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Artificial Light in Commercial Industrialized Fishing Applications: A Review

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ABSTRACT
Fishing with an artificial light stimulus has existed for thousands of years. It started with simple techniques such as burning a large fire on the beach to attract fish, but over the centuries it has become increasingly technologically advanced. Today, the use of artificial light in commercial fishing plays a very important role in contributing to the total catch yield and economy of many industrialized fisheries. In most cases, fishing vessels employ lights at the surface, but more recently, low-powered LED lights installed directly on fishing gear have also become common. Using artificial light in commercial fishing applications appears to produce various outcomes and trade-offs (i.e., positive and negative effects). Positive benefits can include increases in catch rate, reductions in bycatch, and savings in energy, while negative effects can include ecological costs, overfishing, increased bycatch, production of plastic and marine litter, and greenhouse gas emission. This review provides an overview of fish vision in aquatic animals and the use of light in commercial industrialized fisheries, and provides discussion on potential solutions that strengthen the positive effects and minimize the negative effects of using artificial light in fishing applications.

KEYWORDS
Fishing with light; fish vision; visual acuity; effect of light; solving light problem

1. Introduction

Visual systems in marine animals play a key role in their involuntary response to detect prey, shelter, conspecifics, as well as interact with fishing gear and vessels (Arimoto et al., 2010). Visual acuity, spectral sensitivity, and motion detection capability are the main components determining the visual capacity of aquatic animals (Zhang, 1992; Arimoto et al., 2010). Not just who you are, but where you live also matters, as different habitats and marine environments can demand different spectral sensitivities of marine organisms, especially deep species such as decapod crustaceans (see Cronin and Jinks, 2001; Johnson et al., 2002). This paper reviews the technical literature on fish vision and behavior in response to artificial light with the goal of developing and promoting sustainable fishing practices. This includes improvements in fishing efficiency, reduction of bycatch and discards, and the mitigation of interaction with protected species.

Although substantial literature exists on the behavior of marine organisms in response to artificial light, comparatively little knowledge exists on 'why' marine organisms are attracted or repelled by light. Most of the literature has concluded that light color (quality) and intensity (quantity) plays a primary role in attraction by producing an engaging stimulus (e.g., Dragesund, 1958; Lagardère et al., 1995; Ibrahim and Hajisamae, 1999; Ciriaco et al., 2003; Marchesan et al., 2005; Liao et al., 2007; Matsui et al., 2016). Sensitivity levels and resulting patterns of behavior are, however, known to vary across species and their ontogeny (see review by Yami, 1976; Cronin and Jinks, 2001; Wang et al., 2007; Frank et al., 2012; Arimoto, 2013; Fitzpatrick et al., 2013; Rooper et al., 2015). For example, the eye of adult fish often differs from those of younger stages because vision in juvenile fish is required for simple tasks (e.g., vertical migration to avoid predators), while vision at older stages is often employed for more elaborate tasks, including navigation, prey recognition and capture, spatial vision, mate selection, and communication (Cronin and Jinks, 2001).

Fishing with light has become one of the most advanced, efficient, and successful methods for capturing commercially important species on an industrialized

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scale. Applications now include a wide variety of pelagic and benthic species across a range of fixed and mobile gear types (e.g., Yami, 1976; Wang et al., 2010; Yamashita et al., 2012; Hannah et al., 2015; Matsui et al., 2016; Ortiz et al., 2016; Solomon and Ahmed, 2016; Nguyen et al., 2017). Although the positive contributions of artificial light in commercial fishing are undeniable, the argument that artificial light also produces negative effects, is growing. Fishing with artificial light is known to contribute to overfishing, bycatch, plastic, litter, and greenhouse gas emissions. This presents potential challenges for globally sustainable fisheries development in the long term (see IDA, 2002; Wang et al., 2010; IEA Statistics, 2011; Thompson, 2013; Mills et al., 2014; Solomon and Ahmed, 2016; Detloff and Istel, 2016).

While many studies have investigated fish vision and behavior, as well as the use of artificial light in commercial fishing, no technical review has been published on visual systems in aquatic animals in relation to their capture by use of artificial light, together with a discussion on the trade-offs of using artificial lights in commercial industrialized fishing applications were found. This paper provides a review of visual systems in aquatic animals, the development and use of light in commercial industrialized fisheries, and a discussion on potential solutions that strengthen the positive effects and minimizes the negative effects of using artificial light in fishing applications.

2. Understanding vision of aquatic marine species and their behavior relative to artificial light

2.1. Vision in aquatic marine species

For most aquatic vertebrates, vision is a key sensory input for day-to-day survival (Atema, 1980). Understanding these visual systems, especially for commercially important species, is a key step in the development of modern and sustainable fishing technologies and operations (e.g., Arimoto et al., 2010; Sokimi and Beverly, 2010; Arimoto, 2013). A substantial number of studies have been conducted on aquatic vertebrate vision in the last few decades (see Yami, 1976; Detto, 2007; Arimoto et al., 2010; Land and Nilsson, 2012). Although the structure of the eye and the mechanisms of vision have been determined for many marine species, detailed knowledge and understanding of the role of vision in their reaction to fishing gears during capture processes are not well known (Arimoto et al., 2010). There are differences in the structure of eyes between fish, crustaceans (i.e., shrimp, crab, and horseshoe crab), and cephalopods (i.e., squid, cuttlefish, and octopus). The fish eye contains two main components: *optics* and *accommodation* (Land and Nilsson, 2012). Optics involves the collection and formation of an image. The sensitivity and acuity of these components depends on the brightness of an image reaching the retina. The pupil is usually motionless, and light control is performed by the retinomotor mechanism involving movement of melanin granules in the retinal pigment cells (Arimoto et al., 2010). Lens quality, receptor size, and density resolve optical resolution. Images are formed by the refractive properties of the lens as the cornea of most fish eyes has a refractive index almost identical to that of water and contributes little to the optics of the eye (Arimoto et al., 2010). Accommodation refers to the focusing of the image on the retina by movement of the lens. The lens is moved backward to focus an image in teleost fish, moved forward in elasmobranchs, while other species (such as lampreys) involve changing the shape of the cornea (Arimoto et al., 2010). The structure of the teleost fish eye includes main components of cornea, lens, iris, ligament, retina, choroid, sclera, falciform process, and optic verve (Arimoto et al., 2010; Arimoto, 2013).

Unlike fish and cephalopods which have a pair of single eyes, vision in decapod crustaceans typically involves many visual system components, known as compound eyes (Johnson et al., 2002; Detto, 2007). Compound eyes consist of individual receptive units called ommatidia (Doujak, 1985; Martin et al., 2016). Each ommatidium contains a complete optical structure including cornea, lens and crystalline cones stacked on top of a set of fused retinular cells, which form the photoreceptive rhabdom (Figure 1). Decapod rhabdoms are formed by eight retinular cells, with seven of these forming the main proximal part of the rhabdom and the eighth contributing a small distal rhabdomere (Martin et al., 2016). Retinular cells help decapod crustaceans to absorb a wide range of wavelengths. For example, the retinular cells No. 1–7 of the main rhabdom absorb the middle (blue-green) to long (red) wavelengths of light (447–570 nm), while the retinular cells No. 8 are typically sensitive to violet or ultra violet light (360–440 nm; Johnson et al., 2002).

Many fish and crustacean species have the capability to recognize color, with a wide spectrum of color sensitivity and resolution. Some shallow water species can even detect ultraviolet radiation (Swimmer and Brill, 2006; Arimoto et al., 2010; Kroger, 2013). In contrast, most squid and cuttlefish are color blind (Kroger, 2013). Many deep sea species living deeper than 200 m (Douglas et al., 1998) have limited color

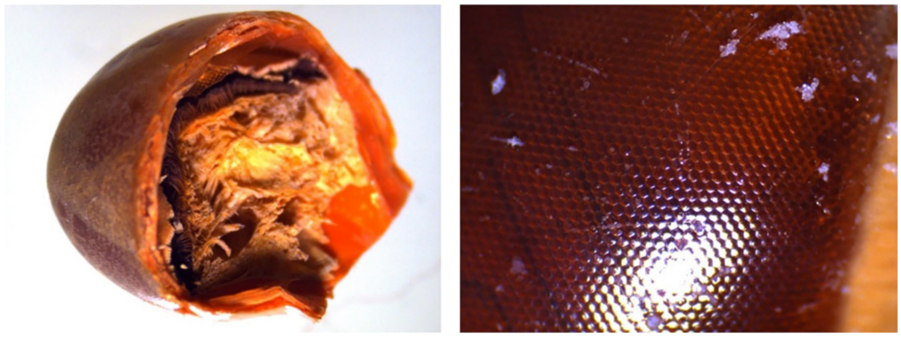

Figure 1. Eye of snow crab (*Chionoecetes opilio*). Left: view under stereomicroscope of the cross-sectional profile. Right: scanning electron micrograph (SEM) of the eye surface.

sensitivity due to the structure of the eye, which consists of only rods and no cones (Munk, 1964). Approximately eight fish species and most invertebrates (i.e., cephalopods and crustaceans) are known to be sensitive to polarized light (Lerner, 2013). Deep organisms often have a better match to the prevailing light conditions (e.g., short wavelength light) (Cronin et al., 2001). Some species have an ability to combine more sensitive cones (i.e., red, green, and blue) of which they can distinguish the wider spectrum (Arimoto et al., 2010). For example, color vision in mantis shrimps *(Haptosquilla trispinosa)* involves up to 16 types of visual pigment (Cronin et al., 2001).

Sufficient ambient light is necessary for most fish to form a visual image. The amount of ambient light present depends on water depth, time of day, and transparency or turbidity of the water. Rods and cones are two main components that adapt to changes in light intensity. To adapt to a wide range of light intensities in the natural environment, functional changes between cone and rod cells are made through shifting of positions of visual cells according to the ambient light intensity. Rods play a greater role at lower light intensities (scotopic vision), while cones are highly sensitive and used for 'photopic' vision during higher light intensities (Arimoto et al., 2010; Arimoto, 2013). Vertical histological sections through the retina allow us to determine the relative positions of the rods and cones, thus, giving insight into the adaptive abilities of the eye under different lighting conditions (Figure 2). The distribution and density of the photoreceptors across the retina can be determined through horizontal sectioning. A growing body of evidence has shown that visual acuity increases with fish size and can vary significantly between species (Figure 3). A number of studies have been conducted during the last few decades to understand the minimum light intensity threshold for fish (Glass and Wardle, 1995; Glass et al., 1995). These studies documented that the contrast of different fishing gears

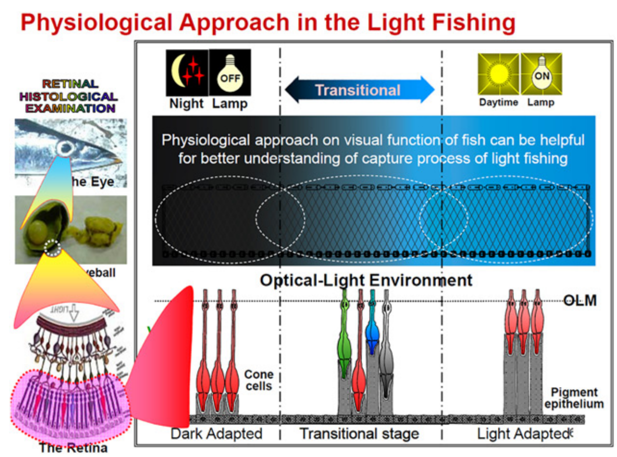

Figure 2. The diagram illustrates the adaption of cones to light intensity (reprinted with permission from Arimoto, 2013).

against different backgrounds and ambient light conditions are key factors affecting fish behavior and catchability. The relationship between the maximum sighting distance and fish length is described by Zhang and Arimoto (1993). The authors showed that visual acuity in simple cases depends on both fish size and the density of cones, while maximum sighting distance for different sizes of visual targets is proportional with the target size, and inversely proportional with the minimum separable angle in radians (Zhang and Arimoto, 1993).

The ability to perceive a moving or flickering image is very important to fish because of the dynamic surrounding environment (Arimoto et al., 2010). The capability of fish to detect a moving image depends on their visual acuity and persistence time (the time taken to process the image), as well as illumination level. The frequency at which flickering images fuse to produce a continuous image is identical to the flicker fusion frequency or critical flicker frequency and is dependent on light intensity, temperature, and flash duration (see Douglas and Hawryshyn, 1990; Arimoto et al., 2010). Most fish have the ability to detect moving images at very low light intensities between 10^{-7}

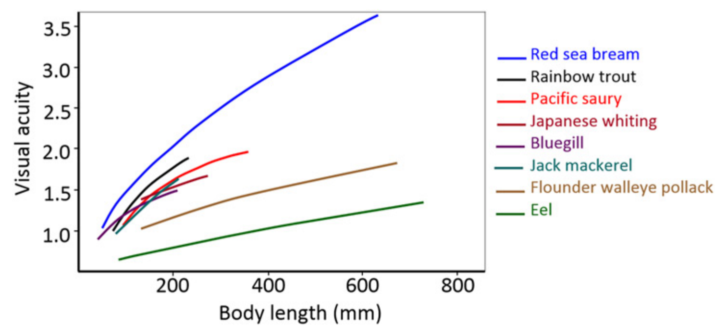

Figure 3. Comparison of visual acuity with body length and species (reprinted with permission from Arimoto, 2013).

Table 1. The visual sensitivity of various aquatic species. A selected review.

Name of species	Scientific name	Sensitive wavelength	Author
Deep-sea shrimp	*Eugonatonotus crassus*	497 nm	Frank et al. (2012)
Deep-sea shrimp	*Heterocarpus ensifer*	497 nm	Frank et al. (2012)
Green turtle	*Chelonia mydas*	580 nm	Eckert et al. (2006)
Hydrothermal vent crab	*Bythograea thermydron*	489 nm	Cronin and Jinks (2001)
Jack mackerel	*Trachurus japonicas*	497.5 nm	Anraku and Matsuoka (2013)
Japanese squid	*Todarodes pacificus*	482 nm	Matsui et al. (2016)
Loggerhead turtles	*Caretta caretta*	580 nm	Eckert et al. (2006)
Mantis shrimp	*Haptosquilla trispinosa*	Could distinguish wide range of wave length from 300 to 720 nm, with sensitivity peaking at wavelengths greater than 600 nm	Cronin et al. (2001); Thoen et al. (2014)
Mantis shrimp	*Gonodactylaceus mutatus*	From 400 to 551 nm	Cronin and Jinks (2001)
Mantis shrimp	*Pullosquilla litoralis*	From 404 to 540 nm	Cronin and Jinks (2001)
Mantis shrimp	*Pullosquilla thomassini*	From 405 to 509 nm	Cronin and Jinks (2001)
Mantis shrimp	*Squilla empusa*	507 nm	Cronin and Jinks (2001)
Shore crab	*Leptograpsus variegatus*	499 nm	Doujak (1985)
Sea isopod	*Booralana tricarinata*	480 nm	Frank et al. (2012)
Squat lobster	*Munidopsis tridentate*	487 nm	Frank et al. (2012)
Squat lobster	*Gastroptychus spinifer*	470 nm	Frank et al. (2012)
Squat lobster	Eumunida picta	490 nm	Frank et al. (2012)
Swimming crab	*Bathynectes longipes*	487 nm	Frank et al. (2012)
Swimming crab	*Callinectes sapidus*	504 nm	Cronin and Jinks (2001)
Walleye pollock	*Theragra chalcogramma*	From 470 to 540 nm	Zhang (1992)

and 10^{-4} lux (Protasov, 1970), but the minimum intensity of light that the animal can function visually is $\sim 4.0 \pm 1.5 \times 10^5$ photons cm^{-2} s^{-1} (Doujak, 1985). Table 1 provides a review of the visual sensitives for various marine organisms published in the scientific literature.

Most species of fish have a pair of eyes that are located on the opposite sides of the head, which produces three visual regions for teleost fish, including binocular vision in front of the fish, monocular vision on the left and right side of the fish, and a blind zone behind the fish (Arimoto et al., 2010). Flatfish are uniquely different of course, with both eyes typically located close together on the dorsal surface (Bao et al., 2011). Most crustacean species with compound eyes bear just two eyes that are located separately and symmetrically, one on each side of the head. This arrangement is called dichoptic (Zeil and Hemmi, 2006). For crab, these compound eyes are located on top of long vertical eye stalks. The black parts of the eye look in the forward direction. The shape of this pseudo-pupil indicates that more receptors look in vertical than in horizontal directions. Thanks to this special characteristic of the eye position, crab have the capability to look in all directions, without the need to move their eyes (Doujak, 1985; Zeil and Hemmi, 2006; Detto, 2007).

2.2. Behavior of marine organisms in response to artificial light

Understanding the behavioural responses of commercially important species toward artificial light is an important step in the development of efficient and sustainable fishing technology (Arimoto et al., 2010; Sokimi and Beverly, 2010; Arimoto, 2013). People discovered that fish could be lured by artificial lights a thousand years ago, yet in many cases the full explanation of how and why fish are attracted toward artificial lights remains unknown (Yami, 1976; Arimoto et al., 2010). Different authors have hypothesized various mechanisms that may explain the response of marine organisms to artificial light. Possible mechanisms include positive phototaxis, preference to certain optimum light intensity, investigatory reflex, feeding on prey attracted to the light, schooling, disorientation, or possibly just curiosity (see reviews by Yami, 1976; Marchesan et al., 2005; Arimoto, 2013).

There are four common patterns of movement in response to light; called phototaxis, photokinesis, aggregation, and vertical diurnal migration (e.g., Yami, 1976; Ciriaco et al., 2003; Marchesan et al., 2005; Ryer et al., 2009; Sokimi and Beverly, 2010). Phototaxis is the bodily movement of animals in response to artificial light, either toward the source of light (positive phototaxis) or away from it (negative phototaxis). Photokinesis is the movement, or lack of movement, in response to light. Aggregation is when animals form a group or cluster in response to light. Vertical diurnal migration is when animals move up and down in the water column in response to the diel cycle (Yami, 1976; Sokimi and Beverly, 2010).

The color (i.e., wavelength) produced by an artificial light can strongly affect behavioral responses in marine organisms (Dragesund, 1958; Lagardère et al., 1995; Ibrahim and Hajisamae, 1999; Ciriaco et al., 2003, An et al., 2009; Marchesan et al., 2005; Jeong et al., 2013; Matsui et al., 2016). Each species has an optimal wavelength and illumination level where they prefer to aggregate (Inoue, 1972; Ciriaco et al., 2003; Marchesan et al., 2005; Villamizar et al., 2011; Kehayias et al., 2016). Table 2 provides a selected

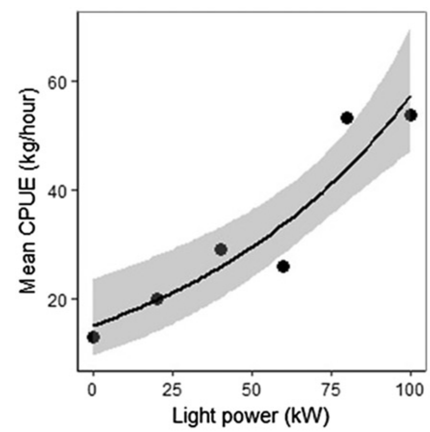

Figure 4. Exponential relationship between the mean catch rate of stick-held dip net and the light power. This relation was calculated by equation: $CPUE = 10.701e^{0.283kW}$ ($R^2 = 0.9114$). Grey area is 95% confident interval (modified from Liao et al., 2007).

Table 2. Behaviour of various aquatic species in response to light colour. A selected review.

Species	Scientific name	Description	Author
Atlantic cod	*Gadus morhua*	Juvenile Atlantic cod grew faster under blue and green light. However, marture cod did not respond to the light colour, but just moved toward the light for feeding prey	Villamizar et al. (2011); Sierra-Flores et al. (2016); Utne-Palm et al. (2018)
Chub mackerel	*Scomber japonicas*	Attract to blue, green, and white lights. No response to red light	Choi et al. (2009); An (2013); Lee (2013)
Herring	*Clupea harengus*	Strongest attraction to the green and blue light	Dragesund (1958)
Japanese squid	*Todarodes pacificus*	Attract to blue, green, and white lights. No response to red light	An et al. (2009); An and Jeong (2011); Jeong et al. (2013); Matsui et al. (2016)
Juvenile leatherbacks	*Dermochelys coriacea*	Juvenile leatherbacks between 5 and 42 days of age were either not attracted to lightsticks and LEDs, or are repelled by them	Gless et al. (2008)
Northern krill	*Meganyctiphanes norvegica*	Krill had a positive phototactic response, and significantly attracted to green (peak wavelength of 530) and broadband white LED light	Utne-Palm et al. (2018); Krafft et al. (2018)
Loggerhead turtles	*Caretta caretta*	Significantly moved toward blue, green, yellow and orange LED lightsticks	Wang et al. (2007)
Rough bullseye	*Pempheris klunzingeri*	Prefer to prey in the red light than blue and white light	Fitzpatrick et al. (2013); Rooper et al. (2015)
Sea bass	*Dicentrarchus labrax*	Stronger response to the shorter wavelength, and reacted to colors such as blue and green with aggregation, inhibition of activity and negative phototaxis	Ciriaco et al. (2003); Marchesan et al. (2005)
Senegal sole	*Solea senegalensis*	Juvenile Senegal sole grew faster under blue and green light	Villamizar et al. (2011)
Silver seabream	*Pagrus auratus*	Attracted to blue and white light	Fitzpatrick et al. (2013); Rooper et al. (2015)
Osuji-ishimochi fish	*Apogon doederleini*	Prefer to prey in the red light than blue and white light	Fitzpatrick et al. (2013); Rooper et al. (2015)
Turbot	*Scophthalmus maximus*	Juvenile turbot grew faster under blue, green, and white light	Sierra-Flores et al. (2016)
Woodward's moray eel	*Gymnothorax woodwardi*	Prefer to prey in the red light than blue and white light	Fitzpatrick et al. (2013); Rooper et al. (2015)
Zooplankton		Actively attracted to the emission of artificial illumination from the electric lamps	Kehayias et al. (2016)

Table 3. Behaviour of various aquatic species in response to light intensity. A selected review.

Species	Scientific name	Description	Author
Anchovy	*Engraulidae*	Preferred the underwater illuminance of 0.03-6.00 lux	Inoue (1972)
Big fin reef squid	*Sepioteuthis lessoniana*	The optimal underwater illumination varied between 1.5 and 25 lux	Ibrahim and Hajisamae (1999)
Mitre squid	*Loligo chinensis*	The optimal underwater illumination varied between 1.5 and 22.5 lux	Ibrahim and Hajisamae (1999)
Mackerel	*Scomber scombrus*	Preferred the underwater illuminance of 2.40–39.50 lux	Inoue (1972)
Japanese squid	*Todarodes pacificus*	Preferred a range of underwater illuminance of approximately 10 lux Although squid moved toward the artificial light, they usually avoided the highly illuminated regions, and often stayed in the shadow zone below the vessel where had low illumination, ranged from 3×10^{-2} lux to 3.4×10^{-3}lux	Inoue (1972); Choi and Arakawa (2001); An (2013)
Pacific saury	*Cololabis saira*	Preferred the underwater illuminance of 0.00-10.00 lux	Inoue (1972)

review of the literature. While some species can function visually under ultraviolet or far red, most fish species perceive light in the 40–750 nm spectrum range (violet to red), however the majority of deep-water species have peak absorbance within the range from 468 to 494 nm, with different fish species possessing different orders of light perception (see reviews by Inoue, 1972; Douglas et al., 1998; Anongponyoskun et al., 2011; Breen and Lerner, 2013).

The illumination intensity produced by an artificial light also strongly affects behavioural responses in fish (see Dragesund, 1958; Ibrahim and Hajisamae, 1999; Ryer and Olla, 2000; Liao et al., 2007; Villamizar et al., 2011; Bradburn and Keller, 2015; Matsui et al., 2016). Figure 4 demonstrates a typical increase in fishing gear efficiency with increasing intensity (kW) of surface-mounted lights. Table 3 provides a selected review of the literature on behavior of various aquatic species in response to light intensity.

3. Use of artificial lights in commercial industrialized fishing applications

3.1. Historical use of artificial fishing light

Fishing with artificial lights (surface light) is one of the most advanced and successful methods to increase the catch rate of squid and pelagic fish (Dragesund, 1958; Yami, 1976; Arimoto et al., 2010; Yamashita et al., 2012). Using artificial light as the stimulus source to attract and accumulate fish prior to harvest has had a long history, dating back thousands of years in many parts of the world (Yami, 1976; Acharl et al., 1998; Sokimi and Beverly, 2010; An, 2013). Historically, it started with simple techniques such as burning a large bonfire on the beach to attract fish. This was conducted as near as possible to the water's edge, which attracted and aggregated fish, and would keep them for some time in the illuminated area. Fishermen with their family members would silently enter the water, encircle the illuminated zone with a net, and drag the net to the shore using only their arms and legs. They would then kill the fish with stones, spears, or clubs (Yami, 1976). Using artificial light in the form of a bonfire on the beach existed until the middle twentieth century in places such as Cameroon, Indonesia, and Australia (Yami, 1976; An 2013; Wisudo et al., 2013). The next development was the use of (mobile) torches made from coconut husk and split bamboo. Fishermen would wade into the water in the dark of night to attract fish, which they would then stun and capture with a basket or spear. Technological advancements occurred during the beginning of twentieth century, with kerosene and electric lamps sequentially introduced (Yami, 1976; An 2013; Wisudo et al., 2013). Lately incandescent, fluorescent, halogen, and metal halide lamps are commonly used because of their high luminescent efficiency (see reviews by Inada and Arimoto, 2007; An, 2013; Solomon and Ahmed, 2016). During the last few decades, light emitting diode (LED) technology has been increasingly adopted. This innovation provides maximum illumination power combined with minimum energy consumption, long lifespan, high efficiency, better chromatic performance, and reduced environmental impact compared to traditional lighting technology (Matsushita et al., 2012; Matsushita and Yamashita, 2012; Yamashita et al., 2012; Breen and Lerner, 2013; Hua and Xing, 2013; Yeh et al., 2014; Nguyen and Tran, 2015; An et al., 2017). Figure 5 provides an illustration of the historical use and technological development of artificial light in fishing applications.

The earliest known use of underwater lights to catch fish was by Okinawan immigrant fishermen to harvest tunas *(Thunnus spp)* in the 1920s in Hawaii (Sokimi and Beverly, 2010). This has advantages over surface light which tends to lose part of its illumination due to reflection at the surface (Beltestad and Misund, 1988; Sokimi and Beverly, 2010). Underwater

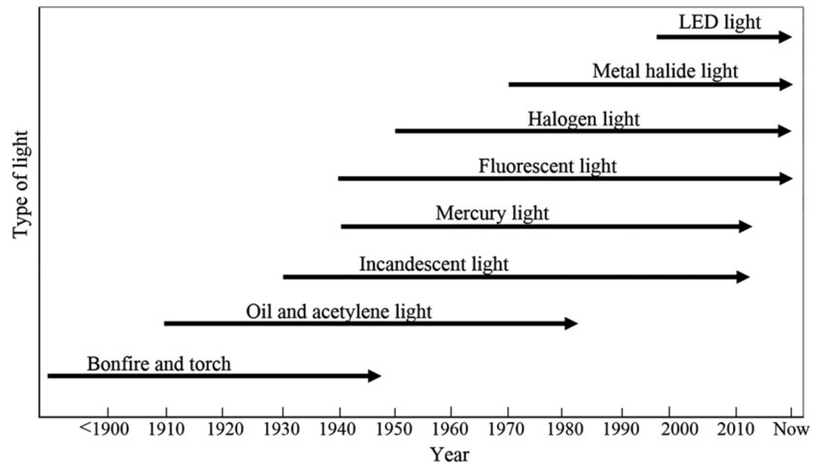

Figure 5. History of technological development of artificial light used in fisheries. Bonfire and torch existed until 1940s. Oil and acetylene light occurred in 1910 and existed until 1980s. Incandescent and mercury light introduced in 1930s and 1940s, respectively, and operated until 2010. Fluorescent, halogen, metal halide and LED light introduced in 1940s, 1950s, 1970s, and 2000s, respectively, and today, only these four types of light are commonly used (modified from An, 2013).

lights were also used to capture squid in Nantucket Sound, USA (Amaral and Carr, 1980). Results from the field experiments, as well as commercial fishery applications, were later deployed by Chinese, Japanese, Korean, and Norwegian scientists (e.g., Beltestad and Misund, 1988; An, 2013; Anraku and Matsuoka, 2013; Fujino et al., 2013; Qian et al., 2013; Wisudo et al., 2013). Underwater fishing lights were also examined for how they could be used to modify the behaviour of fish (e.g., phototaxis, photokinesis; Ciriaco et al., 2003). With advances in LED technology, the use of underwater lights has now spread to large commercial fisheries across a range of target species (see Sokimi and Beverly, 2010; Arimoto, 2013; Hua and Xing, 2013; Masuda et al., 2013; Qian et al., 2013; Watson, 2013; Bryhn et al., 2014; Hannah et al., 2015; Ortiz et al., 2016; Nguyen et al., 2017).

From a historical perspective, fishing with light remains one of the most effective fishing methods, with a well-documented history in many parts of the world, including Africa, China, Indonesia, Japan, Korea, Malaysia, New Zealand, Philippines, Peru, Russia, Thailand, Turkey, and Vietnam (see Yami, 1976; Nguyen, 2006; Inada and Arimoto, 2007; Matsushita et al., 2012; Matsushita and Yamashita, 2012; Yamashita et al., 2012; An, 2013; Qian et al., 2013; Solomon and Ahmed, 2016). Fishing with artificial light has been used in both small-scale fisheries along the coast, as well as large offshore fisheries. Purse seine, stick held lift net, squid jigging, drop net, and scoop net were the major fishing methods using light (see Arakawa et al., 1998; Sudirman and Nessa, 2008; Anongponyoskun et al., 2011; Matsushita et al., 2012; Matsushita and Yamashita, 2012; Yamashita et al., 2012; Breen and Lerner, 2013; Nguyen and Tran, 2015; An et al., 2017). Species of lagoon and reef fish were the main target species during the period of bonfires and hand-held torches (see Yami, 1976; Sokimi and Beverly, 2010). Pelagic fish such as tuna *(Thunnus spp)*, mackerel *(Scomber scombrus)*, anchovy *(Stolephorus sp)*, herring *(Clupea harengus)*, sardine *(Sardina pilchardus)*, sprat *(Sprattus sprattus)* and squid *(Teuthida)* were considered the main target species of light fishing methods when industrial and commercial fisheries developed (see Dragesund, 1958; Yami, 1976; Beltestad and Misund, 1988; Arakawa et al., 1998; Liao et al., 2007; Nguyen and Tran, 2015). See Table 4 for a summary of the historical use of artificial light in different countries.

Although the use of underwater lights in fishing applications is not necessarily a new innovation, application of this technology in commercial industrialized fisheries has been limited in comparison with over-water (surface) lights. The largest known application of underwater lights is the swordfish *(Xiphias gladius)* longline fishery which uses chemically disposable submersible lightsticks to attract swordfish to baited hooks (see Freeman, 1989; Ito et al., 1998; Witzell, 1999; Stone and Dixon, 2001; Hazin et al., 2002; Poisson et al., 2010; Sokimi and Beverly, 2010; Tüzen et al., 2013). The use of underwater lights to attract live baitfish (e.g., squid and scad) or direct target species for pole and line fishing is also widespread in the tuna fishery (Hazin et al., 2002, 2005; Sokimi and Beverly, 2010). This fish aggregating method has since been developed in larger commercial fisheries in some regions. For example, underwater LED light technology has recently been applied in purse seine and large

Table 4. Summary of the historical use of artificial light (overwater/surface) used in fishing.

Country	Period and type of light used	Fishing gear	Target species	Author
China	- Torch-net was popularly used in China in the past - Kerosene fishing lamp has been used in Hong Kong - Electric fishing lamp has been applied in China from the early 20th century to the present - LED lamp has been used in fishing since 2000s - For squid jigging fishery, between 40 and 160 kW of light power are currently used depending on vessel capacity, with equipment of a generator electrical power with a total power output often in the range of 100–360 kW - Fishing light mainly includes filament, halogen tungsten, low-pressure mercury, high-pressure mercury, metal halide, and LED	Purse seine, drop net, lift net, scoop net, squid jigging,	flying squid *(Todarodes pacificus)*, hairtail *(Trichiurus lepturus)*, sardine *(Sardina pilchardus)*, bonito *(Sardini)*, scads *(Decapterus spp)*, mackerel *(Scomber japonicus)*, round herring *(Spratelloides gracilis)*	Liao et al. (2007); Hua and Xing (2013); Qian et al. (2013)
Ghana	- Light fishing was imported into Ghana in 1962 - A typical lamps are fluorescent and incandescent	Purse seine	Herring *(Clupea harengus)*, sardines *(Sardina pilchardus)*, anchovies *(Engraulidae)*, horse-mackerel *(Trachurus trachurus)*, bonitos *(Sardini)*, and cephalopods (squids)	Bannerman and Quartey (2004); Solomon and Ahmed (2016)
Indonesia	- Use of torch in fishing in Indonesia was existed until 1950s - Kerosene lamp has been then introduced and using in some fisheries currently - Electric lamp was introduced by 1972 - A typical lamps that are using commercial fishing currently includes incandescent, mercury, fluorescent, halogen, and metal halide lamp	Purse seine, bagan, squid lift net, hook, and line	Squid *(Teuthida)*, scads *(Decapterus spp)*, Indian mackerel *(Rastrelliger spp)* and sardines *(Sardinella spp)*	Sudirman and Nessa (2008); Wisudo et al. (2013)
Japan	- A long history use of artificial light - Wooden torch was used until 1900s - Kerosene lamp was used between 1910s and 1930s - Incandescent lamp was used between 1930s and 2013s - Mercury, fluorescent, halogen, metal halide lamps have been used since 1950s - LED lamp has been introduced since 2000s	Squid jigging, scoop net, stick-held dip nets, purse seine, and setnet	flying squid *(Todarodes pacificus)*, herring *(Clupea pallasii Valenciennes)*, tuna *(Thunnini)*, mackerel *(Scomber japonicus)*, and yellowtails *(Seriola lalandi)*	Yami (1976); Yamashita et al. (2012); Matsushita et al. (2012); Matsushita and Arakawa (2013)
Norway	- A long history use of artificial light - A mobile torches was used in the past - Electric lamp was introduced by 1885 - Wide application in commercial fishery was in 1930s - Use of underwater light was in 1980s	Purse and beach seining	Herring *(Clupea harengus)*	Dragesund (1958); Yami (1976); Beltestad and Misund (1988)
Thailand	- Use of artificial light in Thailand began with torch or acetylene gas (C_2H_2) - Electric lamp was introduced by 1978 - Currently typical lamps are metal halide, incandescent, and fluorescent	Purse seine, drop net, squid jigging, and lift net	Barracuda *(Sphyraena)*, ponyfish *(Leiognathidae)*, squid *(Teuthida)*, and anchovy *(Stolephorus commersonii)*	Anongponyoskun et al. (2011)
Vietnam	- Fishing with light was imported into Vietnam since 1950 with using kerosene lamp - Electric lamp has been used by 1960 - LED lamp was used in 2015 - A typical lamps that are using commercial fishing currently includes fluorescent and metal halide	Purse seine, drop net, encircling net, lift net, squid hand jigging, and tuna handlining	Yellowtail scad *(Decapterus maruadsi)*, largehead hairtail *(Trichiurus lepturus)*, Anchovy *(Stolephorus commersonii)*, tuna *(Thunnini)*, Mackeral *(Scomber japonicas)*, and squid *(Teuthida)*	Nguyen (2006); Nguyen and Tran (2015)

A selected review of key countries.

scale trap (i.e., set net) fisheries in Japan and the Mediterranean Sea (Arimoto, 2013; Masuda et al., 2013; Virgili et al., 2018), as well as squid jigging fisheries in China (Qian et al., 2013). It has even spread to baited traps (Bryhn et al., 2014; Nguyen et al., 2017), bottom trawls (Hannah et al., 2015), and gillnets (Wang et al., 2010; Darquea et al., 2016; Ortiz et al., 2016) for either improving the catchability of target species or reducing bycatch of unwanted species.

Looking to the future, the greatest opportunity for growth in the use of artificial light will most certainly be in underwater applications. The desire to protect endangered and threatened species as well as the recent change in landing obligations in the European Union (commonly called the 'discard ban') has driven a remarkable increase in research initiatives globally. The ICES-FAO Working Group on Fishing Technology and Fish Behaviour (WGFTFB) has dedicated a significant effort toward the documentation and dissemination of this research (ICES, 2013, 2018).

3.2. Use of artificial light to increase catch rate

Fishing with light is one of the most widespread fishing techniques, producing high catch rates, and contributing a significant amount of product to the total global catch of marine fish (Arimoto et al., 2010). For example, total fish production using light was a little over 1.6 million tonnes in Japan in 2009, with purse seines, stick-held dip nets, and squid jigging contributing 1.2, 0.29, and 0.17 million tonnes, respectively (Matsushita and Arakawa, 2013). In Vietnam, light fishing contributes ~40% to the total marine fish production (Nguyen, 2006). Artificial lights are the primary components for squid luring and harvesting (Inada and Arimoto, 2007). Up to 95% of the world squid catch uses artificial light (Rodhouse et al., 2001).

Some fisheries (e.g., squid jigging, herring purse seine, stick-held dip net, and scoop net) could not effectively operate without the use of artificial lights. For instance, Beltestad and Misund (1988) showed that herring was impossible to catch without the use of light as they usually aggregate toward deep water during the day and migrate to the surface in the evening, but they often stay at a depth of 50 m and were scattered. Similarly, squid jigging with lights is considered a highly effective fishing method in which artificial light plays a key role in gathering squid below the vessel where jigging machines can effectively operate (Arakawa et al., 1998; Matsushita and Yamashita, 2012; Matsushita et al., 2012; Yamashita et al., 2012; Qian et al., 2013). Most fishermen and scientists agree that the catch rate of swordfish increases when lightsticks are present; attaching lightsticks to the branchlines of longlines harvested a higher catch rate of swordfish than did longlines without lightsticks (Freeman, 1989; Ito et al., 1998; Bigelow et al., 1999; Witzell, 1999; Hazin et al., 2002, 2005; Tüzen et al., 2013). Set nets using underwater lights installed 5 m below the surface along the leader net, significantly increased annual catches of all fish species (Masuda et al., 2013). Baited pots are an environmentally-friendly fishing method, with low environmental impact and minimal fuel consumption compared to other gear types (Jørgensen et al., 2017). Pots typically have low fishing performance for many groundfish species, including Atlantic cod *(Gadus morhua)*, due largely to the inhibition of cod to enter small confined spaces (Winger et al., 2016). Artificial lights not only concentrate pelagic species, but also aggregate demersal fish (e.g., cod), as well as attract crustaceans (e.g., snow crab). For example, attaching a low-powered green LED light (peak wavelength of 523 nm) inside the conventional cod pot (baited pot with ~250 g of cut fresh herring) increased the CPUE and Weight Per Unit Effort (WPUE) of legal sized cod (>38 cm) by 74% and 80%, respectively, with no increase in small cod (<38 cm) for either indices of CPUE and WPUE (Bryhn et al., 2014). Similarly, the addition of small low-powered white LED lights (peak wavelength of 456 nm) into baited pots targeting snow crab was shown to increase the CPUE by 77%, while placing the same light in unbaited pots caught comparable amounts of crab to traditional baited traps (Nguyen et at., 2017). Preliminary results have also shown that attaching small low-powered LED lights inside baited pots targeting northern shrimp *(Pandalus borealis)* produced a three-fold increase in catch rate (Ljungberg and Bouwmeester, 2018). Finally, the use advanced laser-based techniques are currently under development by engineers and scientists in Iceland. The research team has successfully equipped a codend with forward looking lasers for the purpose of herding fish/shrimp into a trawl without the need for trawl wings or side-panels (known as *VirtualTrawl*). Preliminary results have shown that the lasers can successfully herd shrimp into the codend with negligible ecological impact (Hreinsson et al., 2018).

3.3. Use of artificial lights to reduce bycatch

Unwanted bycatch and the subsequent discard of non-targeted fish is a global challenge which involves issues of economic, ethical, and ecological impact (Diamond, 2004). One estimate has placed the amount of bycatch near 8% of the global catch from marine capture fisheries, which is estimated to be ~7.3 million metric tonnes (Kelleher, 2005; Zeller et al., 2018). Dozens of gear modifications have been developed in recent decades to help reduce bycatch in commercial fisheries, with well-known examples such as hook size and shape, mesh size and shape, toggle chains, sorting grids, turtle excluder devices, fish eyes, streamer lines, and so on. (e.g., Isaksen et al., 1992; Crowder et al., 1995; Diamond, 2004; Thomas et al., 2007; He and Balzano, 2011; Løkkeborg, 2011).

Recently, artificial lights have been evaluated as a potential method to eliminate bycatch in various commercial fisheries. These include the use of low-powered LED lights to reduce bycatch of small fish in bottom trawls targeting shrimp and *Nephrops* (Rose and Hammond, 2014; Hannah et al., 2015; Larsen et al., 2017, 2018; Melli et al., 2018), reduce bycatch of juvenile fish in groundfish trawls (Grimaldo et al., 2018), reduce bycatch of Chinook salmon *(Oncorhynchus tshawytscha)* in Pacific hake *(Merluccius productus)* midwater trawl (Lomeli and Wakefield, 2014), reduce bycatch of turtles in gillnets in south America (Wang et al., 2010, 2013, 2018; Darquea et al., 2016; Ortiz et al., 2016), and reduce bycatch of turtles in set nets in the Mediterranean Sea (Virgili et al., 2018). The results to date, however, have been varied. A key factor determining success appears to be the proper placement/location of LED lights within the fishing gear (Hannah et al., 2015). For example, Rose and Hammond (2014) demonstrated that the addition of LED light into the footrope of a trawl had significant reduction of southern rock sole *(Lepidopsetta bilinetata)*, while the same lights did not affect escape rates of flathead sole *(Hippoglossoides elassodon)*, and Alaska pollock *(Gadus chalcograma)*. In a similar study, Hannah et al. (2015) attached small low-powered LED lights to a mobile bottom trawl to reduce finfish bycatch while targeting ocean shrimp *(Pandalus jordani)*. The study showed that the addition of green LED lights (centered on 540 nm) along the fishingline dramatically reduced non-target species of fish, with negligible reduction of shrimp. The LED lights reduced eulachon *(Thaleichthys pacificus)* bycatch by 91%, followed by juvenile darkblotched rockfish *(Sebastes crameri)* bycatch with 82%, and reduced other juvenile rockfishes by 56%. LED lights also reduced slender sole and other small flatfishes by 69%. By comparison, attaching the LED lights in the vicinity of the Nordmøre grid actually increased the bycatch up to 104% (Hannah et al., 2015). Similar findings were documented by Larsen et al. (2017, 2018).

The behavior of marine organisms in response to artificial light has also been found to vary across different species. For example, Grimaldo et al. (2018) attempted to stimulate Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) to escape through square mesh side-panels of a demersal groundfish trawl using small low-powered LED lights. Underwater camera observations showed that haddock exhibited noticeably more erratic behavior in response to the lights, which prevented individuals from approaching meshes at the correct angle to escape. In contrast, Atlantic cod remained stationary in front of the lights and appeared to be unaffected by them. Melli et al. (2018) investigated whether small green lights could be used to sort finfish from *Nephrops* in a vertically-partitioned demersal bottom trawl. The experiment showed that cod, whiting, and plaice could shift their preferences between the upper and lower codends depending on the presence of lights, however the results were size-dependent and no clear species-specific phototactic response was identified. Recent studies conducted in Mexico, Peru and Ecuador attached underwater low-powered LED lights in the floatlines of gillnets. Researchers documented a significant reduction in the bycatch of sea turtles by 60% in Mexico, 63.9% in Peru and 85.7% in Ecuador, without affecting the catch rate of the target species (Wang et al., 2010; Darquea et al., 2016; Ortiz et al., 2016). Similarly, no turtles were captured by set nets equipped with ultraviolet LED lights, compared to 16 loggerhead turtles in the control net, with no effect on the catch efficiency of the major commercial species in terms of catch composition or of size of the fish caught (Virgili et al., 2018). The use of LED lights to reduce bycatch of sea turtles in pelagic gillnet fisheries is now widely applied worldwide, including south America, Hawaii, Africa, Adriatic Sea, southeast and south Asia (Wang et al., 2018)

Several other preliminary concepts are currently under development by various companies, universities, and government institutes. These include (i) illuminated 'escape rings' installed in trawl codends to encourage non-targeted fish to escape (Watson, 2013), (ii) illuminated grids to encourage separation of groundfish species into different codends (O'Neill et al., 2018), and (iii) glow-in-the-dark netting to encourage optomotor responses and the separation of groundfish species into different codends (Karlsen et al., 2018). Together, these active research programs highlight the widespread potential application of artificial light as a novel stimuli to separate targeted and non-targeted species toward the goal of reducing bycatch.

3.4. Use of artificial light to reduce fuel consumption

Fuel consumption by the world's capture fisheries in 2000 was ∼50 billion L and this accounted for 1.2% of the global fuel consumption (Tyedmers et al., 2005). For some pelagic fisheries using over-water (surface) lighting, fuel consumption accounts for as much as 40 to 60% of the total operational cost (Matsushita et al., 2012; Nguyen and Tran 2015; Matsui et al., 2016, An et al., 2017). Although the development of LED lights dates back to the 1960s (see reviews by Schubert, 2006), such lights have only been used in fishing applications since the 2000s (see Hua and Xing, 2013; Matsushita et al., 2012; Matsushita and Yamashita, 2012; Yamashita et al., 2012; Qian et al., 2013). Given that LED lights can produce high chromatic performance with lower energy consumption than traditional lights, the application of the technology in overwater (surface) fishing operations has been shown to significantly reduce fuel consumption by vessels (Matsushita et al., 2012; Lee 2013; Mills et al., 2014; Nguyen and Tran, 2015; An et al., 2017; Susanto et al., 2017). Moreover, with pelagic fisheries (i.e., squid and herring), many harvesters believe that catch rates are higher with stronger lights. As a result, there has been a 'light war' among fishermen leading to a dramatic increase in lights in the last few decades (Matsushita et al., 2012; An et al., 2017). In some squid jigging fisheries, the power requirements have reached as high as 200 kW, which consumes ∼900 L of diesel fuel every night, which equates to ∼1700 L of fuel per tonne of landed squid (see Matsushita et al., 2012; Matsushita and Yamashita, 2012; Yamashita et al., 2012; Qian et al., 2013; An and Arimoto, 2013; Matsui et al., 2016). Use of energy-saving LED lights for fishing is therefore recommended (Choi 2006; An and Jeong, 2011, 2012; Matsushita et al., 2012; Jeong et al., 2013; Masuda et al., 2017).

In recent experiments, Japanese scientists demonstrated that replacing traditional metal halide lights with LED lights, reduced the fuel consumption by an average of 0.28 L/kWh, which was estimated to be ∼24%, without decreasing the targeted catch of squid (Matsushita et al., 2012; Yamashita et al., 2012). Similarly, Nguyen and Tran (2015) replaced the traditional 12 kW metal halide and fluorescent lights with 3 kW LED light onboard a purse seine vessel targetting pelagic species, such as scads *(Decapterus macarellus)*, skipjack tuna *(Katsuwonus pelamis)*, Indian mackerel *(Rastrelliger kanagurta)*, largehead hairtail *(Trichiurus lepturus)*, squid *(Teuthida)*. The study showed that purse seine vessels equipped with LED light reduced fuel consumption by 77%, with no significant change in catch rate. An et al. (2017) showed that the catch rate of vessels targeting hairtail *(Trichiurus lepturus)* using only 21.6 kW of LED light was similar to that of vessels equipped with higher power (45–84 kW) metal halide lights. In some cases, the use of LED lights instead of traditional lights has even increased catching efficiency. For example, Susanto et al. (2017) demonstrated that the catch rate of a fixed lift net equipped with LED light for catching anchovy *(Stolephorus sp)* increased ∼30%, while fuel consumption decreased by 35%, compared to similar trials with compact fluorescent light.

Small scale fisheries, which are typical in many developing countries, are critical for food security and employment. The dependence of many of these fisheries on over-water (surface) lighting, however, has led to excessive investment in lighting equipment (Mills et al., 2014; Susanto et al., 2017). Use of solar-powered LED lights as an alternative to fuel-based lighting for small scale fishing was recently evaluated in Africa. The study showed that during night fishing, fuel consumption was significantly reduced when using LED lights, resulting in a significant cost saving for fishing operations (Mills et al., 2014).

4. Negative Impacts

4.1. Ecological effects

Light pollution can produce negative effects on marine animals and is considered a threat to biodiversity (Thompson, 2013; Rajkhowa, 2014). For example, artificial light is known to be harmful to female sea turtles when searching for a beach hatchery, which can produce unbalanced sex ratio of hatchlings, and higher hatchling mortality. Likewise, juvenile turtles in the presence of artificial light are known to be disoriented when finding their way to the sea, which can increase the threat of predators as well as high temperatures after sunrise (IDA, 2002; Rajkhowa, 2014). Artificial lights on fishing vessels not only affects aquatic species, but they can also be harmful to other animals (i.e., seabirds), with direct and indirect negative effects. The use of such lights at night have been shown to increase mass collisions of seabirds, which contributes directly to mortality and the sustainability of seabird populations (Montevecchi, 2006).

Although the above challenges have been primarily reported in the above-water application of light, it is conceivable that comparable effects may exist in the underwater use of light, especially in situations where lights operate in non-natural situations (e.g., deep sea or nighttime). For example, fishing lights have been shown to impact fish foraging and schooling behavior, spatial distribution, predation risk, migration, and reproduction (Nightingale et al., 2006). Feeding of predators increased when artificial light were turned-on because of abundance of prey in the illuminated area, whereas predators had more failures to attack their prey under dark conditions (Becker et al., 2013; Thompson, 2013). Similar results have shown that Atlantic cod, haddock, and turbot had greater feeding success under artificial lights (Downing and Litvak, 2001; Migaud et al., 2009; Sierra-Flores et al., 2016). This has the potential to create unnatural top–down regulation of fish populations (Becker et al., 2013).

4.2. Overfishing effects

Maintaining ecosystem function and stock health are challenges in modern fisheries. Overfishing has occurred in most fisheries and nations, of which some fisheries have been exploited to 40% higher than sustainably recommended (FAO, 2011; Mills et al., 2014). In the case of tuna fisheries, there is still high demand for tuna production from the world's market, and there remains significant overcapacity in global tuna fishing fleets (FAO, 2016), some of which use underwater lights to improve catch rates. Some have argued that fishing with light attraction equipment usually encourages overfishing which can lead to the depletion of the fisheries resources in some regions, especially in open access fisheries and poor management regimes (Mills et al., 2014; Solomon and Ahmed, 2016). For example, the use light fishing in Indonesia increased during the 1990s, during which the total production and CPUE for a variety of species decreased over the same period (Sudirman and Nessa, 2008).

4.3. Bycatch effects

Artificial light has been shown to reduce bycatch of some species in certain fisheries (i.e., gillnet and shrimp trawl), while producing new and unique challenges in other fisheries. In longline fisheries for example, chemical lightsticks play a very important role in attracting target species (i.e., swordfish, tuna), but they also produce a significant source of stimulus for non-target species (i.e., sea turtle, shark, and mammal). Evidence has shown that sea turtles can be injured and sometimes killed because of negative interactions with pelagic longlines equipped with lightsticks, and it has even been identified as a major cause of decline in some sea turtle populations (Witzell, 1999; Bartram and Kaneko, 2004; Lohmann et al., 2006; Wang et al., 2007, 2010; Gless et al., 2008). Three of the five sea turtle species that live in the Pacific Ocean including loggerhead *(Caretta caretta)*, green *(Chelonia mydas)*, and olive ridley *(Lepidochelys olivacea)* are listed under the United States Endangered Species Act of 1973 as threatened. The other two species of leatherback *(Dermochelys coriacea)* and hawksbill *(Eretmochelys imbricata)* are listed as endangered (see review by Swimmer and Brill, 2006). Sea turtles often interact with longlines as they can be highly migratory and rely heavily on their visual senses in their search for food (Bartram and Kaneko, 2004). This is aggravated by the fact that pelagic longline fisheries operate in an area of more than two-thirds of the world's oceans (Bartram and Kaneko, 2004). On average, pelagic longlines kill annually more than 200,000 loggerheads and 50,000 leatherbacks globally (see review by Lohmann et al., 2006). Statistics from the United States pelagic longline fleet operating in the western North Atlantic Ocean during the period of 1992–1995 showed that the average leatherback and loggerhead turtle captured per 1000 hooks was 0.0931 and 0.1051, respectively, for the longline vessels using chemical lightsticks, while these values were 0.0311 for leatherback and 0.0210 for loggerhead turtles with vessels not using lightsticks (Witzell, 1999). This data clearly demonstrates the negative effect of increased bycatch associated with fishing with underwater lights. The authors speculate that the lightsticks may simulate bioluminescent gelatinous prey, increasing the attraction of sea turtles to the baited hooks.

4.4. Plastic and litter effects

Marine litter is a global problem with diverse and complex causes, interconnections, and impacts. World waste of plastics peaked at 311 million tonnes in 2014 and has tripled during the past 25 years (Detloff and Istel, 2016). Although most plastic litter comes from land uses, fisheries activities, shipping, and offshore oil/gas platforms contribute ~20% to plastic and marine debris found in the oceans (e.g., Cho, 2011;

Detloff and Istel, 2016). In particular, plastics produced from oil have created a long-term problem and the most urgent challenges for the environment because they take a long time to degrade – up to 25, 450, and 600 years to decompose plastic bags, plastic bottles, and fishing nets, respectively (Cho, 2011; Detloff and Istel, 2016). The majority of the plastic found in the ocean is composed of tiny pieces less than 1 cm in size, called micro-plastics (Cho, 2011). Evidence has shown that many animals, especially seabirds, whales, and turtles, have starved to death with stomachs full of plastic. More than just litter and accidental food, marine plastics are also known to contain and absorb toxins. When eaten, these toxins can be absorbed in animal tissue and then bio-accumulate up through the food chain (see review by Park et al., 2016).

Litter from chemical lightsticks is considered the largest source of plastic waste from underwater fishing lights that could affect the environment and human health. Lightsticks have a short lifespan, which work ~12 hr and are non-reusable (Ito et al., 1998; Stone and Dixon, 2001; Poisson et al., 2010). After a single day of operation, thousands of spent lightsticks are discarded at sea and constitute a potential toxicant to marine flora and fauna (Poisson et al., 2010). For instance, ~7000 discarded lightsticks were collected within 90 km of the northern coast of Bahia State, Brazil (Oliveira et al., 2014). This highlights the fact that fishing operations using lightsticks contribute to the risk of plastic waste (Oliveira et al., 2014). Although there have been international agreements banning the deposal of waste at sea since the 1970s, it is hard to control and enforce in reality (Detloff and Istel, 2016; Morris et al., 2016).

Besides affecting the ocean environment, lightsticks can directly produce human health risks, as they contain oxalate ester (10–1500 mM), a fluorescer (PAHs, 1–10 mM), a peroxide (anhydrous hydrogen peroxide, 200–15,000 mM), and a catalyst (salicylate derivative, 0.1–1 mM; Oliveira et al., 2014). These chemicals can sting and burn eyes, irritate and sting skin, and can burn the mouth and throat if ingested. If the chemicals are ingested or spilled in the eyes or on the skin, it is recommended the area is rinsed with water and the local poison control center be contacted (Oliveira et al., 2014).

Unfortunately statistics do not yet exist for the global production of marine plastics associated with fishing lights. Nonetheless, assuming artificial lights (i.e., LED light) are applied across a wider scope for purse seine, squid jigging, scoop net, baited pot, gillnet, and longline fisheries, potential context of marine plastic problems could be imagined. These fishing gears are popular throughout the world (e.g., Matsushita and Yamashita, 2012; Matsushita et al., 2012; Yamashita et al., 2012; Qian et al., 2013; Bryhn et al., 2014; Nguyen and Tran, 2015; DFO, 2016, Winger et al., 2016; Jørgensen et al., 2017). For example, the snow crab fishery in the province of Newfoundland and Labrador, Canada, annually deploys ~1.2 million baited traps (DFO, 2009). If every trap was equipped with a low-powered LED light (57.6 g of plastic), this would constitute placing 69.1 tonnes of plastic in the ocean annually. Although the lights are reusable and have a long lifespan, it is impossible to control the number of lights lost. Assuming 8% of traps are lost annually (Miller, 1977), this would contribute 5.5 tonnes of plastic waste into the North Atlantic annually. Hence, it is recommended that the management of marine litter and plastics be discussed in an urgent manner so as to ensure adequate policies can be developed.

4.5. Greenhouse gas effects

Like most modern mechanized fishing operations, fishing with artificial light contributes to greenhouse gas emissions. In the case of above-water applications, operating the additional generators onboard the vessel to produce the required electricity for lights results in the unintended by-product of CO_2 emissions. Burning 1 kg of diesel produces 3.19 kg CO_2 (Matsushita et al., 2012; An et al., 2017). In the case of Tanzania, light fishing produces ~85,000 metric tonnes of CO_2 annually, accounting for 1.3% of total CO_2 emissions of this country (Mills et al., 2014). At this time, adequate statistics do not exist on the amount of greenhouse gases that are produced to serve the global fishing industry. The global statistics on combined agriculture and fisheries activities contributed ~10% of 29 billion tonnes of CO_2 released in 2009 (see IEA Statistics, 2011).

Another potential source of greenhouse gas is the production process that is needed for making fishing lights. Chemicals and plastics often require significant energy sources in order to be manufactured. It's been estimated that 1 kg of polyethylene (PE) plastic produces about 6 kg of CO_2 in the production process (Wong, 2010). Roughly speaking, this means a single small low-powered LED light weighing 57.6 g (used by Hannah et al., 2015; Larsen et al., 2017, 2018; Nguyen et al., 2017; Grimaldo et al., 2018; Melli et al., 2018) will produce ~345.6 g of CO_2 to be manufactured.

This means equipping 1.2 million snow crab traps in the province of Newfoundland and Labrador, Canada, for example, could produce (roughly speaking) 414.7 tonnes of CO_2.

5. Solutions to reduce negative impact

5.1. Technical measures

Although sea turtles interact with longline fishing gear targeting swordfish *(Xiphias gladius)*, mahi mahi *(Coryphaena hippurus)*, or tunas *(Thunnus spp)*, evidence suggests that most of these negative interactions occur with shallow-set gear, and that very few turtles are caught by deep-set (>100 m) longlines (see review by Bartram and Kaneko, 2004). This is because turtles tend to be found at depths <40 m. This suggest that the best fishing gear design could be optimized the safe operating depth that minimizes incidental mortality rate of turtles without reducing catch yield. In 2005, the World Wildlife Fund (WWF) awarded a *SmartGear* cash award of $25,000 USD for the invention of a deep set longlining system (WWF, 2005). This longline gear consists of a weighted mainline that includes twenty to forty branchlines and baited hooks. The system is lowered and fished below 100 m, which is safely out of sea turtle range yet within target species range.

Understanding vision and olfaction, as well as the behavior of target (i.e., swordfish and tuna) and non-target species (i.e., sea turtles) in response to lights is an important step in reducing the negative effect of fishing lights on the environment and co-occurring species (Lohmann et al., 2006). For example, co-occurring species often vary in how and when they overlap. They often vary in their visual acuity, niche portioning, life history, and ontogeny. Understanding all of these differences can assist fisheries biologists in reducing the vulnerability of non-targeted species that co-occur with targeted species.

Size selectivity of target species is commonly achieved through the adoption of technical measures (e.g., mesh/hook shape and size) which can help to avoid the unintended capture of undersized individuals, either because of market preference or life history considerations. Carefully designed selectivity studies can be conducted to properly evaluate the performance of different fishing gear configurations. The resulting catch comparison/catch ratio curves can be used by fisheries managers to produce different outcomes, according to management objectives.

Advances in technology development, including LED lights with better chromatic performance and longer operational life-cycle will continue into the foreseeable future. In order to minimize the negative impacts of artificial lights in commercial fisheries, continued development of environmental-friendly technology (i.e., solar-powered LED light, reusable batteries, and biodegradable plastic) are recommended (Matsushita et al., 2012; Mills et al., 2014; Nguyen and Tran, 2015; Ortiz et al., 2016). In addition, using the optimal number and output power of light, and the combination of underwater and overwater fishing light in some fisheries (i.e., purse seine and squid jigging) are one of the possibilities to reduce the negative effects of light fishing on environment (Yamashita et al., 2012; Qian et al., 2013).

5.2. Regulation and management measures

A number of studies have demonstrated that sea turtles are less vulnerable to capture by large circle hooks (C-hook) than J-hooks (Bartram and Kaneko, 2004). As a result, mandatory use of C-hooks has been enforced in both the Pacific and Atlantic Oceans (see review by Swimmer and Brill, 2006). This small but significant management measure saves thousands of sea turtles from the threat of capture by longlines every year.

In the case of fishing with lights, several governments have enacted management measures to limit competition among fishermen, limit fishing effort, manage overfishing, and mitigate environmental impact. For example, the use of light fishing has been completely banned in the coastal waters of Ghana (Solomon and Ahmed, 2016). In Norway, the total light power of each fishing vessel must not exceed 15 kW (Yami, 1976; Beltestad and Misund, 1988). In Japan, squid jigging vessels greater than 19 gross tonnage cannot exceed 160 kW of total electric power (Yamashita et al., 2012). In Vietnam, regulations stipulate that the total light power of each fishing vessel should not exceed 0.2 kW for inshore lift net fisheries, and 5 kW for purse seine, lift net, squid jigging, and squid drop net fisheries operating offshore (Nguyen, 2006). No regulations, however, can be found in which governments regulate the use of underwater lights. It is therefore necessary to accelerate discussions and adopt specific strategies and regulations on the use of underwater light at local, national, and international scales, in particular for highly migratory, trans-boundary species such as turtles, swordfish, and tunas.

Finally, to limit production of plastic waste and litter from the use of fishing lights, it is necessary to adopt and enforce regulations on their use, handling, and disposal. This includes the United Nations' Regional Seas Conventions (i.e., OSPAR for the North-East Atlantic and the North Sea). Strengthening monitoring, control, and surveillance of light fishing activities would be advisable and necessary.

5.3. Social license

In addition to technical and management measures described above, efforts should be made to increase social license from society toward the use of artificial lights in fishing. This can be accomplished through engagement, awareness, transparency, and education. Seafood consumers are becoming increasingly informed about the sustainability of wild marine resources. Third-party eco-labeling systems have proliferated during the last couple decades, including those from non-governmental organizations, industry sectors, retailers, and the public (FAO, 2010).

Noteworthy is the fact that international regulations on banning deposal of waste at sea have been enforced since the 1970s, but waste that is from sea-based sources (i.e., shipping and fisheries) is increasing (Detloff and Istel, 2016). Educating fishing companies and individual fishermen in the development of sustainable light fishing practices will be necessary to ensure that new waste streams of plastic and litter are not created as a result of a growing use of artificial lights.

In summary, marine fisheries capture activities form an important source of income for many coastal communities around the world (FAO, 2016). Small changes in the CPUE of target species or their operational costs can significantly affect their livelihoods. When adopting new technical or management measures, especially if restrictive, governments should wisely consider providing alternative sources of income support to manage the transition (Mills et al., 2014; Ortiz et al., 2016; Solomon and Ahmed, 2016).

6. Concluding Remarks

This paper reviewed the visual systems of fish and crustaceans, including the morphology of the eye and its visual sensitivity to different wavelengths and intensities of light. The study documents the historical development of light-based fishing around the world, as well as the economic and wide-spread importance of this fishing method globally today. Of specific importance, the paper also discusses the fact that fishing with artificial lights involves important trade-offs. Some of the key positive effects of using artificial lights, such as increased catch rates, reduced bycatch, and energy savings were reviewed. In addition, some of the key negative effects, including ecological impacts, overfishing, bycatch, plastic waste, and greenhouse gas emission were reviewed.

The lessons learned suggest that close cooperation among fishermen, scientists, management, agencies, and other stakeholders is a critical component in reducing negative impacts from the use of fishing lights in commercial fisheries. For example, the implementation of illuminated gillnets to reduce the bycatch of sea turtles will need effort and commitment from government, international non-governmental organizations, and the broader fishing industry. Educating and improving the awareness of fishermen in environmentally safe and friendly use of artificial light, including keeping broken lights aboard the vessel and returning them to recycling places will be an important measure to reduce negative environmental impacts.

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