMs) to preliminarily assess the impact of LED treatment and environmental variables on each CPUE value using the statistical software R. Environmental covariates in the full model included LED type, net location, retrieval date, depth, water visibility, water temperature, retrieval wind speed, retrieval wind direction, salinity, Beaufort sea state, tide direction, tide state, days since Hurricane Florence, previous day average wind speed, previous day primary wind direction, and previous day moon phase.

Results

In total, we completed 18 experimental trials (6 days) and 24 control trials (8 days) from October 4 through October 19, 2018. All captured species too large to fit out of the six-inch escape panels on each net were included in analysis. We captured three species of sea turtles, three identifiable species of flounder, and five identifiable species of elasmobranchs (Table 3**Error! Reference source not found.**).

Table 3. Total number of individuals captured in experimental (EXP; n = 18) and control (CON; n = 24) LED trials, excluding those small enough in size to escape through the six-inch escape panels on each pound net.

	EXP	CON
SEA TURTLES		
green	1	2
Kemp's ridley	1	2
loggerhead	0	3
Total	**2**	**7**
FLOUNDER		
Gulf	2	6
southern	10	26
summer	2	38
unidentified	1	0
Total	**15**	**70**
ELASMOBRANCHS		
Atlantic ray	3	6
butterfly ray	0	14
cownose ray	1	3
southern ray	11	42
unidentified ray	0	1
sandbar shark	1	0
Total	**16**	**66**
OTHER		
horseshoe crab	12	23
other fish	1	30
Total	**13**	**53**

Two sea turtles were captured in experimental nets, with an average CPUE of 0.12, and seven were captured in control nets, with an average CPUE of 0.32 (Figure 2a). These results indicate a 62.50% decline in sea turtle bycatch rate per unit effort in nets equipped with active LEDs. A total of 16 elasmobranchs were captured in experimental nets, resulting in an average CPUE of 0.87, and 66 were caught in control nets, with an average CPUE of 2.91 (Figure 2b). This suggests a 70.10% reduction in elasmobranch bycatch rate. Throughout the trials, 15 flounder were caught in experimental nets with an average CPUE of 0.88, and 70 were captured in control nets, resulting in an average CPUE of 3.14

(Figure 2c). This indicates a 71.97% decline in flounder catch rate. The CPUE for other fish species in experimental nets was 0.77, and in control nets, it was 2.52, resulting in a 69.44% decline in catch of other fish (Figure 2d).

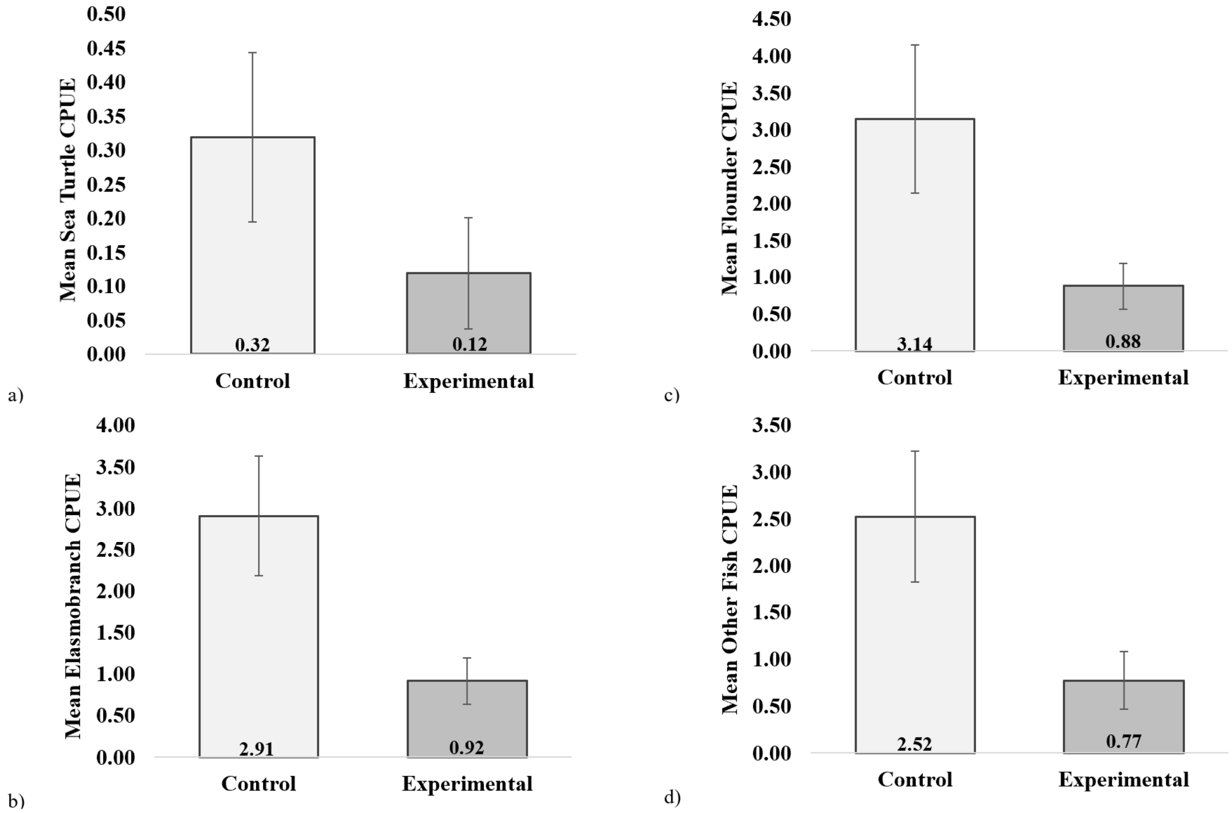

Figure 2. Average catch per unit effort (CPUE) during experimental (n=18) and control (n=24) trials of a) sea turtles, b) elasmobranchs, c) flounder, and d) other fish. The value specified on each bar indicates the CPUE, and the error bars measure standard error.

The catch rate of flounder and elasmobranchs varied widely by day. Flounder catch ranged from zero to 23 flounder per trial, and flounder CPUE ranged from zero to 21.88. Similarly, elasmobranch catch ranged from zero to 13 elasmobranchs per trial, and elasmobranch CPUE ranged from zero to 14.24 per trial. Generally, flounder and elasmobranch catch rate varied more by day than between nets, meaning that it was typically a high or low catch day across nets with a few days accounting for a disproportionate amount of total catch. Sixty percent of flounder catch occurred on two days, October 14 and October 19 (Figure 3. Total catch of a) flounder and b) elasmobranchs per day during experimental (n=18) and control (n=24) LED trials.Figure 3a), and 40.24% of elasmobranchs were captured on October 5 and October 19 (Figure 3b).

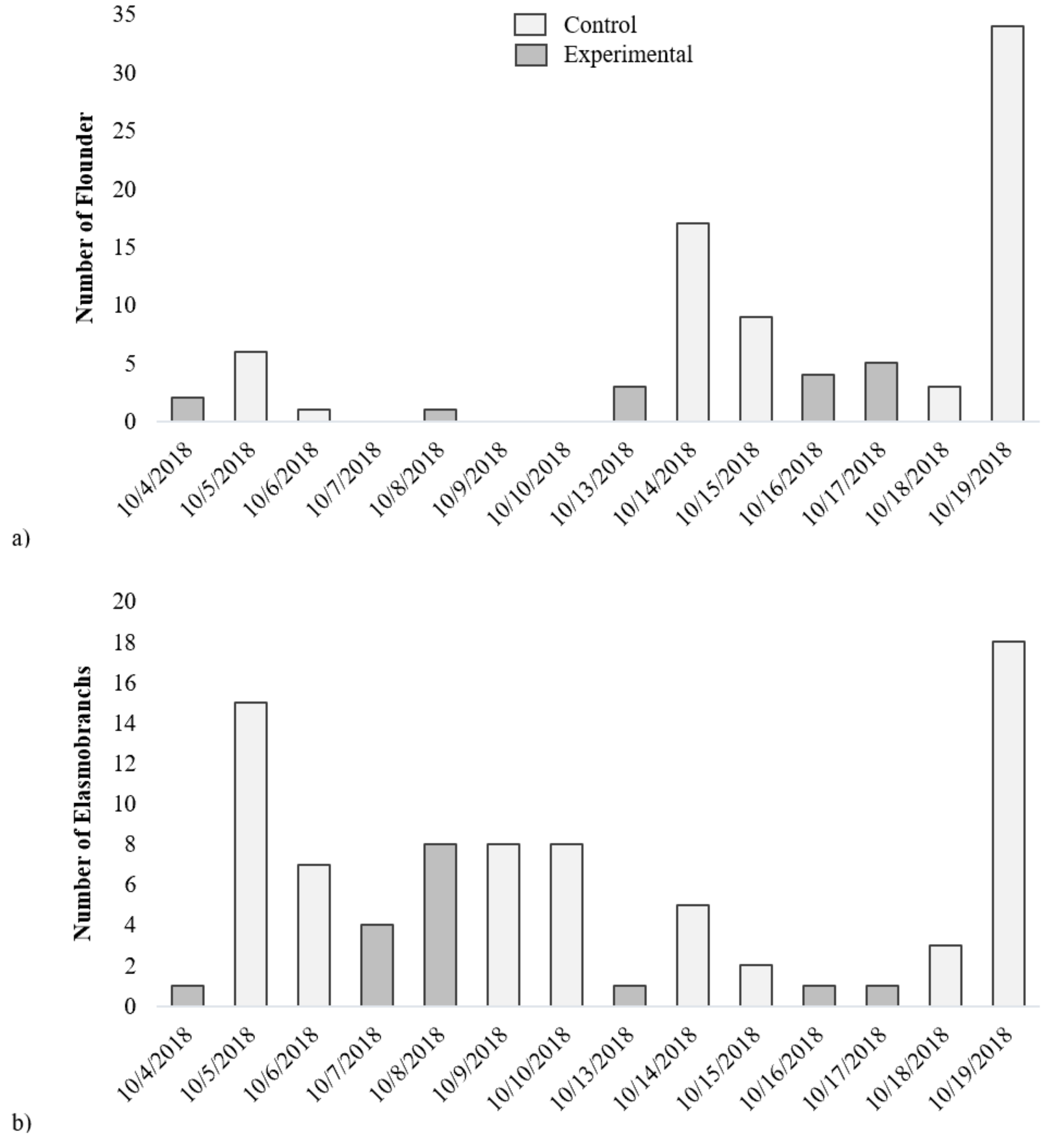

Figure 3. Total catch of a) flounder and b) elasmobranchs per day during experimental (n=18) and control (n=24) LED trials.

GLMs for CPUE of sea turtles, elasmobranchs, flounder, and other fish yielded limited results due to small sample size (Table 4). Models showed high deviance, and some continuous variables, such as previous day average wind speed and previous day moon phase, were excluded by default from models due to singularities. In GLMs for sea turtle CPUE, LED type (control/experimental) was significant in the full model and approaching significance in the simplest model that included only LED type as an explanatory variable. In GLMs for elasmobranch CPUE, LED type was significant in all models, except the full model, and retrieval wind speed approached significance in the LED type + retrieval wind direction model. In flounder CPUE GLMs, LED type was approaching significance or significant in all models except the full model. Both retrieval wind speed and previous day wind speed were also approaching significance in flounder models. In GLMs for the CPUE of other fish, LED type was significant in three of the reduced models, and retrieval wind speed was also approaching significance.

Table 4. Results for generalized linear models (GLMs) for catch per unit effort (CPUE) of bycatch (sea turtles, elasmobranchs), target (flounder), and other commercially valuable species (other fish) using combinations of 16 covariates (LED type, net location, retrieval date (rd), depth, water visibility, water temperature, retrieval wind speed (rws), retrieval wind direction (rwd), salinity, Beaufort sea state, tide direction, tide state, days since Hurricane Florence, previous day average wind speed, previous day primary wind direction, previous day moon phase). The full model included all covariates, and the reduced model included only variables that were significant in the full model. All p-values approaching significance (p < 0.25) are included, and significant p-values (p <0.5) are italicized.

Model	Sea Turtles	Elasmobranchs	Flounder	Other Fish
Full Model	$P_{LED} < 0.5$ $P_{rd} < 0.5$ $P_{rwd} < 0.5$ $P_{rws} = 0.06$ $P_{depth} = 0.10$	No significance	No significance	No significance
Reduced Model	No significance	N/A	N/A	N/A
LED Type	$P_{LED} = 0.22$	$P_{LED} < 0.05$	$P_{LED} = 0.06$	$P_{LED} < 0.05$
LED Type + Retrieval Wind Speed	No significance	$P_{LED} < 0.05$ $P_{rws} = 0.21$	$P_{LED} = 0.06$ $P_{rws} = 0.14$	$P_{LED} < 0.05$ $P_{rws} = 0.12$
LED Type + Retrieval Wind Direction	No significance	$P_{LED} < 0.05$	$P_{LED} = 0.1$	No significance
LED Type + Previous Day Wind Speed	No significance	$P_{LED} < 0.05$	$P_{LED} < 0.05$ $P_{pdws} = 0.09$	$P_{LED} < 0.05$
LED Type + Previous Day Wind Direction	No significance	$P_{LED} < 0.05$	$P_{LED} = 0.07$	No significance

Discussion

Preliminary results suggest that green LEDs reduce sea turtle bycatch rates by 62.50%, reinforcing the declines observed in previous studies (Wang et al. 2010, Ortiz et al. 2016). These results support the notion that visual cues can act as an alert and change sea turtle behavior around fishing gear and could be used to prevent interactions with fishing gear (Wang et al. 2007, Southwood et al. 2008). However, the mechanism behind this is still unclear, and it is possible that the illumination either deters the turtles or alerts them to the presence of the net.

Unlike previous studies, this experiment has expanded the range of net illumination BRTs to pound nets and opened the door to testing their efficacy to other passive gear fisheries. Small-scale passive net fisheries are increasingly acknowledged as one of the primary threats to sea turtle populations, and likely an equal or greater threat than larger, industrial-scale fisheries (Peckham et al. 2007, Temple et al. 2018). Their spatial overlap with important habitats makes it imperative to prioritize bycatch reduction research and development in these fisheries. In North Carolina, specifically, small-scale commercial and recreational fisheries comprise a significant proportion of total fisheries operations (NCDMF 2018), suggesting that if proven effective, net illumination BRTs have the potential to be implemented on a broad scale. However, until now, net illumination BRT studies have occurred exclusively in gillnet fisheries. Although they are the most common passive gear used, they are by no means the only relevant one, particularly on local scales. As such, it is imperative that studies continue to expand research on net illumination BRTs to other passive net fisheries, making their use as widely applicable as possible.

Upon catching a large number of elasmobranchs in our trials, we decided to opportunistically compare elasmobranch bycatch rates, as well. Although in practicality, bycatch reduction measures may specifically target rays, sharks, or individual species, since only one shark was captured during the study, elasmobranchs were assessed as a group. Prior to consideration of environmental variables, we found that green LEDs reduced elasmobranch bycatch by 70.10%, indicating that green LEDs could be useful for multiple species groups in North Carolina pound nets. Wang et al. (2014) previously found that orange LEDs reduced elasmobranch and finfish bycatch; thus, this finding both supports the effectiveness of LEDs for elasmobranch bycatch reduction and indicates that multiple different wavelengths could be used. Green LEDs have also been found to reduce seabird bycatch in two studies in Peru, meaning that we now have evidence of four bycatch taxa that could potentially benefit from net illumination BRTs (Ortiz et al. 2016, Mangel et al. 2018, Wang et al. 2018). Unlike most other devices and technologies that focus on a particular species or species group (Werner et al. 2006), visual cue BRTs could target multiple relevant bycatch species, streamlining the bycatch reduction process and reducing cost and maintenance (Mangel et al. 2018).

However, a BRT is only a viable option if it maintains target catch and catch value. Thus far, preliminary results indicate that the LEDs reduced target catch rates in the North Carolina pound net fishery when comparing total catch without taking into account net location and environmental variables. This could present a drawback to the implementation of net illumination BRTs in pound nets targeting flounder, as fishers will resist the implementation of any device that hinders their catch and puts the viability of their fishery at risk (Wang et al. 2013, Ortiz et al. 2016). CPUE of other fish, some of which may be targeted by fishers, also drastically declined. However, this is a broad category, and without a more species-specific approach, the impact on particular species of interest cannot be determined.

Despite the initial concerns this may raise, these results should be interpreted with caution and only viewed as a very preliminary review as data are still being collected. The existing sample size is small, making it difficult to perform meaningful statistics and fit the variables to a model that accurately reflects trends that may exist. Environmental conditions vary by day and can affect catch rates and composition, making it necessary to accurately account for their influence before drawing conclusions. Considering that flounder and elasmobranch CPUE varied drastically by day, it seems likely that one or many external environmental variables, rather than the LEDs alone, are influencing catch rates. It is also possible that different variables may affect the catch rates of each or some species groups differently. As a result, comparing bycatch and target catch rates without considering the influence of environmental variables does not provide a complete picture and might misconstrue the story the data are telling.

In our preliminary models, we specifically analyzed the influence of retrieval and previous day wind speed and direction on CPUE values, since wind varied considerably by day, while other variables, such as water temperature and salinity, were more stable across our study period. It is also thought by fishers that high wind speeds lead to high catch rates. Since retrieval wind speed's effect on our elasmobranch, flounder, and other fish CPUE values was approaching significance while previous day wind speed was approaching significance for flounder CPUE, it is possible that variation in wind has a notable effect for which we need to account. Existing trends and the impact of wind direction warrant further assessment. As more data are collected during the coming flounder seasons, we will likely have a large enough sample size to better fit models to our data and draw more accurate conclusions. It may also be of value to consider previous day peak wind speed, rather than average wind speed, as short durations of high winds may influence catch and not be accurately reflected in daily average values.

A methodological lesson was also learned from observing environmental variation throughout the study. Previous LED studies on gillnets used a paired design to test the impact of LEDs on bycatch and target catch rates (Wang et al. 2013, Ortiz et al. 2016). However, such a study design is not applicable to pound nets, as a "pair" would either involve two pound nets in different locations fishing at the same time or one pound net fishing at two different times. Since environmental conditions, which can affect catch rates, vary both spatially and temporally, we cannot consider either of these methods a reliable paired trial in which all other conditions are equal. Rather, a statistical framework that allows for the evaluation of multiple predictor variables in relation to a response variable, such as GLMs or generalized additive models, are a more appropriate approach for analyzing catch data from pound net BRT studies.

Conclusion

In summary, this review has synthesized the existing literature related to the effectiveness of visual cue BRTs for the reduction of air-breathing megafauna bycatch in passive gear fisheries. Thus far, both colored nets and net illumination have been shown to successfully reduce the bycatch of some air-breathing megafauna species. This supports the idea that air-breathing megafauna can be alerted to the presence of fishing gear using visual cues, and these visual cues can be used to change their behavior around passive fishing gear. Visual cue BRTs may have several benefits, including their potential effectiveness for multiple species and lack of impact on target catch rates. However, as this research is still in its early stages, many considerations must still be addressed in ongoing and future research and development prior to implementation, such as the cost and maintenance for fishers and the potential existence of unintended consequences, including altering cues for other species. Future research should direct efforts toward high-priority fisheries for implementation and work to expand visual cue BRT research to multi-sensory BRTs and other passive gear types. The case study presented demonstrates ongoing efforts to fill these knowledge gaps, illustrating the preliminary results of the first year of a multi-year study of the effects of green LEDs on sea turtle bycatch rates in the North Carolina pound net fishery. Continued efforts like these are critical to the survival of many species, as fisheries bycatch is consistently identified as a leading cause of population decline for many species of sea turtles, sea birds, and marine mammals.

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