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LED light specifications to reduce marine pollution, mitigate bycatch and increase target catch in pelagic longline fisheries

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Abstract
Pelagic longline fisheries use millions of single-use chemical lightsticks each year. These contribute to plastic and toxic pollution and increase at-risk bycatch. We explored reusable light-emitting diode and phosphorescent lights as potential replacements. We evaluated candidate lights' potential effects on economic viability, practicality, crew safety and at-risk bycatch rates. We measured light properties that are potentially informative predictors of catch rates of target and at-risk bycatch species, including peak wavelengths (λ_{max}), wavelength range, flicker rate, flicker duration, light level (total radiant power and at λ_{max}), diminution and directionality. We compiled and synthesized the sensitivities of species captured in longline fisheries to light spectral, temporal and intensity characteristics, which informed defining criteria predicted to increase commercial species' and reduce at-risk bycatch species' catch rates. For example, to include peak spectral sensitivities of pelagic longline target species while avoiding longer wavelength peak spectral sensitivities of marine turtles, pelagic sharks and possibly other marine megafauna visual predators, we shortlisted lights with λ_{max} between 400-480 nm (violet to blue to humans) and with low or no radiant power at longer wavelengths. We assessed apparent (submerged) weight and activation mechanism, which are attributes that might affect seabird bycatch. Following demonstrations of short-listed lights in three longline fisheries, overall, captains preferred smaller and dimmer LED models, preferred water- or pressure-activation over manual activation, and were ambivalent on preferences for flickering versus constant lights. The study identified characteristics of lights that hold high promise for meeting objectives for commercial viability, bycatch mitigation, and reducing marine pollution.

Keywords: bycatch reduction; gear selectivity; LED lights; marine debris; phototaxis

1. INTRODUCTION

For centuries fishers have used artificial light to increase their fishing efficiency (Sokimi and Beverly 2010; Nguyen and Winger 2018). In the late 1970s, some pelagic longline fisheries, primarily shallow-set fisheries targeting swordfish (*Xiphias gladius*), began using single-use chemiluminescent lightsticks (Ito et al. 1998; Ward et al. 2000; Beverly et al. 2003; Watson et al. 2006; Poisson et al. 2010). Now over 11 million single-use chemical lightsticks are roughly

estimated to be used by global shallow-set pelagic longline fisheries annually (Poisson et al. 2010; Gilman et al. 2017).

Longline lights might increase catch rates due to the direct attraction of the captured species to the lights (i.e., positive phototaxis, an innate behavior response of positive displacement along a light gradient, Jekely 2009) or to the attraction and aggregation of their prey at the lights (Hazin et al. 2005; Martins and Perez 2006; Ward 2008). Fishing lights might simulate disturbed bioluminescent organisms, including bioluminescent prey and bioluminescent organisms that attract baitfish and their prey (Witzell 1999; Widder 2002; Letendre et al. 2024). Light emitting devices with certain characteristics might increase longline catch rates of some at-risk bycatch species, including marine turtles (Wang et al. 2007; Swimmer et al. 2017; Afonso et al. 2021), sharks (Bigelow et al. 1999; Poisson et al. 2016; Afonso et al. 2021), seabirds (McNamara et al. 1999; Sigurdsson 2023), and odontocetes (Monaghan et al. 2024). Shallow-set pelagic longline fisheries can have profound impacts on incidentally captured bycatch species (Gilman 2011; Wallace et al. 2013; Dias et al. 2019), particularly those with low reproductive potential due to long generation lengths, low fecundity and other life history traits that make them especially vulnerable to anthropogenic mortality (Musick 1999; Chaloupka 2002; Forrest and Walters 2009; Pardo et al. 2016; Dulvy et al. 2021).

Chemical lightsticks used by longline fisheries contribute to plastic and toxic marine pollution (Pinho et al. 2009; de Oliveira et al. 2014; Cesar-Ribeiro et al. 2017, 2021). Plastic marine debris, including from lighsticks and other abandoned, lost and discarded fishing gear, is now globally pervasive and a potential planetary boundary threat, causing myriad adverse ecological and socioeconomic effects (Villarrubia-Gomez et al. 2018; Beaumont et al. 2019; Gilman et al. 2023). As one example, discarded lightsticks floating on the sea surface with attached eggs and biofouling organisms are ingested by at-risk wildlife, including adult albatrosses who feed regurgitated biofouled lightsticks to their chicks (Bromhead et al. 2003; Gilman et al. 2023; Shruti et al. 2023).

Lights with light-emitting diodes (LEDs) could potentially replace chemical lightsticks and reduce the bycatch of some at-risk species without compromising catch rates of commercial species (Hazin et al. 2005; Gianuca et al. 2016). LEDs with rechargeable batteries could reduce marine pollution from spent batteries discarded at sea. Reusable, non-toxic phosphorescent lights might also hold promise to replace longline chemical lightsticks. Lights with certain photic characteristics – including peak wavelengths ($\lambda_{max,}$ the wavelength where the emission spectrum of a light source reaches a maximum), wavelength range, flicker frequency, flicker duration, directionality, and light level – could potentially increase pelagic longline catch rates of principal market species including billfishes (Xiphioidei) and tuna and tuna-like species (Scombroidei) without increasing the bycatch risk of marine megafauna of marine turtles, pelagic sharks and possibly other at-risk visual predators (Supplemental Material Section S1).

Some seabird species are attracted to fishing lights, potentially increasing their local abundance, scavenging behavior and catch risk (McNamara et al. 1999; Sigurdsson 2023). Scavenging seabirds might associate longline lights with the availability of baited hooks or the lights might illuminate and increase bait detection. Water- and pressure-activated lights might reduce seabird catch risk relative to lightsticks and manual LED lights by reducing seabirds' detection of the lights and baited hooks during gear setting prior to the activation of the lights. Furthermore, compared to chemical lightsticks, which are buoyant, the use of LED light models that are negatively buoyant, when attached sufficiently close to baited hooks and with a sufficient apparent (submerged) weight, could increase the baited hook sink rate, reducing seabird catch risk (Gianuca et al. 2016; Ochi et al 2017; Gilman et al. 2024).

The underlying mechanism for illuminated pelagic longlines to mitigate megafauna bycatch is potentially the opposite of that for gillnets. Adding lights to gillnets reduces megafauna bycatch possibly because the lights *increase* their detection of panels of netting, enabling them to avoid capture (e.g., Bielli et al. 2020; Senko et al. 2022; Burgher et al. 2026).

Conversely, pelagic longline lights with certain characteristics might *reduce* at-risk bycatch species' detection or attraction to the gear relative to conventionally used chemical lightsticks.

This study explored reusable, battery-powered, LED fishing lights and reusable and non-toxic phosphorescent lights as potential replacements for chemical lightsticks conventionally used in some shallow-set pelagic longline fisheries. With an overarching aim of identifying fishing light characteristics that are predicted to be commercially viable, mitigate at-risk bycatch, and reduce marine pollution, the study objectives were to:

- Identify, through a targeted literature review and synthesis, the sensitivities of commercial and at-risk bycatch species of pelagic longline fisheries to light spectral, temporal and intensity characteristics;
- Measure candidate longline fishing lights' spectral, temporal, spatial and intensity characteristics that are potentially informative predictors of catch rates of target and at-risk bycatch species, to identify light models that possess characteristics that are predicted to increase commercial species' and reduce at-risk bycatch species' catch rates;
- Measure the apparent weight and identify the activation mechanism of candidate light models, to identify the most promising models for mitigating seabird bycatch risk;
- Identify fishers' preferred fishing light designs to meet their objectives for practicality, crew safety and economic viability.

To achieve these objectives, candidate lights were evaluated against a suite of criteria to identify those that hold the highest promise for replacing lightsticks by considering predicted effects on economic viability, practicality, crew safety, and catch rates of at-risk bycatch species. We compiled and synthesized the accumulated evidence of the sensitivities of commercial and at-risk bycatch species of pelagic longline fisheries to light spectral, temporal and intensity characteristics through a targeted literature review, which informed our definitions of screening criteria on light properties of fishing lights to identify models that are predicted to maintain acceptable catch rates of commercial species and minimize the bycatch of species of conservation concern. Exploratory demonstrations of promising LED light models were conducted in three longline fisheries to determine fisher perspectives on their commercial viability. Results inform the design of field experiments to compare target and bycatch catch rates of alternative light emitting devices and identify priorities for research and development to optimize characteristics of pelagic longline fishing lights. Findings promise to contribute to reducing marine plastic and toxic debris and improving the conservation status of populations of at-risk bycatch species of pelagic longline fisheries.

2. Methods

2.1. Literature Review and Synthesis of Light Spectral, Temporal and Intensity Sensitivities

We conducted a targeted literature review to compile and synthesize evidence of light spectral, temporal and intensity sensitivities of commercial and at-risk bycatch species of pelagic longline fisheries. This included attributes of peak spectral sensitivity (i.e., the wavelength with maximal detection or sensitivity, due to peak photon absorption by visual pigment molecules inside of photoreceptor cells, Ebrey and Koutalos 2001; Carleton et al. 2020), peak and critical flicker fusion frequency (FFF, temporal speed of vision), and light intensity. Peak FFF refers to the FFF with the highest sensitivity, and critical FFF is a limit threshold above which flickering lights are detected as steady and dim.

2.2. Candidate Lights Assessment and Screening

We identified candidate fishing lights that are potentially suitable for use in pelagic longline fisheries by reviewing websites of commercial fishing gear suppliers and manufacturers, contacting longline fishery associations and fishing companies, and by conducting a targeted literature review. LED models were shortlisted for potential inclusion in fisheries demonstrations if they met the criteria listed below, which apply to both flashing and constant models. Input from the fishers that participated in exploratory fishing demonstrations (described below) and the results of the light characteristics sensitivities review informed the definitions of the screening criteria.

- Have a reported depth rating of ≥150m, making them suitable for most shallow-set pelagic longline fisheries (Gilman et al. 2007);
- Are not too bulky or heavy: Length does not exceed about 30 cm (*ca* double the length of some conventional lightsticks) and the weight (including batteries) in the air < 150g;
- The peak radiant power (Φe) by wavelength within the 440-480nm wavelength range (blue to humans) is the same order of magnitude as Φe at λ_{max}. This wavelength range includes the peak spectral sensitivities of principal commercial species while avoiding the range of longer wavelength peak spectral sensitivities of at-risk bycatch species, including marine turtles and possibly pelagic sharks and seabirds (Section 3.1, Supplemental Material Section S1, Table S1);
- Have a wavelength range that excludes or otherwise has low radiant power per wavelength within the wavelength range of *ca* 555-580 nm (yellow and green to humans), where the peak Φe per wavelength within the 555-580nm range is an order of magnitude lower than Φe at λ_{max}. This range of longer wavelengths includes the peak spectral sensitivities of age classes of some hardshelled marine turtle species that are susceptible to longline capture (Results section and Section S1);
- Are commercially available for bulk orders;
- The cost for bulk purchases of ≥200 units (excluding shipping and government import fees) is (1) < USD$20 per unit for models with replaceable batteries, and (2) <USD$10 for LED models with non-replaceable batteries;
- Total Φe at t_0 is ≥50% of the mean of measured lightstick models at t_0;
- Φe at λ_{max} at t_0 is ≥50% of the mean of measured lightstick models at t_0;
- Total Φe at $t_{5\ days}$ for both LED models with replaceable and non-replaceable batteries and at $t_{15\ days}$ for models with non-replaceable batteries is at least within an order of magnitude of the mean lightstick Φe at t_0 (the latter was calculated as the mean of measurements of Φe of two units each of four lightstick models at t_0); and
- Have no systematic negative customer reviews on quality.

We also explored two designs of phosphorescent rectangular prisms visible to humans as cyan, with model names “Tab” and “Glostick” (UV Paqlite 2025a,b), and a phosphorescent lightstick “Scooblite”, which is commercially available only in what is visible to humans as green (UV Paqlite, 2025c). While we predicted that the Scooblite would not meet the criterion on having a sufficiently low Φe per wavelength in the 555-580 nm range, we included it in the light measurements to determine whether the unique design of this phosphorescent light met other criteria. These phosphorescent lights are non-toxic and have persistent organic luminescence through absorbing and releasing light energy (Van der Heggen et al. 2022). We measured the light characteristics of the phosphorescent lights to determine how their initial and diminution of radiant power compare to conventional chemical lightsticks. As with reusable LED lights, to be considered for inclusion in demonstrations, the phosphorescent light models also had to meet the first six criteria listed above for LED lights. We also applied the same thresholds as LED

lights for: total Φe at t_0 and Φe per wavelength at λ_{max} at t_0. Furthermore, for diminution, the phosphorescent lights had to have a total Φe at 6, 12, 18 and 24 hours that is ≥50% of the mean total Φe of measured lightstick models at these same durations from activation (noting however that the duration of the pelagic longline gear soak varies substantially by fishery, from <5 hours to >20 hours; e.g., Ward et al. 2004; Gilman et al. 2008).

In addition to measuring the above characteristics to inform short-listing, we also assessed lights for the following additional characteristics to support captains' evaluations:

- What is the relative degree of directionality and which directions have relatively high light intensity?
- What is the light's true weight (in air) and apparent weight (submerged in water) and how will this affect where and how fishers would attach it to the gear? Apparent weight was measured using a hanging scale accurate to 1g with lights submerged in seawater;
- Are they water- or pressure (depth)-activated or manually activated?
- Are they flashing or continuous? If flashing, what is the flash rate and flash duration?
- What is the light level (total and at λ_{max})?
- What are the dimensions of the light and how will this affect where and how fishers attach it to the gear?
- How might the shape, size, apparent weight, and where on the gear fishers would attach the model affect the action (movement in the water) of baited hooks?
- For models with replaceable batteries, is it practical to replace the batteries and to maintain the LED (e.g., grease and periodically replace an O-ring)?
- Is the light easy to attach and remove from the gear?

2.3. Measurement of Light Properties

We measured the following intensity, spectral, spatial, and temporal light properties of five candidate LED and three phosphorescent lights, and of four chemical lightsticks commonly used in the longline fisheries that participated in demonstrations (discussed in the following section):

- Radiant power (Φe, mW, also referred to as radiant flux), the total, integrated radiant power emitted over the entire measured spectral range, at t_0;
- Φe by wavelength (mW nm^{-1}), which enables identifying λ_{max} and wavelength range;
- Diminution of total Φe at 5 and 15 days for LEDs, and every 3 hours over 1 day for the conventional lightstick and phosphorescent lights;
- Directionality, measured as irradiance (*Ee*, radiant power per unit area, mW m^{-2}) (i.e., total irradiance over the entire measured spectral range) at t_0 at an orientation of 0°, 45° and 90° relative to the light sensor (Karlsen et al. 2021; Cerbule et al. 2025);
- Flicker frequency (Hz), for flashing LED models; and
- Flash duration, for flashing LED models.

We used radiometric units, which are appropriate for studies on animals with a spectral sensitivity that differs from humans. We did not use photometric units which are weighted according to human's spectral sensitivity and are restricted to the subset of the electromagnetic spectrum that is visible to humans (Yochum et al. 2024).

Measurements were obtained for two units each of the short-listed LED models and of the chemical lightsticks for Φe at t_0 and Φe per wavelength at t_0. Mean values and 95% CIs are reported for these estimates. Other assessed light properties for the LED lights and lightsticks were obtained from a single unit. A single unit of the phosphorescent lights were used for all light characteristic measurements. Only new lights were measured because used lights might, for example, have scratched housings that could reduce their transparency, and used lights that use non-replaceable batteries would have reduced light levels. We used new alkaline batteries

of the same brand in all LED models that use replaceable batteries (including models that can also be used with lithium batteries). Phosphorescent lights were exposed to direct sunlight for four hours prior to light measurements. Water- and pressure-activated LED models were activated using copper wire.

We used Wondershare Filmora X video editor software to measure the LED flicker rate and LED flash duration to the nearest 0.03s (30 frames per second) (Wondershare 2021).

We used an Everfine High Accuracy Array Spectroradiometer sensor model HAAS-2000 to measure light properties (wavelength accuracy < 0.2 nm, wavelength repeatability < 0.1 nm, and stray light ≤0.5%; Everfine 2024a). We used the spectroradiometer sensor in an Everfine Integrating Sphere model R98_V3 (2m diameter, luminous power uncertainty=2.3%, correlated color temperature (CCT) uncertainty =18 K, Everfine 2024b), which eliminates the influence of the angle and position of the light source within the sphere. The integrating sphere provided a spatially mixed measurement of wavelength-resolved radiant power (Φe), where multiple reflections from the diffusely reflecting sphere walls produce a spatially mixed and approximately uniform radiation field at the sensor port. See Maucoski et al. (2022) for an example of the use of an integrating sphere to produce a “Gold Standard reference value” for Φe output in dentistry research. We used a spectroradiometer sensor in the integrating sphere to measure the spatially-average, integrated, total Φe and Φe by wavelength, and the diminution of total integrated Φe over a wavelength range of 380-780 nm. Total integrated Φe was calculated as the sum of wavelength-resolved Φe over the measured wavelength range (Johnsen 2012; Yochum et al. 2024).

We measured directionality at t_0 using the Everfine Spectroradiometer sensor (not within an integrating sphere), adapting the methods of Karlsen et al. (2021) and Cerbule et al. (2025). We measured *Ee* (mW m^{-2}) and *Ee* per wavelength (mW m^{-2} nm^{-1}) at t_0 (with new batteries) over 380-780nm with lights oriented at 0°, 45° and 90° relative to the sensor’s probe, where 0° is with the light parallel to and thus pointing at the probe, and 90° is perpendicular to the probe. We attached lights to a tripod to adjust the light angle. Directional testing was not conducted for chemical lightsticks nor phosphorescent lights because their *Ee* levels were below the sensor detection limit. LED lights were positioned 40 cm from the spectroradiometer sensor’s probe. Based on the dimensions of the LED light models that we tested, the required minimum measurement distance was 40 cm. A light source needs to be far enough from the detector to be measured as a point source rather than a surface or 3D object. If the sensor is too close, the measurements will be inaccurate due to the physical size and geometric angles of the emitting surface – this is especially the case for lights with a narrow beam. A general, conservative rule is that the measurement distance should not be less than 15 times the maximum dimension of the light-emitting aperture.

The sensor continuously collected data at a sampling frequency of 250 Hz, which is faster than the highest flickering rate and shortest flash duration of the LED models that we tested, enabling the sensor to capture the properties of the flashes. For flashing models, in order to capture a value close to the peak irradiance during a flash, we used the maximum observed irradiance value among 10 successive readings displayed by the sensor. Measurements were obtained directly from the sensor and not from data logged to a computer in order to avoid the computer’s slow display refresh rate and data transfer speeds.

2.4. Exploratory Fishing Demonstrations

Exploratory fishing demonstrations of short-listed light models were conducted in three shallow-set pelagic longline fisheries: the US central north Pacific Ocean Hawaii-based swordfish longline fishery, the Australian east coast Southern bluefin tuna (*Thunnus maccoyii*) longline fishery, and the La Réunion, France swordfish longline fishery. These fisheries conventionally use chemical lightsticks and have bycatch of species of conservation concern (BioInspecta 2025; Control Union 2025, 2026). These three fisheries predominantly use green lightsticks but

occasionally use other colors. Globally, pelagic longline swordfish fisheries have been reported to most frequently use green or blue-green chemical lightsticks (Hazin et al. 2005; Afonso et al. 2021). A total of six captains fished with the candidate LED lights during a total of 96 sets.

Upon completing the demonstration fishing, we conducted a survey of the captains to obtain their perspectives on the commercial viability (practicality, crew safety and economic viability) of fishing with the five candidate LED lights relative to their conventional chemical lightsticks. We adapted a fisher survey form used in previous gear technology longline demonstrations (Gilman et al. 2022). Most survey questions used a 5-level Likert-type response scale with 'no apparent difference' as the neutral anchor. The survey also collected information on reasons for captains' decisions on whether they plan to continue using any of the trialed LED models and identified additional information that the captains would want to support a more informed decision.

3. RESULTS

3.1. Light Spectral, Temporal and Intensity Sensitivities

Supplemental Material Section S1 presents results of the literature review on longline commercial and bycatch species' sensitivities to light's spectral, temporal and intensity properties. Wavelengths between *ca* 400-480 nm (perceived as violet to blue by humans) includes most peak spectral sensitivities of swordfish and other commercial species such as bigeye tuna (*Thunnus obesus*) and yellowfin tuna (*T. albacares*) (Section S1, Table S1) and also contains the bioluminescence λ_{max} in blue water pelagic systems of *ca* 475 nm (Widder 2002, 2010; Letendre et al. 2024). This wavelength range might avoid the range of longer wavelengths of peak spectral sensitivities of species of pelagic sharks and pelagic seabirds, and of adult, sub-adult and large juvenile marine turtles (Section S1). These are the age classes of marine turtles that are susceptible to pelagic longline capture, which also have the largest effect on population viability (Heppell 1998; Chaloupka 2002, 2003; Lewison and Crowder 2007; Baez et al. 2013). For instance, the peak spectral sensitivity for green (*Chelonia mydas*) and loggerhead (*Caretta caretta*) turtles is *ca* 555-580 nm (yellow to humans) and is 500 nm (cyan or greenish-blue to humans) for leatherback turtles (*Dermochelys coriacea*) (Section S1). However, the entire spectra detected by leatherback turtles overlaps that of swordfish and istiophorid billfishes, particularly at night (Section S1), and so adjusting fishing light wavelength peaks and range to provide a potential bycatch mitigation solution will be more challenging for leatherbacks than for hardshelled marine turtles such as loggerheads.

There is limited information on the spectral sensitivities of species of pelagic seabirds and elasmobranchs that are captured in pelagic longline fisheries (Section S1). The wedge-tailed shearwater (*Puffinus pacificus*), a procellariform seabird species exposed to pelagic longline bycatch for which estimated retinal spectral sensitivity was found, has peak and secondary peak sensitivities over a broad range of 406-566 nm (violet to green to humans) (Table S1), overlapping with commercial teleost species. However, the peak spectral sensitivities of four pelagic shark species (blue *Prionace glauca*, common thresher *Alopias vulpinus*, great white *Carcharodon carcharias*, shortfin mako *Isurus oxyrinchus*) range from 492 to 518 nm (cyan to green to humans) (Section S1). Thus, as with hardshelled marine turtles, fishing lights with a wavelength range limited to *ca* 400-480 nm might enable peak detection by longline commercial teleost species while avoiding the peak spectral sensitivities of some pelagic sharks. However, the peak spectral sensitivity values estimated for mesopelagic sharks are closer to the values of longline commercial teleosts. No estimates of peak spectral sensitivity were identified for the main epipelagic sharks (silky *Carcharhinus falciformis* and oceanic whitetip *C. longimanus*) nor main ray species (pelagic stingray, *Pteroplatyrgon violacea*) captured in global pelagic longline fisheries (Gilman 2011). Section S1 reviews cone (brighter,

daytime) condition peak spectral sensitivity values under mesopic and photopic conditions, and rod scotopic, low light, nighttime condition and cone brighter condition peak spectral sensitivity values of coastal and demersal sharks, which might serve as a proxy for epipelagic elasmobranchs.

Different flicker rates and flicker durations of flashing lights might also have different degrees of attraction and detection capabilities by principal commercial species of longline fisheries, marine turtles, and possibly some pelagic elasmobranchs (Section S1). At low light levels, marine turtles have substantially lower flicker sensitivity than billfishes (Table S1). Turtles may detect rapidly flickering lights as constant and dimmer, reducing the lights' visibility to turtles relative to a non-flickering, constant light of the same light level (Fritsches and Warrant 2006; Johnsen 2006; Crognale et al. 2008). However, peak and critical FFF increase with increasing water temperature and light intensity, and under bright conditions during the daytime and near the surface, marine turtles as well as epipelagic fishes have a higher flicker rate sensitivity than swordfish and other mesopelagic species (Fritsches et al. 2005; Fritsches and Warrant 2006). But with low light levels, green and loggerhead turtles are most responsive to lights with relatively low flicker rates of between 16 and 24 Hz and leatherback turtles to flicker rates of between 4 and 12 Hz (Table S1). Leatherbacks have a particularly low flicker sensitivity, where fishing lights with a flicker rate >16 Hz would be detected as flickering by swordfish, which hunt fast-moving prey, but not leatherbacks, presenting a potentially effective mitigation approach for this turtle species (Fritsches et al. 2005; Crognale et al. 2008). Lohmann et al. (2006) found that a captive juvenile loggerhead turtle was attracted to a 45 Hz LED light while in a small tank and in the dark, indicating that loggerhead turtles can still detect lights that are flickering faster than their critical FFF limit, at least when in close proximity. This suggests that lights flickering faster than a critical flickering detection level might reduce but not eliminate marine turtle detection and attraction.

We found no estimates of peak or critical FFF values for any species of pelagic sharks. Critical FFF values for coastal and demersal sharks range from 10 to 44 Hz, and peak flicker sensitivity might fall in the range of *ca* 1-5 Hz (Gruber 1969; McComb et al. 2010; Kalinoski et al. 2014; Hart and Collin 2015; Ryan 2016). Temporal resolution might be lower in mesopelagic shark species with predominantly nocturnal foraging than shallow-habitat sharks (McComb et al. 2010). Based on peak and critical FFF values for coastal and demersal shark species, as with marine turtles, lights with sufficiently high flicker rates might reduce elasmobranch detection, especially for mesopelagic sharks, relative to constant or slower flickering lights. However, chemiluminescent and phosphorescent lightsticks do not flicker, and unfortunately commercially available flashing LED fishing lights flicker at rates that are substantially below the critical and limit threshold FFF above which it appears constant and dimmer to marine turtles or pelagic elasmobranchs (Table S1).

Somerville et al. (2026) found no difference in interaction rates of a coastal, demersal shark species (small-spotted catshark *Scyliorhinus canicular*) between 4 Hz and continuous LED lights. Ryan et al. (2017) found that 5 to 10 Hz LED lights with wavelengths visible to humans as white had a repellent effect on benthic, coastal shark species, but no effect on the behavior of white sharks (*Carcharodon carcharias*). The flicker rates used in these studies were likely below sharks' critical FFF and probably closer to their peak flicker sensitivity (Gruber 1969; McComb et al. 2010; Kalinoski et al. 2014; Hart and Collin 2015; Ryan 2016), and it is unclear which factors (λ_{max}, intensity, flicker rate) caused the observed aversive response of the benthic, coastal shark species or lack of response by white sharks. In general, higher trophic level species and age classes of sharks might exhibit more bold behavior and be attracted to novel stimuli such as bright and flashing lights relative to lower trophic level predator-averse individuals (Ryan et al. 2017).

Marine turtles are less capable of detecting low light intensities relative to swordfish and istiophorid billfishes (Fritsches and Warrant 2006). Dimmer lights might reduce turtle catch risk

but it is unclear what effect this has on catch rates of commercial species and other at-risk bycatch species. For example, apex predators with bold behaviors might be more likely to be attracted to novel stimuli such as bright and flickering lights relative to lower trophic level species and age classes with stronger traits for shyness, and species with low-light, scotopic vision might exhibit a stronger aversive response to fishing lights with high intensity at certain wavelengths relative to species with photopic vision (Ryan et al. 2017).

3.2. Assessments of Shortlisted Lights and Conventional Lightsticks

Some key characteristics varied amongst the five LED light models and three phosphorescent lights that were shortlisted after screening over 100 candidate models (Tables 1a, 1b, S2a, Section S2) and amongst the conventionally used chemical lightsticks (Tables 1b, S2b).

The phosphorescent lights did not meet several of the screening criteria (Tables 1b, 2b). All three of the phosphorescent lights had too low Φe upon activation, too low Φe at λ_{max} upon activation, too high peak Φe per wavelength within the 555-580 nm wavelength range, and diminution was too fast over 24 hours.

The Catch All and ProGlow Ultrabright LED models had a primary λ_{max} visible as blue to humans and secondary peaks in the violet/UV range, and the blue UltraGlo chemical lightstick (used in the Australia fishery) had a peak in the violet/UV range and secondary peak in blue (Figures 1 and 2, Table 1a,b). The Gloweez pink chemical lightstick had a λ_{max} in the violet/UV range and secondary peaks visible as red and blue to humans, and the Gloweez green lightstick had a peak visible as green to humans and secondary peak in the violet/UV range (Figure S3, Table 1b). The ProGlow Superbright, DYP-100 and SY-66 LED models had single λ_{max} visible as blue to humans and no secondary peaks (Figures 1 and S1, Table 1a). The green chemilures superclips chemical lightstick had a single λ_{max} visible as green to humans (Figure 2, Table 1b). The two phosphorescent lights identified by the manufacturer as being blue had peaks visible to humans as cyan (blue-green) (Figure S2, Table 1b). The phosphorescent Scooblite had a λ_{max} visible as green to humans (Figure S2, Table 1b). The DYP-100 and SY-66 LED models had an order of magnitude higher Φe than the Catch All and the two ProGlow models (Table 1a).

The short-listed LED lights met all of the diminution screening criteria (Table 2a), while the phosphorescent light models did not meet any of these criteria (Table 2b). The chemical lightsticks, which are typically discarded after 1 or 2 sets, had reductions in Φe over 24 hours of between 38% to >99% (Table 2b). Catch All, the one LED with non-replaceable batteries, had a reduction in Φe of 55% over 15 days, while the 4 LED models that use replaceable batteries had reductions of between 51% and 93% over 15 days (Table 2a). The FishTek Superbright model, despite being described by the manufacturer as being dimmer than the Ultrabright model, had higher Φe at all three measured points in time (Table 2a). But, as predicted by the manufacturer, Ultrabright had a 69% faster diminution over 15 days (51% and 86% reductions in Φe for the Superbright and Ultrabright models, respectively, Table 2a).

Of the five LED models used in the demonstrations, the Catch All did not meet the definition used here for multi-directionality of having the same order of magnitude of total *Ee* at 0º, 45º and 90º (Table S3). The other four LED models met this criterion on multi-directionality (Table S3).

3.3. Fisher Perspectives Derived from Exploratory Fishing Demonstrations

The six captains that participated in the exploratory fishing demonstrations provided their perspectives on the practicality, safety and economic viability of alternative LED light models relative to conventional lightsticks. In addition to the captains' survey responses summarized in Table 3, the captains provided the following additional perspectives from their trials of the LED lights:

- Two captains preferred flashing over constant LED lights, one preferred constant, and three were unsure.
- Two captains preferred LED models that are brighter but with a shorter battery life and would attach these models far from the hook, and four preferred dimmer LEDs with a longer battery life.
- One captain found that the contacts of the water-activated DYP-100 quickly rusted, and one found the same issue with the ProGlow models.
- Two captains noted that occasionally a small proportion of ProGlow lights did not immediately turn on following immersion in water. One captain noted that occasionally the ProGlow models would remain on following retrieval likely due to their recessed contact points retaining water.
- Three captains were unable to use the collar on the ProGlow models because their branchline diameter is too large. These captains attached these and the CatchAll lights with rubber bands, which is the same methods that they use to attach chemical lightsticks.
- Four captains attached the larger and brighter DYP-100 and SY-66 LED models far from the hook (either at the upper end of the branchline or on the mainline, *ca* 15 m from the hook) and attached the smaller and dimmer Catch All and ProGlow models close to hooks (between ca 0.8 m and 3.5 m). One of these four captains attached some of the larger LED models far from and some close to hooks. Reasons for attaching larger lights far from the hook included wanting to avoid: (1) altered action of baited hooks, (2) increased safety risk to crew from flybacks of a large object, (3) reduced commercial species catch rates from having a large object near the hook, (4) increased shark interactions (catch rates and bite-offs) - which reduces commercial catch - from having a relatively bright light close to hooks, and (5) interference with a “spider” grapple-like device (also referred to as a “tuna missile”) that fishers use to land large catch. The tuna missile is attached to a heavy line and slides down the leader of the branchline, where it clamps onto the head of the fish so that the crew can then haul the fish up using the heavy line, reducing the risk of losing the catch due to the leader breaking (Beverly et al. 2003). This captain found that only the larger and not the smaller LED models obstructed his use of the tuna missile. One captain attached all LED models far from hooks, and one captain attached all LED models close to hooks.
- One captain preferred smaller LED models because they could potentially be left on the branchlines when stored in bins, if done properly to avoid tangles, which would save crew time.
- All six captains prefer water-activated over manually activated LED lights because they are more convenient. Crew do not have to reduce their hook setting rate or take time during the haulback to turn the lights on and off. Two captains commented that a pressure-activated model would be preferable over water-activation because it would eliminate problems with corrosion of water-activated contact points, and problems with the ProGlow models remaining on following retrieval.
- Two captains believed that the SY-66 model and one captain believed that both the SY-66 and DYP-100 had higher shark catch and bite-off rates than the other LED models and their conventional lightsticks due to being relatively brighter. One captain believed that all LED models had higher shark catch and bite-off rates than lightsticks.

4. DISCUSSION AND CONCLUSIONS

The study identified models of LED fishing lights that possess characteristics that are preferred by pelagic longline fishers and are predicted to mitigate the bycatch of at-risk species. A small

proportion of assessed LED fishing light models met our screening criteria on bycatch mitigation and commercial viability. LED models are needed that meet requirements for practicality, safety, economic viability and bycatch mitigation that are both affordable and commercially available to global shallow-set longline fisheries.

We discuss captains' perspectives and identify research and development priorities to address information gaps as well as to augment LED longline fishing lights' designs to meet objectives for commercial viability and bycatch mitigation. In Section S4 we discuss additional research priorities of collateral ecological effects of light pollution from brighter longline fishing lights, seabird density and catch rate responses to brighter lights, and considerations for defining a control and replicates for field experiments of alternative longline fishing lights.

Fishing light wavelength peak and range

There is an extremely limited evidence base of species-specific responses to pelagic longline fishing light λ_{max} and wavelength ranges, comprised of mechanistic physiological studies (Section S1) and a single longline field trial (Afonso et al. 2021). This available, limited information suggests that changing from green lightsticks to violet to blue lights might reduce the bycatch of hardshelled turtles and some pelagic sharks but with an economic cost tradeoff (Section S1; Afonso et al. 2021; Somerville et al. 2026). Blue lights are expected to increase target species catch rates relative to not using a light, but possibly not to the extent of green lights (Section S1, Afonso et al. 2021).

Two LED models included in the fishing demonstrations as well as the Gloweez 'blue' lightstick had dual λ_{max} in the violet and blue wavelength ranges. The other three LED models had single peaks in the blue range (Table 1). Catch rates of a larger number of commercial species might be higher with lights with multiple λ_{max} in the UV, violet and blue wavelength ranges than lights with a single peak within this wavelength range, based on mechanistic physiological studies on peak spectral sensitivities (Table S1). Field trials are needed to test this.

A longline field trial of longline LED fishing lights found that LEDs with a λ_{max} of 525 nm (green to humans) had higher catch rates of target billfishes and tunas as well as of bycatch species of blue sharks and marine turtles relative to a LED with a 465 nm λ_{max} (blue to humans) (Afonso et al. 2021). However, there might have been confounding by other potentially informative predictors of catch rates that differed between the two LED lights other than λ_{max} that were not reported by Afonso et al. (2021), such as wavelength range and Φe. Changing from a green to a blue light to reduce bycatch of some at-risk marine turtle and pelagic shark species might entail an economic cost tradeoff: blue lights might increase target species catch rates relative to not using a light, but possibly not to the extent of green lights.

The findings from Afonso et al. (2021) and mechanistic studies of spectral sensitivities (Section S1) suggest that, for some commercial longline species, the overlap or mismatch between peak spectral sensitivity and λ_{max} might be a weak predictor of catch risk. While a species' wavelength of peak spectral sensitivity indicates a strong ability to detect a light source emitting light at that wavelength, the ability to detect that wavelength does not necessarily mean that will trigger a behavioral response of attraction to the light and increased catch risk on the longline hook more so than with lights with λ_{max} that differs from their peak sensitivity. For example, a species with peak detection of a wavelength perceived by humans as green might also detect wavelengths visible to humans as blue, and for some reason might be more attracted to blue than green lights. In this hypothetical case, a fishing light with a blue peak wavelength and with a wavelength range that includes green could increase the catch risk of that species relative to using a light with a green peak. Predictors that affect the attraction and aggregation of prey species, such as light properties that simulate characteristics of bioluminscent prey, might be more important predictors of longline catch risk than peak spectral sensitivity. Given the limited evidence base of which single factors are important explanatory

predictors of catch risk on different longline lights, including λ_{max}, it is a priority to obtain much stronger, direct evidence by conducting numerous randomized, controlled field trials across variable conditions and by conducting robust meta-syntheses, discussed in the Conclusions section below.

Size and light intensity

Overall, captains preferred smaller and dimmer LED models. Captains were split and a few were ambivalent on how the five LED models affected catch rates of commercial species relative to their lightsticks, including on adjacent branchlines without lights. Half of the captains predicted that dimmer, flashing, smaller models, which most captains attached close to hooks, had higher catch rates of commercial species than lightsticks and four captains preferred the dimmer and smaller LED models to the brighter and bulkier LED models. Most captains attached the two larger LED models, which also happened to be the brightest, with an order of magnitude higher Φe at t_0 than the smaller LED models (Table 1a), far from baited hooks. Reasons included to avoid: affecting the action of the terminal tackle, reducing commercial species catch rates from having a very bright and large object near the hook, interfering with catch retrieval, and increasing safety risks to crew. Lights that are larger and heavier (in air) pose a risk to crew safety from terminal tackle flybacks during gear haulback (ACAP, 2024). Some captains perceived that the LED SY-66, which had the highest Φe (Table 1a), had the highest shark bite-offs and captures. This is consistent with findings of Denamur and Rowe (2020) who found that Australian longline fishers perceived brighter lights increased shark attraction and bite-offs.

It is a research priority to assess the effects of light intensity on catch rates of at-risk and commercial species. Dimmer lights might reduce turtle catch risk (Fritsches and Warrant, 2006) but there is a lack of evidence of the effect of Φe on catch rates of other species (Section S1). It is also not well understood what affect Φe of fishing lights has on the attraction of prey of pelagic longline commercial and bycatch species, which might be an important predictor of catch risk for some species.

We included measurements of each fishing light's Φe (integrated, total radiant power) using an integrating sphere, eliminating the influence of the angle and position of the light source within the sphere, which is a gold standard reference value (e.g., Maucoski et al. 2022). This radiometric property measurement has not been consistently employed in previous fishing light bycatch mitigation research (Yochum et al. 2024).

Flicker frequency and duration

Captains were split or ambivalent on preferences for a flickering or constant light. Flashing lights that closely simulate disturbed, flickering bioluminescent organisms might have higher catch rates for some species relative to constant lights (Widder 2002; Hazin et al. 2005; Letendre et al. 2024). Flickering lights might have higher catch rates of some commercial species and might reduce marine turtle catch risk relative to continuous lights (Widder 2002; Lohmann et al. 2006; Letendre et al. 2024).

None of the LED models, however, had flicker rates that exceed marine turtles' critical FFF (Table S1). It is therefore a priority to develop fishing lights that flicker at rates that exceed the critical FFF above which the lights appear constant and dimmer to marine turtles. Flashing LED models might have a longer battery life than continuous models (Yochum et al. 2024), which would be considered as part of life cycle and economic analyses, discussed below.

The effect of flicker duration is another light property of flickering LED lights with an unknown effect on species-specific longline catch rates. The underlying mechanisms of detection and attraction to lights of different flicker duration are also not well understood, which might be related to the bioluminescence flash rates of prey and of organisms that attract baitfish and their prey (Widder 2002).

Directionality

The effect of light directionality on species-specific catch rates in longline fisheries is not understood. For example, does the relatively low directionality of the Catch All LED model cause lower detection by predators and prey and lower catch rates of certain species relative to models with broader directionality?

Directionality of *Ee* might not change linearly when rotating some models of lights. Therefore, measuring *Ee* only at a few selected orientations as we did in this study and as conducted in previous assessments of fishing lights (Karlsen et al. 2021) might not provide the clearest basis for comparing directionality between models. Furthermore, directionality might not be an important predictor of catch rates when fishers fasten lights to the gear in a manner that allows for a large degree of movement, such as attaching a light with a clip and swivel.

Apparent weight, activation method and seabird bycatch mitigation

All five LED models included in the fishing demonstration were negatively buoyant and four were water-activated (Table 1a). However, discussed above, most captains were only willing to attach the smaller and dimmer LED models close to hooks. The smaller Catch All and the bulkier DYP models have similar apparent weights, while the smaller ProGlow has an apparent weight in between the two bulkier models (Table 1a). Research is needed to determine whether there is a net benefit to seabirds from placing LED lights close to hooks. Attaching negatively buoyant LED lights close to hooks is expected to increase the baited hook sink rate, reducing seabird catch risk, noting that seabird bycatch in longline fisheries is problematic mainly at higher latitudes (Gianuca et al. 2016; Ochi et al. 2017; Gilman et al. 2024). But light might also attract seabirds to the area where baited hooks are being deployed (McNamara et al. 1999; Sigurdsson 2023), increasing their catch risk. It is unclear which mechanism has a stronger effect on the catch risk of different seabird species.

The captains preferred water-activation over manual activation. Some captains believe pressure (depth)-activated LEDs (such as produced by Lindgren-Pitman, which was not short-listed due to exceeding the cost criterion) would overcome issues identified with the water-activated models of corroding contact points, inconsistently turning off following retrieval, and possibly the need to rinse with freshwater. Water- and pressure-activated lights might reduce seabird catch risk relative to manually-activated lights. Some seabird species are attracted to fishing lights (McNamara et al. 1999; Sigurdsson 2023). Scavenging seabirds might learn to associate lights with the presence of baited hooks or the lights might illuminate and increase their visual detection of baited hooks. Relative to lightsticks and LEDs that are manually activated by crew prior to setting, water-activated lights might reduce seabird catch risk during nighttime setting, and pressure-activated lights might reduce seabird catch during both night setting and nighttime hauling. During setting, the water- and pressure-activated lights would limit illumination of baited hooks to when water-activated lights contact the water and when pressure-activated lights reach their programmed depth. During hauling, pressure-activated lights would turn off before baited hooks reach the surface, potentially reducing detection by some seabird species. It might also be more convenient for use by crew by not having to manually turn the lights on and off.

Phosphorescent and fluorescent lights and biodegradable lightsticks

The phosphorescent lights did not meet our assessment criteria, suggesting that they might have too low a light level and have too rapid diminution for effective use in pelagic longline fisheries. Phosphorescent lights have substantial economic and practicality benefits: they are reusable likely with a long lifetime, rechargeable with ambient and artificial light, and are relatively inexpensive. It is a research priority to determine if a phosphorescent light with higher

radiant power with slow diminution can be designed to at least match that of conventional chemical lightsticks, and with optimal wavelength peaks and range, size and apparent weight.

There is existing luminescent fishing gear, such as phosphorescent beads and fluorescent lures used by recreational fishers (Lokkeborg et al. 2014; Radinger et al. 2026), and longline sliding weights with a luminescent nylon (polyamide) coating that are reported by the manufacturer to glow for up to six hours (e.g., FishTek Marine 2026a; Fishing International 2026). These warrant investigation for their potential to replace lightsticks. A single-use biodegradable, non-toxic, chemiluminescent yellow lightstick with the model name Lume is under development (Lux Bio 2025), also warrants investigation as a potential replacement to conventional chemical lightsticks. Lume uses enzymes to produce chemiluminescence that mimics the chemical reactions of bioluminescence, and uses a biodegradable housing (Lux Bio 2025).

Life cycle and economic analyses

Captains were split or ambivalent on whether the costs for the Catch All and the two ProGlow LED models are acceptable, while most captains found the DYP-100 and SY-66 models to be too expensive. Some captains plan to continue to use the Catch All and ProGlow models. One captain who already uses the SY-66 intends to begin to also use the DYP-100. Longer-term assessments are needed to determine the durability and practicality of these LED models.

Comprehensive life cycle assessments and economic cost-benefit analyses of changing from conventional chemical lightsticks to LED fishing lights are needed to determine whether LED lights with certain properties would have a smaller environmental footprint and lower economic cost than conventional lightsticks. For example, research is needed to determine how much CO_2 and other greenhouse gases are emitted during the production process for one LED light and batteries compared to the equivalent number of lightsticks that would be used over the life of that LED light (Nguyen and Winger, 2018). A comparison of the environmental impact across the full life cycles of conventional lightsticks and LED lights and batteries, including environmental impacts from the acquisition of materials, production of each component, and supply chain carbon footprint would be instrumental for informing whether certain LED models are improvements over the status quo. LED models that use replaceable batteries, that can be used with rechargeable batteries, have a long battery life, are durable and long-lasting, and can be recycled at end-of-life are examples of characteristics that might minimize their adverse environmental effects.

An economic assessment could account for the initial outlay cost of the lights and LED batteries if replaceable, ongoing costs to replace batteries if relevant, and ongoing costs to replace end-of-life, damaged and lost lights. The latter point would need to account for whether the model is predicted to increase shark bite-offs relative to lightsticks. The assessment could determine whether more durable but more expensive models are more or less economically preferrable to less durable and less expensive models, if all other parameters were equal (which would enable evaluating the suitability of the screening criterion on cost used in this study). Diminution rates (Table 2a) would inform estimates of battery replacement rates or light replacement rates for disposable models. Another consideration is whether the model can be used with rechargeable batteries. The assessment would also need to account for effects on commercial species catch rates and sizes; effects on rates of depredation (the removal or damage of catch and bait from fishing gear) of commercial catch and bait by sharks, odontocetes and squids; and costs from gear damage such as from a change in terminal tackle bite-off rates by sharks. Furthermore, changes in costs resulting from modified fishing effort and the amount of purchased expendables such as fuel, bait and gear and salaries for crew in response to a change in catch rates and value would need to be accounted for in the assessment.

The assessment could also evaluate the environmental and economic impacts of the fate of end-of-life lights and of disposable and rechargeable batteries. This includes both when the unwanted lights are batteries are disposed of as prescribed by port waste reception facilities, and when abandoned, lost or discarded at sea.

Rechargeable versus disposable batteries

While having the potential to reduce waste, environmental impacts and human health impacts relative to single-use batteries (Parsons 2006; Dolci et al. 2016), using rechargeable batteries in LED fishing lights might require several years of use for an operator to recoup the higher initial outlay costs. Rechargeable batteries are more expensive than disposable alkaline batteries and require recharging devices. Rechargeable batteries experience diminished capacity and power with repeated cycles of discharging and recharging, and eventually, after several hundred cycles of use, reach end-of-life (Parsons 2006).

Because rechargeable batteries have a lower capacity and shorter battery life compared to disposable alkaline batteries (Parsons 2006; Dolci et al. 2016), fishers would have to recharge and replace rechargeable batteries more frequently than they would need to replace disposable batteries. Making LEDs that can undergo bulk and rapid wireless recharging of batteries through electromagnetic induction while at-sea could make the use of rechargeable batteries more convenient (e.g., the FishTek SharkGuard is capable of induction charging when stored in branchline storage bins, FishTek Marine 2026a). This would, however, likely result in an uncompetitively high cost for the LED lights with induction charging capacity in addition to the induction chargers (personal communication, Robert Enever, FishTek, 7 May 2025). If management authorities required the use of only LEDs with rechargeable batteries and created broad fishing industry demand, this could incentivize the development at scale of affordable induction charge-capable LED fishing lights.

Conclusions and next steps

Results from the exploratory fishing demonstrations and literature review identified characteristics of fishing lights that meet objectives for practicality, safety, economic viability and bycatch mitigation. Findings also inform the design of field experiments to assess target and bycatch catch rates and identify priorities for research and development to optimize fishing light characteristics. These findings, combined with some longline fisheries having partially (e.g., Australian bluefin tuna and eastern tuna and billfish fisheries) or completely (e.g., Japan Kesen-numa swordfish longline fishery) transitioned from using lightsticks to LED lights, suggest that LED lights hold promise for replacing single-use lightsticks.

Most captains preferred water- or pressure-activated models, which might reduce seabird access and bycatch risk. Captains also preferred dimmer models and perceived a very bright LED model to have increased shark interactions. Most captains attached only smaller and dimmer LED models close to hooks, where they contribute to mitigating seabird bycatch by increasing hook sink rates, and were concerned that attaching bulkier and brighter LED models close to hooks would affect the action of the terminal tackle, increase safety risks to crew, reduce commercial species catch rates, and interfere with catch retrieval. One captain preferred smaller LED models because crew could leave them on branchlines when stored in bins. Most captains plan to continue using some of the assessed LED models.

There was low risk of bias from captains intentionally providing false responses because the expert elicitation study component did not collect sensitive data such as on the bycatch of protected and at-risk species or production of marine litter. However, the in-depth exploratory demonstrations derived fisher perspectives from a very small sample size of six captains of three pelagic longline fisheries. Conducting additional exploratory trials of alternative LED models in a broader range of pelagic longline fisheries by a larger number of fishers by following a probability sampling design would provide stronger certainty of the generalizability

and representativeness of responses by reducing the risk of various sources of bias of expert elicitation surveys (e.g., from undercoverage, nonresponse, and prevailing paradigm bias, Choi and Pak 2005; Brick 2011; Sarstedt et al. 2018; Downes and Carlin 2020) and might identify preferred characteristics that are specific to any unique fishing operations of individual fisheries.

The study identified research and development priorities to address information gaps and augment LED longline fishing lights' designs to better meet objectives for commercial viability and bycatch mitigation:

- Stronger evidence, including through randomized, controlled field trials and meta-analytic syntheses, is needed to determine commercial and bycatch species' catch rate responses to various light spectral, temporal, intensity and spatial properties of longline fishing lights, including total Φe, single and various combinations of λ_{max}, Φe at λ_{max}, wavelength range, directionality, flicker frequency versus constant, and flash duration. LED lights with flicker rates *ca* >16Hz that exceed the critical FFF of marine turtles (Table S1) currently are not commercially available. It is a priority to develop LED longline fishing lights that flicker at rates that reduce marine turtle detection.
- Phosphorescent lights have several economic and practicality benefits but require research and development to provide higher Φe and slower diminution to make them suitable for longline fisheries. A biodegradable chemical lightstick (Lux Bio 2025) is under development and holds promise to replace toxic lightsticks.
- Comprehensive life cycle assessments and economic cost-benefit analyses are needed to determine whether LED lights with certain characteristics would have a smaller environmental footprint and lower economic cost than conventional lightsticks.
- While having the potential to reduce waste, environmental impacts and human health impacts of single-use batteries (Parsons 2006; Dolci et al. 2016), rechargeable batteries might require several years of use to provide an economic benefit and are less practical for fishers. Bulk and rapid wireless induction recharging of LED fishing lights could address practicality costs but might only be cost-effective with broad uptake.
- Research is needed to determine whether using brighter LED lights in place of dimmer lightsticks would exacerbate collateral effects of underwater light pollution, including altering ecological processes and behavior of pelagic species (Section S4).
- Evidence is needed to determine the effects on the local abundance and catch rates of seabirds of using negatively buoyant and brighter LED lights in place of buoyant and dimmer conventional lightsticks, and of the distance between lights and baited hooks (Section S4).
- While attaching lights >1m from the hook, especially small models with streamlined shapes, might have minimal effect on the action of baited hooks, additional research is needed to investigate this.

Tuna and other relevant regional fisheries management organizations have not adopted management measures on pelagic longline light emitting devices (CCSBT 2026; GFCM 2025; IATTC 2026; ICCAT 2026; IOTC 2026; WCPFC 2026). While there is strong evidence of increased catch rates of both commercial species and at-risk marine megafauna bycatch in response to the use of longline fishing lights (McNamara et al. 1999; Ward et al. 2000; Watson et al. 2006; Poisson et al. 2010, 2016; Swimmer et al. 2017; Afonso et al. 2021; Sigurdsson 2023; Monaghan et al. 2024), a substantially more robust evidence base is needed to determine which individual light characteristics are meaningful explanatory predictors of species-specific catch rates and could be managed to effectively mitigate bycatch rates of species of conservation concern while augmenting catch rates of principal market species.

Additional individual randomized, controlled field trials, the gold standard of individual studies, as well comparative experiments and quasi-experimental studies of observational data (Gilman and Chaloupka 2023) are needed. See Section S4 for considerations for designing the control and replicates in fishing light experiments. Once sufficient evidence has accumulated from individual field studies, then meta-analytic synthesis studies would provide the most robust and generalizable findings. Results from a single study might be context-specific and lack external validity - the results from a single study might not be applicable under different conditions (Deaton and Cartwright 2018). By synthesizing estimates from a mixture of independent and context-specific studies, the overall estimated effect from meta-syntheses is generalizable and relevant over diverse settings (Pfaller et al. 2018). These field studies and meta-syntheses are needed to assess a broad range of individual predictors of catch rate responses and to assess fishing light factors affecting commercial viability.

Our study identified lights that hold high promise for meeting objectives for commercial viability, bycatch mitigation, and reducing toxic and plastic marine pollution from pelagic longline fisheries. LED fishing lights promise to meet the economic, social and ecological components of the triple-bottom-line, providing a powerful addition to the fisheries bycatch mitigation toolbox.

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5. REFERENCES

ACAP (2024) ACAP Review of Mitigation Measures and Best Practice Advice for Reducing the Impact of Pelagic Longline Fisheries on Seabirds. Agreement on the Conservation of Albatrosses and Petrels, Hobart, Australia

Afonso A, Mourato B, Hazin H, Hazin F (2021) The effect of light attractor color in pelagic longline fisheries. Fisheries Research 235:105822

Baez J, Macias D, Caminas J et al (2013) Bycatch frequency and size differentiation in loggerhead turtles as a function of surface longline gear type in the western Mediterranean Sea. Journal of the Marine Biological Association of the United Kingdom 93:1423-1427

Beaumont N, Aanesen M, Austen M et al (2019) Global ecological, social and economic impacts of marine plastic. Marine Pollution Bulletin 142:189-195

Beverly S, Chapman L, Sokimi W (2023) Horizontal Longline Fishing Methods and Techniques. A Manual for Fishermen. ISBN 982-203-937-9. Secretariat of the Pacific Community, Noumea, New Caledonia

Bielli A, Alfaro-Shigueto J, Mangel J, et al (2020) An illuminating idea to reduce bycatch in the Peruvian small-scale gillnet fishery. Biological Conservation 241:108277

Bigelow K, Boggs C, He X (1999) Environmental effects on swordfish and blue shark catch rates in the US North Pacific longline fishery. Fish Ocean 8:178–198

BioInspecta (2025) Australia Southern Bluefin Tuna Longline and Minor Line Fishery. Public Certification Report. BioInspecta, Frick, Switzerland
Brick J (2011) The future of survey sampling. Public Opin Q 75:872-888. doi:10.1093/poq/nfr045
Bromhead D, Graham S, Kalish J (2003) National Fishery Report 2003 – Australia. IOTC-SC-Inf. 13. Indian Ocean Tuna Commission, Mahe, Seychelles
Burgher K, Wang J, Barkan J et al (2026) Artificial light reduces elasmobranch bycatch in gillnets across multiple wavelengths and taxonomic groups. Biological Conservation 315:111732
Carleton K, Escobar-Camacho D, Stieb S, Cortesi F, Marshall N (2020) Seeing the rainbow: mechanisms underlying spectral sensitivity in teleost fishes. Journal of Experimental Biology 223: jeb193334. Doi: 10.1242/jeb.193334.
CCSBT (2026) Operational Resolutions and other Important Documents. Commission for the Conservation of Southern Bluefin Tuna, Deakin, Australia
Cerbule K, Herrman B, Grimaldo E, et al (2025) Does soak time influence the effect of artificial light on catch efficiency in snow crab (*Chionoecetes opilio*) pot fishery? Aquaculture and Fisheries 10:330-343. DOI: 10.1016/j.aaf.2023.11.004.
Cesar-Ribeiro C (2021) Chemical contents of disposed light sticks affect the physiology of rocky crab *Pachygrapsus transversus* and gray shrimps *Litopennaeus vanammei*. Bull Environ Contam Toxicol 107:370–377
Cesar-Ribeiro C, Rosa H, Rocha D et al (2017) Light-stick: A problem of marine pollution in Brazil. Marine Pollution Bulletin 117:118-123
Chaloupka M (2002) Stochastic simulation modelling of southern Great Barrier Reef green turtle population dynamics. Ecol Modell 148:79–109
Chaloupka M (2003) Stochastic simulation modelling of loggerhead sea turtle population dynamics given exposure to competing mortality risks in the western south Pacific. p 274-294, In: Bolten AB, Witherington B (Eds) Loggerhead Sea Turtles. Smithsonian Institution Press, Washington, DC, USA.
Choi B, Pak A (2005) A catalog of biases in questionnaires. Prev Chronic Dis 2:A13. PMCID:PMC1323316
Control Union (2025) Marine Stewardship Council Second Surveillance Audit Report for the Hawaii Longline Swordfish, Bigeye Tuna and Yellowfin Tuna Fishery. Control Union, Hampshire, UK
Control Union (2026) Marine Stewardship Council Third Surveillance Audit Report for the Reunion Island Longline Swordfish Fishery. Control Union, Hampshire, UK
Crognale M, Eckert S, Levenson D, Harms C (2008) Leatherback sea turtle *Dermochelys coriacea* visual capacities and potential reduction of bycatch by pelagic longline fisheries. Endanger Species Res 5:249–256
de Oliveira T, da Silva A, de Moura R, et al (2014) Luminescent threat: toxicity of light stick attractors used in pelagic fishery. Scientific Reports 4:5359. https://doi.org/10.1038/srep05359
Deaton A, Cartwright N (2018) Understanding and misunderstanding randomized controlled trials. Soc Sci Med 210:2–21. doi:10.1016/j.socscimed.2017.12.005
Denamur C, Rowe S (2020) *Great Barrier Reef Source Reduction Plan for Professional Fishing Related Chemical Light Sticks*. OceanWatch Australia, Pyrmont, Australia
Dias M, Martin R, Pearmain E, et al (2019) Threats to seabirds: a global assessment. Biol Conserv 237:525–537
Dolci G, Tua C, Grosso M et al (2016) Life cycle assessment of consumption choices: a comparison between disposable and rechargeable household batteries. Int J Life Cycle Assess 21:1691–1705
Downes M, Carlin J (2020) Multilevel regression and poststratification versus survey sample weighting for estimating population quantities in large population health studies. Am J Epidemiol 189:717–725. doi:10.1002/bimj.201900023
Dulvy N, Pacoureau N, Rigby C et al (2021) Overfishing drives over one third of all sharks and rays toward a global extinction crisis. Curr. Biol. 31:4773-4787. https://doi.org/10.1016/j.cub.2021.08.062
Ebrey T, Koutalos Y (2001). Vertebrate photoreceptors. Prog Retin Eye Res 20:49-94. doi:10.1016/S1350-9462(00)00014-8
Eckert S, Levenson D, Crognale M (2006) The sensory biology of sea turtles: What can they see, and how can this help them avoid fishing gear? IN Swimmer Y, Brill R (Eds). Sea Turtle and Pelagic Fish Sensory Biology: Developing Techniques to Reduce Sea Turtle Bycatch in Longline Fisheries. NOAA Technical Memorandum NMFS-PIFSC-7. National Marine Fisheries Service, Pacific Islands Fisheries Science Center, Honolulu, pp. 8-16
Everfine (2024a) HAAS-2000 High Accuracy Array Spectroradiometer User's Manual. Version 3.03. Everfine Photo-E=Info Co., Ltd., Hangzhou, China
Everfine (2024b) Integrating Sphere User's Manual. Version 4.06. Everfine Photo-E=Info Co., Ltd., Hangzhou, China
Fishing International (2026) Genuine GloLead. https://fishinginternational.com.au/wp/product/genuine-glolead-100-gram/. Fishing International Supplies and Hardware, Mooloolaba, Australia
FishTek Marine (2026a) Shark Guard. https://www.fishtekmarine.com/design-development-testing/projects/sharkguard/. FishTek Marine Ltd., Dartington, Totnes, Devon, UK
FishTek Marine (2026b) Lumolead. https://www.fishtekmarine.com/product/lumolead/. FishTek Marine Ltd., Dartington, Totnes, Devon, UK
Forrest R, Walters C (2009) Estimating thresholds to optimal harvest rate for long-lived, low-fecundity sharks accounting for selectivity and density dependence in recruitment. Can J Fish Aquat Sci 66:2062-2080
Fritsches K, Bril R, Warrant E (2005) Warm eyes provide superior vision in swordfishes. Current Biology 15:55-58

Fritsches K, Warrant E (2006) Differences in the visual capabilities of sea turtles and blue water fishes – implications for bycatch reduction. IN Swimmer Y, Brill R (Eds). Sea Turtle and Pelagic Fish Sensory Biology: Developing Techniques to Reduce Sea Turtle Bycatch in Longline Fisheries. NOAA Technical Memorandum NMFS-PIFSC-7. National Marine Fisheries Service, Pacific Islands Fisheries Science Center, Honolulu, pp. 1- 7

GFCM (2025) Compendium of GFCM Decisions. Version 9.1. General Fisheries Commission for the Mediterranean, Rome

Gianuca D, Sant'Ana R, Neves T (2016) Influence of electric fishing lights on sink rates of baited hooks in Brazilian pelagic longline fisheries: implications for seabird bycatch. Braz J Oceanogr 64:95–100. https://doi.org/10.1590/S1679-87592016092306401

Gilman E (2011) Bycatch governance and best practice mitigation technology in global tuna fisheries. Marine Policy 35:590-609

Gilman E, Antonelis K, Drinkwin J et al (2023) Introduction to the Marine Policy special issue on abandoned, lost and discarded fishing gear: Causes, magnitude, impacts, mitigation methods and priorities for monitoring and evidence-informed management. Marine Policy:105738. https://doi.org/10.1016/j.marpol.2023.105738

Gilman E, Chaloupka M (2023) Applying a sequential evidence hierarchy, with caveats, to support prudent fisheries bycatch policy. Rev Fish Biol Fisheries 33:137-146

Gilman E, Chaloupka M, Debski I et al (2024) Synthesizing a network of evidence on a seabird bycatch mitigation measure. Fish and Fisheries 26:30-44. https://doi.org/10.1111/faf.12864

Gilman E, Clarke S, Brothers N et al (2007) *Shark Depredation and Unwanted Bycatch in Pelagic Longline Fisheries: Industry Practices and Attitudes, and Shark Avoidance Strategies*. ISBN: 1-934061-06-9. United Nations Environment Programme and Western Pacific Regional Fishery Management Council, Nairobi, Kenya and Honolulu, USA

Gilman E, Clarke S, Brothers N et al (2008) Shark interactions in pelagic longline fisheries. Marine Policy 32:1-18.

Gilman E, Musyl M, Wild M, et al (2022) Investigating weighted fishing hooks for seabird bycatch mitigation. Scientific Reports 12:2833. https://doi.org/10.1038/s41598-022-06875-4

Gilman E, Suuronen P, Chaloupka M (2017) Discards by global tuna fisheries. Marine Ecology Progress Series 582:231-252

Gruber S (1969) The Physiology of Vision in the Lemon Shark, *Negaprion brevirostris* (Poey): A Behavioral Analysis. PhD diss. University of Miami, Coral Gables

Hart N, Collin S (2015) Sharks senses and shark repellents. Integrative Zoology 10:38-64

Hazin H, Hazin F, Travassos P, Erzini K (2005) Effect of light-sticks and electralunie attractors on surface-longline catches of swordfish (*Xiphias gladius*, Linnaeus, 1959) in the southwest equatorial Atlantic. Fish Res 72:271–277. https://doi.org/10.1016/j.fishres.2004.10.003

Heppell S (1998) An application of life history theory and population model analysis to turtle conservation. Copeia 1998**:**367–375. https://doi.org/10.2307/1447430

IATTC (2026) All Active Resolutions. Inter-American Tropical Tuna Commission, La Jolla, USA

ICCAT (2026) Compendium. Management Recommendations and Resolutions Adopted by ICCAT for the Conservation of Atlantic Tunas and Tuna-like Species. Version 2026.01. International Commission for the Conservation of Atlantic Tunas, Madrid

IOTC (2026) Compendium of Active Conservation and Management Measures for the Indian Ocean Tuna Commission. Version 1 January 2026. Indian Ocean Tuna Commission, Victoria, Mahe, Seychelles

Ito R, Dollar R, Kawamoto K (1998) The Hawaii-based longline fishery for swordfish. In: Barrett I, Sosa-Nishizaki O, Bartoo N (eds). Biology and Fisheries of Swordfish, *Xiphias glacius*. Papers from the International Symposium on Pacific Swordfish, Ensenada, Mexico, 11-14 December 1994. NOAA Tech Rep 142. National Marine Fisheries Service, Honolulu

Jekely G (2009) Evolution of phototaxis. Phil Trans R Soc B 364:2795-2808. https://doi.org/10.1098/rstb.2009.0072

Johnsen S (2006) Mathematical model of the visual abilities of sea turtles and pelagic fishes. IN Swimmer Y, Brill R (Eds). Sea Turtle and Pelagic Fish Sensory Biology: Developing Techniques to Reduce Sea Turtle Bycatch in Longline Fisheries. NOAA Technical Memorandum NMFS-PIFSC-7. National Marine Fisheries Service, Pacific Islands Fisheries Science Center, Honolulu, pp. 18-23

Johnsen S (2012) The Optics of Life: A Biologist's Guide to Light in Nature. Princeton: Princeton University Press

Kalinoski M, Hirons A, Horodysky A, Brill R (2014) Spectral sensitivity, luminous sensitivity, and temporal resolution of the visual systems in three sympatric coastal shark species. Journal of Comparative Physiology A 200:997-1013

Karlsen J, Melli V, Krag L (2021) Exploring new netting material for fishing: The low light level of a luminous netting negatively influences species separation in trawls. ICES Journal of Marine Science 78:2818-2829

Letendre F, Twardowski M, Blackburn A et al (2024) A review of mechanically stimulated bioluminescence of marine plankton and its applications. Front Mar Sci 10:1299602. https://doi.org/10.3389/fmars.2023.1299602

Lewison R, Crowder L (2007) Putting longline bycatch of sea turtles into perspective. Conservation Biology 21:79-86

Liu X (2014) Statistical power analysis for the social and behavioral sciences: basic and advanced techniques. Routledge, New York, USA

Lohmann K, Wang J, Boles L et al (2006) Development of turtle-safe light sticks for use in longline fisheries. Pp. 65-76 IN Swimmer Y and Brill R (Eds). Sea Turtle and Pelagic Fish Sensory Biology: Developing Techniques to Reduce Sea Turtle Bycatch in Longline Fisheries. NOAA Technical Memorandum NMFS-PIFSC-7. Pacific Islands Fisheries Science Center, National Marine Fisheries Service, Honolulu

Lokkeborg S, Siikavuopio S, Borre O et al (2014) Towards more efficient longline fisheries: Fish feeding behaviour, bait characteristics and development of alternative baits. Rev Fish Biol Fisheries 24:985-1003

Lux Bio (2025) Lume. Website https://www.luxbio.ca/lume, accessed 29 August 2025. Lux Bio, Vancouver, BC, Canada

Martins R, Perez J (2006) Cephalopods and fish attracted by night lights in coastal shallow-waters off southern Brazil with the description of squid and fish behavior. Revista de Etologia 8:27-34
Maucoski C, Price R, Arrais C, Sullivan B (2022) Power output from 12 brands of contemporary LED light-curing units measured using 2 brands of radiometers. PLoS ONE 17:e0267359. https://doi.org/10.1371/journal.pone.0267359
McComb D, Frank T, Hueter R, Kajiura S (2010) Temporal resolution and spectral sensitivity of the visual system of three coastal shark species from different light environments. Physiological and Biochemical Zoology 83:299–307
McNamara B, Torre L, Kaaialii G (1999) Final Report: Hawaii Longline Seabird Mortality Mitigation Project. Western Pacific Regional Fishery Management Council, Honolulu
Monaghan E, Ravanello P, Ellis D et al (2024) Fishing behaviour and environmental variability influence depredation of pelagic longline catch by toothed whales. Fish Res 273:106959
Musick J (1999) Criteria to define extinction risk in marine fishes: the American Fisheries Society Initiative. Fisheries 24:6-14
Nguyen K, Winger P (2018) Artificial light in commercial industrialized fishing applications: a review. Rev. Fish. Sci. Aquacult. 27:106-126
Ochi D, Katsumata N, Oshima K (2017) An At-sea Trial of Seabird Mitigation Gears including Three Weighted Branch Line Specifications for Tuna Longline Fisheries. WCPFC-SC13-2017/EB-IP-17 Rev 1. Wester and Central Pacific Fisheries Commission, Kolonia, Federated States of Micronesia
Pardo S, Kindsvater H, Reynolds J, Dulvy N (2016) Maximum intrinsic rate of population increase in sharks, rays, and chimaeras: the importance of survival to maturity. Can J Fish Aquat Sci 73:1159-1163
Parsons D (2006) The environmental impact of disposable versus re-chargeable batteries for consumer use. The International Journal of Life Cycle Assessment 12:197-203
Pfaller J, Chaloupka M, Bolten A, Bjorndal K (2018) Phylogeny, biogeography and methodology: a meta-analytic perspective on heterogeneity in adult marine turtle survival rates. Sci Rep 8:5852
Pinho G, Ihara P, Fillmann G (2009) Does light-stick content pose any threat to marine organisms? Environ Toxicol Phar 27:155–157
Poisson F, Crespo F, Ellis J et al (2016). Technical mitigation measures for sharks and rays in fisheries for tuna and tuna-like species: Turning possibility into reality. Aquatic Living Resources *29*:402
Poisson F, Gaertner J, Taquet M et al (2010) Effects of lunar cycle and fishing operations on longline-caught pelagic fish: fishing performance, capture time and survival of fish. Fish Bull 108:268–281
Radinger J, Braun M, Jechow A et al (2026) Effectiveness of fluorescent angling lures on catch outcomes in European perch (Perca fluviatilis) under ambient light conditions. Can J Fish Aquat Sci 83. https://doi.org/10.1139/cjfas-2025-0084
Ryan L (2016) A Shark's Eye View: Motion Vision and Behaviour in Apex Predators. PhD Diss. School of Animal Biology and Oceans Institute, University of Western Australia, Crawley, Australia.
Ryan L, Chapuis L, Hemmi J et al (2017). Effects of auditory and visual stimuli on shark feeding behaviour: The disco effect. Marine Biology 165: 11. https://doi.org/10.1007/s00227-017-3256-0
Sarstedt M, Bengart P, Shaltoni A, Lehmann S (2018) The use of sampling methods in advertising research: A gap between theory and practice. Int J Advert 37:650-663. doi:10.1080/02650487.2017.1348329
Senko J, Peckham S, Aguilar-Ramirez D, Wang J (2022) Net illumination reduces fisheries bycatch, maintains catch value, and increases operational efficiency. Current Biology 32:911-918
Shruti V, Katralam-Muniasamy G, Perez F (2023) Putting eggs on marine litter: Towards an understanding of a cause for concern. Marine Pollution Bulletin 190:114900
Sigurdsoon G (2023) Increase in bycatch rates of plunge- and surface-feeding seabirds observed while setting and hauling bottom set gillnets equipped with LED lights. Marine Ecology Progress Series 720: 191-194
Sokimi W, Beverly S (2010) Small-Scale Fishing Techniques Using Light: A Manual for Fishermen. Secretariat of the Pacific Community, Noumea, New Caledonia
Somerville J, Blount J, Stevens M (2026) Visual modelling to predict behavioural responses of catsharks, skates and plaice to artificial light for use in bycatch reduction. Fisheries Management and Ecology. https://doi.org/10.1111/fme.70034
Swimmer Y, Gutierrez A, Bigelow K, et al (2017) Sea turtle bycatch mitigation in US longline fisheries. Front Mar Sci. 4:260
UV Paqlite (2025a) UV Tab Necklace Blue. Website https://www.uvpaqlite.com/uv-tab-necklace-blue.html, accessed 29 August 2025. UV Paqlite, Montrose, Colorado, USA
UV Paqlite (2025b) Glostock. Website https://www.uvpaqlite.com/UVGloStik.html, accessed 29 August 2025. UV Paqlite, Montrose, Colorado, USA
UV Paqlite (2025c) Scooblite. Website https://www.uvpaqlite.com/Scooblite-6in.html, accessed 29 August 2025. UV Paqlite, Montrose, Colorado, USA
Van der Heggen D, Joos J, Feng A et al (2022) Persistent luminescence in Strontium Aluminate: A roadmap to a brighter future. Advance Functional Materials 32:2208809
Villarrubia-Gomez P, Cornell S, Fabres J (2018) Marine plastic pollution as a planetary boundary threat: The drifting piece in the sustainability puzzle. Marine Policy 96:213-220
Wallace B, Kot C, DiMatteo A et al (2013) Impacts of fisheries bycatch on marine turtle populations worldwide: toward conservation and research priorities. Ecosphere 4:1-49

Wang J, Boles L, Higgins B, Lohmann J (2007) Behavioral responses of sea turtles to lightsticks used in longline fisheries. Animal Conservation 10:176-182
Ward P, Porter J, Elscot S (2000) Broadbill swordfish: Status of established fisheries and lessons for developing fisheries. Fish Fish 1:317-336
Ward P. 2008. Empirical estimates of historical variations in the catchability and fishing power of pelagic longline fishing gear. Rev Fish Biol Fisheries 18:409-426
Ward P, Myers R, Blanchard W (2004) Fish lost at sea: The effect of soak time on pelagic longline catches. Fish Bull 102:179-195
Watson J, Kerstetter D (2006) Pelagic longline fishing gear: A brief history and review of research efforts to improve selectivity. Marine Technology Society Journal 40:6-11
WCPFC (2026) Conservation and Management Measures (CMMs) and Resolutions of the Western Central Pacific Fisheries Commission (WCPFC). Version 8 May 2026. Western Central Pacific Fisheries Commission, Kolonia, Federated States of Micronesia
Widder E (2002) Bioluminescence and the pelagic visual environment. Marine and Freshwater Behaviour and Physiology 35:1-26
Widder E (2010) Bioluminescence in the ocean – origins of biological, chemical and ecological diversity. Science 328:704-708
Witzell W (1999) Distribution and relative abundance of sea turtles caught incidentally by the U.S. pelagic longline fleet in the western North Atlantic Ocean, 1992-1995. Fish Bull 97:200-211
Wondershare (2021) Wondershare Filmora X. Version 10.2.0.32. Wondershare Technology Co
Yochum N, Karlsen J, Senko J et al (2024) Guidelines for evaluating artificial light to mitigate unwanted fisheries bycatch. Reviews in Fisheries Science and Aquaculture 32:612-656

Table 1. Characteristics of short-listed LED lights (Table 1a) and short-listed phosphorescent lights and chemical lightsticks (Table 1b). Characteristics are categorized by main objective that they are predicted to effect. λ_{max}=wavelength where the emission spectrum of a light source reaches a maximum; Φe=radiant power; Hz=hertz, number of cycles per second.

Table 1a. LED lights.

Characteristic	Threshold	Light model[a]				
		Catch All deep drop blue	ProGlow Superbright blue	ProGlow Ultrabright blue	DYP-100 blue	SY-66 blue
Light category	no threshold	LED	LED	LED	LED	LED
Bycatch mitigation - marine turtles						
λ_{max} [b] (nm)	no threshold	468, 382	465	465, 382	455	456
λ_{max} color visible to humans [b]	violet to blue, 1 or more peak in blue	blue, violet	blue	blue, violet	blue	blue
Φe at λ_{max}, t_0 (mW nm^{-1}) [c]	≥$4.9*10^{-3}$ [d]	$9.6*10^{-3}$ ($\pm4.8*10^{-3}$)	$2.2*10^{-2}$ ($\pm3.9*10^{-3}$)	$2.9*10^{-2}$ ($\pm2.6*10^{-2}$)	$3.1*10^{-1}$ ($\pm2.9*10^{-2}$)	1.1 (±0)
Peak Φe per wavelength in 440-480nm range ≥10% Φe per wavelength at λ_{max}?	yes	yes	yes	yes	yes	yes
Peak Φe per wavelength within 555-580nm range t_0 (mW nm^{-1})	≤ 10% Φe per wavelength at λ_{max} t_0	$1.8*10^{-4}$ ($\pm1.7*10^{-4}$)	0 (±0)	$2.4*10^{-4}$ ($\pm5.9*10^{-5}$)	$6.3*10^{-4}$ ($\pm2.7*10^{-4}$)	$1.7*10^{-3}$ (±0)
Φe t_0 (mW) [d,e]	≥$3.25*10^{-1}$	$3.7*10^{-1}$ ($\pm2.8*10^{-1}$)	$4.8*10^{-1}$ ($\pm1.4*10^{-1}$)	$7.5*10^{-1}$ ($\pm4.9*10^{-1}$)	7.9 ($\pm8.8*10^{-1}$)	25.0 (±0)
Multidirectional: Total irradiance when parallel, 45° and perpendicular to the sensor probe are within one order of magnitude	no threshold	no	yes	yes	yes	yes
Flicker rate (Hz) or constant	no threshold	0.67	1.50	1.55	constant	1.57
Flash duration (s)	no threshold	0.03	0.33	0.33	constant	0.23

Bycatch mitigation - seabirds, and crew safety						
Activation method	no threshold	water contact	water contact	water contact	water contact	manual
Weight in air (LEDs including batteries) (g)	< 150g	37	46	46	128	110
Apparent weight (in seawater, LEDs including batteries) (g)	no threshold	12	18	18	13	26
Economic viability						
Cost per unit, ≥200 units, USD (excluding shipping and customs)	< USD$20 reusable; <USD$10 single-use	7.79	5.00	5.00	17.25	8.30
Replaceable batteries?	no threshold	no	yes	yes	yes	yes

Table 1b. Phosphorescent lights and conventionally used chemical lightsticks. Values shaded grey did not meet the specified threshold.

Characteristic	Threshold	Light model[a]						
		Paqlite GloStick blue	Paqlite Tab blue	Paqlite Scooblite	Chemilures green	Gloweez green	Gloweez pink	Gloweez blue
Light category	no threshold	Phosphorescent	Phosphorescent	Phosphorescent	Chemical lightstick	Chemical lightstick	Chemical lightstick	Chemical lightstick
Bycatch mitigation - marine turtles								
λ_{max} (nm) [b]	no threshold	492	491	522	518	530, 380	380, 636, 436	380, 450
λ_{max} color visible to humans [b]	violet to blue, 1 or more peak in blue	cyan (blue-green)	cyan (blue-green)	green	green	green, violet	violet, red, blue	violet, blue
Φe at λ_{max}, t_0 (mW nm^{-1}) [c]	≥4.9*10^{-3} [d]	2.0*10^{-3}	3.0*10^{-4}	9.4*10^{-4}	1.2*10^{-2} (±2.2*10^{-1})	1.2*10^{-2} (±0)	7.5*10^{-3} (±0)	7.2*10^{-3} (±0)
Peak Φe per wavelength in 440-480nm range ≥10% Φe per wavelength at λ_{max}?	yes	yes	yes	yes	no	no	yes	yes
Peak Φe per wavelength within 555-580nm range t_0 (mW nm^{-1})	≤ 10% Φe per wavelength at λ_{max} t_0	3.3*10^{-4}	3.7*10^{-5}	6.1*10^{-4}	6.5*10^{-3} (±1.3*10^{-2})	7.5*10^{-3} (±0)	2.3*10^{-4} (±3.9*10^{-5})	4.1*10^{-4} (±0)

Φe t_0 (mW) [d,e]	≥$3.25*10^{-1}$	$1.3*10^{-1}$	$1.8*10^{-2}$	$7.8*10^{-2}$	$8.0*10^{-1}$ (±1.6)	$9.3*10^{-1}$ (±0)	$3.4*10^{-1}$ (±0)	$5.3*10^{-1}$ (±0)
Bycatch mitigation - seabirds, and crew safety								
Activation method	no threshold	continuous	continuous	continuous	manual	manual	manual	manual
Weight in air (LEDs including batteries) (g)	< 150g	12	4	32	13	7	6	6
Apparent weight (in seawater, LEDs including batteries) (g)	no threshold	0<x<1	0<x<1	6	<0	<0	<0	<0
Economic viability								
Cost per unit, ≥200 units, USD (excluding batteries, shipping, customs import fee)	< USD$20 reusable; <USD$10 single-use	3.38	6.15	8.87	0.48	0.15	0.15	0.15

[a] See Supplemental Material Section S2 for additional details on the light models.
[b] If multiple values for λ_{max} are listed, then they are listed from highest values.
[c] Mean and 95% CIs reported for models where 2 units were measured, otherwise the value from measurement of a single unit is reported.
[d] Threshold is 50% of the mean of the 4 conventionally used chemical lightsticks.
[e] Both flashing and constant models underwent the same measurement method for total, integrated radiant power.

Table 2. Diminution of short-listed LED lights (Table 2a), and of phosphorescent lights and conventionally used chemical lightsticks (Table 2b). λ_{max}=wavelength where the emission spectrum of a light source reaches a maximum; Φe=radiant power. Φe measured over the wavelength range 380-780nm.

Table 2a. Diminution of short-listed LED lights.

Characteristic	Threshold	Light model [a]				
		Catch All bullet deep drop blue	FishTek ProGlow Superbright blue	FishTek ProGlow Ultrabright blue	DYP-100 blue	SY-66 blue
Φe t_0 (mW)	≥$3.25*10^{-1}$	$5.1*10^{-1}$	$5.5*10^{-1}$	$5.0*10^{-1}$	8.3	25.0
Φe $t_{5\ days}$ (mW)	≥$6.5*10^{-2}$ [b]	$4.0*10^{-1}$	$4.6*10^{-1}$	$2.5*10^{-1}$	3.6	5.8
Φe $t_{15\ days}$ (mW)	≥$6.5*10^{-2}$ [b,c]	$2.3*10^{-1}$	$2.7*10^{-1}$	$7.0*10^{-2}$	2.9	1.7

Table 2b. Diminution of phosphorescent lights and conventionally used chemical lightsticks. Values shaded grey did not meet the specified threshold.

Characteristic	Threshold	Phosphorescent light model[a]			Chemical lightstick model[a]			
		Paqlite GloStick blue	Paqlite Tab blue	Paqlite Scooblite	Chemilures green	Gloweez green	Gloweez pink	Gloweez blue
Φe t_0 (mW)	≥$3.25*10^{-1}$	$1.3*10^{-1}$	$1.8*10^{-2}$	$7.8*10^{-2}$	1.6	$9.3*10^{-1}$	$3.4*10^{-1}$	$5.3*10^{-1}$
Φe $t_{6\ hours}$ (mW)	≥$1.3*10^{-1}$	$1.3*10^{-2}$	$4.6*10^{-3}$	$8.7*10^{-3}$	$1.5*10^{-1}$	$3.3*10^{-1}$	$2.8*10^{-1}$	$2.6*10^{-1}$
Φe $t_{12\ hours}$ (mW)	≥$9.2*10^{-2}$	$2.1*10^{-3}$	$2.3*10^{-3}$	$2.3*10^{-3}$	$5.6*10^{-2}$	$2.3*10^{-1}$	$2.3*10^{-1}$	$2.2*10^{-1}$
Φe $t_{18\ hours}$ (mW)	≥$7.9*10^{-2}$	0.0	0.0	0.0	$1.4*10^{-2}$	$2.0*10^{-1}$	$2.1*10^{-1}$	$2.1*10^{-1}$
Φe $t_{24\ hours}$ (mW)	≥$7.8*10^{-2}$	0.0	0.0	0.0	$7.1*10^{-3}$	$2.0*10^{-1}$	$2.1*10^{-1}$	$2.1*10^{-1}$

[a] See Supplemental Material Section S2 for additional details the light models.
[b] Threshold is mean of 2 measurements each of the 4 chemical lightsticks (see Table S2).
[c] Threshold applies to single-use LEDs with non-replaceable batteries.

Table 3. Summary of six longline captains' perspectives on the practicality, safety and economic viability of alternative LED light models. Questions 3 through 12 are relative to fishing with conventionally used chemical lightsticks. N=number of respondents.

Question	LED model			
	Catch All deep drop blue flash	**ProGlow blue flash[a]**	**DYP-100 blue constant**	**SY-66 blue flash**
If some were damaged or malfunctioned, what was the cause?	None damaged (N=6)	None damaged (N=2) Very few damaged, cause not known (N=2) Shark bites (N=1) Corrosion of contact points (N=1)	None damaged (N=4) Very few damaged, cause not known (N=1) Corrosion of contact points (N=1)	None damaged (N=5) Very few damaged, cause not known (N=1)
Did you leave the LED lights attached to branchlines when stored in bins or remove them after each haul?	Both (N=1) Remove after each haul (N=5)	Remove after each haul (N=6)	Remove after each haul (N=6)	Remove after each haul (N=6)
Effect on building branchlines	No difference (N=3, attach with rubber bands or tape) Slightly more difficult (N=3, attach two points instead of a single point on a lightstick, attach with rubber bands instead of clipping lightsticks, an additional component to crimp)	No difference (N=3, attach with rubber bands or collar) Slightly more difficult (N=3, attach with rubber bands instead of clipping lightsticks)	Slightly easier (N=5, clip on instead of attach with rubber bands) No difference (N=1, both clip on)	Slightly easier (N=5, clip on instead of attach with rubber bands) No difference (N=1, both clip on)
Effect on number of branchlines that can be stored in a bin	No difference (N=5, removed before storing) No difference (N=1, left some on branchlines coiled in bins)	No difference (N=6, removed before storing)	No difference (N=6, removed before storing)	No difference (N=6, removed before storing)

Effect on frequency of gear tangling in bins	No difference (N=4, removed before storing) Slightly more frequent (N=1, left some on branchlines coiled in bins)	No difference (N=6, removed before storing)	No difference (N=6, removed before storing)	No difference (N=6, removed before storing)
Effect on setting	No difference (N=3) Slightly more difficult (N=3, more time to attach)	No difference (N=3) Slightly more difficult (N=3, more time to attach)	Slightly easier (N=4, less time to attach) No difference (N=1) Slightly more difficult (N=1, the lights are bulky attached close to hooks)	Slightly easier (N=4, less time to attach) No difference (N=1) Slightly more difficult (N=1, the lights are bulky attached close to hooks)
Effect on hauling	No difference (N=3) Slightly more difficult (N=3, more time to remove)	No difference (N=3) Slightly more difficult (N=3, more time to remove)	Slightly easier (N=4, less time to remove) No difference (N=1) Slightly more difficult (N=1, the lights are bulky attached close to hooks)	Slightly easier (N=4, less time to remove) No difference (N=1) Slightly more difficult (N=1, the lights are bulky attached close to hooks)
Effect on crew safety	No difference (N=2, retrieve branchlines in a way that avoids flybacks coming on deck, attached far from hooks) Slightly less safe (N=4, increased risk to crew from flybacks as the light is bigger/heavier)	No difference (N=2, retrieve branchlines in a way that avoids flybacks coming on deck, attached far from hooks) Slightly less safe (N=4, increased risk to crew from flybacks as the light is bigger/heavier)	No difference (N=5, attached far from hooks, retrieve branchlines in a way that avoids flybacks coming on deck) Slightly less safe (N=1, increased risk to crew from flybacks as the light is bigger/heavier attached close to hooks)	No difference (N=5, attached far from hooks, retrieve branchlines in a way that avoids flybacks coming on deck) Slightly less safe (N=1, increased risk to crew from flybacks as the light is bigger/heavier attached close to hooks)
Effect on rate of damage and loss of terminal tackle or other gear components	No difference (N=5) Slightly more frequent (N=1, increased shark captures and bite-offs)	No difference (N=4) Slightly more frequent (N=2, collar pinches the branchline, increased shark captures and bite-offs)	No difference (N=4) Slightly more frequent (N=2, increased shark captures and bite-offs)	No difference (N=2)

				Much more frequent (N=4, increased shark captures and bite-offs)
Effect on catch rates of commercial species	Slightly higher (N=3) No difference (N=1) Not sure (N=1) Slightly lower (N=1)	Slightly higher (N=3) No difference (N=1) Not sure (N=1) Slightly lower (N=1)	Slightly higher (N=1) No difference (N=2) Not sure (N=2) Slightly lower (N=1)	Slightly higher (N=1) No difference (N=2) Not sure (N=1) Slightly lower (N=1) Much lower (N=1)
How did the LED light affect catch rates on immediately adjacent branchlines without lights?	Slightly higher (N=2) No difference (N=2) Not sure (N=2)	Slightly higher (N=2) No difference (N=2) Not sure (N=1) Slightly lower (N=1)	Slightly higher (N=1) No difference (N=2) Not sure (N=2) Slightly lower (N=1)	Slightly higher (N=2) No difference (N=1) Not sure (N=2) Much lower (N=1)
Is the cost for the LED model acceptable?	Acceptable (N=1) Not sure (N=2) Slightly too expensive (N=2) Much too expensive (N=1)	Acceptable (N=1) Not sure (N=3) Slightly too expensive (N=1) Much too expensive (N=1)	Acceptable (N=1) Much too expensive (N=5)	Acceptable (N=1) Not sure (N=1) Slightly too expensive (N=1) Much too expensive (N=3)
Do you plan to continue to use the LED model?	Yes (N=3, might increase commercial catch relative to lightsticks, might be a cost-effective replacement for lightsticks) Undecided (N=2) No (N=1, might not improve or might reduce commercial catch relative to lightsticks, might increase shark captures and bite-offs)	Yes (N=3, might increase commercial catch relative to lightsticks, might be a cost-effective replacement for lightsticks, likes that it can be used with rechargeable batteries) Undecided (N=1) No (N=2, might not improve or might reduce commercial catch relative to lightsticks, might increase shark captures and bite-offs, corrosion of the contact points)	Yes (N=1, it is similar to the SY-66, already used by this respondent, and about the same price from a local supplier) Undecided (N=1) No (N=4, too expensive, might reduce commercial catch relative to lightsticks, might increase shark captures and bite-offs, corrosion of the contact points)	Yes (N=1, already used by this respondent) Undecided (N=1) No (N=4, too expensive, might reduce commercial catch relative to lightsticks, might increase shark captures and bite-offs)

[a] Responses for the ProGlow Superbright and Ultrabright models were identical and therefore a single record is provided for the two models.

FIGURE CAPTIONS

Figure 1. Total, uniform spectral power distribution from spectroradiometer measurements within an integrating sphere of LED fishing lights. *Y*-axis of radiant power (Φe) by wavelength is normalized to a scale of 0 to 1. (a) Catch All Tackle bullet blue flashing, 1.0=$1.2*10^{-2}$ mW nm^{-1}, Φe at t_0=$5.1*10^{-1}$ mW (total Φe across the measured spectrum); and (b) FishTek ProGlow Superbright blue flashing, 1.0=$2.4*10^{-2}$ mW nm^{-1}, Φe at t_0=$5.5*10^{-1}$ mW.

Figure 2. Total, uniform spectral power distribution from spectroradiometer measurements within an integrating sphere of two chemical lightsticks. Radiant power (Φe) by wavelength is normalized to a scale of 0 to 1. (a) green Chemilures Superclips, used by a US north central Pacific Ocean swordfish longline fishery, 1.0=$2.3*10^{-2}$ mW nm^{-1}, Φe at t_0=1.6 mW (total Φe across the measured spectrum); and (b) blue UltraGlo Universal Deep/Surface Light Stick, one of three types of lightsticks used by an Australian south Pacific southern bluefin tuna longline fishery, 1.0=$7.2*10^{-3}$ mW nm^{-1}, Φe at t_0=$5.3*10^{-1}$ mW.

FIGURES

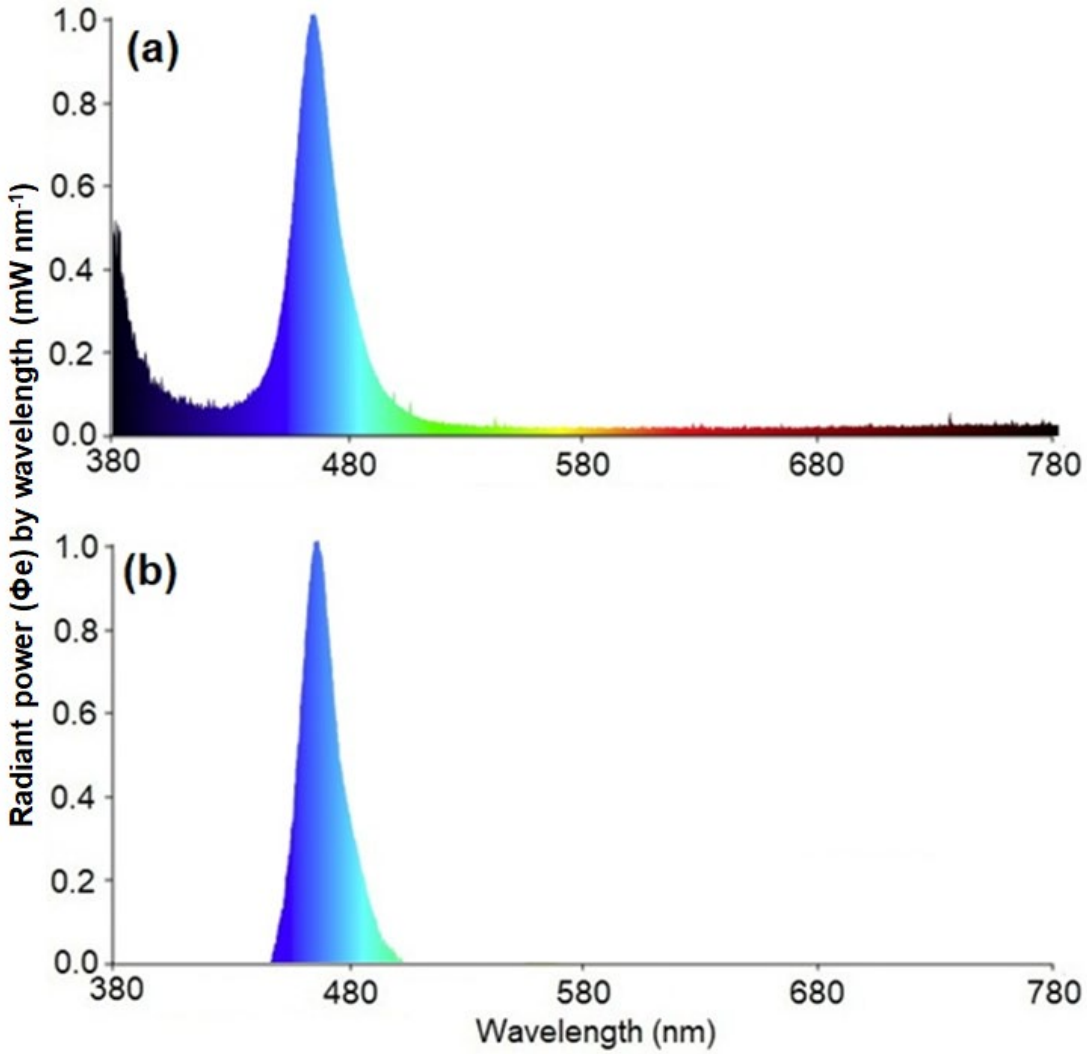


Figure 1

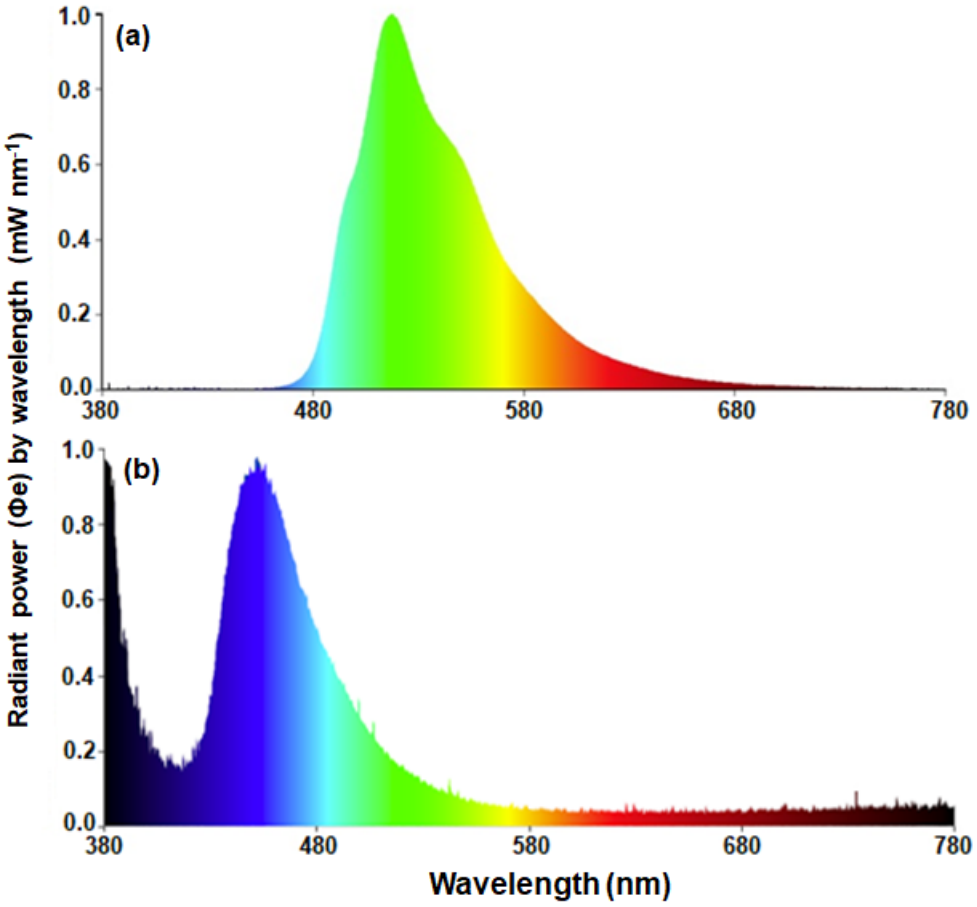

(a)
(b)
1.0
0.8
0.6
0.4
0.2
0.0
380
480
580
680
780
Radiant power (Φe) by wavelength (mW nm-1)
Wavelength (nm)

Figure 2

Supplemental Material

Exploring LED and phosphorescent lights to replace single-use lightsticks to reduce plastic pollution and mitigate fisheries bycatch

Eric Gilman, Cheng Zhou, Milani Chaloupka, Eric Kingma, Brendan Godley, Francois Poisson, Ochi Daisuke

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S1. Spectral and Flicker Frequency Temporal Sensitivities of Marine Turtles, Large Pelagic Teleosts, Pelagic Sharks and Pelagic Seabirds

Table S1 summarizes the maximum spectral sensitivities (λ_{max}), the peak or maximum flicker fusion frequency (FFF) sensitivities (i.e., the FFF with the highest sensitivity), and critical (i.e., limit threshold above which flickering lights are detected as steady and dim) FFF sensitivity of adult marine turtle, commercial teleost, pelagic shark, and pelagic seabird species that are captured in shallow-set pelagic longline fisheries. Estimates are derived from various approaches such as microspectrophotometry (MSP) and electroretinography (ERG) methods, measured for various age classes, and measured at various light levels and temperatures.

Table S1. Synthesis of estimates of maximum spectral sensitivity (λ_{max}), maximum flicker fusion frequency (FFF), and critical FFF for species of marine turtles, commercial teleosts, pelagic sharks, and pelagic seabirds that are susceptible to capture in shallow-set pelagic longline fisheries.

Species	λ_{max} (nm)	Peak FFF (Hz)	Critical FFF (Hz)	Citations
Marine Turtles				
Green	555, 580	10	30, 36, 40-57	Levenson et al. 2004; Eckert et al. 2006; Fritsches and Warrant 2006; Southwood et al. 2008
Leatherback	500, 509, 600	5	16	Eckert et al. 2006; Crognale et al. 2008
Loggerhead	520, 580	8-16	40	Levenson et al. 2004; Johnsen 2006
Pelagic Marine Teleosts				
Bigeye tuna	485	No estimate	12, 23, 34[a]	Fritsches et al. 2005; Fritsches and Warrant 2006
Dolphinfish	No estimate	No estimate	81	Fritsches and Warrant 2006

Species	λ_{max} (nm)	Peak FFF (Hz)	Critical FFF (Hz)	Citations
Pacific bluefin tuna	479, 474-494	No estimate	No estimate	Matsumoto et al. 2009, 2011
Striped marlin	436, 488, 525, 531	No estimate	56	Fritsches et al. 2003; Fritsches and Warrant 2006; Johnsen 2006
Southern bluefin tuna	No estimate	No estimate	35	Fritsches and Warrant 2006
Swordfish	434	No estimate	32, 38, 50[b]	Fritsches et al. 2005; Fritsches and Warrant 2006
Yellowfin tuna	426, 483, 485	No estimate	38, 79, 80[c]	Loew et al. 2002; Fritsches et al. 2005; Fritsches and Warrant 2006; Southwood et al. 2008
Pelagic Sharks				
Blue	503, 518[d]	No estimate	No estimate	Hart et al. 2025
Common thresher	492, 505[d]	No estimate	No estimate	Hart et al. 2025
Great white	501, 503[d]	No estimate	No estimate	Hart et al. 2025
Shortfin mako	501, 503[d]	No estimate	No estimate	Hart et al. 2025
Pelagic Seabirds				
Wedge-tailed shearwater	502[e]	No estimate	No estimate	Hart 2004; Hart and Vorobyev 2005

[a] In addition to the influence of light levels, bigeye tuna critical FFF values vary by temperature, for instance with a critical FFF of 12 Hz at 15°C and 23 Hz at 22°C (Fritsches et al. 2005).

[b] Swordfish maintain eye and brain temperatures between 19 and 28°C. In addition to the influence of light levels, limit FFF varies by temperature with for example a critical FFF of 20 Hz at 19°C and >50 Hz at 25°C at daytime 100m depth light levels (Fritsches et al. 2005).

[c] Estimated critical FFF of 38 Hz at 22°C at daytime 100m depth light levels (Fristches et al. 2005).

[d] Rod λ_{max}: 503 nm for blue, great white and shortfin mako sharks and 404 nm for common thresher shark. Cone λ_{max}: 518 nm for blue shark, 492 nm for common thresher shark, and 501 nm for great white and shortfin mako sharks.

[e] Value is rod λ_{max} which had the highest absorbance of rod and cone λ_{max}. Cone λ_{max} = 406 nm, 450 nm, 503 nm, and 566 nm (Hart 2004).

Implications for Pelagic Longline Bycatch Mitigation

- Wavelengths between *ca* 400-480 nm (perceived as violet to blue by humans) includes the maximum spectral sensitivity (λ_{max}) of swordfish and other pelagic longline commercial teleost species such as bigeye and yellowfin tunas and avoids the longer wavelength range of λ_{max} of adult, sub-adult and large juvenile marine turtles. The λ_{max} for green and loggerhead turtles is *ca* 555-580 nm, perceived as yellow by humans, and 500 nm for leatherback turtles, perceived as cyan or greenish-blue by humans (Loew et al. 2002; Levenson et al. 2004; Eckert et al. 2006; Fritsches et al. 2003; Fritsches and Warrant 2006; Wang et al. 2007; Crognale et al. 2008; Southwood et al. 2008). The λ_{max} of commercial species of pelagic longline fisheries, including swordfish, tunas and istiophorid billfishes, are within the range of 426 to 531 (visible to humans as violet, blue, cyan and green), corresponding to wavelengths that penetrate below 50m, but most of their λ_{max} values are within the violet to blue range (Table S1).
- The spectra detected by leatherback turtles is similar to and overlaps with that of swordfish and other billfishes, particularly at night. As a result, adjusting lightstick/LED wavelength to provide a bycatch mitigation solution would be more challenging for leatherbacks than for hardshelled turtles.
- At low light levels, marine turtles have substantially lower flicker sensitivity than billfishes. Turtles may detect rapidly flickering lights as steady and dimmer, reducing the lights' visibility to turtles relative to a non-flickering, steady light of the same light level (Fritsches

and Warrant 2006; Johnsen 2006; Crognale et al. 2008). In dim light, green and loggerhead turtles are most responsive to lights with relatively low flicker rates of between 16 and 24 Hz and leatherback turtles to flicker rates of between 4 and 12 Hz (Eckert et al. 2006; Crognale et al. 2008). LEDs flickering between 16 and 32 Hz would be difficult for adult leatherback turtles to detect as flickering but would be seen as flickering by swordfish (Fritsches et al. 2005; Crognale et al. 2008).

- Flicker fusion frequency sensitivity increases with increasing temperature and light intensity. Under bright conditions and near the surface, marine turtles and epipelagic fishes have a higher flicker rate sensitivity than swordfish and other mesopelagic species (Fritsches et al. 2005; Fritsches and Warrant 2006).
- Marine turtles have lower optical sensitivity than billfishes – turtles are less capable of detecting low light intensities relative to swordfish and istiophorid billfishes (Fritsches and Warrant 2006; Southwood et al. 2008).
- Witherington and Bjorndal (1991) observed hatchling loggerheads to have an aversion to 560 to 600 nm light. Wang et al. (2007) found captive-reared juvenile loggerheads were attracted to peak 548 nm (perceived as yellow by humans) lightsticks and peak 595 nm (perceived as orange by humans) LED lights. However, much of the spectral emissions of these two lights found by Wang et al. (2007) to attract juvenile loggerheads falls outside of the narrow spectral range found to elicit an aversion response by hatchlings. A light with wavelengths that fall within the narrow spectral range determined by Witherington and Bjorndal (1991) to repel loggerhead hatchlings might also repel older age classes of some turtle species without repelling commercial fishes, and requires testing.
- Estimates of the scotopic (low light, nighttime) conditions rod λ_{max} values of four pelagic shark species (blue *Prionace glauca*, common thresher *Alopias vulpinus*, great white *Carcharodon carcharias*, and shortfin mako *Isurus oxyrhinchus*) are between 503-505 nm (green to humans) and cone (brighter, daytime) conditions λ_{max} values ranged from 492 to 518 nm (cyan to green to humans) (Hart et al. 2025). Based on limited information on the spectral sensitivity of pelagic elasmobranchs that are captured in pelagic longline fisheries, their λ_{max} range includes wavelengths visible to humans as cyan and green. Thus, as with hardshelled marine turtles, the use of fishing lights with a wavelength range of *ca* 400-480 nm might enable peak detection by longline commercial teleost species while avoiding the peak spectral sensitivity of some pelagic sharks. However, the λ_{max} estimated for mesopelagic sharks are closer to the λ_{max} values of commercial teleosts relative to hardshelled turtles and therefore this bycatch mitigation approach might have a smaller effect on shark catch risk than for hardshelled turtles.
- The λ_{max} of rod visual pigments in elasmobranchs might be correlated with the spectrum of light available at their habitat depth. Species that predominantly occur in shallow waters or are active during the daytime have rod scotopic (low light, nighttime) condition λ_{max} values mainly in the wavelength range visible as green to humans. Predominantly deeper habitat or nocturnally-active species have blue-shifted, shorter wavelength rod λ_{max} values (either because this is suitable for the light conditions of their habitat and nocturnal activity or because it matches the spectral peaks of bioluminescence) (McComb et al. 2010; Kalinoski et al. 2014; Hart et al. 2006, 2011, 2025). In general, deeper-habitat mesopelagic and bathypelagic species typically possess vision optimized for extreme sensitivity in low light environments, and have poor or no color sensitivity (e.g., Douglas et al. 1998). Cone (brighter, daytime) condition λ_{max} values under mesopic and photopic conditions shift into longer wavelengths (mainly in the range that is green to humans) (Hart et al. 2011). While few estimates of λ_{max} values for pelagic sharks were available, and no estimates for the main epipelagic sharks (silky *Carcharhinus falciformis* and oceanic whitetip *C. longimanus*) nor main ray species (pelagic stingray, *Pteroplatyrgon violacea*)

captured in global pelagic longline fisheries (Gilman 2011) to evaluate these hypothesized general patterns, the large body of literature on peak spectral sensitivity of coastal and demersal sharks provides a basis for predictions for epipelagic elasmobranchs. Rod λ_{max} values of coastal and demersal sharks range from 470 to 530 nm (blue to green to humans) and cone λ_{max} values range from 518 to 561 nm (green to humans) (Tamura and Niwa 1967; Niwa and Tamura 1975; Cohen and Gruber 1985; Crescitelli et al. 1985; Cohen 1990; Crescitelli 1991; Gacic et al. 2006; McComb et al. 2010; Kalinoski et al. 2014; Hart et al. 2011, 2025).

- Based on peak and critical FFF values for coastal and demersal shark species (reviewed in the article Results section), as with marine turtles, lights with sufficiently high flicker rate might reduce elasmobranch detection, especially for mesopelagic species. However, no commercially available LED lights have sufficiently fast flashing rates to achieve this.
- Based on only spectral sensitivity estimates for a single pelagic seabird species that is susceptible to pelagic longline bycatch, seabirds might be able to detect light emitting devices across most of the visible spectrum, from violet to yellow to humans. Seabirds scavenging from pelagic longline vessels might learn that the presence of a lightstick or LED light indicates the presence of baited hooks or the light might illuminate and increase seabirds' visual detection of terminal tackle.
- Characteristics of fishing lights other than species-specific detectability such as due to λ_{max}, flicker rate, and irradiance might also affect the species selectivity of longline catch, such as effects on attracting and aggregating prey species, and degree of simulating characteristics of their prey.

S2. Fishing Light Characteristics

Table S2a provides information on the characteristics of short-listed LED models and phosphorescent lights and Table S2b provides details for conventionally employed lightsticks. The Chemilures superclips lightstick and the Gloweez lightstick were used by Hawaii-based and Australian vessels that participated in the LED light demonstration, respectively. We did not measure light characteristics of two lightsticks (visible to humans as blue and green) used by the La Réunion longline fishery. The La Réunion vessel that participated in the LED light demonstration uses a generic model, purchased from a local supplier who imports the lightsticks from Korea, for which the manufacturer could not be identified.

Table S2. Characteristics of short-listed LED and phosphorescent lights (Table S2a), and conventionally-employed chemical lightsticks (Table S2b).

Table S2a. LED and phosphorescent lights.

Characteristic	**Light model**							
Light category	LED	LED	LED	LED	LED	phosphorescent	phosphorescent	phosphorescent
Manufacturer	Catch All Tackle	FishTek Marine	FishTek Marine	Dongyang Engineering Co	Marine Delta	UV Paqlite	UV Paqlite	UV Paqlite
Model	Bullet Deep Drop Strobe Lights with glow head flashing blue	ProGlow Superbright blue flash	ProGlow Ultrabright blue flash	DYP-100 blue	SY-66 blue	UV blue GloStick	Tab blue	Scooblite 6"
Lowest wavelength (nm) with radiant power per wavelength >0	<380	430	<380	<380	<380	424	454	463
Highest wavelength (nm) with radiant power per wavelength >0	>780	529	>780	>780	>780	752	579	670
Attachment method	thread line	collar or ring	collar or ring	clip	eye or ring	eye	eye	eye
Dimensions (cm)	8x2x2	9.1x2.7x1.4	9.1x2.7x1.4	11.7x5.5x5.5	13.6x4.0x4.0	8.89X1.91x1.27	5.1x2.54x0.635	15.24x1.625
Can be used with replaceable lithium batteries?	NA	yes	yes	not reported	no	NA	NA	NA
Size of replaceable batteries	NA	AAA	AAA	AA	AA	NA	NA	NA
Number of replaceable batteries	NA	2	2	2	2	NA	NA	NA
Reported depth rating (m)	600	1000	1000	700	300	not reported	not reported	not reported

Table S2b. Chemical lightsticks.

Characteristic	Light model			
Manufacturer	World Plastics	Gloweez International	Gloweez International	Gloweez International
Model	Chemilures superclips 6" green	Gloweez 4" Green ISO 9001 UltraGlo Universal Deep/Surface Light Stick	Gloweez 4" Pink ISO 9001 UltraGlo Universal Deep/Surface Light Stick	Gloweez 4" Blue ISO 9001 UltraGlo Universal Deep/Surface Light Stick
Lowest wavelength (nm) with radiant power per wavelength >0	383	<380	<380	<380
Highest wavelength (nm) with radiant power per wavelength >0	>780	>780	>780	>780
Method to attach to branchlines	clip or rubber band	clip or rubber band	clip or rubber band	clip or rubber band
Dimensions (cm)	15.5x1.2x1.2	11.5x1.0x1.0	11.5x1.0x1.0	11.5x1.0x1.0
Reported depth rating (m)	not reported	990	990	990



Five short-listed LED fishing lights, from left to right as listed in Table S2a: CatchAll Bullet Deep Drop, ProGlow Superbright with a locking collar, ProGlow Ultrabright with a ring, DYP-100 with a clip, and SY-66 with a ring.

The following are links to three short video clips show the ProGlow and DYP-100 LED models when deployed on pelagic longline branchlines:

- Proglow with baited hook and baitfish
- DYP100 with baited hook
- DYP100 with baited hook and striped marlin strike

S3. Results of Measurements of Fishing Light Directional and Spectral Properties

Table S3 presents the results of measurements of directionality of five short-listed LED models.

Table S3. Directionality of five short-listed LED models, assessing total irradiance *Ee* (mW m^{-2}) and irradiance *Ee* per wavelength (mW m^{-2} nm^{-1}) at t_0 (with new batteries) over a wavelength range of 380-780nm with the light oriented at 0° (light pointing towards the spectroradiometer sensor probe), 45° and 90° (perpendicular to the spectroradiometer sensor probe), using an Everfine High Accuracy Array Spectroradiometer HAAS-2000.

Measurement	Catch All deep drop blue flash	ProGlow Superbright blue flash	ProGlow Ultrabright blue flash	DYP-100 blue constant	SY-66 blue flash
0° total irradiance, t_0 (mW m^{-2})	$5.7*10^{-3}$	$3.1*10^{-4}$	$3.7*10^{-4}$	$3.8*10^{-3}$	$2.6*10^{-3}$
45° total irradiance, t_0 (mW m^{-2})	$3.0*10^{-4}$	$3.2*10^{-4}$	$8.4*10^{-4}$	$4.1*10^{-3}$	$1.1*10^{-2}$
90° total irradiance, t_0 (mW m^{-2})	$1.5*10^{-4}$	$2.1*10^{-4}$	$2.7*10^{-4}$	$1.1*10^{-3}$	$2.5*10^{-3}$
Is multi-directional, such that the total irradiance at t_0 of each measured orientation are within one order of magnitude?	no	yes	yes	yes	yes
Peak wavelength(s) λmax (nm) of all three orientations	464	464	464	455	457
Irradiance at peak wavelength mW m^{-2} nm^{-1} of all three orientations	$2.2*10^{-4}$	$1.2*10^{-5}$	$3.4*10^{-5}$	$1.7*10^{-4}$	$4.8*10^{-4}$
Orientation with highest irradiance at peak wavelength	0°	45°	45°	45°	45°

Figures S1, S2 and S3 show the absolute, spatially-averaged spectral measurements of radiant power (Φe) by wavelength (mW nm^{-1}) from measurements within an integrating sphere. These three figures show the peak wavelength(s) λ_{max} and wavelength range measured between 380 to 780 nm for the unit of each model that is included in Tables 1 and S1 for which diminution was assessed. Figure S1 presents results for three of the LED light models, with new batteries, that were included in fishery demonstrations, Figure S2 presents results for three phosphorescent lights immediately following four hours of charging in direct sunlight, and Figure S3 presents results for two of the conventional chemical lightsticks upon activation (t_0) that are used in the Australian east coast bluefin tuna longline fishery.

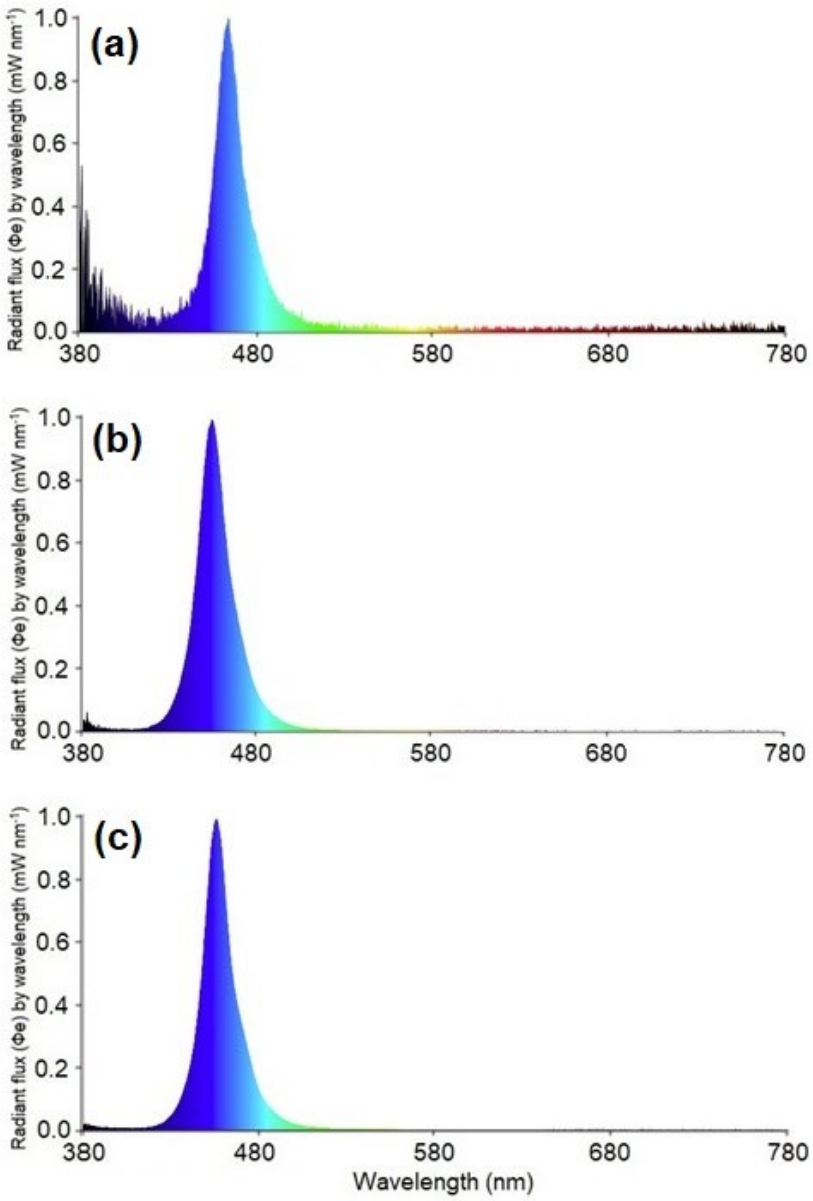


Figure S1. Total, uniform spectral power distribution from spectroradiometer measurements within an integrating sphere of LED fishing lights. *Y*-axis of radiant power (Φe) by wavelength is normalized to a scale of 0 to 1. (a) FishTek ProGlow Ultrabright blue flashing, $1.0=1.5*10^{-2}$ mW nm^{-1}, Φe at $t_0=5.0*10^{-1}$ mW (the total radiant power across the measured spectrum); (b) Dongyang Engineering Co. DYP-100 blue constant, $1.0=3.2*10^{-1}*10^{-1}$ mW nm^{-1}, Φe at $t_0=8.3$ mW; and (c) SY-66 blue constant, 1.0=1.1 mW nm^{-1}, Φe at $t_0=25.0$ mW.

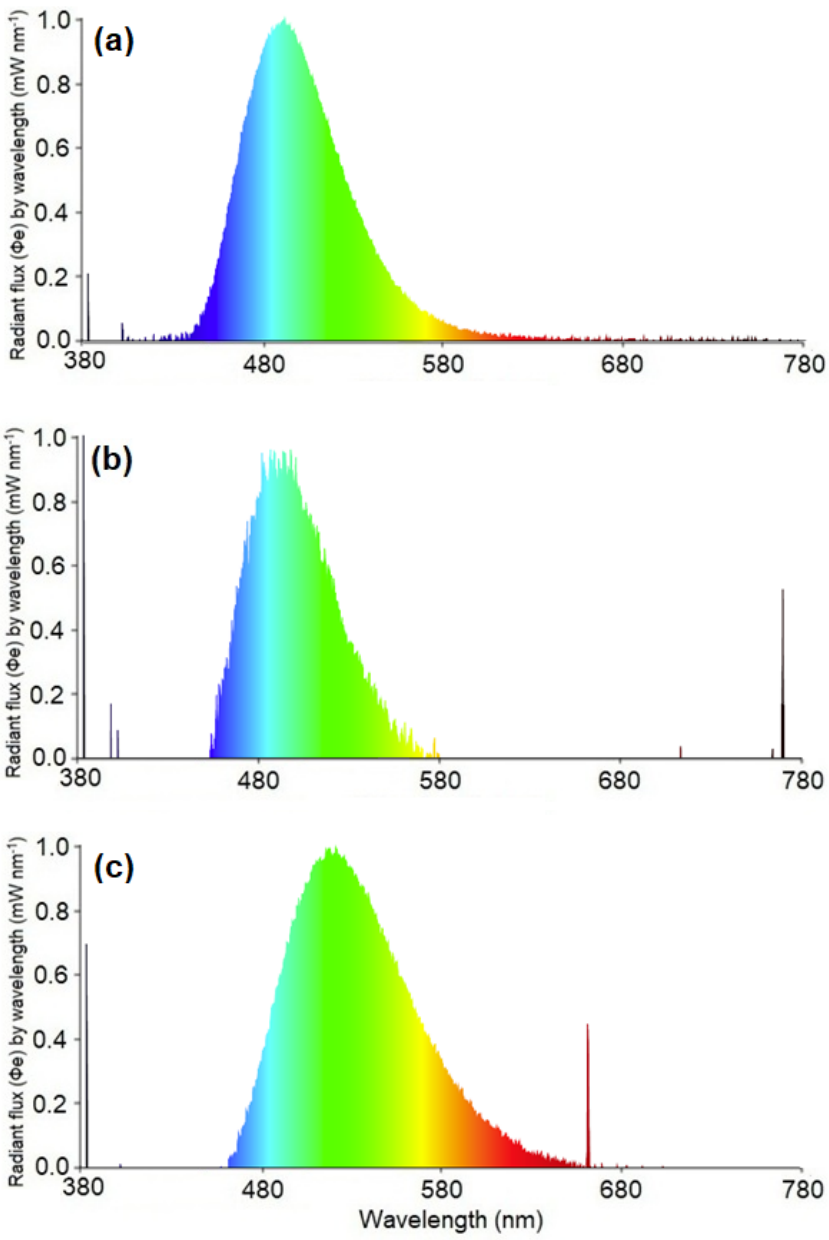


Figure S2. Total, uniform spectral power distribution from spectroradiometer measurements within an integrating sphere of three phosphorescent lights. *Y*-axis of radiant power (Φe) by wavelength is normalized to a scale of 0 to 1. (a) UV Paqlite blue GloStick, $1.0=2.0*10^{-3}$ mW nm^{-1}, Φe at $t_0=1.3*10^{-1}$ mW (the total radiant power across the measured spectrum); (b) UV Paqlite Tab blue, $1.0=3.0*10^{-4}$ mW nm^{-1}, Φe at $t_0=1.8*10^{-2}$ mW; and (c) UV Paqlite Scooblite 6 inch, $1.0=9.4*10^{-4}$ mW nm^{-1}, Φe at $t_0=7.8*10^{-2}$ mW.

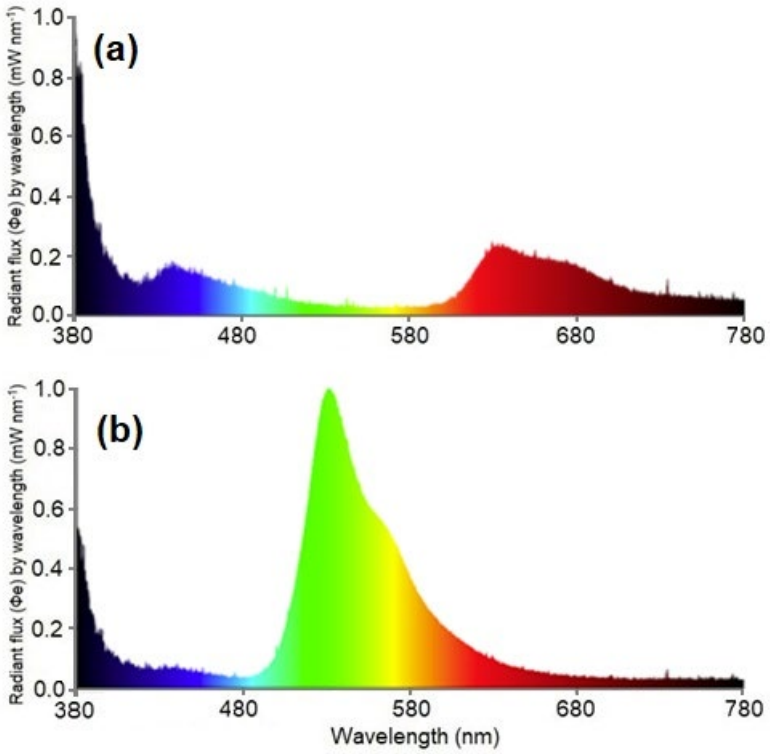


Figure S3. Total, uniform spectral power distribution from spectroradiometer measurements within an integrating sphere of two conventional chemical lightsticks that are used in the Australian east coast bluefin tuna longline fishery. *Y*-axis of radiant power (Φe) by wavelength is normalized to a scale of 0 to 1. (a) Gloweez 4" Pink ISO 9001 UltraGlo Universal Deep/Surface Light Stick, 1.0=$7.5*10^{-3}$ mW nm^{-1}, Φe at t_0=$3.4*10^{-1}$ mW (the total radiant power across the measured spectrum); and (b) Gloweez 4" Green ISO 9001 UltraGlo Universal Deep/Surface Light Stick, 1.0=$1.2*10^{-2}$ mW nm^{-1}, Φe at t_0=$9.3*10^{-1}$ mW.

S4. Information Gaps and Research Priorities

This section discusses additional research and development priorities, expanding on the Discussion and Conclusions section of the article.

Cumulative, collateral, adverse impacts of longline artificial lights: There is limited understanding of the cumulative indirect impacts of pelagic longline artificial lights on the ecological processes and behavior of pelagic species, including on predator-prey interactions, diurnal depth and geospatial distributions, residence time at the illuminated fishing gear, and disruption to schooling. Using brighter LED lights in place of dimmer lightsticks might exacerbate any underwater light pollution effects of pelagic longline fisheries. Longline lights might alter pelagic species' ecological processes and behavior, such as altering schooling behavior, altering the diel vertical migration cycles of pelagic predators and their prey and attracting or repelling species from adjacent areas (Davies et al. 2014; Nightingale et al. 2006). Longline lights might alter predator-prey interactions by causing facilitated predation of live released catch and increased predation risk of nocturnal foraging prey by diurnal and crepuscular predators (Gilman et al. 2013; Davies et al. 2014; Marangoni et al. 2022). Scotopic species (low ambient light, e.g., nocturnal and mesopelagic and bathypelagic species) could experience protracted or permanent visual impairment from close exposure to very bright artificial lights (Magel et al. 2017). The use of brighter longline lights or with other light

characteristics might contribute to fisheries-induced evolution if the lights cause selective fishing mortality within populations based on heritable physiological, morphological and behavioral traits (Heino et al. 2015, Hollins et al. 2018).

Seabird bycatch response to brighter pelagic longline lights: It is a research priority to determine how the use of brighter LED lights in place of dimmer lightsticks by pelagic longline fishing vessels affect long-term seabird catch rates, including effects on predictors that might explain seabird catch risk, including long-term seabird density at fishing vessels and seabird scavenging and competitive behavior (Gilman et al. 2021). Similar to the effect of discarding offal, spent bait and dead discarded catch to distract scavenging seabirds away from baited hooks (Abraham et al. 2009; Pierre et al. 2012; Gilman et al. 2021), the use of fishing lights when attached sufficiently far from baited hooks might have a positive short-term benefit of reducing seabird catch rates. But in the long-term, fishing lights might increase the local abundance of seabirds scavenging from fishing vessels and increase seabird catch rates relative to vessels that do not use lights, and the use of brighter LED lights in place of dimmer conventional lightsticks might result in higher seabird densities attending vessels. However, very bright fishing lights could reduce the density of some seabird species attending longline fishing vessels. Exposure to artificial light causes disorientation and an avoidance response in some seabird species under certain circumstances such as at breeding colonies, with a stronger avoidance response to shorter wavelengths (blue and green as visible to humans) than longer wavelengths (red to humans) and to higher light intensity (Syposz et al., 2021; Atchoi et al., 2024). It is unclear, however, how this observed response translates to responses of seabird species scavenging from pelagic longline vessels using LED fishing lights with Φe (radiant power) within the range of the LED models assessed here (0.4 to 25 mW, Table 1a) given that albatrosses and potentially other pelagic seabird species are attracted to and not repelled by longline branchlines containing green lightsticks (McNamara et al. 1999) (Φe of 0.8 to 0.9 mW, Table 1b).

Control and replicates: Additional field experiments are needed to improve the evidence base on longline catch rate responses to individual characteristics of fishing lights. Employing systematic treatment assignment (a form of probability-based sampling) might be preferable to a ‘simple randomization’ or haphazard design (Gilman and Chaloupka, 2023). A replicate of sections of gear within a set (e.g., multiple ‘baskets’ of branchlines between two floats) is appropriate due to the potential influence of branchlines with treatment LEDs or lightsticks on the catch response of adjacent branchlines.

In controlled field experiments of fishing light treatments, the control should be inactivated LED fishing lights and/or inactivated or spent conventional chemical lightsticks. Including gear without lights, and including conventionally-used lightsticks might also provide important pseudo-controls. However, gear with no lights attached might cause responses that are substantially different from gear with lights (both on and inactivated/spent), and therefore inactivated/spent lights would be a proper control. For example, some bycatch reduction devices used in pelagic longline fisheries when attached very close to baited hooks reduced catch rates of some species, potentially due to the visual detection of the device (e.g., fishing weights Gilman et al., 2022, and an electrical shark deterrent, WPRFMC, 2026). Attaching a light close to longline hooks might cause changes in species-specific catch rates relative to gear without lights due directly or indirectly (e.g., prey attraction) to the energy emission or other underlying mechanism such as being attracted or repelled to the detection of the object. Therefore, including replicates with inactivated/spent lights as a control, in addition to no lights or conventionally used lightsticks as pseudo controls, can provide conclusive evidence of responses to energy emitted from fishing lights.

S5. References

Abraham E, Pierre J, Middleton D, et al. (2009) Effectiveness of fish waste management strategies in reducing seabird attendance at a trawl vessel. *Fish Res* 95:210–219

Atchoi E, Mitkus M, Machado B, et al (2024) Do seabirds dream of artificial lights? Understanding light preferences of Procellariiformes. Journal *of Experimental Biology* 227: 247665

Cohen J, Gruber S (1985) Spectral input to lemon shark (*Negaprion brevirostris*) ganglion cells. *J Comp Physiol A* 156:579–586

Cohen J (1990) Adaptations for scotopic vision in the lemon shark (*Negaprion brevirostris*). *J Exp Zool* 256(suppl.)S5: 76–84

Crognale M, Eckert S, Levenson D, Harms C (2008) Leatherback sea turtle *Dermochelys coriacea* visual capacities and potential reduction of bycatch by pelagic longline fisheries. *Endanger*. *Species Res*. 5: 249–256

Crescitelli F (1991) Adaptations of visual pigments to the photic environment of the deep-sea. *J Exp Zool* (Suppl) 5: 66–75

Crescitelli F, McFall-Ngai M, Horwitz J (1985) The visual pigment sensitivity hypothesis: further evidence from fishes of varying habitats. *J Comp Physiol A* 157: 323–333

Davies T, Duffy J, Bennie J, Gaston K (2014) The nature, extent and ecological implications of marine light pollution. *Front Ecol Environ* 12: 347-355

Douglas R, Partridge J, Marshall N (1998) The eyes of deep-sea fish I: lens pigmentation, tapeta and visual pigments. *Prog Retin Eye Res* 17: 597–636

Eckert S, Levenson D, Crognale M (2006) The sensory biology of sea turtles: What can they see, and how can this help them avoid fishing gear? IN Swimmer Y, Brill R (Eds). Sea Turtle and Pelagic Fish Sensory Biology: Developing Techniques to Reduce Sea Turtle Bycatch in Longline Fisheries. NOAA Technical Memorandum NMFS-PIFSC-7. National Marine Fisheries Service, Pacific Islands Fisheries Science Center, Honolulu, pp. 8-16

Fritsches K, Bril R, Warrant E (2005) Warm eyes provide superior vision in swordfishes. *Current Biology* 15: 55-58

Fritsches KA, Litherland L, Thomas N, Shand J (2003) Cone visual pigments and retinal mosaics in the striped marlin. *J Fish Biol* 63: 1347–1351

Fritsches K, Warrant E. 2006. Differences in the visual capabilities of sea turtles and blue water fishes – implications for bycatch reduction. IN Swimmer Y, Brill R (Eds). *Sea Turtle and Pelagic Fish Sensory Biology: Developing Techniques to Reduce Sea Turtle Bycatch in Longline Fisheries*. NOAA Technical Memorandum NMFS-PIFSC-7. National Marine Fisheries Service, Pacific Islands Fisheries Science Center, Honolulu, pp. 1- 7

Gacic Z, Damjanovic I, Mickovic B, et al. (2006) Spectral sensitivity of the dogfish shark (*Scyliorhinus canicula*). *Fish Physiol Biochem* 33: 21–27

Gilman E (2011) Bycatch governance and best practice mitigation technology in global tuna fisheries. *Marine Policy* 35: 590-609

Gilman E, Chaloupka M, Ishizaki A, et al (2021) Tori lines mitigate seabird bycatch in a pelagic longline fishery. *Rev Fish Biol Fisheries* 31: 653–666

Gilman E, Musyl M, Wild M, et al (2022) Investigating weighted fishing hooks for seabird bycatch mitigation. *Scientific Reports* 12: 2833. DOI: 10.1038/s41598-022006875-4

Gilman E, Suuronen P, Hall M, Kennelly S (2013) Causes and methods to estimate cryptic sources of fishing mortality. *Journal of Fish Biology* 83: 766-803

Hart N (2004) Microspectrophotometry of visual pigments and oil droplets in a marine bird, the wedge-tailed shearwater *Puffinus pacificus*: Topographic variations in photoreceptor spectral characteristics. *The Journal of Experimental Biology* 207: 1229-1240

Hart N, Lisney T, Collin S (2006) Visual communication in elasmobranchs. IN Ladich F, Collin S, Moller P, Kapoor B (Eds). Communication in Fishes. Science Publishers Inc., Enfield, New Jersey, USA; pp. 337-392

Hart N, Pozo-Montoro M, Seeger O, et al (2025) Widespread and convergent evolution of cone monochromacy in Galeomorph sharks. *Molecular Biology and Evolution* 42: 1-17

Hart N, Theiss S, Harahush B, Collin S (2011) Microspectrophotometric evidence for cone monochromacy in sharks. *Naturwissenschaften* 98: 193–201

Hart N, Vorobyev M (2005) Modelling oil droplet absorption spectra and spectral sensitivities of bird cone photoreceptors. *Journal of Comparative Physiology A* 191: 381-392
Hart N, Pozo-Montoro M, Seeger O, et al (2025) Widespread and convergent evolution of cone monochromacy in Galeomorph sharks. *Molecular Biology and Evolution* 42: 1-17
Heino M, Pauli B, Dieckmann U (2015) Fisheries-induced evolution. *Annu Rev Ecol Evol Syst* 46:461-480
Hollins J, Thambithurai D, Koeck B et al (2018) A physiological perspective on fisheries-induced evolution. *Evol Appl* 11:561–576
Johnsen S (2006) Mathematical model of the visual abilities of sea turtles and pelagic fishes. IN Swimmer Y, Brill R (Eds). Sea Turtle and Pelagic Fish Sensory Biology: Developing Techniques to Reduce Sea Turtle Bycatch in Longline Fisheries. NOAA Technical Memorandum NMFS-PIFSC-7. National Marine Fisheries Service, Pacific Islands Fisheries Science Center, Honolulu, pp. 18-23
Kalinoski M, Hirons A, Horodysky A, Brill R (2014) Spectral sensitivity, luminous sensitivity, and temporal resolution of the visual systems in three sympatric coastal shark species. *Journal of Comparative Physiology A* 200: 997-1013
Levenson DH, Eckert SA, Crognale MA, et al (2004) Photopic spectral sensitivity of green and loggerhead sea turtles. *Copeia* 908–914
Loew ER, McFarland WN, Margulies D (2002) Developmental changes in the visual pigments of the yellowfin tuna, *Thunnus albacares. Mar Freshw Behav Physiol* 35: 235–246
Magel C, Ryer CH, Brill R (2017) Recovery of visual function in Pacific halibut (*Hippoglossus stenolepis*) after exposure to bright light. *Fishery Bulletin* 115:566–575
Marangoni L, Davies T, Smyth T, et al (2022) Impacts of artificial light at night in marine ecosystems: A review. *Global Change Biology* 28: 5346-5367
Matsumoto T, Ihara H, Ishida Y, et al (2009) Electroretinographic analysis of night vision in juvenile Pacific bluefin tuna (*Thunnus orientalis*). *Biol Bull* 217: 142-150
Matsumoto T, Okada T, Sawada Y, Ishibashi Y (2011) Changes in the scotopic vision of juvenile Pacific bluefin tuna (*Thunnus orientalis*) with growth. *Fish Physiol Biochem* 37: 693-700
McComb D, Frank T, Hueter R, Kajiura S (2010) Temporal resolution and spectral sensitivity of the visual system of three coastal shark species from different light environments. *Physiological and Biochemical Zoology* 83: 299–307
McNamara B, Torre L, Kaaialii G (1999) Final Report: Hawaii Longline Seabird Mortality Mitigation Project. Western Pacific Regional Fishery Management Council, Honolulu
Nightingale B, Longcore T, Simenstad C (2006) Artificial night lighting and fishes. In: Rich C; Longcore T (Eds.). Ecological Consequences of Artificial Night Lighting. Washington DC, USA: Island Press, pp. 257–276
Niwa H, Tamura T (1975) Investigation of fish vision by means of S-potentials. III. Photoreceptors and spectral sensitivity in elasmobranch's retinae. *Bull Jpn Soc Sci Fish* 41: 393–401
Pierre J, Abraham E, Richard Y, et al (2012) Controlling trawler waste discharge to reduce seabird mortality. *Fish Res* 131:30–38
Southwood A, Fritsches K, Brill R, Swimmer Y (2008) Sound, chemical, and light detection in sea turtles and pelagic fishes: Sensory-based approaches to bycatch reduction in longline fisheries. *Endangered Species Research* 5: 225-238
Syposz M, Padget O, Willis J, et al (2021) Avoidance of different durations, colours and intensities of artificial light by adult seabirds. *Sci Rep* 11: 1-13
Tamura T, Niwa H (1967) Spectral sensitivity and color vision of fish as indicated by S-potential. Comp Biochem Physiol 22: 745–754
Wang J, Boles L, Higgins B, Lohmann J (2007) Behavioral responses of sea turtles to lightsticks used in longline fisheries. *Animal Conservation* 10: 176-182
WPRFMC (2026) Shark Depredation and Mitigation in the Pacific Islands Region Workshop. Western Pacific Regional Fishery Management Council, Honolulu
Witherington B, Bjorndal K (1991) Influences of wavelength and intensity on hatchling sea turtle phototaxis: implications for sea-finding behaviour. *Copeia* 1991: 1060–1069