Lighten Up: Using Artificial Light to Improve the Capture Efficiency of Fishing Gears

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ABSTRACT

Snow crab (*Chionoecetes opilio*) is an important commercial shellfish and one of the most valuable fisheries in eastern Canada. The Newfoundland and Labrador snow crab fishery has been the world's largest for the past two decades. Total landings grew substantially between the 1980s and 1990s, but more recently, the industry has been faced with new challenges including decreases in stock abundance (i.e., poor pre-recruitment), changes in environmental condition (i.e., warming ocean water temperatures), conflicts with shrimp trawlers, effects of seismic exploration, and increases in operating costs. Maintaining the economic viability of small fishing businesses in the presence of these new stressors can be a challenge. In output-controlled fisheries such as snow crab, improving the catch rate of existing traps is an effective method of improving the financial viability of small fishing businesses. In this thesis, I conducted a comprehensive examination of the behaviour of snow crab in response to artificial light (i.e., Light-Emitting Diode (LED) lights and luminescent netting), including laboratory and field experiments, to address the primary goal of improving the catch rate of small conical traps commonly used for catching snow crab in the North Atlantic Ocean.

First, I conducted a literature review regarding the use of artificial light in commercial industrialized fisheries. The review provides valuable knowledge and reference for scientists, managers, and fishermen on animal behaviour in response to artificial light. It also addresses the trade-off between positive effects such as increased catch rate and reduced bycatch with negative effects such as the production of increased

plastic, ocean litter, and greenhouse gas emission. Second, I conducted 7 experiments to investigate the behaviour of snow crab in response to artificial light, including 2 laboratory studies and 5 field studies, to address the primary goal of improving the catch rates of snow crab traps. Results from the laboratory experiments indicated that snow crab responded differently to different light colours. Field experiments in 2016 demonstrated that equipping baited traps with small low-powered LED lights increased the Catch Per Unit Effort (CPUE; number of crab per pot) of the traps (i.e., 77% and 47% for white and purple LED lights, respectively). Next, I examined the effect of installing underwater LED lights in different locations and orientations inside baited traps targeting snow crab off the coast of Newfoundland and Labrador, Canada. Results from this field experiment in 2017 revealed that the location and orientation of lights does not appear to be important. Next, I conducted a comparative fishing study onboard a large offshore fishing vessel targeting snow crab in the Barents Sea, off the coast of Norway. Results revealed that equipping baited traps with purple lights increased the CPUE by 11.6%, although the results varied with the density of crab.

Finally, I examined the potential application of luminescent netting as a source of artificial light to determine whether it could be used to improve the CPUE of traps. A benchtop laboratory experiment was conducted to measure the duration of luminescence using time-lapse photography. I found that luminescent netting can be activated to emit light and that the resulting intensity and duration of luminescence emitted over time, depends on the initial duration of UV exposure and the source of light. A follow-up field experiment in 2018 showed that luminescent traps significantly increased the catch rate of snow crab compared to traditional traps.

Overall, the results of my PhD research demonstrate that artificial light can improve the catch rates of snow crab traps, with examples from different light sources (i.e., LED light, luminescent netting) and locations (Barents Sea, Newfoundland and Labrador). These results suggest that the application of artificial light in commercial snow crab fisheries could improve the financial viability of fishing enterprises.

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Chapter 1. Introduction and Overview

1.1. Snow Crab Distribution and Biology

The snow crab, also known as Queen crab (*Chionoecetes opilio*), is a crustacean like lobster and shrimp, with a flat, almost circular, body and five pairs of spider-like legs with four pairs of walking legs and one large pair of claws. Their eyes are green or greenish blue. Snow crab are prized for their sweet, delicate flavour. The snow crab is a subarctic species, belonging to the family *Oregoniidae*. The species has been found in the northern cold water regions in the North Pacific, the Sea of Japan, the Sea of Okhotsk, the Bering Sea north of the Alaska Peninsula, the west coast of Greenland, along the east coast of Canada from Nova Scotia to Labrador, and Casco Bay in Maine, USA (Jadamec et al., 1999; Mullowney et al., 2018; DFO, 2018a). Snow crab also inhabit the Arctic Ocean, the Beaufort Sea to Cape Perry and the shelf of the Laptev Sea, and the East Siberian Sea (Jadamec et al., 1999). Snow crab have also recently invaded and become permanently established in the Arctic Ocean in portions of the Barents Sea (Alvsvåg et al., 2009; Kaiser et al., 2018). The global snow crab distribution is shown in Figure 1.1. Snow crab are found in a wide range of depths between 20 and 2,000 m, on sandy or muddy substrates, with smaller crab found in shallower water than the larger crab, with most commercial fishing occurring in depths less than 350 m (Hébert et al., 2001; Alvsvåg et al., 2009; Winger and Walsh, 2011; Mullowney et al., 2018; DFO, 2018a). As a stenothermal species, their living temperature is from -1.5^0 to 11^{0}C, but the preferred temperature is below 5^{0}C with salinities in the range of 20–35‰ (Hardy et al., 1994; Yamamoto et al., 2014, 2015; Siikavuopio et al., 2017; Mullowney et al., 2018). Water temperature has a significant effect on survival, food intake, oxygen consumption, growth, molting, reproduction, movement, and mortality rate (Siikavuopio et al., 2017; Mullowney et al., 2018).

The life cycle of males is about a maximum of 19 years in duration, while females is about 13 years (Comeau et al., 1998). Snow crab start to sexually mature at about four years of age. Females carry the eggs for 1 to 2 years, and can produce up to 160,000 eggs between the late spring and early summer, depending on ambient temperatures, food availability, water temperature, and their age (Comeau et al., 1999; Burmeister, 2002). Larvae then become a pelagic plankton for about 5 months before settling to the sea floor (Comeau et al., 1998; DFO, 2018a). As crab mature and increase in size, they migrate from shallow (50m) hard bottom toward deeper (>300m) soft bottoms of mud, sand and gravel (Comeau et al., 1998; Dawe and Colbourne, 2002). Snow crab are sexually dimorphic with mature males having proportionally greater carapace width (CW), longer legs, and larger claws than females (Comeau et al., 1998).

In order to grow, the hard outer shell is periodically shed in a process called molting that mostly occurs in late winter or spring (Conan and Comeau, 1986; Hébert et al., 2001; Mullowney et al., 2014; 2018). After molting, crab have a soft shell for a period of 8 to 10 months (DFO, 2018a). The soft-shelled crab is defined by shell hardness. The term "white crab" describes both new-soft and clean hard-shelled crab. The snow crab attains its terminal molt somewhere between instars 9 and 14, at the size range of about 40–150 mm CW for males, and instars 9 to 11, at the size range of about 30–95 mm CW for females

(Conan and Comeau, 1986). Terminal size is associated with temperature, with cold water promoting terminal molt at smaller sizes (Sainte-Marie and Hazel, 1992; Dawe et al., 2012). Once reaching their terminal molt, adult crab can live a maximum of about 6-8 years under optimal conditions, but they commonly live for 5 to 6 years (Dawe et al., 2012; DFO, 2018a). The maximum size found in Atlantic Canada is about 95 mm carapace width (CW) for females and 150 mm CW for males (Mullowney et al., 2018; DFO, 2018a), while individuals up to 178 mm CW have been reported in the Russian Far East (Grigoryeva, 2010). As a slow growth species, males need from 8 to 11 years to reach the size of 95 mm (i.e., recruit to the fishery), generally earlier in warm areas due to less frequent molting at low temperatures (Dawe et al., 2012; Mullowney et al., 2018).

Snow crab provide a predatory and scavenging role in many ecosystems. The diet of snow crab consists of a great variety of prey items depending on every life-stage and habitat (Kolts et al., 2013). In a larval stage, it feeds mostly on phytoplankton, i.e., algae. While in a juvenile and larger chelae stage they are able to feed on larger prey items, including gastropods (*Gastropoda*), bivalves (*Bivalvia*), shrimps, clams, brittle stars (*Ophiuroidea*), polychaete worms *(Polychaeta)*, fish, and other crustaceans, even soft-shelled snow crab (Squires and Dawe, 2003; Kolts, 2012; DFO, 2018a). Moreover, males prey more on fish, while females feed more on shrimps (Squires and Dawe, 2003). Predators of snow crab include cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), halibut (*Hippoglossus stenolepsis*), wolffish (*Anarhichas sp.*), thorny skates (*Raja spp.*), other snow crab, and seals (*Phocidae*) (Squires and Dawe, 2003; DFO, 2018a).

1.2. Newfoundland and Labrador Snow Crab Fishery and Management

The Newfoundland and Labrador snow crab fishery had a slow beginning in the 1960s, but grew to become the largest snow crab fishery in the world during the past two decades, while maintaining Marine Stewardship Council certification since 2013 (MSC, 2013; Dawe and Mullowney, 2016). The Crab Management Areas (CMA) have no biological relevance, and the resource status is assessed by larger units based on the Northwest Atlantic Fisheries Organization (NAFO) Divisions, with some inshore and offshore regions considered separately (Figure 1.2). A small-scale fishery targeting snow crab began in Trinity Bay in 1968 (i.e., CMA 6A, DFO 2018a). With new fishing grounds of snow crab being found almost every year in the following three decades, the fishery developed rapidly thereafter. In the beginning, snow crab were considered as bycatch in gillnet fisheries targeting groundfish. The fishery slowly expanded along the northeast coast (NAFO Divisions 3K, 3L) in 1979 and the south coast of Newfoundland (NAFO Division 2 J) in 1985, and it has moved further offshore since the mid-1980s (e.g., NAFO Divisions 3O, 3N). This small-scale inshore fishery remained stable until the early 1990s when significant expansion began. Following the collapse of many groundfish stocks during the early 1990s, the snow crab fishery quickly became the most important in terms of social and economic value (Dawe and Mullowney, 2016; Mullowney et al., 2018). The crab fishery continued to expand in Newfoundland and Labrador during the 1990s as a result of growing Japanese market demand and industry diversification (Mullowney et al., 2018). Landings and the commercial catch per unit effort (CPUE; number of crab per pot) first peaked in 1981 but the resource then declined during the early 1980s (DFO, 2018a). The resource was fully exploited by 1999 when landings peaked at 69,000 mt, largely due to expansion of the fishery to offshore areas, but the resource has generally declined during the past 20 years, although landings remained at high volumes compared to the 1980s, with around 50,000 mt in most years. Landings steadily increased somewhat between 2005 and 2009. However, the overall allocated quota then dramatically decreased 45% from 53,500 mt in 2009 to only 29,390 mt in 2018 (DFO 2018a, see Figure 1.3).

Corresponding to the rise and fall of this natural resource, the number of fishing licenses allocated has also changed over time. Very few vessels (<50) were involved in the early 1980's, growing to over 3,500 fishing licenses in 1999, but this number has declined since the mid-2000s to about 2,600 active licenses in 2018 (DFO, 2018a).

The first landings of snow crab took place as bycatch in gillnets targeting groundfish, but have since switched to the top-entry, Japanese-style conical traps set in longlines and normally baited with squid (*Illex illecebrosus*) or a mixture of squid and herring (*Clupea harengus*) (Cyr and Sainte-Marie, 1995; Grant and Hiscock, 2009; Winger and Walsh, 2011; DFO, 2018a). Traps consist of four primary components including a steel frame, net walls, plastic entrance funnel, and a closed container or free hanging hook (skiver) for bait. Currently, the Newfoundland and Labrador snow crab fishery uses a trap having an inside bottom ring diameter of about 130cm and the volume is approximately 2 m^3 (Cyr and Sainte-Marie, 1995; Winger and Walsh, 2011). Traps are equipped with a minimum mesh size of 135 mm stretched mesh netting with a small zipper made of biodegradable twine in the net wall to prevent ghost fishing in the event traps are lost (Winger et al., 2015). A circular, rigid, funnel-shaped plastic skirt is normally used as an entrance to encourage ingress and discourage egress once captured. Bait plays an important role in attracting animals to traps (Thomsen et al., 2010; Winger et al., 2016). Chemical attractants are released from the bait and transported downstream by the current, producing an odour plume, whose shape, orientation, and area strongly depends on the amount of bait, the current speed, direction, and turbulence, losing its effectiveness over time as the bait is depleted (Sainte-Marie and Turcotte, 2003; Thomsen et al., 2010; Winger and Walsh, 2011; Winger et al., 2016). Like other marine animals, snow crab are attracted to baited traps by olfaction, and will move toward the bait by walking/swimming upcurrent to seek the odour source (Vienneau et al., 1993; Winger and Walsh, 2011; Winger et al., 2016). Use of bait protection containers to prevent scavenging species (amphipods) from attacking the bait varies among fishing enterprises, depending on the fishing location, abundance of amphipods encountered and traditional experience. Several studies have demonstrated that the catch rate of traps is significantly reduced with unshielded baits, while some others report that exposed baits using a snap shackle created visual stimulation for conspecifics outside the trap resulting in attracting more crab toward the trap (Miller, 1990; Cyr and Sainte-Marie, 1995; Araya-Schmidt, 2017).

As a commercially important species, strict regulations have been adopted and enforced to ensure conservation objectives and fishery sustainability. The snow crab resource in Newfoundland and Labrador is currently managed under a three-year

Integrated Fisheries Management Plan (DFO, 2014). Management tools include both input and output controls:

(1) Input controls include fleet capacity, trap limits, individual quotas, trip limits, fishing areas restrictions, and seasonal limitations:

- Several communal fleet sectors exist in the fishery: Inshore fleet, consisting of <35 ft. vessels fishing in near-shore regions and bays. The small supplementary fleet consists of predominately by small vessels (i.e., 35-45 ft.) operating offshore. The fulltime fleet, generally represented by large vessels (i.e., 45-65 ft.) operating offshore.
- Netting on traps must have a minimum stretched mesh size of 135 mm or minimum mesh bar length of 65 mm to allow escape of females and sublegal males (DFO, 2018a).
- The fishing season typically starts in early April and is finished by the end of August (DFO, 2018b). However, harvesting does not necessarily last the whole period due to changes in landed price, weather, and molting (Pinfold, 2006). An analysis of landings data showed that more than 90% of the snow crab capture occurs during April-June (Mullowney et al., 2018).
- A soft-shelled protocol was initiated in 2004 within the larger crab fishing areas to assess the incidence of soft-shelled (recently molted) crab capture. If a high proportion of soft-shell crab are caught, the fishery will close for the remainder of the season in that particular grid. The closure thresholds differ by

management area, but in most cases, when 20% of the catch in a grid is comprised of soft shell crab, that grid is closed (DFO, 2018a).

(2) Output controls include minimum landing size, total allowable catches, and vessel monitoring systems:

- The management approach for snow crab is based on maintaining the harvesting rate at a moderate level when stock status is healthy. The minimum carapace width (CW) for harvesting snow crab in Newfoundland and Labrador has been 95 mm since 1973 (Conan and Comeau, 1986). At this size, most males have had the opportunity to mate at least once (Comeau et al., 1998). The fishery excludes females (DFO, 2018a). Females, undersized males, and uncaught legal sized males are assumed to be sufficient to maintain the reproductive potential of the resource (Comeau et al., 1998; Dawe and Mullowney, 2016). Under-sized and soft-shelled males that are retained in the traps must be returned to the sea (DFO, 2018a).
- A total allowable catch (TAC) and quota allocation management system was initiated by the late 1980s. The TAC to be fished is determined from scientific and industry input. Advisory Committees submit recommendations on the TAC based on acceptable exploitation rates that are adjusted based on biological evidence. TACs are partitioned as individual quotas (IQs) among fishing enterprises. An IQ does not guarantee that all crab will be landed. Each fishing enterprise is allocated an IQ to be harvested within a specific crab

management area, toward achieving a broad spatial distribution of fishing efforts (Mullowney and Dawe, 2009).

- Licence holders are allocated a specific IQ and a maximum number of traps during the fishing season within a specific CMA.
- A vessel monitoring system (VMS) was fully implemented in the offshore fleets in 2004. The system ensures compliance with CMA regulations (DFO, 2018a). Other regulations include mandatory completion and submission of fishing logbooks and at sea observer coverage on 10% of commercial trips (Mullowney and Dawe, 2009).

In addition to conservation and harvesting plans specific to each CMA, the fishery is governed by a suite of legislation, regulations, and policy including but not limited to:

- Fisheries Act
- Coastal Fisheries Protection Act, 1985
- Oceans Act, 1996
- Species at Risk Act, 2002
- Atlantic Fishery Regulations (AFR), 1985
- Fishery (General) Regulations, 1993
- Aboriginal Communal Fishing Licences Regulations, 1993
- Commercial Fisheries Licensing Policy for Eastern Canada 1996
- A Policy Framework for the Management of Fisheries on Canada’s Atlantic Coast
- Sustainable Fisheries Framework: Conservation and Sustainable Use policies

- A Fishery Decision-Making Framework Incorporating the Precautionary Approach
- Policy on New Fisheries for Forage Species
- Managing Impacts of Fishing on Benthic Habitat, Communities and Species
- Policy on Managing Bycatch

1.3. Barents Sea Snow Crab Fishery and Management

As an invasive species, snow crab was first found in the Barents Sea in 1996, outside their native range that previously included the North Pacific, Beaufort Sea, Arctic, and Northwest Atlantic. When and how they arrived there, remains somewhat of a mystery for the scientific community (Kuzmin et al., 1999; Alvsvåg et al., 2009). Historically, the first five snow crab (1 female and 4 males) were accidentally captured by the Russian bottom trawl fishery. Following this, snow crab were found in the process of trawl-acoustic surveys, which were performed by research vessels (Agnalt et al., 2011). After that, the Russians collected 15 additional individuals in the eastern Barents Sea by the end of 1999 (Agnalt et al., 2011). Since then the abundance and distribution of snow crab has increased steadily every year (Hansen, 2016). In Norwegian coastal waters, fishermen reported observing two snow crab off Finnmark in 2003 as bycatch (Alvsvåg et al., 2009). More crab have since been reported, mainly captured as bycatch in commercial bottom trawls (Agnalt et al., 2011). First, the snow crab occurred mainly in the eastern part of the Barents Sea (Russian waters). Later on, more crab were found over a much larger area, including south of Novaya Zemlya, southeastern and central Barents Sea, southern St. Ann Trough, i.e., north of Novaya Zemlya Island at the entrance to the Kara Sea (Alvsvåg et al., 2009; Agnalt et al., 2011). Crab were found mainly at depths between 40 and 380 m, with temperatures ranging from -0.8 to 3.4^{0}C (Alvsvåg et al., 2009; Agnalt et al., 2010). The sizes ranged from 5 to 166 mm CW (Alvsvåg et al., 2009).

Several surveys to assess distribution and abundance have been conducted during the past several years. Russian scientists conducted targeted surveys in 2007 and estimated the stock at 6.22 million individuals, while the results of a similar survey conducted in 2008 put the stock at 19 million individuals, 500 times as large as in 2004 (Agnalt et al., 2011). The population was predicted to grow to 370 million individuals, with a total estimated biomass of 188,260 mt in the near future (Dvoretsky and Dvoretsky, 2015).

A commercial snow crab fishery in the Barents Sea started in 2012 and is rapidly expanding (Lorentzen et al., 2018). Snow crab have become a potentially important species for the Norwegian seafood industry (Lorentzen et al., 2018). Commercial landings increased from 4,000 mt, representing an export value of approximately $13 million USD (NOK 100 mil) in 2015, to 5,300 mt representing $40 million USD (NOK 338 mil) in 2016 (Lorentzen et al., 2016, 2018). The total export value is expected to reach $880 million USD in the next 15 years (Hansen, 2016). Currently there are 56 licenses for snow crab and only 10-15 vessels regularly operating. Similar to the Newfoundland and Labrador snow crab fishery, conical traps are the most commonly used fishing gear in the

Barents Sea. The traps are typically baited with squid or a combination of squid and herring (Lorentzen et al., 2018).

The fishery is based on males and regulated by a minimum legal size of 100 mm CW. The quota was set at 4,000 mt for 2018, with a closure from mid- June to mid-September to protect the crab post-molting. In addition, the maximum allowable percentage of soft shell crab is set at 20%, in which case the vessels must leave the area. The traps are not permitted to soak more than 3 weeks.

Currently, the Barents Sea snow crab fishery is facing several challenges including:

- Ecological impact: as a non-native species, snow crab threaten global biodiversity and are regulated by international law (Hansen, 2016).
- Transboundary: the crab distribution spreads across a continental shelf shared between Norway and Russia, is harvested outside economic zones and has the status of sedentary (Hansen, 2016).
- Disputed regime: a large part of the future Norwegian fishery is expected to take place around Svalbard, an area of highly disputed resource rights (Hansen, 2016).
- High operating cost: the stock is distributed offshore, requiring large vessels with significant operating costs

1.4. Use of Artificial Light in Commercial Fisheries

The use of artificial light in fishing operations is a technique to attract and aggregate fish and eventually capture them using various fishing gears such as purse seines, stick held lift nets, squid jigging, scoop net, drop nets, and hook-and-line (Ben-Yami, 1976; Arimoto et al., 2010; Yamashita et al., 2012; An et al., 2017; Susanto et al., 2017). Fishing with lights is one of the most advanced and successful methods for catching squids and other pelagic species for centuries. Historically, fishermen started with artificial light in the form of bonfire on the beach. This was used for thousands of years when fishermen discovered that some fish were attracted to light at the beach and would silently enter the water with nets, encircle the illuminated zone, and drag the fish to the shore (Ben-Yami, 1976). The next development was the use of torches. These were made from coconut husk, split bamboo, carried by fishermen wading in water in the dark night (Ben-Yami, 1976). Over time, and due to technological development, incandescent, mercury, fluorescent, halogen, and metal halide lights were sequentially introduced and used around the world because of their high luminescent efficiency. With advances in technology, Light Emitting Diode (LED) lights with minimum energy consumption, extremely long lifespan, higher efficiency, better chromatic performance, and reduced environmental impact compared to traditional lighting technology, have been introduced in recent years (Yamashita et al., 2012; Hua and Xing, 2013; Okpala et al., 2017). While the use of artificial light has mostly occurred in overwater applications to date, there is now growing interest in its application underwater. Potential opportunities exist to improve catch rates, size-selectivity, and reduce the bycatch of non-targeted species.

Today, the best known example of the use of underwater fishing lights is the swordfish (*Xiphias gladius*) longline fishery which uses chemically disposable submersible lightsticks to attract swordfish to baited hooks (Ito et al., 1998; Witzell, 1999; Stone and Dixon, 2001; Hazin et al., 2005; Tüzen et al., 2013). Underwater lights are also commonly used in tuna fisheries (Hazin et al., 2005), purse seine and large scale trap (i.e., set net) fisheries in Japan (Arimoto, 2013; Masuda et al., 2013), as well as squid jigging fisheries in China (Qian et al., 2013). More recently, they have even been tested in baited traps for cod (Bryhn et al., 2014; Humborstad et al., 2018) and shrimp (Ljungberg and Bouwmeester, 2018) for improving the catch rate of target species. Underwater lasers are also being developed for the herding of shrimp and fish into a virtual trawl (Hreinsson et al., 2018). These examples demonstrate that underwater light can be employed to increase the catching efficiency of certain commercial fishing operations, although in many cases functional explanations remain unclear as to why and how light attracts animals.

While artificial light may be used as an attractive stimulus for some species, in other cases it may work to deter them or simply help animals to seek an escape route. 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* (Hannah et al., 2015; Rose and Hammond, 2014; Larsen et al., 2017, 2018; Melli et al., 2018; Lomeli 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 trawls (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 special topic group has been formed within the ICES Working Group on Fishing Technology and Fish Behaviour to document current knowledge and address the apparent knowledge gap (ICES-FAO, 2013, 2018).

1.5. Objectives of Research

The primary goal of this thesis is to contribute in the development of a sustainable, efficient, and profitable snow crab fishery by improving the catch rate of traditional baited traps. Five key objectives include:

(1) Literature review of marine animal behaviour in response to artificial light, with an emphasis on commercial industrialized fisheries.

(2) Investigate the behaviour and catch rate of snow crab in response to different LED light colours under laboratory and field conditions.

(3) Evaluate whether the location and orientation of lights in traps affects catch rate.

(4) Evaluate whether results in eastern Canada are transferrable to the snow crab fishery in the Barents Sea.

(5) Evaluate whether luminescent netting has potential to increase the catch rate of baited traps.

1.6. Chapter Outline

In Chapter One, I provide an overview of snow crab in Newfoundland and Labrador as well as the Barents Sea. I briefly describe its distribution, biology, fisheries, and management. I also provide an introduction to the use of artificial light in commercial fisheries, including a brief description on the historical development, technological advancement, and two of its useful applications: a) increasing catch rates, and b) reducing bycatch. I then outline the objectives of the thesis and provide an outline of the chapters.

In Chapter Two, I provide a literature review of vision in aquatic animals and the use of artificial light in commercial industrialized fisheries. The first part of the chapter is an overview of vision in aquatic species and behaviour of marine organisms in response to artificial light in which I describe the eye structures of marine species, provide a selected review of the visual sensitivity of various aquatic species, and discuss their behaviour in response to light colour and intensity. I then synthesize known applications of artificial light in commercial industrialized fishing operations, including historical use of artificial fishing light, use of artificial light to increase catch rate, to reduce bycatch, and to reduce fuel consumption. I also discuss potential negative impacts, including ecological costs, overfishing, increased bycatch, production of plastic and marine litter, and greenhouse gas emission. This chapter was an important prerequisite to conducting experiments using artificial light (i.e., my subsequent chapters).

In Chapter Three, I examine the behaviour and commercial catch rate of snow crab in response to different LED light colours under laboratory and field conditions. I examine the behaviour of snow crab in response to various LED lights. I begin with a laboratory experiment, followed by two field experiments in the inshore and offshore waters of eastern Canada. The laboratory experiment was conducted in a controlled tank environment at Fisheries and Oceans Canada (St. John's) to investigate behavioural responses toward 5 different colour lights including blue, green, red, purple and white. Two field experiments are then described and documented, in which I investigated whether the lights increased CPUE during the 2016 commercial snow crab fishery off the coast of Newfoundland and Labrador.

In Chapter Four, I investigate whether installing underwater LED lights in different locations and orientations within a trap affects CPUE. I hypothesize that the position and orientation of a light within a trap will produce different patterns of illumination, resulting in differences in catch rate of target and non-target species. In this Chapter, I test the null hypothesis that light position and orientation do not affect the CPUE of legal-sized crab, and sublegal-sized crab. Five experimental treatments are investigated. The results are discussed in relation to functional explanations for why snow crab are attracted to lights.

In Chapter Five, I describe an experiment in which the positive results from Chapter Three are transferred to the Barents Sea to determine whether snow crab in that fishery respond to artificial light. I test whether there are differences in catch rate between traditional baited pots and identical traps equipped with purple or white LED lights. Two field experiments were conducted in 2017 and 2018 in collaboration with research scientists at the Institute for Marine Research, Bergen, Norway.

In Chapter Six, I examine the potential for luminescent netting, an alternative to LED lights, as a means to increase catch rates of snow crab. The product is called EuroGlow™ netting, manufactured by Euronete in Portugal. I began with a benchtop laboratory experiment to investigate the intensity and duration of luminescence using time-lapsed photography. I then conducted a small fishing experiment to test the null hypotheses that the glow in the dark traps do not differ in their CPUE or size-selectivity compared to traditional traps of the same mesh size. I compare my results to recent research using LED lights and discuss its possible application to commercial fishing operations.

In Chapter Seven, I provide an overall summary of the results and conclusions from each chapter. I discuss the potential application of artificial light in commercial snow crab fisheries, limitations of my experimental approach, and recommendations for future research.

1.7. Co-Authorship Statement

I am the major intellectual contributor and principal author of all chapters presented in this thesis. I contributed to all practical aspects of the research, including design of the experiments, data collection and analysis, interpretation of results, and subsequent manuscript preparation. However, my work would never have been able to start or finish without direct guidance and excellent supervision of my supervisor Dr. Paul Winger, valuable support from the supervisory committee members Dr. Scott Grant, Dr. Corey

Morris, and Dr. Shannon Bayse, and cooperative contribution of several individuals. I prepared the manuscripts and revised them based on the advice and comments from my co-authors. The contribution and involvement of each individual is recognized below.

Chief collaborator for Chapter Two was Paul Winger. Dr. Winger discussed the primary ideas, reference collection, supervision and advice throughout the study, and provided the comprehensive editorial reviews of the manuscript. This chapter was published in the journal *Reviews in Fisheries Science and Aquaculture* in 2019 (27:106-126). I am the primary author and Dr. Winger is the second author.

Chief collaborators for Chapter Three were Paul Winger, Corey Morris, and Scott Grant. Dr. Winger directly contributed to the research proposal, the experimental design, the data interpretation, field work arrangement, and provided editorial reviews of the manuscript. Dr. Morris provided equipment and specimens for the laboratory experiment, data collection of the second field experiment, and provided editorial reviews of the manuscript. Dr. Grant contributed to the statistical methods and edited the manuscript. This chapter was published in the journal *Aquaculture and Fisheries* in 2017 (2:124-133). I am the primary author and Dr. Winger, Dr. Morris, and Dr. Grant are second, third, and fourth authors, respectively.

Chief collaborator for Chapter Four was Paul Winger. Dr. Winger contributed to the research proposal, the experimental design, and field work arrangement, aided with the data interpretation, and provided the editorial reviews of the manuscript. This chapter was published in the journal *Aquaculture and Fisheries* (In Press). I am the primary author and Dr. Winger is the second author.

Chief collaborators for Chapter Five were Odd-Børre Humborstad, Svein Løkkeborg, Paul Winger, and Shannon Bayse. I was invited to Norway by Dr. Humborstad to conduct collaborative field experiments in the Barents Sea (Project SnowMap) with permission to include the work in my thesis. Dr. Humborstad proposed the research ideas and hypotheses, designed the experiment, arranged and participated with the field work, discussed the statistical methods, aided with the data interpretation and provided editorial reviews of the manuscript. Dr. Løkkeborg directly participated with the field work, discussed data analysis, and provided editorial reviews of the manuscript. Dr. Winger contributed to the experimental design, interpreted the data, and provided editorial reviews of the manuscript. Dr. Bayse contributed to the data analysis, interpretation of results, and editorial reviews of the manuscript. This chapter was published in the journal *ICES Journal of Marine Science* (In Press). I am the primary author, Drs. Humborstad, Løkkeborg, Winger, and Bayse are co-authors 2 through 5, respectively.

Chief collaborators for Chapter Six were Paul Winger, Jessica Wood, Meghan Donovan, Odd-Børre Humborstad, Svein Løkkeborg, and Shannon Bayse. Dr. Winger contributed to the research proposal, the experimental design, field work arrangement, supervision, and advice throughout the study, aided with the data interpretation, and editorial reviews of the manuscript. Jessica Wood assisted with laboratory and field experiment, participated in the design of the study, and helped draft the manuscript. Drs. Humborstad, Løkkeborg, and Bayse participated in data analysis and provided editorial reviews of the manuscript. This chapter was published in the journal *Marine and Coastal Fisheries* (In Press). I am the primary author and Dr. Winger, Wood, Donovan, Drs. Humborstad, Løkkeborg, and Bayse are co-authors 2 through 7, respectively.

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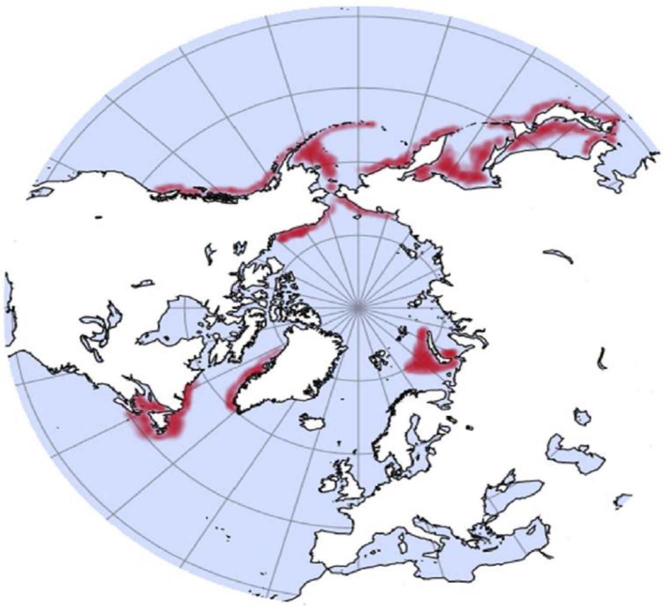

Figure 1.1. Snow crab distribution in the Pacific and Atlantic Ocean. The red areas indicate natural distribution (Kaiser et al., 2018).

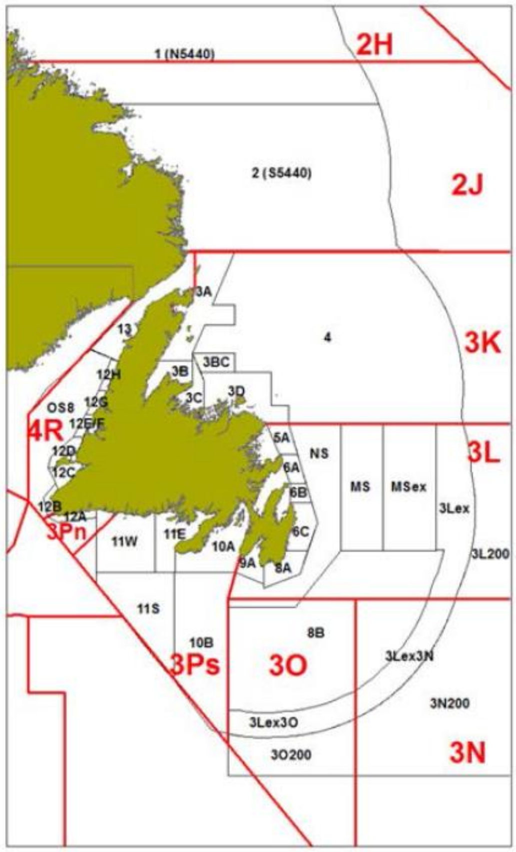

Figure 1.2 Management Areas of the snow crab fishery for the Newfoundland and Labrador Region. Red lines represent NAFO Divisions. Black lines represent Newfoundland and Labrador Snow Crab Management Areas (DFO, 2018a).

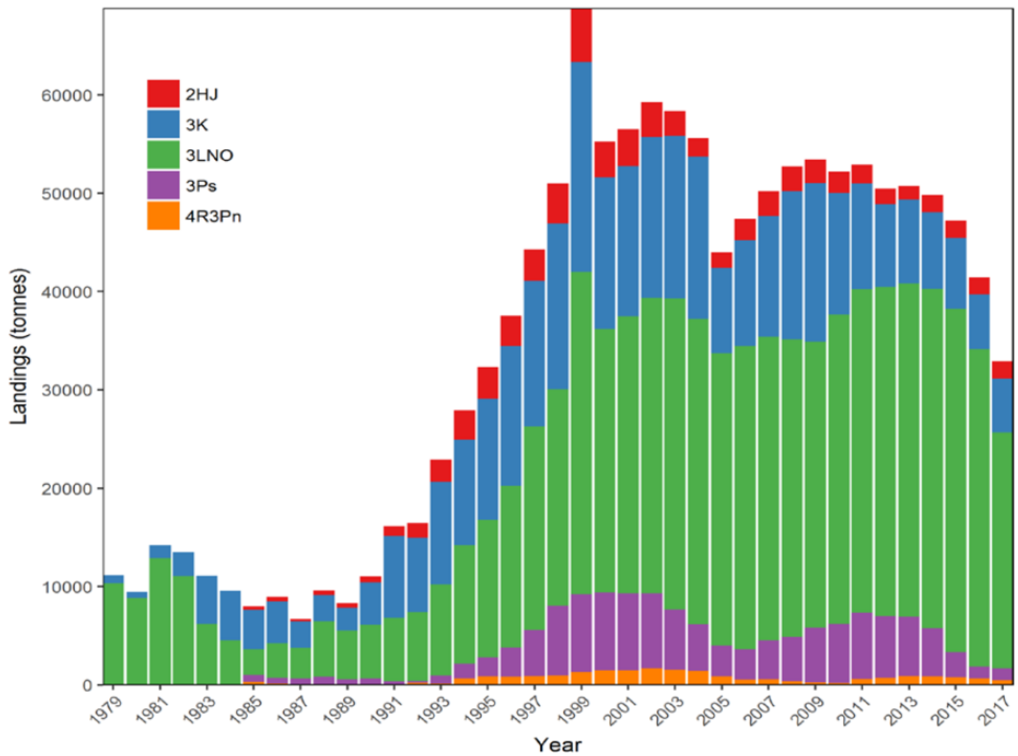

Figure 1.3 Annual landings of snow crab by NAFO Division (DFO, 2018a).

Chapter 2. Artificial light in commercial industrialized fishing applications: a review

2.1. 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

2.2. Introduction

Vision 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). The living environment is an important factor affecting fish vision, as different habitats and aquatic environments can demand different spectral sensitivities of marine organisms, especially deep-water species such as decapod crustaceans (see Cronin and Jinks, 2001; Johnson et al., 2002). This paper reviews the technical literature on fish vision and behaviour 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 behaviour 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 colour (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 behaviour are, however, known to vary across species and their ontogeny (see review by Ben-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 scale. Applications now include a wide variety of pelagic and benthic species across a range of fixed and mobile gear types (e.g., Ben-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, greenhouse gas emissions, and light pollution (IEA Statistics, 2011; Gaston et al., 2012; Solomon and Ahmed, 2016; Detloff and Istel, 2016; Luarte et al., 2016; Rodríguez et al., 2017). 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 behaviour, as well as the use of artificial light in commercial fishing, to my knowledge 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.

2.3. Understanding vision of aquatic marine species and their behaviour relative to artificial light

2.3.1. 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 Ben-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 nerve (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 2.1). 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 colour, with a wide spectrum of colour 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 colour blind (Kroger, 2013). Many deep sea species living deeper than 200 m (Douglas et al., 1998) have limited colour 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 sea 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, colour 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. Fishes have become adapted to their environment with rods and cones depending on the light intensity available to specific habitats. 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 2.2). 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 2.3). 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 against different backgrounds and ambient light conditions are key factors affecting fish behaviour 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 from 10^{-7} to 10^{-4} lux (Protasov, 1970), but the minimum intensity of light that the animal can function visually is approximately $4.0 \pm 1.5 \times 10^{5}$ photons cm^{-2} s^{-1} (Doujak, 1985).   Table 2.1 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, 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 capacity to look in all directions, without the need to move their eyes (Doujak, 1985; Zeil and Hemmi, 2006; Detto, 2007).

2.3.2. Behaviour 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 (Ben-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 Ben-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., Ben-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 (Ben-Yami, 1976; Sokimi and Beverly, 2010).

The colour (i.e., wavelength) produced by an artificial light may strongly affect behavioural responses in some 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). Some marine organisms have been shown to have 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 2.2 provides a selected review of the literature. While some species can function visually under ultraviolet or far red, most fish species perceive light in the 400 to 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 2.4 demonstrates a typical increase in fishing gear efficiency with increasing intensity (kW) of surface-mounted lights. Table 2.3 provides examples of the literature on behaviour of various aquatic species in response to light intensity.

2.4. Use of artificial lights in commercial industrialized fishing applications

2.4.1. 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; Ben-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 (Ben-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 (Ben-Yami, 1976). Using artificial light in the form of a bonfire on the beach existed until the middle 20th century in places such as Cameroon, Indonesia, and Australia (Ben-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 the 20th century, with kerosene and electric lamps sequentially introduced (Ben-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 by using less energy (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 2.5 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 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 Ben-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 Ben-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; Ben-Yami, 1976; Beltestad and Misund, 1988; Arakawa et al., 1998; Liao et al., 2007; Nguyen and Tran, 2015). See Table 2.4 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 overwater (surface) lights. The largest known application of underwater lights today 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, 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 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).

2.4.2. 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 approximately 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 were difficult to catch without the use of light as they usually aggregated toward deep water during the day and migrated to the surface in the evening, but they often stayed 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; Yamashita et al., 2012;

Matsushita et al., 2012; Matsushita and Yamashita, 2012; Qian et al., 2013). 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 (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 approximately 250g of cut fresh herring) in the Baltic Sea increased the CPUE and Weight Per Unit Effort (WPUE; fish weight per pot) 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 of 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).

2.4.3. 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 approximately 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, etc. (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* (Hannah et al., 2015; Rose and Hammond, 2014; 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%, reduced juvenile darkblotched rockfish (*Sebastes crameri*) bycatch by 82%, and reduced other juvenile rockfishes by 56% (Hannah et al., 2015). 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 behaviour 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 behaviour 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.

2.4.4. Use of artificial light to reduce fuel consumption

Fuel consumption by the world's capture fisheries in 2000 was approximately 50 billion litres 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 Yamashita et al., 2012; Matsushita et al., 2012; Matsushita and Yamashita, 2012; Hua and Xing, 2013, 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 using less power than traditional light 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, and 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 approximately 900 litres of diesel fuel every night, which equates to approximately 1,700 litres 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 approximately 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*), which 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 180 W LED light substituting 540 W fluorescent light for catching anchovy (*Stolephorus sp.*) increased approximately 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).

2.5. Negative Impacts

2.5.1. 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 behaviour, spatial distribution, predation risk, migration, and reproduction (Nightingale et al., 2006). Feeding of predators increased when artificial light were turned-on because the abundance of prey in the illuminated area increased and could be more easily targeted by fish predators, whereas predator foraging was less successful 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 (Migaud et al., 2009; Downing and Litvak, 2001; Sierra-Flores, 2016). This has the potential to create unnatural top–down regulation of fish populations (Becker et al., 2013).

2.5.2. Overfishing effects

Maintaining ecosystem function and stock health are challenges in modern fisheries management. 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 of 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).

2.5.3. 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 and shark). 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, leatherback (*Dermochelys coriacea*) and hawksbill (*Eretmochelys imbricata*) turtle, 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, 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.

2.5.4. 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 approximately 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 years, 450 years, 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 5 mm in size, called micro-plastics (Moore, 2008; Cho, 2011; Wagner et al., 2014). 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 (Derraik, 2002; Moore, 2008).

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 approximately 12 hours 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, approximately 7,000 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 (10–1,500 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 et al., 2012; Matsushita and Yamashita, 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 approximately 4.6 million baited traps (DFO, 2009). If every trap was equipped with a low-powered LED light (57.6 grams of plastic), this would constitute placing 265 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 21.2 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.

2.5.5. 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 approximately 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 approximately 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 1kg 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 approximately 345.6 g of CO_2 to be manufactured. This means equipping 4.6 million snow crab traps in the province of Newfoundland and Labrador, Canada, for example, could produce (roughly speaking) 1,589.8 tonnes of CO_2.

2.6. Solutions to reduce negative impact

2.6.1. 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 (>100m) longlines (see review by Bartram and Kaneko, 2004). This is because turtles tend to be found at depths less than 40 m, therefore, fishing gear set at greater depths would minimize incidental mortality rate of turtles without reducing catch yield of target species. 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 behaviour 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 the environment (Yamashita et al., 2012; Qian et al., 2013).

2.6.2. Regulation and management measures

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 (Ben-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. 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, could benefit fisheries management.

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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.

2.6.3. 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-labelling 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 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 consider alternative sources of income support to manage the transition (Mills et al., 2014; Ortiz et al., 2016; Solomon and Ahmed, 2016).

2.7. Concluding Remarks

This chapter 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 chapter 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.

2.8. Way Forward

Although this chapter does not specifically review the behaviour of snow crab in response to artificial light, the literature review does expand our understanding of the motivations and responses of marine animals to various light stimuli, including snow crab. This chapter suggests a potential application of underwater light (i.e., LED light) to improve the catch rate of snow crab traps, which were successful deployed in other fisheries (e.g., cod and shrimp traps).

In order to understand how snow crab respond to artificial light, in the next chapter I will examine the behaviour of snow crab in response to various LED lights. I will conduct a laboratory experiment to examine the behaviour of snow crab toward different light colours, followed by field experiments in the commercial snow crab fishery in both the inshore and offshore waters of eastern Canada, with and without the presence of a bait.

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2.10. References

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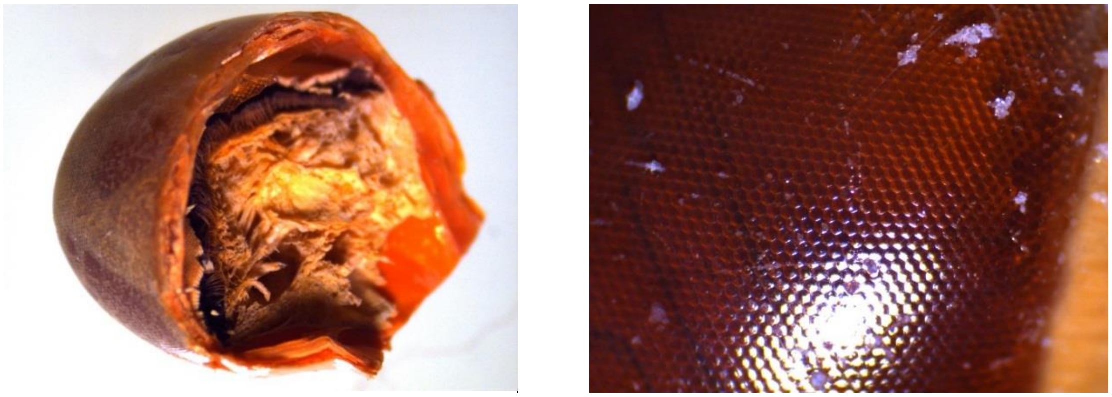

Figure 2.1. Eye of snow crab (*Chionoecetes opilio*). Left: view under stereomicroscope of the cross-sectional profile. Right: scanning electron micrograph (SEM) of the eye surface.

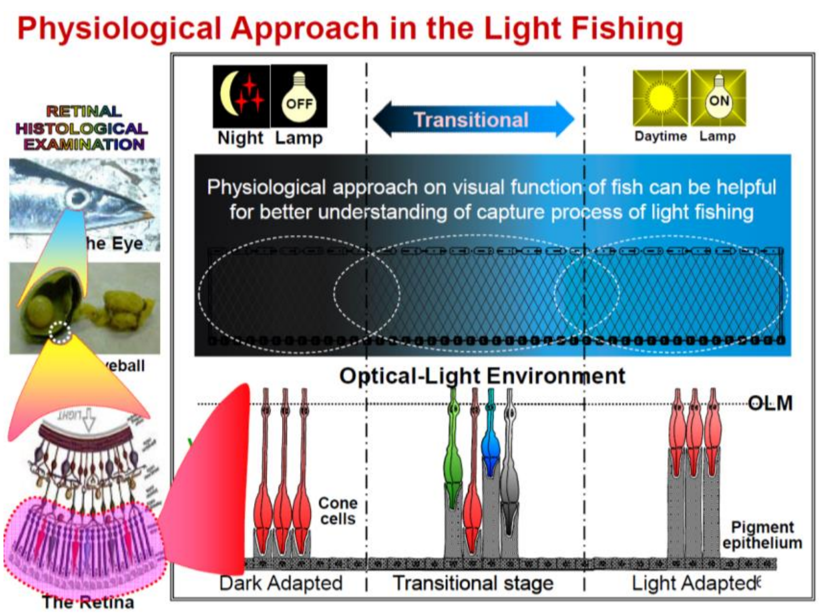

Figure 2.2. The diagram illustrates the adaption of cones to light intensity (reprinted with permission from Arimoto, 2013).

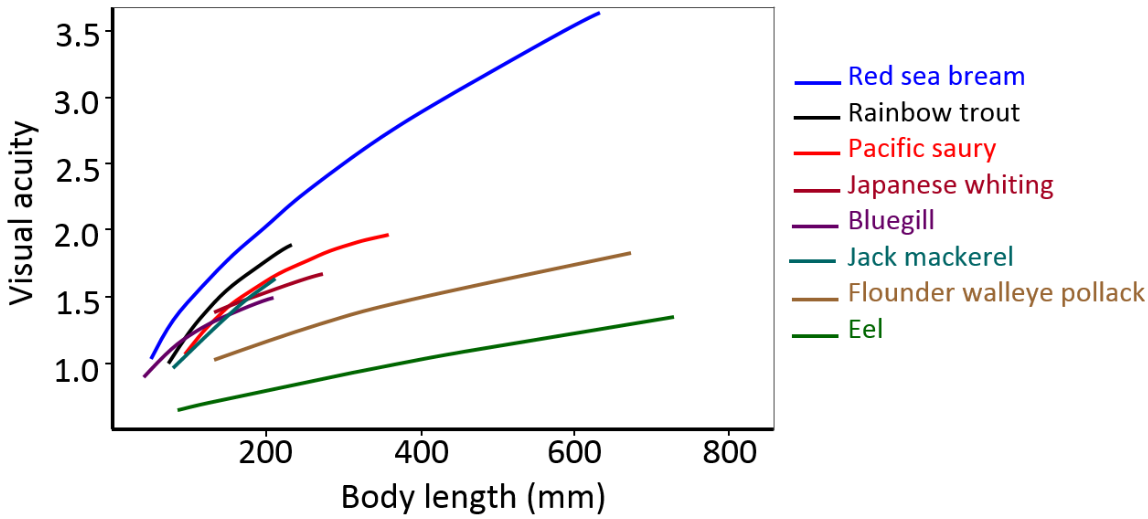

Figure 2.3. Comparison of visual acuity with body length and species (reprinted with permission from Arimoto, 2013).

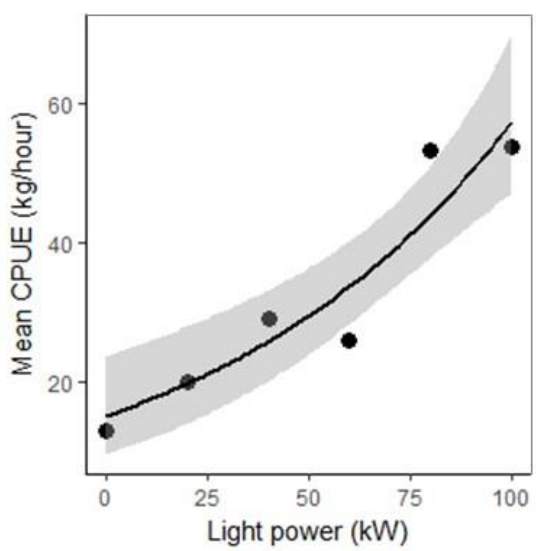

Figure 2.4. Exponential relationship between the mean catch rate of stick-held dip net and the light power. This relation was calculated by equation: CPUE = $10.701e^{0.283kW}$ (R^2 = 0.9114). Grey area is 95% confident interval (modified from Liao et al., 2007).

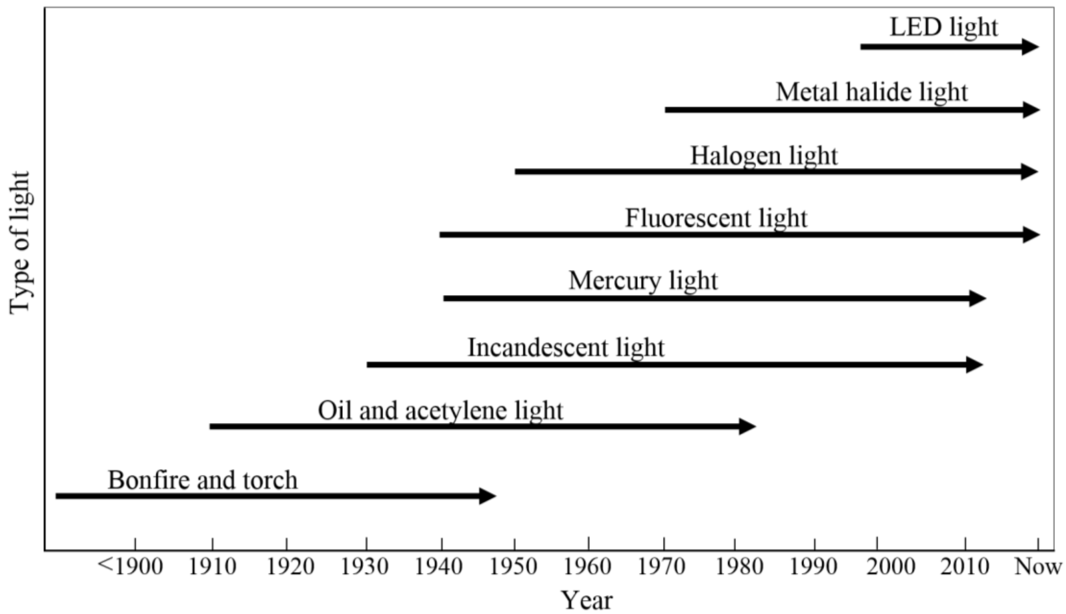

Figure 2.5. History of technological development of artificial light used in fisheries. Bonfire and torch existed until 1940s. Oil and acetylene light occurred in 1910 and existed until 1980s. Incandescent and mercury light introduced in 1930s and 1940s, respectively, and operated until 2010. Fluorescent, halogen, metal halide and LED light introduced in 1940s, 1950s, 1970s, and 2000s, respectively, and today, only these 4 types of light are commonly used (modified from An, 2013).

Table 2.1. The visual sensitivity of various aquatic species. Examples of literature 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 cral	*Bythograea thermydron*	489 nm	Cronin and Jinks, 2001
Jack mackerel	*Trachurus japonicas*	497.5 nm	Anraku & 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 at el. 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

Table 2.2. Behaviour of various aquatic species in response to light colour Examples of literature 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 colours 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 2.3. Behaviour of various aquatic species in response to light intensity. Examples of literature 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 $3x10^{-2}$ lux to $3.4x10^{-3}$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

Table 2.4. Summary of the historical use of artificial light (overwater/surface) used in fishing. Examples of literature review of key countries.

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*,	Bannerman and Quartey, 2004;

			horse-mackerel *Trachurus trachurus*, bonitos *Sardini*, and cephalopods (squids)	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

Chapter 3. Artificial lights improve the catchability of snow crab (*Chionoecetes opilio*) traps

3.1. Abstract

This study investigated the behaviour and commercial catchability of snow crab (*Chionoecetes opilio*) in response to different low-powered LED lights under laboratory and field conditions. We created a novel choice-experiment in a laboratory setting in which we investigated the behaviour of snow crab in response to coloured LED lights. The results showed that snow crab movement was dependent on light colour, with animals choosing to move toward blue and white lights, away from purple lights, and no detectable effect for green and red lights. We then conducted two field experiments to investigate the effect of the same LED lights on the catch rates of commercial traps during the 2016 snow crab fishery on the east coast of Newfoundland and Labrador. Results from the first field experiment showed that adding white and purple LED lights into baited traps significantly improved Catch Per Unit Effort (CPUE) by 77% and 47% respectively. Results from the second field experiment showed that unbaited traps equipped with only LED lights (no bait), could also catch snow crab in comparable amounts to traditional baited traps, with soak time and depth explaining some of the variation in CPUE. Taken together, these experiments suggest that fishing enterprises can improve their catching performance and profitability by adding LED lights to their traps, or by using LED lights as a bait replacement.

Keywords

Chionoecetes opilio, snow crab, LED light, catchability, crab behaviour

3.2. Introduction

The snow crab (*Chionoecetes opilio*) fishery in Newfoundland and Labrador (Canada) began in 1968 (Dawe et al., 2002). A Total Allowable Catch (TAC) and quota allocation management system was applied by the late 1980s (DFO, 2016a). Since 1973, regulating the minimum legal landing size to > 95 mm carapace width (CW) and excluding the capture of females has provided an effective precautionary approach to fisheries management (Conan and Comeau, 1986; Dawe and Mullowney, 2016). By the early 1990s, snow crab had become a very important commercial fishery and a major economic contributor to Canada's most eastern province. Landings in 2015 were 47,310 metric tons accounting for CAD $258 million in landed value, representing more than 50% of landed value of finfish and shellfish combined in Newfoundland and Labrador (DFA, 2015). However, the current snow crab resource has shown signs of population decline, leading to a reduction in the Total Allowable Catch (TAC) in recent years, including an overall quota level decrease of approximately 13% from 2015 to 2016 (DFO, 2016a). The fishing season typically starts in early April and is completed by the end of August (DFO, 2009). There were approximately 2,600 fishing licenses (DFO, 2016a), sharing a TAC of 43,802 tonnes of snow crab in 2016 (DFO, 2016b). The small Japanese-style conical trap is the only legal gear type, with a minimum mesh bar length of 65 mm or minimum mesh size of 135 mm (DFO, 2016a).

Given the important contribution of snow crab to the economy of eastern Canada, a substantial number of studies have been conducted during the past few decades on its capture and selectivity. Underwater video of snow crab behaviour around baited traps has contributed much to the understanding of the capture process (see Chiasson et al., 1993; Vienneau et al., 1993; Winger and Walsh, 2011). Several technical measures and operational methods have been evaluated over a number of studies to improve trap selectivity and performance, including variations in trap shape, mesh size, plastic barriers, escape mechanisms, biodegradable twine, bait choice, and soak time (e.g. Coulombe and Beaulieu, 1987; Chiasson et al., 1993; Vienneau et al., 1993; Hébert et al., 2001; Atkins et al., 2002; Winger and Walsh, 2007, 2011; Grant and Hiscock, 2009; Winger et al., 2015).

Using light as a stimulus to attract and accumulate fish has existed for thousands of years, ranging from simple torches to sophisticated artificial illumination systems using multiple vessels (Breen and Lerner, 2013), including application both overwater and underwater (e.g. An, 2013; Bryhn et al., 2014, Ortiz et al., 2016). Given the often dark and murky nature of the underwater environment, the introduction of light as a stimulus can have forthright and profound effects on the behaviour of aquatic animals (Breen and Lerner, 2013). Historically, purse seines, stick held lift nets, squid jigging, and drop nets were the major fishing methods using light (e.g. Matsushita et al., 2012; Matsushita and Yamashita, 2012; Yamashita et al., 2012; Breen and Lerner, 2013). However, the use of light has now spread to other fishing methods and greater depths, including: traps, pots, trawls, longlines and gillnets for improving the catchability of target species as well as reducing the bycatch of non-target species (e.g. Wang et al., 2007; Bryhn et al., 2014; Hannah et al., 2015; Ortiz et al., 2016). Advances in fishing technology including the application of Light Emitting Diode (LED) lights that last longer, are more efficient, and have better chromatic performance than other lights, (e.g. Matsushita et al., 2012;

Matsushita and Yamashita, 2012; Yamashita et al., 2012; An, 2013; Breen and Lerner, 2013; Kroger, 2013; Bryhn et al., 2014; Nguyen and Tran, 2015). LED lights are an important contribution towards improving modern fisheries which face increasing demand, higher harvesting costs, and a responsibillity to ensure ecologically responsible methodologies.

To our knowledge, there has been no scientific investigation on the behaviour of snow crab in response to coloured artificial lights and its relevance to fisheries applications. The only piece of incidental information came from a study by Murphy (2014) during the development of baited traps for flatfish. The study accidentally discovered that unbaited traps equipped with an LED light captured occasional snow crab as bycatch. This was the first evidence that underwater LED lights might be an effective stimulus for capturing snow crab.

The purpose of this study was to investigate the behaviour and commercial catchability of snow crab in response to LED lights under laboratory and field conditions. In our laboratory experiment, we created a novel choice-experiment in a controlled tank environment (similar to Y-maze or T-maze experiments in fish, king crab, blue crab, green crab and mud crab) (e.g. Ryback, 1969; Olsén, 1985; Zhou and Shirley, 1997; Truong, 2008). We gave individual snow crab the opportunity to choose to move toward or away from LED lights of different colour. We then conducted two field experiments to investigate the effect of LED lights on the catch rates of traps during the 2016 commercial snow crab fishery. In our first field experiment, we tested the effect of adding

LED light to baited traps to evaluate the effects on Catch Per Unit Effort (CPUE; number of crab per pot). In our second field experiment, we tested the effect of adding LED lights to unbaited traps to determine the likelihood of catching snow crab with only light as the stimulus (i.e. no bait).

3.3. Materials and methods

3.3.1. LED lights

Lindgren-Pitman LED Electralume® fishing lights were used in both laboratory and field experiments, which had a forward voltage of 3.2 V, luminous intensity of 4.7 cd, forward current of 35 mA, and power dissipation of 124 mW. The lights had an operating temperature range of -30 to 85^{o} C, a maximum operating depth of 850 m (1270 psi), and a battery life of approximately 300-500 consecutive hours, depending on the type of AA battery used as a power source.

Five colours of lights were purchased and used in this study: blue, green, purple, red, and white. We evaluated the distribution of spectral wavelengths emitted from each light using a benchtop spectrofluorometer. The steady-state luminescence spectra were acquired using a Photon Technologies International (PTI) QuantaMaster 6000 spectrofluorometer, with wavelength selection provided by a Czerny-Turner f/3.4 grating monochromator. Luminescence was detected by a Hamamatsu R-928 five-stage photomultiplier tube (PMT) in photon-counting mode contained within a PTI Model 814 PMT housing, which in turn was enclosed in a Products for Research S600 PHOTOCOOL Peltier cooling device to minimize contributions from dark current spectral artifacts. Peak wavelengths were 464 nm for blue lights, 519 nm for green lights, 446 nm for purple lights, 632 nm for red lights, and 456 nm for white lights (Figure 3.1).

3.3.2. Laboratory experiment

3.3.2.1. Snow crab

Snow crab were collected approximately 360 km southeast of Newfoundland from the Lilly and Carson Canyons in September 2015 by using baited traps deployed at an ocean depth of 150 m. The crab were transported to holding facilities at the Northwest Atlantic Fisheries Centre, located in St. John's, Newfoundland, and held in circular holding tanks (1.25 m diameter, 0.8 m high) with water temperature controlled between 0.8 to 1.7^0 C and salinity near 30‰. Crab were fed chopped herring or squid *ad libitum* three times a week. All crab used in the experiment were hard-shelled legal sized (CW was larger than 95 cm) males with good apparent health.

3.3.2.2. Experimental cage and pool tank

A small rectangular experimental cage was designed and built for holding an individual snow crab. It consisted of an aluminum frame, black plastic walls, and a mesh floor and ceiling. Dimensions of the cage were 60 cm long, 30 cm wide, and 30 cm high. The walls at both ends of the cage were hinged at the bottom and rigged to open simultaneously from a remote location.

The experiment was performed in a large covered pool tank with dimensions 4.9 m long, 2.7 m wide, and 0.8 m deep (see Figure 3.2). The inner walls of the pool tank were dark blue in colour. During the experiment, the water temperature and salinity in the pool tank were kept stable at approximately 1^0 C and 30‰ salinity. In addition, to avoid bias during the choice experiment, water flow to the tank was shut off, ambient light in the tank room was low, and there were no odor or food sources in the tank. In order to identify the position of the crab when leaving the experimental cage, we equally divided the bottom of the pool tank into 4 regions: right up (I), right down (II), left down (III), and left up (IV). The floor of the tank was equipped with Passive Integrated Transmitter (PIT) antennas for the purpose of alerting the researcher that the crab had left the experimental cage.

The light was suspended at the end of the pool tank in a manner that allowed direct visual line of sight upon opening the cage. To limit the amount of light emitted, we suspended the LED light in a vertically oriented 64 mm diameter black polyvinyl chloride (PVC) tube. The light aligned with a small 22 mm diameter hole that was 20 cm from the floor of the pool tank. This created a small focused light pattern with the source approximately 2.3 m from the cage.

3.3.2.3. Data collection

Choice experiments were conducted from January 28 to February 19, 2016. A total of 110 individual untrained naïve crab were examined. Each trial began by randomly selecting a light colour and light position (left or right end of the pool tank). A single crab was then randomly removed from a holding tank, temporarily tagged with a PIT tag, placed in the experimental cage, and then the cage was lowered into position in the middle of the pool tank. The total duration out of water was less than 1 min. The cover was then returned over the pool tank, removing all external stimuli. After waiting 15 minutes for acclimation, the cage was remotely triggered and the doors of the cage were opened. An audible alarm sounded when the crab exited the cage, at which time we recorded the time until exit and then removed the tank cover to determine the crab's direction (left or right, toward or away from the light) and position of the crab on the floor of the tank (I, II, III, or IV).

The first ten trials were conducted without LED lights to ensure crab movement was random upon opening the cage. In the absence of any experimental treatments (i.e. a dark tank), we wanted to confirm that crab showed no innate preference to move left or right, and ensuring there was no bias of the pool tank or the experimental cage. Experimental treatments were subsequently conducted using the five LED light colours of blue, green, purple, red, and white. Each light colour was randomly selected and replicated 10 times at each end of the pool tank (x2), for a total of 20 replicates per colour.

3.3.3. Field Experiment No. 1

This experiment was conducted aboard an inshore fishing vessel (*F/V The Phoenix,* 10.7 m LOA) targeting snow crab, approximately 20 nautical miles southeast of Petty Harbour, Newfoundland and Labrador (Latitude between 47°14'10.56"N and 47°23'51.12"N, Longitude between 52°31'41.16"W and 52°16'50.58"W) from April 26 to May 23, 2016 (see Figure 3.3). The depth at the sampling site ranged from 165 to 173 m.

Small Japanese-style conical traps with a bottom diameter of 101.5 cm, top diameter of 55.5 cm, height of 44 cm, and mesh size of 135 mm were used, typical for this fishery (e.g. Hébert et al., 2001; Winger and Walsh 2007, 2011; Grant and Hiscock, 2009; Winger et al., 2015; DFO, 2016a). Inspection of the traps was conducted prior to sea trials to ensure the traps were identical in all aspects. Three experimental treatments were investigated: (1) Control trap – baited trap with 453 g of mixed squid and herring in a perforated plastic jar; (2) Purple Light trap – baited similar to Control trap, with the addition of a purple LED light; (3) White Light trap – baited similar to Control trap, with the addition of a white LED light.

All traps were fished in long-lines with a distance of 36.6 m between individual traps. The three trap treatments were randomly positioned within these fleets and multiple fleets were deployed in close proximity. The lights were attached close to the bait jar in the centre of each trap. A total of 596 trap hauls (402 control traps, 76 purple light traps, 118 white light traps) were successfully carried out during six fishing trips. All legal-sized male crab (>95 mm CW) were counted and the number recorded per trap haul was defined as the CPUE. In the event sub-legal males or females were captured they were immediately returned to the sea and not recorded. A random sample of crab were removed from each treatment and the carapace width (CW) was measured to the nearest mm throughout the course of the experiment.

3.3.4. Field Experiment No. 2

This experiment was conducted aboard an offshore fishing vessel (*F/V Atlantic Champion*, 19.8 m LOA) targeting snow crab along the Newfoundland and Labrador continental shelf, between May and June 2016. Depth at the sampling site ranged from 80 to 300 m. The trap and bait types, as well as fishing technology used and the LED light attachment methods were similar to Field Experiment No.1. Six experimental treatments were investigated: (1) Baited trap – baited trap without light, and treatments 2-6 which consisted of traps equipped with an LED light and no bait. Five light colours were used in treatments 2-6: blue, green, purple, red, and white. These treatments did not include bait in order to compare their effectiveness against baited traps. Trap numbers 40, 70, and 71 were selected to attach LED lights for consistency. The legal-sized male crab were counted in baited trap numbers 25, 39, 41, 69, and 80 and all functioning LED light traps. A total of 208 trap hauls (131 baited traps and 77 LED light traps) were evaluated during the experiment.

3.3.5. Statistical analysis

For the Laboratory Experiment, we used a chi-square (χ^2) test to confirm crab direction was random in the absence of any experimental treatment. A χ^2 test was also used to determine whether movement direction of a crab depended on LED light treatments. Crab direction was defined by a binary variable (i.e. toward or away from the LED light). A binomial logit link generalized linear model was used to compare departure time (explanatory variable), crab size (explanatory variable), and direction (response variable). A general linear model regression was used to determine the relationship between crab size and time leaving the experimental cage.

For Field Experiment No. 1, CPUE was analyzed using a two-way ANOVA to assess the effects of the experimental treatments and fishing trips as factors affecting catch rate. A two-way ANOVA was also used to compare mean size of snow crab caught by the experimental treatments for different trips. Pairwise post hoc comparisons were conducted using Tukey's HSD. For the two-way ANOVA we tested and found that assumptions were met with regard to homogeneity of variance, normal distribution of errors, independence of errors, and errors sum to zero. Kolmogorov-Smirnov two-sample test was used to compare the snow crab size frequency distributions between the treatment factors, as well as between fishing trips.

For Field Experiment No. 2, CPUE was compared between baited traps and illuminated traps using non-parametric Wilcoxon rank-sum test and also evaluated graphically. A general linear model regression was used to determine the relationship between CPUE and soak time. An ANCOVA was used to compare the slopes of the CPUE - soak time relationships between illuminated traps and baited traps. Generalized linear models based on the Bayesian Model Average multiple regression were used to estimate the effects of light treatment, soak time, and depth on CPUE. The log-transformed catch rate (LnCPUE) is described as a linear combination of the explanatory variables and its error according to the equation:

$$LnCPUE = \beta_0 + \beta_T T + \beta_{ST} ST + \beta_D D + \varepsilon$$

where, β_0 is the intercept (constant); β_T, β_{ST} and β_D are the coefficients for the trap treatment, soak time, and depth, respectively. Similarly T, ST and D are the light treatment, soak time, and depth factors, respectively, while ε is error. The most parsimonious model was chosen based on the lowest BIC and highest posterior probability.

Only data from successful trap hauls were used in the above analyses. Data was excluded in cases where the lights malfunctioned, traps appeared damaged, or the bait jar was missing. Analyses were carried out with R, version 3.2.3 for Windows. A confidence level of $p < 0.05$ was used for most analyses, except where multiple tests were conducted for post hoc comparisons, in which case a Bonferroni correction was applied to the probability level to reduce the family-wise error rate (i.e. an α of 0.05 was divided by the number of tests to reduce the risk of making a type 1 error).

3.4. Results

3.4.1. Laboratory Experiment

In the absence of a light treatment, our results showed that crab randomly moved out from the experimental cage, showing no preference for either the left or right exits ($\chi^2 = 0.4$, $p = 0.527$). No significant difference was found among the crab positions after exiting the experimental cage. Of the 110 snow crab tested, 30, 22, 27, and 31 were distributed in the position I, II, III and IV, respectively ($\chi^2 = 1.782$, $p = 0.619$). There were 29 crab that moved toward and 21 crab away from the all LED light colour combined ($\chi^2 = 1.28$, $p = 0.258$) when placing LED lights in the left side of pool tank. Similarly, placing

LED light in the right side of the tank, 28 crab moved toward the LED light and 22 crab toward no light side respectively (χ^2= 0.72, p = 0.396).

Movement toward light was statistically significant (χ^2 = 5, p = 0.025) for blue and white LED lights, accounting for 75% of the observations, whereas purple light appeared to have a negative effect on crab behaviour, with 85% of crab observed moving away from the purple light (χ^2 = 9.8, p = 0.002). No significant difference in crab movement (toward or away) from LED lights was observed when using green or red lights (χ^2 = 1.8, p = 0.180; χ^2 = 0.2, p = 0.655, respectively). See Table 3.1 for a summary of results.

The departure time of crab from the experimental cage varied from 10 to 1782 s. Mean departure time was 179.13 s (± 28.86 standard error-SE) with 65% of crab leaving the cage in less than 120 s. Only 13% of crab stayed in the cage more than 300 s. Crab tended to leave the experimental cage very quickly in the white LED light treatment (mean = 99.85 s ±18.62 SE), whereas crab took substantially longer in the red LED treatment (mean = 386.05 s ± 106.36 SE). The departure time of crab with blue, purple, and green LED lights was 154.3 s (± 86.71 SE), 166.95 s (± 47.13 SE), and 183.19 s (± 69.19 SE), respectively. It took on average 100.95 s (± 19.47 SE) for crab to exit the experimental cage when deployed with no light. Figure 3.4 illustrates the time until crab moved out corresponding with different light colours.

No relationship between crab movement direction and departure time was detected using Logit Models for binary data (95% Confidence Interval of Odds ratio = 0.998-

1.001, Odds ratio = 0.999; $p = 0.195$). Similarly, a binomial Generalized Linear Model using a logit function showed that there was no relationship between crab movement direction and their size (95% Confidence Interval of Odds ratio = 0.961 -1.044, Odds ratio = 1.002; $p = 0.939$). However, our results showed that larger crab left the experimental cage significantly faster than smaller individuals according to the equation: Departure Time = 895.566 - 6.476*CW.

3.4.2. Field Experiment No. 1

Attaching artificial lights in the baited traps had a statistically significant positive effect on CPUE (Table 3.2). The two-way ANOVA for treatment and trip factors indicated significant differences for trap treatment ($F = 85.484$, $p < 0.001$), fishing trips ($F = 38.086$, $p < 0.001$) as well as the interaction of these factors ($F = 1.965$, $p = 0.035$).

The CPUE observed for the different treatments are shown in Figure 3.5 and Table 3.2. Traps equipped with white lights produced the highest catch rates, yielding a mean CPUE of 21.5 (± 0.85 SE) crab/trap, followed by the purple light trap, yielding 17.8 (± 1.13 SE) crab/trap, and finally the control trap, with only 12.1 (± 0.38 SE) crab/trap. This corresponds to a 77% and 47% increase in the mean CPUE when adding white and purple lights to baited traps. Post-hoc comparisons revealed a significant difference between the white light traps and control traps (t =9.361; $p < 0.001$) as well as a significant difference between the purple light traps and control traps ($t = 5.679$; $p < 0.001$), and also the white light traps and purple light traps ($t = 3.681$; $p = 0.002$) (Table 3.2).

Comparison of the mean and median CPUE across different fishing trips and light treatments is shown in Figure 3.6 and Table 3.3. With the exception of Trip 5, the median CPUE tended to decrease in the control traps, whereas it was generally more variable in the white light traps. The mean CPUE in the first two trips and the last two trips (i.e. trip 1 and 2; trip 5 and 6) were higher than the middle two trips (trip 3 and 4) for all experimental treatments. Post-hoc comparisons are shown in Table 3.3. The CPUE using white light traps were statistically higher than control traps for all trips. Purple light traps were statistically higher than control traps for trips 2, 3, 4, and 6, but not different in trips 1 and 5. White light traps were statistically higher than purple traps for trips 3 and 4, but not different in trips 1, 2, 5, and 6 (Table 3.3).

The size frequency distribution of legal male crab captured in the different trap treatments are shown in Figure 3.7. Mean CW of crab caught by control traps (n = 171), purple light traps (n = 235), and white light traps (n = 219) were 104.8 mm (± 0.60 SE), 107.68 mm (± 0.55 SE), and 105.4 mm (± 0.48 SE), respectively. Results of the Two-way ANOVA revealed that the mean crab size varied significantly between the trap treatments (F= 9.137, $p < 0.001$). Subsequent pairwise comparisons of crab size distribution indicated a significant difference between purple light traps and control traps (Kolmogorov-Smirnov test: D = 0.176, $p = 0.006$), as well as purple light traps and white light traps (Kolmogorov-Smirnov test: D = 0.155, $p = 0.008$), but no statistical difference between white light traps and control traps (Kolmogorov-Smirnov test: D = 0.120, $p = 0.125$). Although a statistical difference in the size of crab was detected across fishing trips (two-way ANOVA, F= 12.883, $p < 0.001$), no obvious trend was apparent over time as the season progressed. Figure 3.8 shows the mean CW for crab caught during each fishing trip, with values ranging from a low of 104.03 mm (±0.72 SE) to 109.09 mm (±0.81 SE) during field experiment No.1.

3.4.3. Field Experiment No. 2

The CPUE observed for the different experimental treatments (baited and 5 light colours without bait) are shown in Figure 3.9. Mean CPUE ranged from 9.8 to 13.1 crab/trap haul (Table 3.4). No statistical differences in CPUE among the baited traps and illuminated traps (without bait) were detected using Non-parametric Wilcoxon Rank-Sum Test (Table 3.4). The degree of variance was highest among green light traps (SE = 3.41) and lowest among the baited traps (SE = 0.69).

Although there are four appropriate models to describe CPUE, the most parsimonious model included only parameters for soak time and the depth (based on lowest BIC and highest posterior probability) (Table 3.5). The probability of the regression coefficient being different from zero for the trap treatment factor was very low, only 12.0%, compared to 58.5% and 100.0% for the depth and soak time factors, respectively (Table 3.6). A negative coefficient for depth (D) indicates lower CPUE was observed with increasing depth (fishing depth varied between 80 and 300 m). The positive coefficient for soak time (ST) indicates higher CPUE was observed with increasing soak time which ranged from 27 to 195 hours.

Further description of the relationship between average CPUE and soak time bins is illustrated in Figure 3.10. The linear regression model for the illuminated traps is $CPUE_{\text{illuminated trap}} = 6.72 + 0.07*(\text{soak time})$, while this model for the baited traps is $CPUE_{\text{baited trap}} = 7.5 + 0.04*(\text{soak time})$. All parameters are statistically significant ($p < 0.001$). The slope of regression line was significantly different from zero ($p < 0.001$) using ANCOVA. The positive slopes indicate CPUE increased for both illuminated traps and baited traps with increasing soak time. Analysis of covariance indicated the slopes of the CPUE versus soak time relationships for illuminated traps differed significantly from the baited traps ($p < 0.001$). These results suggest that longer soak times disproportionally benefit illuminated traps compared to baited traps.

3.5. Discussion

In this study we found that LED lights affect snow crab behaviour. Different wavelengths of light (i.e. colours) produced different behavioural responses in both laboratory and field conditions. Field experiments indicated that the catch rate of baited traps significantly increased with the addition of LED lights (Field Experiment No.1), and that substantial numbers of crab entered traps when only LED lights were used as the stimulus (Field Experiment No.2).

The laboratory experiment indicated that, like many aquatic species (e.g. herring, anchovies, mackerel, tuna, squid, cod, largehead hairtail, scad and other pelagic species) (Ben-Yami, 1976; Marchesan et al., 2005; Matsushita et al., 2012; Matsushita and Yamashita, 2012; Yamashita et al., 2012; Nguyen and Tran, 2015) snow crab could be lured using artificial light colours. In our study, crab responded differently to different LED light colours, and there was evidence to suggest that behaviour was dependent on crab size. Crab moved towards blue light and white light, were not affected by red or green light, and moved away from purple light. The lack of response to red light in our study is consistent with previous studies which have suggested crustaceans do not respond to that part of the visual spectrum (e.g. Zhou and Shirley, 1997; Truong, 2008; Butler et al., 2014). The results of our laboratory experiment were consistent with Marchesan et al. (2005) who suggested that fish responded differently when exposed to different light colours. Evidence suggests that the observed response could be related to eye structure and physiology. For example, Matsui et al. (2016) noted that the pupillary and reticular response in Japanese flying squid was very sensitive under low-powered blue, green, and white LED lights, but much less sensitive and exhibited a weaker response to red LED light. While much is known about vision in decapod crustaceans (e.g. Porter and Cronin, 2006), to our knowledge there is limited knowledge of the structure and function of the crab eye as it relates to their behaviour, suggesting a potential avenue for future research.

The capture efficiency of crab traps is known to depend on animal density, fishing season, type of bait, level of satiation, trap size and shape, size and position of entrances, soak time, and oceanographic conditions (e.g. Hébert et al., 2001; Winger and Walsh, 2007, 2011; Grant and Hiscock, 2009). Field Experiment No.1 indicated that the addition of white LED light significantly increased the catch of crab, accounting for a 77% increase in CPUE compared to the control trap (Table 3.2). Similarly, our Field

Experiment No.2 demonstrated that crab were strongly attracted by blue, green, and white LED lights. These results are consistent with our laboratory experiment in which crab moved toward the blue and white lights. They are also consistent with Murphy (2014) who documented crab entering unbaited flatfish traps equipped with only a green LED light (no bait). Bryhn et al. (2014) found that attaching a green LED light inside a baited pot increased the mean catch weight of legal sized Atlantic cod by 80%. An (2013) noted that catch rates of squid were highest using blue and white lights and lowest using red lights. Similarly, Lee (2013) found that chub mackerel responded positively to blue, yellow, and white LED light, while no effect was observed with using red LED light.

Some of our results are however, inconsistent across our experiments. While our laboratory experiment suggested crab move away from purple light, both field experiments suggest crab are not hindered whatsoever from entering traps with purple lights. Additionally, laboratory experiment indicated that the green light did not affect crab behaviour, while the trap with quipping only green light (no bait) caught the comparable CPUE with the control trap (field experiment No. 2), which is consistent with Murphy (2014). These observations highlight the fact that the underlying functional explanations for crab behaviour toward LED light are still unclear. Many questions remain unanswered about detection thresholds and motivations in crab. For example, in some cases, animals appear attracted to prey which are attracted by the light (e.g. Ben-Yami, 1976; Marchesan et al., 2005; An, 2013; Bryhn et al., 2014). It could also be possible that in a dark and barren environment, the light accentuates the presence of shelter or structure. Evidence has shown that crab will enter unbaited traps in the absence of any stimulus or bait (e.g. Murphy, 2014), suggesting the species may simply be "trap-happy" to some extent. Another hypothesis is that light enables crab to detect the trap entrance and/or conspecifics inside the trap. It remains unclear how crab see and perceive light and we do not fully understand their behavioural responses toward light stimuli.

In some cases, LED lights can attract animals, while in other cases deter them. For instance, Hannah et al. (2015) installed green LED lights along the fishing line of a bottom trawl, which significantly reduced non-targeted bycatch of several finfish species with no effect on target species of ocean shrimp (*Pandalus jordani*). Ortiz et al. (2016) demonstrated that bycatch of green turtle (*Chelonia mydas*) decreased by 63.9% when attaching green LED light to gillnets. Wang et al. (2007) showed that juvenile loggerhead turtles (*Caretta caretta*) significantly moved toward blue, green, yellow and orange LED lightsticks.

With regard to crab size and their behaviour, Field Experiment No.1 showed that the purple light traps caught larger crab than both the control traps and white light traps. In contrast, our laboratory experiment detected no relationship between crab size and movement direction (i.e. toward or away from the LED light), however larger crab exhibited a faster exit time from the cage than smaller crab. A significant difference in crab size was found between trips, but it varied around 104 and 109 mm with no evidence that crab size changed throughout the commercial fishing season (i.e. across fishing trips). We speculate that very large male crab could behave differently than smaller crab in response to various stimuli.

Field Experiment No.2 provides evidence to suggest baited traps will have a higher CPUE than non-baited illuminated traps when soak times were short, while traps with lights performed better as soak times increased. The regression coefficent for the illuminated trap was twice that for baited trap (0.07 versus 0.04), while the intercept of the baited trap model is larger than the illuminated trap (7.5 versus 6.72). We speculate that bait plays a pivotal role in the first few days of soaking, but as the odor depletes, illuminated traps begin to perform better as they continue to attract crab irrespective of bait. The catch of illuminated traps may therefore be better when long soak times are employed. In addtion, results from Field Experiment No.2 suggest that the LED lights (either blue, white, or green) may work as a suitable replacement to traditional bait. Fishing enterprises could theoretically reduce bait costs through LED light substitution, or enhance existing catch rates of baited traps by simply adding an LED light. The financial trade-off depends on many factors, not least of which includes the cost of bait, lights, fuel, and crew wages. The findings warrant an economic analysis of the risks and benefits on how best to operationalize these findings. Longer soak times would also promote more sorting on the bottom and potentially improve size selectivity.

The mean CPUE for all three treatments combined during Field Experiment No.1 was 14.7 (± 0.37 SE) (12.1 ± 0.38 for control trap, 17.8 ± 1.13 for purple light trap and 21.5 ± 0.85 for white light trap), and 11.3 (± 0.57 SE) for all six treatments combined during Field Experiment No.2. This equates to a mean weight of 7.35 kg per trap for Field Experiment No.1 and 5.65 kg per trap for the Field Experiment No.2. These catch rates are lower than those documented by DFO (2016a), who reported 5 to 10 kg per trap in the Northeast and over 25 kg per trap in the Southeast of Newfoundland, between 2013 and 2015. This implies that the crab resource could be in a period of decline, or the experiments were conducted in areas of low crab density. Comparing the CPUE between Field Experiment No.1 and Field Experiment No.2, it appears the crab density in the offshore study area may have been lower than the inshore study area. These results suggest that LED lights could substitute bait when crab density is low.

Our laboratory experiment showed that crab reacted relatively quickly in response to LED light. Observing 110 individual crab (i.e. 100 unique crab tested with lights and 10 unique crab tested with no light), 87.3% of the individuals moved out the experimental cage within the first five minutes after opening the doors. The response duration of crab was also different depending on the light colours. These results agreed with Matsui et al., (2016) who found that the pupillary response in Japanese flying squid varied for different colours, but appeared after one minute when the illumination provided for all colours of blue, green, red and white.

The proportion of crab that actually enter a trap when approached is an important contributing factor in the capture efficiency of a crab trap. Bryhn et al. (2014) found that the visual stimuli of a green light inside a cod pot created a positive effect on near-field and ingress behaviour of cod entering the pot. Therefore, the increased CPUE in the lighted trap may be attributed to an increase in the proportion of crab that actually enter a trap when approached. More detailed studies, such as the use of under water camera research is recommended to better understand and further improve the effectiveness of using lights as a supplemental stimuli in the crab fishery.

Although no evidence exists to suggest low-powered underwater light harms or disturbs ecosystem function, there is potential for negative trade-offs in situations where underwater fishing lights are operated in non-natural situations (e.g. deep sea or nighttime). For example, the use of above-water fishing lights have been shown to affect fish foraging and schooling behaviour, spatial distribution, predation risk, migration, and reproduction (Nightingale et al. 2006). The density of predators has also been reported to increase when artificial lights were used (Becker et al. 2013), feeding of predators increased with prey density in high light intensity experiments, whereas under dark conditions increased prey levels failed to elicit a similar increased feeding response (Thompson 2013). These effects have the potential to create unnatural top–down regulation of fish populations (Becker et al. 2013). Further research into whether low-powered underwater lights affect ecosystem, fish stock, as well as the vulnerability of threatened species (e.g. wolffish *Anarhichas lupus*) and marine mammals is therefore recommended.

In conclusion, this study found that LED lights affect snow crab behaviour. The laboratory experiment demonstrated that white and blue LED lights attracted crab better than green LED lights, while the purple LED light deterred them. Red LED light colour did not affect crab movement direction. Field Experiment No.1 showed that white and purple light could attract crab, but the white light increased CPUE more than purple light.

Field Experiment No.2 suggested that blue, green and white LED light could substitute traditional sources of bait when the CPUE is low and soak times are long. Taken together, these experiments suggest that fishing enterprises can improve their catching performance by adding LED lights to their baited traps, or by using LED lights as a bait replacement. Economic benefits are yet unclear, but widespread use of lights could potentially reduce operating cost by spending less days on the water, reducing fuel consumption, reducing labor effort while fishing, and reducing bait expenses.

3.6. Way Forward

This is the first time research has been conducted on the behaviour of snow crab in response to artificial light, as well as using artificial light in catching snow crab. Although the results from this chapter demonstrated that equipping baited traps with a low-powered LED light significantly increased the CPUE of snow crab compared to control traps, the mechanism of why underwater lights attract and concentrate snow crab remains unknown. We hypothesize that the position and orientation of an Electralume@ light within a crab trap will produce different patterns of illumination, resulting in differences in catch rate of target and non-target species. The next chapter will examine the null hypothesis:

H_0: light position and orientation do not affect the CPUE of legal sized crab and sublegal crab.

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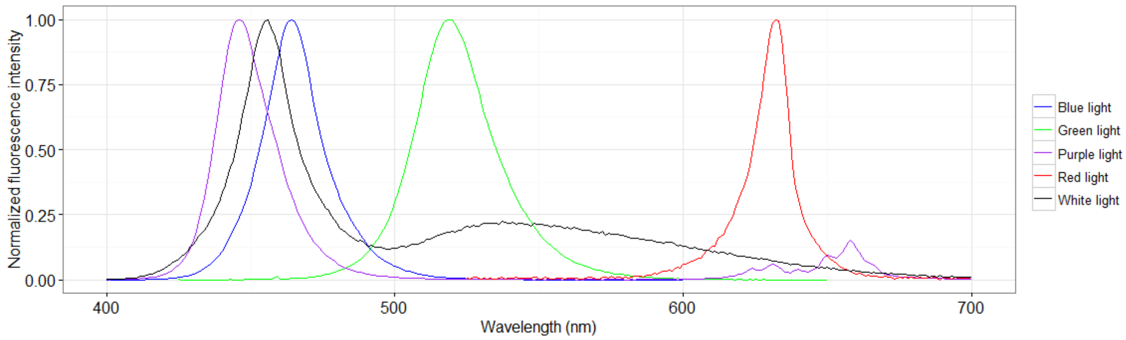

Figure 3.1. Normalized fluorescence of Lindgren-Pitman LED Electralume lights. Peak wavelengths were 464 nm for blue lights, 519 nm for green lights, 446 nm for purple lights, 632 nm for red lights, and 456 nm for white lights.

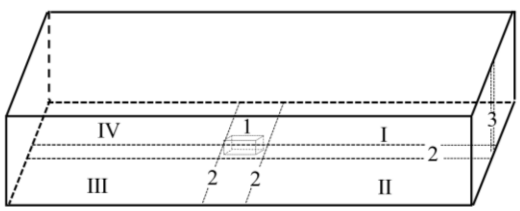

Figure 3.2. A schematic of the experimental tank with (1) a small rectangular experimental cage; (2) PIT antennas; and (3) a light orientation black PVC tube, which was either located in the left or in the right side of the tank; (I, II, III, IV) are temporary regions to identify the position of the crab when leaving the experimental cage.

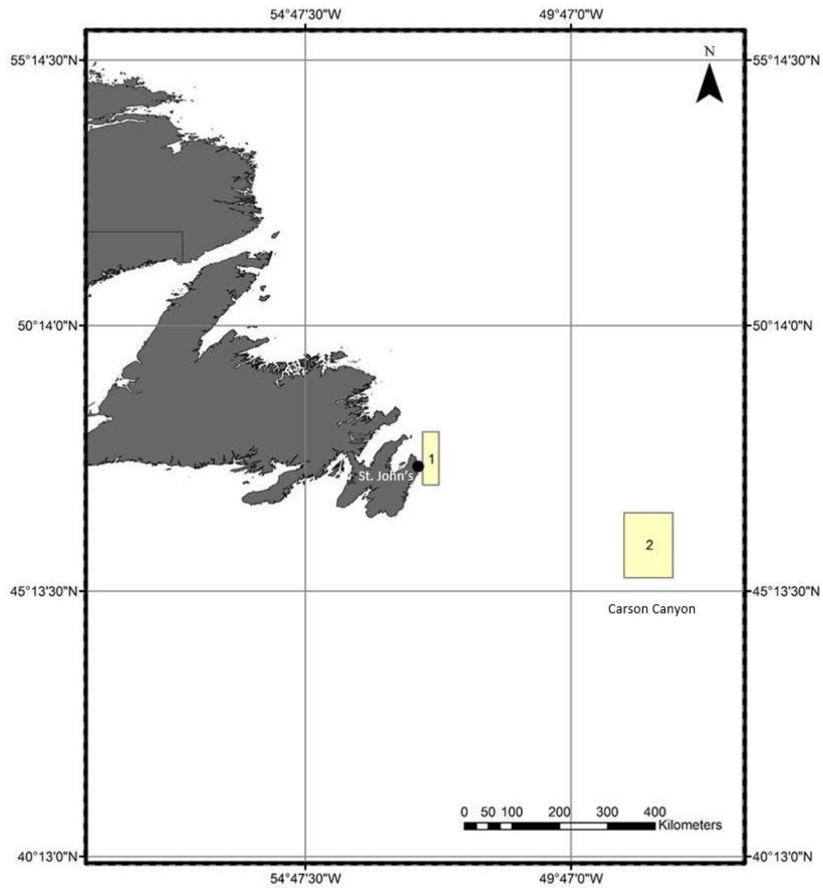

Figure 3.3. Map of the at-sea study area. Boxes denote locations of Field Experiment No.1 and No. 2.

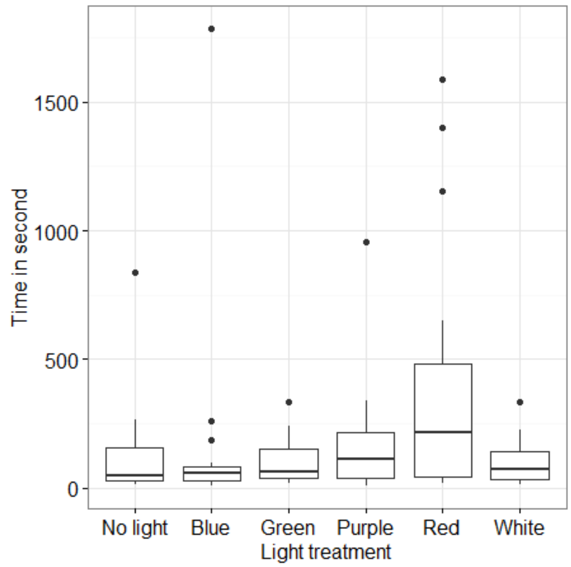

Figure 3.4. The time until crab moved out of the experimental cage by different light treatments.

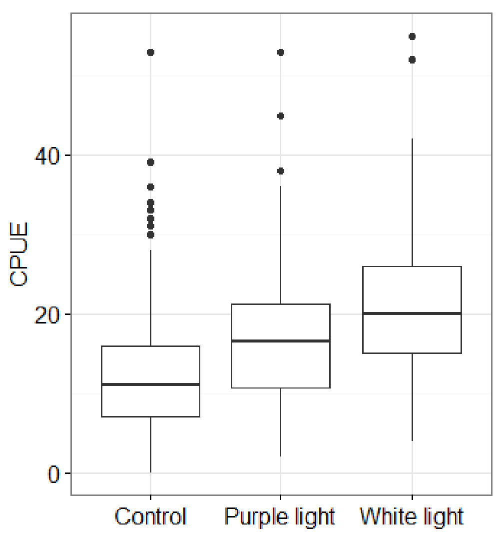

Figure 3.5. Boxplots of CPUE of snow crab for the different trap treatments evaluated in Field Experiment No.1.

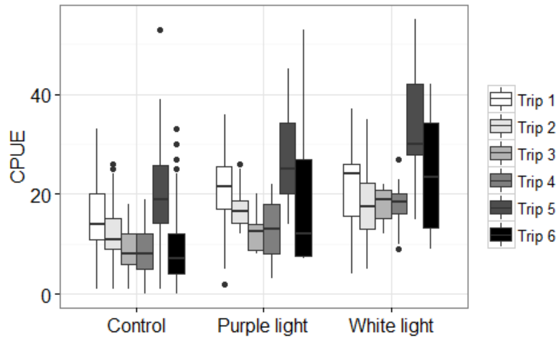

Figure 3.6. Boxplots of CPUE of snow crab for the different trap treatments by fishing trip, evaluated in Field Experiment No. 1.

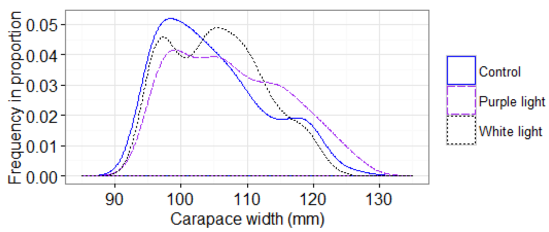

Figure 3.7. Size frequency distribution of carapace width of legal male crab captured in the different trap treatments in Field Experiment No. 1.

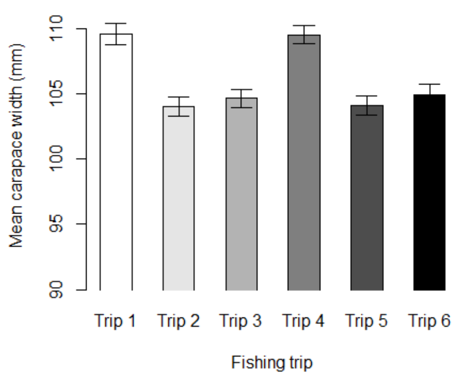

Figure 3.8. Mean CW of male snow crab captured during each of the six fishing trips during Field Experiment No.1.

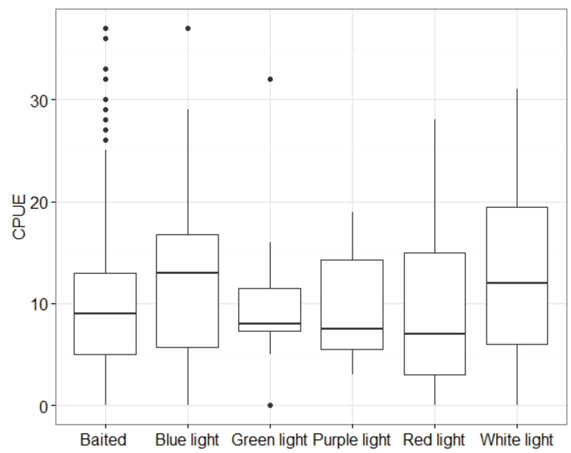

Figure 3.9. Boxplots of CPUE of snow crab for the different trap treatments evaluated in Field Experiment No.2 (n = 131 for control, 12 for blue, 8 for green, 8 for purple, 13 for red, and 36 for white light traps). Soak time varied between 27 and 195 hours.

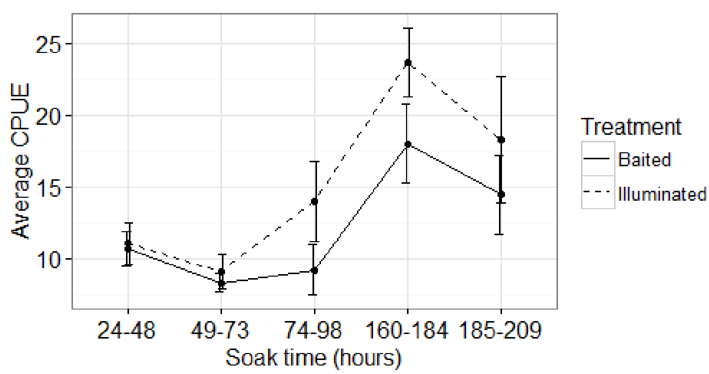

Figure 3.10. Average CPUE in relatives to soak time bins for Field Experiment No.2. Vertical bars are standard errors.

Table 3.1. Summary of snow crab responses to the LED lights during the laboratory experiment.

Treatment	Sample size	Towards the light	Away from the light	χ^2	p-value
Blue light	20	15	5	5	0.025
Green light	20	13	7	1.8	0.180
Purple light	20	3	17	9.8	0.002
Red light	20	11	9	0.2	0.655
White light	20	15	5	5	0.025

Table 3.2. Mean CPUE of snow crab for the different trap treatments in Field Experiment No.1, including their pairwise post hoc comparison using Tukey's HSD. SE is standard error of the mean and CI is confident interval.

Trap category	Number of traps	CPUE	SE	Change of CPUE of purple and white light trap compared to control trap (%)
Control	402	12.1	0.38	
Purple light	76	17.8	1.13	+ 47.0
White light	118	21.5	0.85	+ 77.4

Treatment comparison	*t-value*	95% CI	p-value
White light versus Control	9.36	7.59 to 11.13	<0.001*
Purple light versus Control	5.68	3.57 to 7.79	<0.001*
White light versus Purple light	3.68	1.20 to 6.17	0.002*

*Significantly different at Bonferroni's adjusted alpha level ($p < 0.0167$)

Table 3.3. Mean CPUE of snow crab for the different trap treatments in each fishing trip in Field Experiment No.1, including their pairwise post hoc comparison using Tukey's HSD. (NS) indicates no significant difference. (+) indicates significant difference detected. SE is standard error of the mean.

Treatment	CPUE (± SE)					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Control	14.9 ± 0.82	12.2 ± 0.66	8.7 ± 0.59	8.5 ± 0.45	20.6 ± 1.44	9.9 ± 1.14
Purple light	20.4 ± 3.37	17.5 ± 1.23	12.5 ± 1.18	13.2 ± 1.20	27.3 ± 2.77	19.8 ± 4.51
White light	22.3 ± 1.31	18.0 ± 1.51	17.9 ± 1.09	17.9 ± 0.93	34.5 ± 3.60	24.5 ± 3.77
Average total	17.2 ± 0.75	14.1 ± 0.60	10.6 ± 0.61	10.7 ± 0.50	24.0 ± 1.40	13.5 ± 1.35
Treatment comparison						
White light versus Control	+	+	+	+	+	+
Purple light versus Control	NS	+	+	+	NS	+
White light versus Purple light	NS	NS	+	+	NS	NS

+Significantly different at Bonferroni's adjusted alpha level (p <0.0167)

Table 3.4. Mean CPUE of snow crab for the different trap treatments in Field Experiment No.2. p-values describe statistical difference uncertainty according to Non-parametric Wilcoxon Rank-Sum Test. SE is standard error of the mean.

Trap category	Number of traps	CPUE	SE	Change of CPUE of LED light traps compared to baited trap (%)	W-value from Non-parametric Wilcoxon Rank-Sum Test	p-value of difference
Baited	131	10.7	0.69			
Blue light	12	13.6	3.13	26.6	665	0.380
Green light	8	10.9	3.41	1.3	547	0.839
Purple light	8	9.8	2.2	-9.2	542.5	0.871
Red light	13	10.2	2.49	-4.7	915	0.660
White light	36	13.1	1.39	21.9	1946	0.109

Table 3.5. Bayesian Model Average multiple regression describing CPUE for the Field Experiment No.2. (T) is treatment; (ST) is soak time; (D) is depth.

Model	Equation	R^2	BIC	Posterior probability
1	CPUE = 7.25 + 0.05*ST	0.121	-21.38	0.364
2	CPUE = 13.17 - 0.06*D + 0.06*ST	0.146	-22.08	0.516
3	CPUE = 6.51 + 0.32*T + 0.05*ST	0.127	-17.46	0.051
4	CPUE = 12.40 + 0.30*T - 0.06*D + 0.06*ST	0.151	-18.05	0.069

Table 3.6. Estimated coefficients.

Parameter	Regression coefficient probability being different from zero (%)	Expected value	Standard deviation
Intercept	100.0	10.62	3.59
Treatment (T)	12.0	0.04	0.14
Depth (D)	58.5	-0.03	0.03
Soak Time (ST)	100.0	0.06	0.01

Chapter 4. A trap with low-powered light-emitting diode (LED) lights: evaluating the effect of location and orientation of lights on the catch rate of snow crab

4.1. Abstract

This study investigated the effect of installing underwater LED lights in different locations and orientations inside baited traps targeting snow crab (*Chionoecetes opilio*) off the coast of Newfoundland and Labrador, Canada. Four experimental treatments were evaluated, including: high upright, high upside down, low upright, and low upside down in comparison with traditional baited traps (control). Our results showed each of these treatments produced significantly higher (39-57%; 48% on average) catch per unit effort (CPUE; number of crab per pot) compared to the control traps, with no significant differences for both legal and sublegal-sized crab among the different experimental treatments. Longer soak times significantly increased the CPUE of the illuminated traps, but did not affect the catch rate of the control traps. Our results also indicated there were no significant differences in crab size distributions between pairwise comparisons, although an increase in the CPUE of sublegal-sized crab was documented. Our results suggest that fishing enterprises could improve their catching performance by adding LED lights to their traps, but the location and orientation of the lights appears unimportant.

Keywords

Underwater light, crab harvesting, inshore fishery, catchability

4.2. Introduction

Snow crab (*Chionoecetes opilio*) is a commercially important species on the east coast of Canada, in particular the provinces of Quebec, New Brunswick, Nova Scotia, and Newfoundland and Labrador (Hébert et al., 2001; Dawe and Mullowney, 2016; DFO, 2016). This fishery has been the world's largest snow crab fishery for the last few decades, with total landings of 93,519 mt annually (DFO, 2015; Dawe and Mullowney, 2016). This fishery targets only adult male crab with a minimum landing size of 95 mm carapace width (CW). The fishery is managed using individual quota allocations, effort controls (trap and trip limits), gear restrictions (trap type and mesh size), and time/area closures in order to achieve conservation and management objectives (DFO, 2016).

In Newfoundland and Labrador, the commercial fishery for snow crab began in the 1960s (Dawe and Mullowney, 2016). Landings were initially low, but dramatically increased from approximately 10,000 mt in 1970 to 69,000 mt in 1999 (Dawe and Mullowney, 2016; DFO, 2016). However, landings have gradually decreased from 53,500 to 47,000 mt between 2009 and 2015 (DFO, 2016). In 2017, a further 22% reduction in the overall quota was experienced, with a total quota of 35,419 mt shared among 2600 license holders (DFO, 2016, 2017). This has resulted in the year-over-year shrinking of individual quotas allocated to fishing enterprises, and this trend is expected to continue for the foreseeable future (Wassmann et al., 2011; Mullowney et al., 2014). While market prices for snow crab are currently higher than past prices (FFAW, 2017) and thus mitigating significant financial impact on fishing enterprises, this trend may not continue. Finding methods to improve the profitability of fishing enterprises is a worthwhile approach as it can improve business viability when quotas are low. Past approaches have included 1) methods to improve size-selectivity to minimize labour associated with "picking" through the catch (Winger and Walsh, 2011), 2) the development of novel baits to reduce bait costs (Grant and Hiscock, 2009), and 3) the use of novel stimuli such as low-powered LED lights to increase the catch rates of baited traps (Nguyen et al., 2017).

Fishing with artificial lights is a well-developed method of increasing the catch rate in recreational and commercial fisheries (Ben-Yami, 1976; Solomon and Ahmed, 2016; Okpala et al., 2017; Nguyen and Winger, 2018). Using artificial light as a stimulus to attract and concentrate fish prior to harvest has a long history over thousands of years, starting soon after humans discovered fire, and this has led to the development of fishing with light in many parts of the world (Ben-Yami, 1976; Solomon and Ahmed, 2016; Okpala et al., 2017; Nguyen and Winger, 2018). While initially developed for above-water applications in pelagic fisheries, the use of artificial light has now spread to underwater applications for deep-water species such as cod, swordfish, and snow crab (Stone and Dixon, 2001; Hazin et al., 2005; Tüzen et al., 2013; Bryhn et al., 2014, Nguyen et al., 2017).

Nguyen et al. (2017) demonstrated that attaching a low-powered light emitting diode (LED) light inside a baited trap significantly increased the Catch Per Unit Effort (CPUE; number of crab per pot) of snow crab compared to similar traps without lights. However, our understanding of why underwater lights attract and concentrate marine animals confronts us with many competing hypotheses. A common understanding is that animals are simply attracted to the light (Ben-Yami, 1976; Ito et al., 1998). However, for other species the mechanism could be more complicated. In some cases, fish appear to be attracted to the light to feed on prey which are themselves attracted by the light (Ben-Yami, 1976; Marchesan et al., 2005; Bryhn et al., 2014; Utne-Palm et al., 2018). It could also be possible that underwater lights better enable animals to see and find structure or refuge in an otherwise dark and barren landscape. Alternatively, underwater lights may help individual animals identify conspecifics already inside a baited trap, thereby encouraging entry through social facilitation (Winger et al., 2016). Conversely, underwater lights help animals detect trap entrances when approaching traps. The lack of functional explanations highlights that much is unknown regarding the mechanisms determining animal behaviour in response to artificial light. In many cases, we still do not know how certain animals even perceive light, and we do not fully understand their response to light stimuli (Bryhn et al., 2014; Nguyen et al., 2017).

For trap and pot fisheries, bait plays a key role in attracting targeted animals (Dawe and Mullowney, 2016; Winger et al., 2016; Jørgensen et al., 2017). Underwater observations have shown that animals usually travel up-current to seek the chemical odour source that has spread down-current from bait (Zhou and Shirley, 1997; Winger and Walsh, 2011; Winger et al., 2016; Jørgensen et al., 2017). The shape and size of the odour plume determines the area/volume of water under influence by the trap, and thus the number of animals that are vulnerable to capture. If the velocity of the water current is low, then the area/volume of attraction will be small. Adding LED lights to baited traps offers a stimulus that is able to travel in all directions and is not dependent on water current (Nguyen et al., 2017). This has the potential to increase the effective area that a trap can "fish" (i.e., area of influence). However, due to the shape of many underwater light housings, it is difficult to illuminate a trap in a truly omni-directional fashion. This means that underwater lights tend to project their light unevenly around the trap. How this affects attraction of target and non-target species remains unknown.

Building on the previous research by Nguyen et al. (2017) and the research gaps mentioned above, the objective of this study was to evaluate the effect of light location and orientation on catch rates of legal and sublegal-sized snow crab in a commercial trap fishery.

4.3. Methods

4.3.1. Sea trials

Experimental fishing was carried out utilizing the 11.89 m LOA snow crab fishing vessel, *F/V The Flat Rock Byes*, register number 154021, from May to June, 2017. The experiment was conducted in the nearshore waters of Newfoundland, directly east from the town of Pouch Cove (Latitude between 47°43'30"N and 47°47'48"N, Longitude between 52°25'15"W and 52°37'24"W) (see Figure 4.1). The average depth of fishing was approximately 190 to 200 m. Japanese-style conical traps which are typical for this fishery were used (see Winger and Walsh, 2011 for further description). All traps, including control and experimental traps, were identical in every manner. Baiting was standardized, with each trap receiving 1362 g (3 lbs.) of whole squid (*Illex sp.*) hung in the entrance of the trap using a snap shackle. Traps were deployed in fleets, with each fleet containing between 60 and 70 traps spaced at intervals of 36.6 m. The fleets were soaked for several days and retrieved between 4-15 days, depending on the weather.

Lindgren-Pitman LED Electralume® fishing lights (white, 456nm in wavelength) were used in this experiment. See Nguyen et al. (2017) for technical specifications. Like many commercially available underwater LED lights, this product does not disperse light evenly in all directions. Designed primarily for pelagic longlines targeting swordfish, they work particularly well at dispersing light horizontally and downward with very little light travelling in the upward direction. Thus, we hypothesized that location and orientation of the light in a trap could affect how it is perceived by snow crab and the resulting catchability of the trap. To test this hypothesis, we evaluated five experimental treatments:

(1) Control trap - traditional baited trap without light (commonly used by industry);

(2) High Upright (HU) - traditional baited trap with a light suspended in the upright orientation, higher off the seabed;

(3) High Upside Down (HUD) - traditional baited trap with a light suspended in the upside down orientation, higher off the seabed;

(4) Low Upright (LU) - traditional baited trap with a light suspended in the upright orientation, close to the seabed; and

(5) Low Upside Down (LUD) - traditional baited trap with a light suspended in the upside down orientation, close to the seabed.

Figure 4.2 illustrates the subtle differences in light dispersion using the different locations and orientations. In treatments where the light was in the upright orientation, the seabed is accentuated by the light emitted. By comparison, treatments where the light was in the upside down orientation tended to accentuate the plastic collar by the light emitted. Distance from the seabed to the light was 23 cm for the high location and 9 cm for the low location. All lights were hung in the entrance of the trap directly opposite the bait.

Each fleet of traps consisted of all five experimental treatments randomly placed throughout the fleet for comparative purposes. A total of 10 fleets with 580 traps were successfully deployed and retrieved during the study, containing 364 control traps, 50 HU traps, 46 HUD traps, 60 LU traps, and 60 LUD traps. In some cases, apparent disturbance of a trap was observed upon haul-back (e.g., light malfunction, broken meshes, or upside down) and these traps were omitted from the analysis. We also omitted the first and last three traps in each fleet as our experience indicates these "end" traps tend to "dance" with the upward pull of the vertical down-ropes, potential lowering their fishing performance (Bungay at al., 2015).

For each trap hauled, the number of legal-sized and sublegal-sized crab were separated, counted and recorded as the catch per unit effort (CPUE). A random selection of traps from each treatment were chosen to measure carapace width (CW) of all crab to determine crab size, to the nearest mm using Vernier calipers. Animals with CW $\leq$ 94 mm were recorded as sublegal-sized, and animals with CW $\geq$ 95 mm were recorded as legal-sized. A total of 296 crab were measured during the experiment. Non-targeted animals (e.g., female crab and other species) were also counted and measured for size. Only legal-sized male crab were retained for commercial purposes and placed in the hold of the vessel. All other individuals were immediately returned alive over the side of the vessel into the sea.

4.3.2. Analysis

The CPUE data examined in this study have inherent characteristics that need to be accounted for during statistical analysis. Our catch data violated many of the assumptions needed for conventional approaches (e.g. ANOVA), which were count data and did not follow a normal distribution. In addition, traps representing 5 experimental treatments were nested within a fleet of commercial traps, and multiple fleets were tested during the sea trials. Sine each trap within fleet shared a sampling site, traps on same fleet were not considered to be independent in a statistical sense. Techniques such as generalized linear mixed-effect modeling (GLMM) enable us to measure the effect of trap treatment on CPUE, while accounting for the non-normal distribution and data with a nested structure (Zuur et al., 2009). Evidence suggested that the data were overdispersed – noted by the dispersion parameter for quasipoisson family greater than 1 (3.26 for legal-sized and 3.13 for sublegal-sized crab) thus a negative binomial distribution was used. Residuals met the assumptions for homogeneity, normality, and independence. In our initial model, we tested the fixed effects of trap treatments consisting of control, high upright, high upside down, low upright and low upside down, and soak time containing three values of 4 days, 6 days, and 15 days (explanatory variables), and fleet number (IDfleet) was included as a random effect on the CPUE (response variable). The model included an interaction between trap treatments and soak time. In order to improve statistical power we then conducted stepwise model simplification, dropping non-significant terms one at a time until all terms in the model were statistically significant.

To fit the model we used the *glmmadmb* function in the R package *glmmADMB*, in RStudio. A preliminary analysis indicated that zeroinflation was not significant and therefore dropped. The catch data of legal and sublegal-sized crab were tested separately. The model structure was as follows:

```
model= glmmadmb(CPUE~Treatment+(1|IDfleet),
family="nbinom", zeroInflation=F,data = Data)
```

Wilcoxon Rank-Sum Test was then used to compare the mean CPUE of legal and sublegal-sized crab among experimental treatments, including the effects of light location, light orientation, and soak time. Comparison of the mean CW of crab caught by different treatments was conducted using ANOVA. Post-hoc comparisons were carried out using Tukey's SHD method. Size frequency distributions were compared using Kolmogorov-Smirnov two-sample Z test. GLMM was not used in this analysis because visual inspection of data suggested that CW was not associated with IDfleet, we therefore could not include the ID as a random effect. In addition, CW data was normally distributed. Thus, parametric tests were used, and all assumptions were met with regard to homogeneity of variance, normal distribution of errors, and independence of errors.

4.4. Results

Results from the GLMM revealed there was no significant interaction between trap treatments and soak time ($p > 0.05$) for both legal-sized and sublegal-sized crab. The interaction term was therefore dropped from the model. In the reduced model, we found that soak time was not statistically significant, and this term was also sequentially omitted from the model. The final model included only trap treatment, which was statistically significant ($p < 0.001$) for both legal-sized and sublegal-sized crab (Tables 4.1, 4.2).

Illuminated traps captured a mean of 48% (95%CI: 1.37 - 1.59) more legal-sized crab than the control traps, including 57%, 51%, 48%, and 39% in the HU, LU, HUD, and LUD traps, respectively (Figure 4.3, Table 4.1). Based on the model parameters, the predicted CPUE was 13.2, 20.7, 19.9, 19.5, and 18.35, for control, HU, LU, HUD, and LUD treatments, respectively. Illuminated traps also captured a mean of 45% (95%CI: 1.29 - 1.62) more sublegal-sized crab than the control traps, including 42%, 49%, 41%, and 48% in the HU, LU, HUD, and LUD traps, respectively (Figure 4.3). Based on the model parameters, the predicted CPUE was 4.5, 6.4, 6.7, 6.3, and 6.7, for control, HU, LU, HUD, and LUD treatments, respectively. However, subsequent pairwise comparisons of CPUE indicated no significant differences among the four light treatments for both legal and sublegal-sized crab ($p > 0.05$) (Figure 4.3).

Further examination revealed that there were no significant differences in CPUE of both legal and sublegal-sized crab between the high positions (i.e. high upright and high upside down combined) and low positions (i.e. low upright and low upside down combined) (W = 6086.5, p = 0.475 for legal sized and W = 5434.5, p = 0.475 for sublegal sized crab) (Figure 4.4). Similar results were observed for the light orientations (upright, upside down). No significant differences in CPUE were detected between traps having lights in the upright position (including high upright and low upright combined) and upside down (including high upside down and low upside down combined) position (W = 6643, p = 0.076 for legal-sized and W = 5700.5, p = 0.778 for sublegal sized crab) (Figure 4.4).

Soak time did not affect the CPUE of the control traps for legal-sized crab (Figure 4.5). Pairwise comparisons showed no statistical difference between 4 and 6 days (Wilcoxon rank sum test, W = 8483, p = 0.607), no statistical difference between 4 and 15 days (Wilcoxon rank sum test, W = 7318.5, p = 0.688), and no statistical difference between 6 and 15 days (Wilcoxon rank sum test, W = 5928, p = 0.5638) (Table 4.3). In contrast, longer soak times produced significantly higher CPUE in the illuminated traps for legal-sized crab (Figure 4.5). Illuminated traps soaked for 15 days harvested the highest catch, producing a mean CPUE of 23.2 crab/trap, followed 20.1 crab/trap when soaked 6 days, and 18.4 crab/trap when soaked 4 days (Table 4.3). For sublegal-sized crab, the mean CPUE decreased with increasing soak time (Figure 4.5). The number of sublegal crab decreased from 5.9 and 9.1 crab/trap when soaked 4 days, down to 2.8 and 4.8 crab/trap when soaked 15 days, for control and illuminated traps, respectively.

Legal sized crab dominated the catch in all experimental treatments. The proportion of legal-sized and sublegal-sized crab accounted for 73% and 27%, respectively for both control and illuminated traps. Pairwise comparisons of crab size distribution indicated no significant differences between control traps and illuminated traps, as well as among illuminated traps using Kolmogorov-Smirnov test ($p > 0.05$ for all pairwise comparisons), except high upright and low upside down comparison (Kolmogorov-Smirnov test, D = 0.3, $p = 0.023$) (Figure 4.6). Mean CW ranged from 99.01 to 100.95 mm for the different treatments (Table 4.4). The illuminated traps had no significant effect on mean CW using ANOVA (F = 0.834, $p = 0.504$). Mean size of crab and pairwise comparisons are shown in the Table 4.4.

4.5. Discussion

Compared to control traps (without light), the addition of LED lights inside the traps produced a significant increase in CPUE in this study. The catch rate of legal-sized crab increased on average 48% in traps equipped with white LED lights, with no significant difference among the different locations and orientations of the lights. These results suggest that 'how' the trap is illuminated is immaterial to snow crab. We speculate then, that whatever the light illuminates (e.g., the trap, the seafloor, or even conspecifics), is less important than the light itself. These findings lend support for the hypothesis that snow crab simply find white LED light to be a novel stimulus in a dark and barren landscape. In other words, simply the presence of the light, and not what the light illuminates, appears to be important.

Our finding that artificial lights increase CPUE in stationary fishing gears is consistent with previous comparative fishing experiments. For example, the CPUE of large scale fish-traps, cod traps, and snow crab traps were shown to increase up to 200%, 80%, and 77%, respectively with the addition of underwater lights inside the fishing gear (Masuda et al., 2013; Bryhn et al., 2014; Nguyen et al., 2017). Recent research in Sweden has also shown that underwater lights (green, purple, and white) can increase the catch rates of Northern shrimp (*Pandalus borealis*) in baited traps (Ljungberg and Bouwmeester, 2018). However performance is known to vary across different fishing gears and species. For example, lightsticks play a role in attracting target species (i.e., swordfish, tuna) to pelagic longlines, but may affect the capture of sea turtles (Witzell, 1999). How much sea turtles are affected is unclear. Lohmann et al. (2006) and Wang et al. (2007) found that turtles were attracted to light used by lightsticks, but Gless et al. (2008) found the opposite conclusion and stated there were too many confounding factors to conclude that lightsticks attracted sea turtles to longlines. For gillnets and set-nets, the use of LED lights were found to help sea turtles avoid the fishing gear (Wang et al., 2010; Darquea et al., 2016; Ortiz et al., 2016, Virgili et al., 2018).

Assuming an average 48% increase in CPUE is representative for commercial fishing enterprises in the province of Newfoundland and Labrador, the wide spread use of LED lights is predicted to substantially increase the profitability of the fishery. While a detailed economic analysis has not been completed, our rough calculations indicate that an investment of LED lights will produce high variable costs in the short term for a fishing enterprise, but over time it would recover the investment, at which point they would earn profit due to increased catch rates and reduced operating time (i.e., trips). Our review of the scientific literature in which the economic benefits of making such adjustments to fishing gears resulted in surprisingly few examples (e.g., O'Neill et al., 2014; SEAFISH, 2017). By comparison, several studies have investigated the benefits of above-water use of LED lights in different fishing applications. An et al. (2017) showed that replacing traditional metal halide lights with LED lights on vessels targeting hairtail (*Trichiurus lepturus*) around the Korean Peninsula, increased their initial investment cost, but fishing enterprises would achieve a "break-even" point relatively quickly depending on the fuel price and number of fishing trips per year. Similar economic benefits have been documented for squid jigging fisheries in Japan (e.g., Matsushita et al., 2012), purse seine fisheries in Vietnam (e.g., Nguyen and Tran, 2015), and lift-net fisheries in Indonesia (e.g., Susanto et al., 2017).

Our results revealed several positive benefits of longer soak times when using LED lights in crab traps. Increasing the soak time from 4 to 6 days, and from 4 to 15 days, increased the catch of legal crab by 9.2% and 26.0% on average, respectively. These findings are consistent with Nguyen et al. (2017) who reported that snow crab traps with lights performed better as soak time increased. The authors speculated that bait plays a pivotal role in the first few days of soaking, but as the odor depletes, illuminated traps begin to perform better as they continue to attract crab irrespective of bait. The findings from this study support this hypothesis. We also found that increasing soak time significantly reduced the capture of sublegal crab. While increased soak times are known to generally promote sorting and improve trap selectivity (Winger and Walsh, 2011; Olsen et al., 2018), the effect appears to be enhanced when traps are equipped with lights. Functional explanations for this finding are unclear, but it may be related to small crab finding and escaping through the exterior walls of the traps with greater efficiency due to enhanced visual capability (i.e., small crab are able to see and feel their way through the meshes).

However, our results showed that traps equipped with LED lights also harvested a higher CPUE of sublegal-sized crab compared to control traps, yielding on average 45% higher CPUE of sublegal crab than control traps. This suggests that white LED lights increase the vulnerability of both legal and sublegal-sized crab to capture. While this suggests a potential conservation issue associated with the unnecessary handling of pre-recruit crab (Grant, 2003), this impact must be considered in the context of a) fishing enterprises are simultaneously catching their allocated quota of legal size snow crab faster, thus reducing the overall number of trips and trap hauls over the fishing season, and b) the survival of hard-shelled crab released over the side of the vessel is generally high when done properly (Dufour et al., 1997; Grant, 2003).

Although there is currently no scientific literature demonstrating negative effects of underwater light on habitat and marine ecosystems, evidence has revealed that the nocturnal activities of marine animals (i.e. seabirds) have been affected by surface lights such as oil and gas platforms, lighthouses, and costal lighting (Montevecchi, 2006). Thus, it is not unreasonable to expect that the use of underwater lights could produce unexpected ecological costs, including overfishing, increased bycatch, plastic production, and greenhouse gas emission (see review by Nguyen and Winger, 2018). With approximately 4.6 million snow crab traps deployed in the province of Newfoundland and

Labrador, Canada (DFO, 2009), it is conceivable that a significant area in the seafloor would be "illuminated" in the event LED lights were to be widely applied. We recommend future research investigate whether the wide-spread use low-powered underwater lights (such as those used in this study) could disturb or harm animal behaviour and ecosystem function.

In conclusion, this study demonstrated that installing low-powered LED lights in snow crab traps produced an average increase in CPUE of legal-sized crab by 48% and that the location and orientation of the light does not appear to be important. For Canadian fishing enterprises, using LED lights to increase CPUE of snow crab traps permits the opportunity to catch individual quotas with greater efficiency. This means potentially fewer days on the water and the possibility of reduced operating costs (e.g., less bait, fuel, labour), thereby improving the financial viability of thousands of small owner-operated businesses.

4.6. Way Forward

Field experiments in chapters three and four indicate that LED lights significantly increased the catch rate of baited traps. However, are the results transferrable to other snow crab fisheries? The next chapter will investigate the suitability of purple and white LED lights in the snow crab fishery off the coast of Norway in the Barents Sea. Working with collaborators at the Institute for Marine Research, I conduct a comparative fishing experiment aboard the largest snow crab fishing vessel in the world (*M/S Tromsbas*) during the 2017 and 2018 commercial fisheries.

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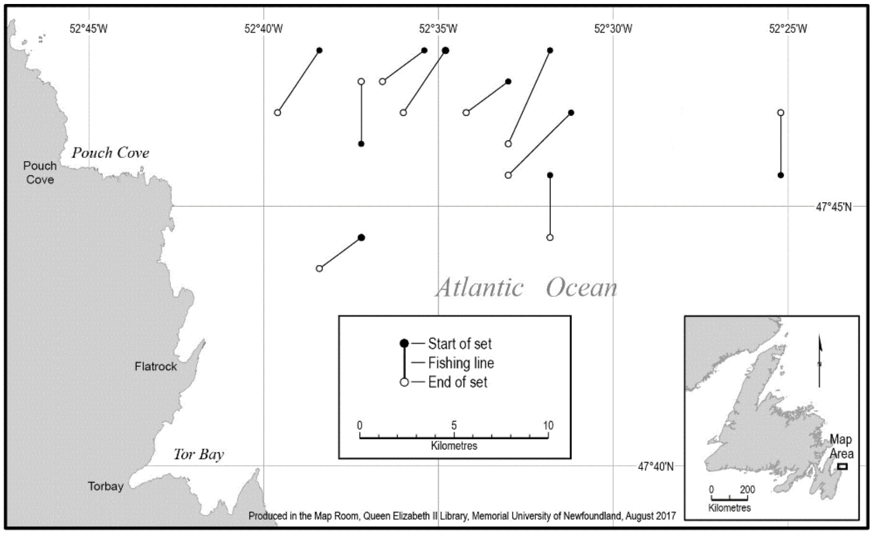

Figure 4.1. Location of the study area, along the northeast coast of the island of Newfoundland.

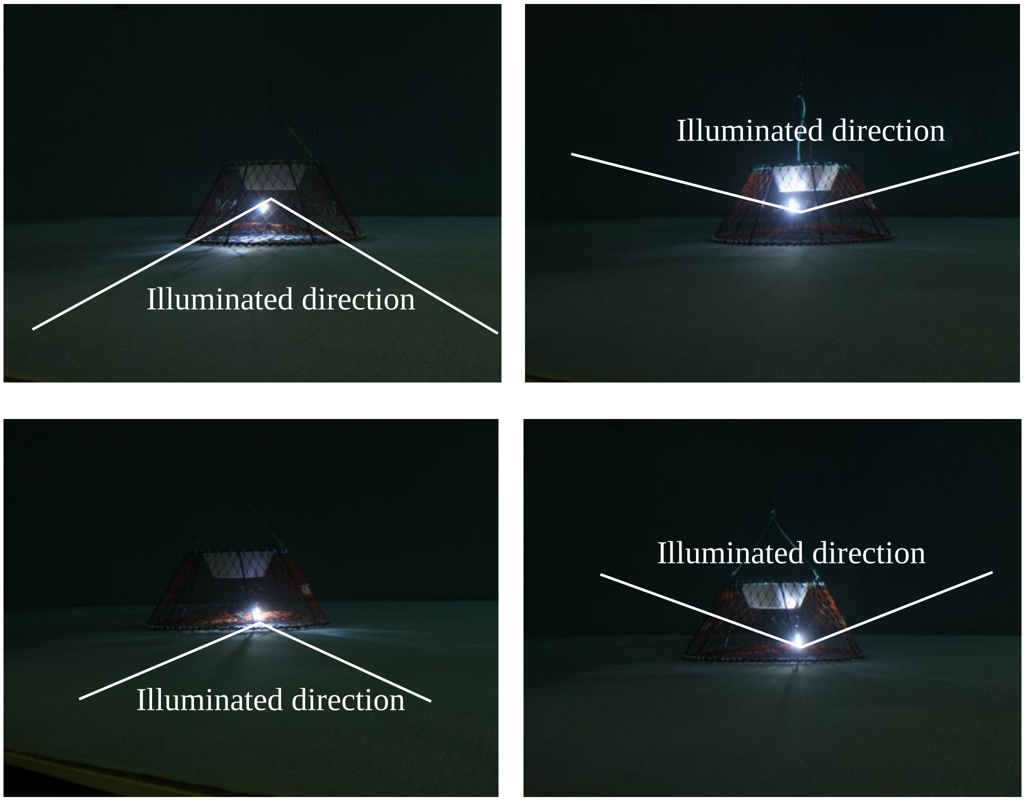

Figure 4.2. Four light treatments photographed in an underwater tank. Top left panel is High Upright treatment; Top right panel is High Upside Down treatment; Bottom left panel is Low Upright treatment; Bottom right panel is Low Upside Down treatment.

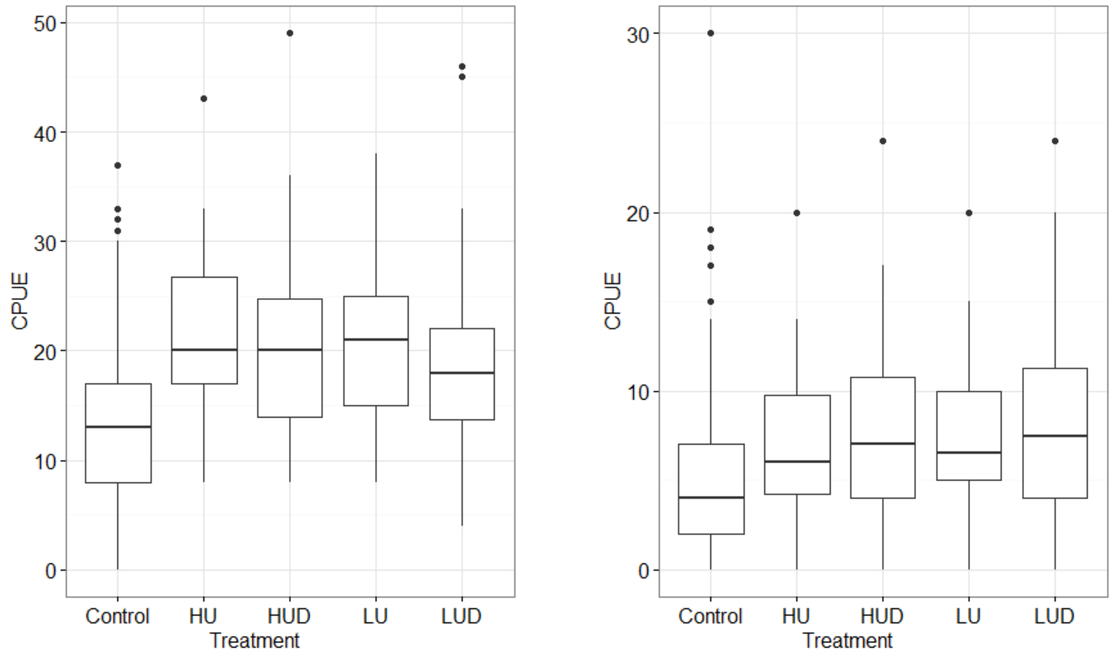

Figure 4.3. Boxplots of CPUE of male snow crab captured by different experimental treatments. Left panel: legal-sized crab. Right panel: sublegal-sized crab. HU is high upright (n = 50). HUD is high upside down (n = 46). LU is low upright (n = 60), and LUD is low upside down (n = 60).

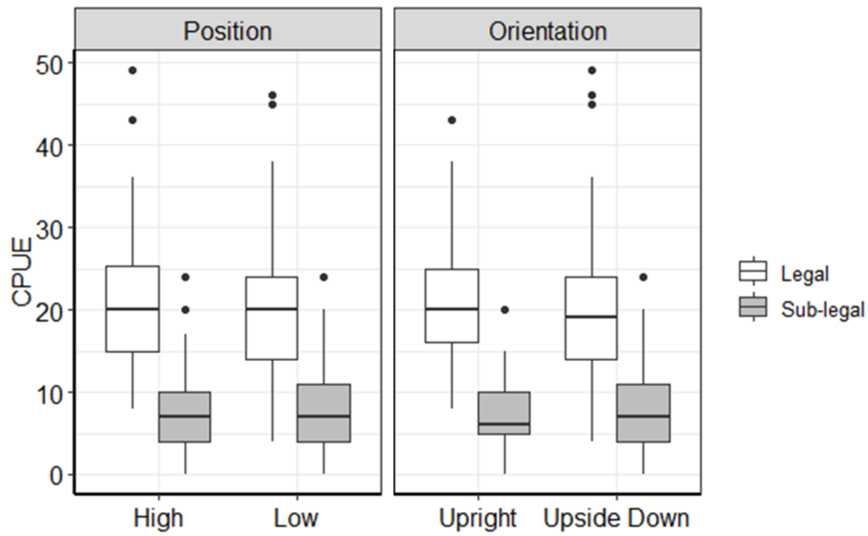

Figure 4.4. Boxplots of CPUE of crab classified by legal and sublegal size for the different light locations (e.g., high combined and low combined; left panel) and orientations (e.g., upright combined and upside down combined; right panel).

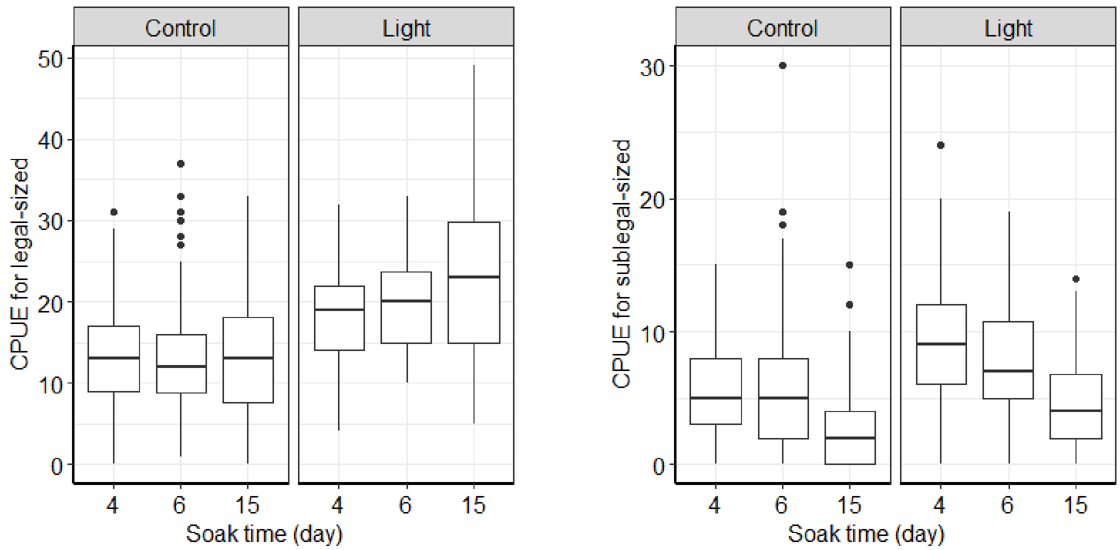

Figure 4.5. Boxplots of CPUE of snow crab classified by different soak time. The left panel represents legal-sized crab and the right panel represents sublegal-sized crab caught. Figures denoted as Light include all 4 light treatments combined.

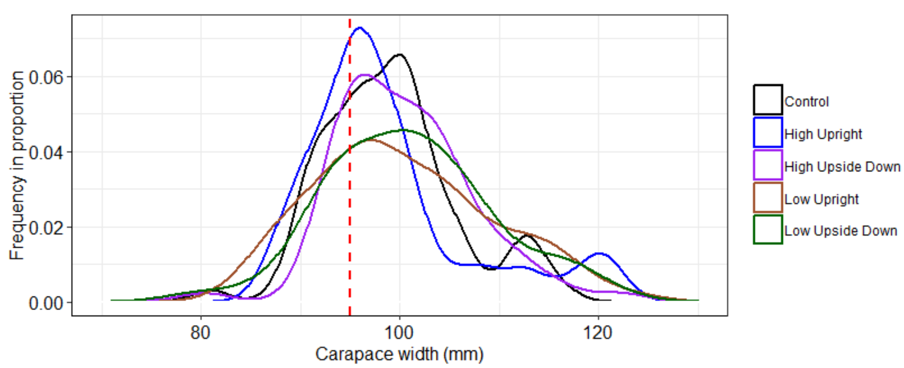

Figure 4.6. Length distribution of male snow crab recorded in the different experimental treatments. Red dashed line is minimum landing size (95 mm CW).

Table 4.1. Parameter estimates and fit statistics of the GLMM model, with negative binomial distribution of catches of legal-sized crab. HU is High Upright; HUD is High Upside Down; LU is Low Upright; and LUD is Low Upside Down.

Predictor	Estimate	SE	z-value	p-value
Intercept	2.58	0.07	39.31	< 0.001
HU	0.45	0.06	6.98	< 0.001
HUD	0.39	0.07	5.90	< 0.001
LU	0.41	0.06	6.78	< 0.001
LUD	0.33	0.06	5.41	< 0.001

Table 4.2. Parameter estimates and fit statistics of the GLMM model, with negative binomial distribution of catches of sublegal-sized crab. HU is High Upright; HUD is High Upside Down; LU is Low Upright; and LUD is Low Upside Down.

Predictor	Estimate	SE	z-value	p-value
Intercept	1.51	0.15	10.12	< 0.001
HU	0.35	0.10	3.47	< 0.001
HUD	0.40	0.10	3.88	< 0.001
LU	0.34	0.09	3.70	< 0.001
LUD	0.39	0.09	4.36	< 0.001

Table 4.3. Mean CPUE of legal and sublegal size crab captured by the different soak times and their comparisons using Non-parametric Wilcoxon Rank-Sum Test. As mean ± standard error. (NS) indicates no significant difference. (S) indicates significant difference detected.

Soak time	Mean CPUE legal-sized crab		Mean CPUE sublegal-sized crab	
	Control	Light pot	Control	Light pot
4 days	13.0 ± 0.53	18.4 ± 0.62	5.9 ± 0.34	9.1 ± 0.52
6 days	13.1 ± 0.60	20.1 ± 0.74	5.7 ± 0.45	7.9 ± 0.54
15 days	13.9 ± 0.81	23.2 ± 1.28	2.8 ± 0.3	4.8 ± 0.46
Soak time comparison				
4 days vs. 6 days	NS	NS	NS	NS
4 days vs. 15 days	NS	S	S	S
6 days vs. 15 days	NS	NS	S	S

Table 4.4. Mean CW recorded for the different treatments and their pairwise post hoc comparison using Tukey's HSD. CW is carapace width. SE is standard error. CI is confidence interval. HU is High Upright; HUD is High Upside Down; LU is Low Upright; and LUD is Low Upside Down.

Treatment	Number of crab measured	Mean CW	SE
Control	70	99.01	0.81
HU	48	98.83	1.23
HUD	68	100.5	0.82
LU	59	100.38	1.16
LUD	51	100.95	1.17
Treatment comparison	t-value	95% CI	p-value
Control vs. HU	-0.19	-4.21 to 3.84	0.999
Control vs. HUD	1.49	-2.17 to 5.14	0.798
Control vs. LU	1.37	-2.43 to 5.17	0.859
Control vs. LUD	1.93	-2.02 to 5.89	0.665
HU vs. HUD	1.68	-2.37 to 5.72	0.787
HU vs. LU	1.56	-2.62 to 5.73	0.844
HU vs. LUD	2.12	-2.20 to 6.44	0.662
HUD vs. LU	-0.12	-3.94 to 3.70	0.999
HUD vs. LUD	0.45	-3.53 to 4.42	0.998
LU vs. LUD	0.56	-3.54 to 4.67	0.996

Chapter 5. Light-Emitting Diode (LED) lights improve catch rate of snow crab pots at relatively high population densities

5.1. Abstract

Since its introduction as a new commercial fishery in 2012, snow crab (*Chionoecetes opilio*) has become an important species for the Norwegian seafood industry. However, periodically catch rates can be low, causing a financial strain on the fishery. Thus, improving the capture efficiency of existing pot designs has the potential to significantly improve the profitability of fishing enterprises. In this study, we investigated whether the addition of low powered purple and white light-emitting diode (LED) lights inside the pots improved the catch rate. Field experiments were conducted in the Barents Sea during 2017-2018, and showed that the effect of LED light on Catch Per Unit Effort (CPUE) was dependent on crab density. When the background density of CPUE was moderate to high (> 2), pots equipped with purple lights caught 25% more legal-sized crab than baited pots (control), while pots equipped with white lights caught 15% more. However, the CPUE of pots with lights did not increase when background CPUE was low (≤ 2). At all background densities combined, pots with purple lights harvested 12% higher CPUE of legal-sized crab than control pots, while pots with white light did not catch significantly more crab. Pots equipped with only light (no bait) caught very few crab and were not considered a viable alternative. The economic benefits of using underwater lights in pots remains unclear given the high capital investment required and positive effects on CPUE were only observed at moderate and high background densities.

Knowledge of temporal and spatial variation in catch rates is recommended before a potential widespread use of LED lights in the commercial fishery can be advocated.

Key words

Underwater fishing light, snow crab, Barents Sea fishery, catchability, invasive species

5.2. Introduction

Snow crab (*Chionoecetes opilio*) are a subarctic and Arctic species belonging to the family *Oregoniidae*. Snow crab have a wide distribution and have been found in cold waters of the Sea of Japan, the Bering Sea, the West Coast of Greenland, and along the East Coast of Canada from Nova Scotia to Labrador (Puebla et al., 2008). Snow crab live in a wide range of depths between 20 and 1,200 m on sandy or muddy substrates. Since smaller crab are found in shallower depths, large crab are targeted commercially at deeper depths, but typically less than 350 m (Comeau et al., 1998; Morris et al., 2018; Mullowney et al., 2018). As a stenothermal species, their temperature range is -1.5 to 11^0C, but prefer temperatures below 5^0C (Hardy et al., 1994; Siikavuopio et al., 2017; Mullowney et al., 2018). Males can reach a maximum size of 160 mm carapace width (CW), while females do not exceed 95 mm CW (Mullowney et al., 2018). Snow crab grow by molting their exoskeleton, and stop growing after a terminal molt, which typically occurs between instars 9 to 14 for males (size range of 40–150 mm CW), and 9 to 11 for females (size range of 30–95 mm CW). After their terminal molt, adult crab can live up to 8 years under optimal conditions (Dawe et al., 2012).

In 1996, snow crab were first discovered in the Barents Sea as an invasive species, and are now permanently settled (Kuzmin et al., 1999; Alvsvåg et al., 2009; Agnalt et al., 2011). Although the population has not been fully assessed, the stock size of the Barents Sea continental shelf population (including Norway and Russia) has been estimated at 19 million individuals (Bakanev and Pavlov, 2009), and predicted to grow to 370 million individuals, with a total estimated biomass of 188,260 mt in the near future (Dvoretsky and Dvoretsky, 2015). In order to adapt to this situation, a substantial number of studies have been conducted during the last few years to understand snow crab biology, distribution, and habitat (Alvsvåg et al., 2009; Agnalt et al., 2010, 2011; Siikavuopio et al., 2017; Mullowney et al., 2018). Several studies on commercialization have been conducted, i.e., management, fishing, processing, and storage (e.g., Agnalt et al., 2011; Hansen, 2016; Siikavuopio et al., 2017).

The Norwegian snow crab commercial pot fishery started in 2012, and has become an important economic contributor to the seafood industry, with total landings of 5,300 mt, accounting for approximately $40 million USD in 2016 (Lorentzen et al., 2018). The main exports are cooked and frozen products sent to Japan, South-Korea, and USA markets. The quota was set at 4,000 mt for 2018, with a closure from mid-June to mid-September to protect the crab following molting. The fishery targets only adult male crab, with a minimum legal landing size of 100 mm CW. Small Japanese-style conical pots baited with squid and arranged in fleets (line of connected pots), similar to Newfoundland and Labrador (Winger and Walsh, 2011; Morris et al., 2018), have become the industry norm in the Barents Sea fishery. Baited pots are a traditional fishing method used in demersal fisheries around the world. Compared with other fishing technologies, baited pots tend to produce less bycatch, effective species and size selectivity, limited benthic habitat disturbance, and require smaller vessels and energy consumption (Miller, 1990; Furevik and Løkkeborg, 1994; Suuronen et al., 2012). Finding methods to improve catching efficiency has the potential to significantly improve the profitability of fishing enterprises. For snow crab, several studies have been undertaken during the last two decades to improve pot design (Hébert et al., 2001), study crab behaviour around baited pots (Winger and Walsh, 2011), and evaluate various bait compositions (Cyr and Sainte-Marie, 1995; Grant and Hiscock, 2009; Araya-Schmidt, 2017).

For hundreds of years, above-water lights have been used to improve the catch efficiency of fishing gears. These lights can gather and concentrate fish to the surface, which can then be harvested using a surrounding net (e.g. purse seines, drop net, lift net), baited hooks (e.g. tuna handlining and hairtail angling), or jigging devices (e.g. squid jigging) (see review by Nguyen and Winger, 2019). Over time with technological advancement, especially the development of LED fishing lights, the use of underwater light in fishing applications has grown substantially. Several studies have investigated their use in reducing bycatch in gillnets, shrimp trawls, and setnets (e.g., Hannah et al., 2015; Ortiz et al., 2016; Virgili et al., 2018; Lomeli et al., 2018), improving the catch efficiency of baited pots for fish and crustaceans (Bryhn et al., 2014; Nguyen et al., 2017; Humborstad et al., 2018; Ljungberg and Bouwmeester, 2018), and studying basic fish behaviour in response to lights (Marchesan et al., 2005; Grimaldo et al., 2018; Larsen et al., 2017, 2018; Melli et al., 2018). A new approach using underwater LED fishing lights to improve the catch rate of pots was recently developed in Canada. An incidental discovery showed that unbaited pots targeting flatfish equipped with a low-powered LED fishing light captured occasional snow crab as bycatch (Murphy, 2014). This was the first evidence that underwater LED fishing lights might be an effective stimulus for capturing snow crab. Subsequent work by Nguyen et al. (2017) showed that attaching purple (peak wavelength of 446 nm) and white (peak wavelength of 456 nm) LED fishing lights into the pot significantly increased the CPUE of legal-sized crab.

The purpose of this study was to extend recent findings in Canada (Nguyen et al., 2017) to the snow crab fishery in the Barents Sea. In particular, we investigated whether the addition of low powered LED fishing lights inside baited pots could improve catch rates of snow crab. Thus, the catch rate and size selectivity from experimental pots was compared to the control pots without lights during two field experiments in the Barents Sea.

5.3. Methods

5.3.1. Gear Description

Japanese-style conical pots with a volume of 1.7 m^3 were used in the experiment, which are typical for harvesting snow crab in the Barents Sea and Newfoundland and Labrador (Winger and Walsh, 2011; DFO, 2017; Araya-Schmidt, 2017; Lorentzen et al., 2018). The dimensions and additional details of the pots are shown in Figure 1. The pot frame was made from round-stock steel with a diameter of 12 mm for the top ring and vertical portions, and 15 mm for the bottom ring. The pot was covered by orange polyethylene netting (135 mm stretched mesh), and a single top mounted, conical white plastic entrance. The pots were connected to a ground line (fleet) at an interval of 25 m by a polypropylene rope (branch line) of approximately 3.5 m length. All pots were randomly inspected in every manner to ensure the pots were identical.

For all sea trials, pots were baited with 0.5 kg of frozen squid (*Illex illecebrosus*). To prevent scavenging of the bait by non-targeted animals, the bait was placed in a perforated polyethylene bait protection bag, typical for the crab fishery in the Barents Sea. The bait bags were green, 40cm long, and had a stretched mesh size of 21 mm.

5.3.2. Sea Trials

The study was carried out onboard the commercial fishing vessel *M/S Tromsbas*, 68.10 m LOA, which operated 24 hours per day, carried 10,000 pots, and had the capacity of retrieving and deploying an average of 2,000 pots per day. Comparative fishing experiments were conducted in June 2017 and February 2018, in the Barents Sea, along the Norwegian continental shelf (Latitude between 74°04'N and 76°09'N, Longitude between 33°48'E and 37°59'E) (Figure 2). Depth at the fishing sites ranged between 190 and 290m. The seabed temperature was between 0.3 and 0.9^{0}C measured by electronic temperature loggers. The experiment was conducted using Electralume® fishing lights manufactured by Lindgren Pitman (Pompano Beach, FL, USA). Purple and white LED lights, with a peak wavelength of 446 nm and 456 nm, respectively were used (see Nguyen et al. (2017) for technical specifications).

In 2017, we evaluated six experimental treatments:

(1) Baited pot (B) for control;

(2) Baited purple light pot (BP) – similar to (1), with addition of a purple LED light;

(3) Baited white light pot (BW) – similar to (1), with addition of a white LED light;

(4) Unbaited purple light pot (P) – pot equipped with only a purple LED light (no bait);

(5) Unbaited white light pot (W) – pot equipped with only a white LED light (no bait),

(6) Empty pot (E) – pot with no bait nor LED light.

Based on the results of the first experiment, we designed a comparative experiment in 2018, however, only baited treatments (1, 2 and 3) were tested due to very low catch rates in the three unbaited treatments (4, 5 and 6) in the first year.

The lights were mounted under the entrance of the pot directly opposite the bait bag in the manner similar to Nguyen et al. (2017). In 2017, each fleet consisted of 200 pots. In order to sample more sites, we modified the experiment in 2018 so as to use only half a fleet (100 pots) for experimental purposes, with the remaining pots in the fleet not recorded. All experimental pots were randomly attached within a fleet for comparative purposes. A total of 5 fleets in 2017 and 10 fleets in 2018 were successfully deployed and retrieved. The total numbers of pots sampled by treatments (1 to 6) were 708, 400, 428, 141, 133, and 21 respectively.

The soak time varied between 43 and 268 hours. Upon the retrieval of each pot, all crab were counted and the number of crab per pot was defined as the Catch Per Unit Effort (CPUE). Bycatch of non-targeted species were recorded simply as count data (numbers of individuals per species for each treatment). Only legal-sized male crab were retained for commercial purposes. All non-targeted animals (under-sized male crab, female crab, and fish) were immediately returned to the ocean. In cases where uncertainty was noted (e.g. light malfunction, broken meshes, pots appeared damaged, upside down pot, or missing bait bag), the data was excluded from the analysis. For each treatment, we randomly sampled the pots to measure carapace width (CW) of all crab using a Vernier caliper with an accuracy of 0.1 mm. A total of 1,626 crab were measured during the experiment.

5.3.3. Statistical analysis

We estimated the effect of pot treatments on CPUE of crab using a generalized linear mixed-effect model (GLMM) based on the Poisson regression, following procedure outlined in Zuur et al. (2016). A generalized modelling approach was used because our catch data violated many of the assumptions needed for parametric tests. The Poisson regression considers CPUE as count data in which CPUE values could only be non-negative integers, where integers were counts rather than ranks. Additionally, mixed-effect models were used to measure variability between fleets (pots nested within fleet). Each model was determined to have overdispersion, the dispersion parameter for the quasipoisson family was greater than 1 (1.96 for legal-sized crab and 2.43 for sublegal-sized crab), thus the negative binomial distribution was used. Residuals met the assumptions for homogeneity, normality, and independence. The GLMM was fit using the *"glmmadmb"* function based on packages *"R2admb"*, and 95% confidence intervals were generated using the *"confint"* function. The model structure was as follows (M1):

```
M1 = glmmadmb(CPUE~Treatment+(1|FleetID),
family="nbinom", zeroInflation=TRUE,data = dat)
```

The percent change (PC) in catch between pot light treatments was compared to the control by:

$PC = 100[\exp(E) - 1]$, where E is the estimated value obtained from the fitted model.

The same GLMM procedure was used to compare CPUE between experimental treatments at high and low catch densities. High density pots were determined to be fleets that averaged greater than 2 crab per pot and low density pots averaged less than and equal to 2 crab per pot (i.e. above and below modeled average for control pots).

The analysis of catch proportion at each length class for crab retained from control pots and experimental pots was performed using the GLMM procedure outlined in Holst and Revill (2009). In this procedure, the GLMM was used to plot the relationship between proportions of catch in illuminated pots versus control pots at each length class. The statistical model used catch proportion as a response variable (see M2 below), CW as the explanatory variables (fixed effect), and subsample ratio as an offset. We included the fleet number (FleetID) as a random effect. The analysis was preceded by fitting the highest order polynomials followed by subsequent reductions until all terms showed a significance ($p < 0.05$), with removal of one term at each step to determine the best-fit model. Analyses were performed separately for different treatments using RStudio for Windows via the *"glmmPQL"* function from the *"MASS"* package.

```
M2= glmmPQL[(expt/(expt +ctr)) ~1+ CW + I(CW^2) +
I(CW^3) + offset(log(q.expt/q.ctr)), random=~1|FleetID,
family=binomial, weights=(expt+ctr),data=CWdata]
```

where *expt* is number of crab at each CW class measured for the experimental pot; *ctr* is number of crab at each CW class measured for the control pot.

5.4. Results

5.4.1. Effects of artificial light on catch rates

Generally, the CPUE of crab was low throughout the experiment, indicating a low abundance of snow crab in the Barents Sea during experimental fishing. Catch per unit effort ranged from 0 to 14 individuals per pot (Figure 3). The baited purple light pots (BP pots) harvested an 11.6% higher CPUE of legal-sized crab than control pots, and this difference was significantly different from the control (Table 1). The baited white light pots (BW pots) caught 2.0% more legal-sized crab than control pots, but this result was not significantly different. Unbaited purple light pots, unbaited white light pots, and empty pots caught significantly less crab than control pots (> 89.1% less than the control for each treatment). The modelled catch rate of legal-sized crab was 1.9 for control pots, 2.1 for BP pots, 1.9 for BW pots, 0.1 for unbaited purple light pots, 0.1 for unbaited white light pots, and 0.2 for empty pots (Table 1). There were no significant differences in CPUE of sublegal-sized crab between BP pots and control pots, as well as BW pots and control pots (Table 2). The modelled catch rate of sublegal-sized crab for control pots, BP pots and BW pots was 0.03, 0.3, and 0.8, respectively.

The effect of LED light on CPUE was dependent on crab density (Figure 4, Table 3). A selection of all fleets that had a mean CPUE greater than 2 in control pots (fleet 5, 8, 10, 13, 14, and 15) showed that the BP and BW pots harvested significantly more crab than the control pots, 24.9% and 15.2% increase respectively (Table 3). Fleets that contained a mean CPUE of less than or equal of 2 (fleet 1, 2, 3, 4, 6, 7, 9, 11, and 12) had no statistically significant differences in CPUE between control (1.42) and BP (1.56) and BW (1.43) pots (Table 3). Catch per unit effort was shown to not be affected by fishing site or soak time.

5.4.2. Selectivity and bycatch

The CW ranged from 66.5 to 158.5 mm across all treatments (Figure 5). Figure 6 illustrates the size-based selectivity analysis of male crab for the different pot treatments. While the logit-quadratic curve was the best fit for the purple light pot, the logit-constant model was the best explanation for the white light pot. The model showed that the purple light pots caught more crab at CWs less than 80 mm and greater than 120 mm than the control pot. The constant curve indicated no significant differences in catch proportion for snow crab of any size between white light pots and control pots, due to the confidence intervals overlapping 0.5. In other words, no size-based selectivity was found for the white light pot in comparison with the control pot.

Bycatch of non-targeted species was low throughout the experiment. Table 4 shows the numbers of individuals captured by species and treatment, including wolffish (*Anarhichas sp.*), Dover sole (*Microstomus pacificus*), and Atlantic cod (*Gadus morhua*). The majority of wolffish were observed in control pots. In addition, 11 female crab were recorded during the experiment (3 for control pot, 6 for purple light pot, and 2 for white light pot).

5.5. Discussion

Adding LED light to a trap was shown to increase the CPUE of snow crab in the Barents Sea when crab were caught at relatively high densities. These results build on a study in the Newfoundland and Labrador snow crab fishery where pronounced increases in CPUE by using artificial light (47-77%) were obtained under conditions where control pots caught ~12 crab/pot (Nguyen et al., 2017), compared to control pots catching ~2 crab/pot in this study. Based on these results we speculate that LED lights motivate crab to enter pots, but do not attract crab from large distances, and suggest that application of light in commercial fishing could enhance the catch rate, but only at high population densities.

Although pots equipped with purple LED light caught 11.6% more crab than the control pots, the economic performance is uncertain due to the high cost of LED lights (~$50 USD each) and batteries. Widespread use of LED lights in the commercial fishery must be considered carefully, and future research is recommended to determine the economic benefits of using light in the Barents Sea snow crab fishery. Moreover, a future study with an alternative, less expensive light stimuli that could attract the target species (e.g., luminescent netting) is recommended.

Our results indicated that the purple LED light was more efficient than the white LED light. This finding is inconsistent with Nguyen et al. (2017) who found that both purple and white LED light could improve the catch rate of snow crab pots, but white light performed better than purple light (increase of 77% for white LED light vs. 47% for purple LED light). Although both studies were conducted at comparable depths (200 to 300 m), it is likely that the bottom characteristics of the two sites (e.g., substrate, current, temperature, salinity, transparency, habitat, and benthic condition) may be different (Petrie and Anderson, 1983; Agnalt et al., 2011; Dvoretsky and Dvoretsky, 2015), as well as a difference in snow crab abundances. These differences might explain the contradictory results. It is well known that marine animal vision and their behaviour in response to artificial light is dependent on their living environment, and for some species the mechanism could be more complicated (Marchesan et al., 2005). Contrary results have also been demonstrated for shrimp trawl fisheries carried out in different fishing sites. For example, attaching low-powered LED lights along the fishing line of a bottom trawl targeting ocean shrimp (*Pandalus jordani*) off the coast of Newport, Oregon, USA significantly reduced bycatch of fish, which is contrary to what was observed in the Barents Sea (Hannah et al., 2015; Lomeli et al., 2018; R. Larsen, the Arctic University of Norway, pers. comm.).

Functional explanations for why LED lights increase the CPUE of snow crab in baited traps remains unknown at this time. The light could directly concentrate animals, or indirectly stimulate crab to enter the pot by attracting potential prey, or just help them to find the entrance to the pot (Nguyen et al., 2017). For example, attaching a green LED light inside a baited cod pot significantly increased the CPUE of Atlantic cod (*Gadus morhua*) by 74% (Bryhn et al., 2014), however it appeared that cod did not respond to artificial light, but rather swam into the pot to feed on krill (*Thysanoessa inermis*), which were attracted to the light (Humborstad et al., 2018; Utne-Palm et al., 2018).

The catchability of baited fishing gear is known to depend on various conditions, such as animal density, satiation level, bait quantity and type, soak time, fishing season, pot design, and oceanographic conditions (e.g., Cyr and Sainte-Marie, 1995; Hébert et al., 2001; Winger and Walsh, 2007, 2011; Grant and Hiscock, 2009). Our results support the previous research by Nguyen et al. (2017) that novel stimuli in the form of artificial light can increase the CPUE of snow crab pots. However, our results show that in order to increase the *vulnerability* of crab to capture, they must also be present and available to the fishing gear. We found that LED lights did not affect CPUE when the control catch was low and had a positive effect only in places which had moderate and high background crab densities (i.e., ≥ 2). This suggests that the effective application of LED light in the commercial fishery could depend on the availability/density of animals to capture, and that this may vary with colour of light, fishing location, season, and year.

The proportion of sublegal-sized crab recorded in this study was high, accounting for 32% of the CPUE. Given that the selectivity of snow crab pots is influenced by mesh size and soak time (Hébert et al., 2001; Winger and Walsh, 2011), we recommend fishing vessels either increase their mesh size, soak time, or both. Another alternative is to decrease the minimum landing size from 100 mm CW to 95 mm CW, similar to Canada, which would have increased the landings of this study by 11%. However, LED light had no effect on the CPUE of sublegal-sized snow crab in this study.

In terms of size selectivity, the white LED light did not have an effect on the size of snow crab captured, which reflects the results of the CPUE analysis for white LED light when all catch densities were considered. Alternatively, the purple LED light did have an effect on size selectivity, capturing small and large snow crab more frequently. This result also mirrors results from the CPUE comparisons at all densities, with purple LED capturing more snow crab. The reason for this specific size selectivity is unknown, perhaps at different life stages juvenile and adult snow crab are more responsive to light. The effects of artificial light on fish behaviour often vary between species and are effected by environmental conditions, lifestyle, level of satiation, and feeding strategies (Marchesan et al., 2005). Additionally, characteristics of the light source (i.e., light intensity and colour, mode of intensity change, order of colour presentation, length of exposure) can also affect animal responses towards artificial illumination (Marchesan et al., 2005). Crab behaviour in response to the artificial light was dependent on size, with larger crab moving faster toward the light source than small animals (Nguyen et al., 2017).

In conclusion, this study has shown that equipping baited pots with artificial light had a positive effect on CPUE when crab were at relatively high densities. When the background CPUE density was moderate to high (> 2), pots equipped with purple lights caught 25% more legal-sized crab than control pots, while pots equipped with white lights caught 15% more. However, the CPUE of pots with lights did not increase when background CPUE was low (≤ 2). Thus, widespread application of LED lights in the Barents Sea commercial snow crab fishery should use caution, and carefully consider the economic benefits before a large-scale shift to using lights is made.

5.6. Way forward

Experiments conducted during the commercial snow crab fishery in 2016 and 2017 in Newfoundland, as well as during 2017 and 2018 in the Barents Sea revealed that attaching an LED light inside the traditional trap significantly increased CPUE of snow crab. Potential application of these findings into the commercial fishery could improve the financial viability of small fishing enterprises. However these lights are costly to purchase (approx. $55 CND each) and require regular exchange of batteries. Recently, a local gear supplier in St. John’s (ESL Marine Supplies Ltd.) introduced a novel alternative solution – a luminescent snow crab trap, with netting manufactured by the Euronete Company (Maia, Portugal). This trap costs only $5 CND higher than the traditional trap ($55 CND vs. $60 CND). However, whether this trap improves the catch rate is still unclear.

The next chapter evaluates the performance of traps equipped with luminescent netting. I conduct a benchtop laboratory experiment to investigate the intensity and duration of luminescence using time-lapsed photography, followed by a small fishing experiment to compare the catching performance of the experimental traps against traditional crab traps under commercial fishing conditions.

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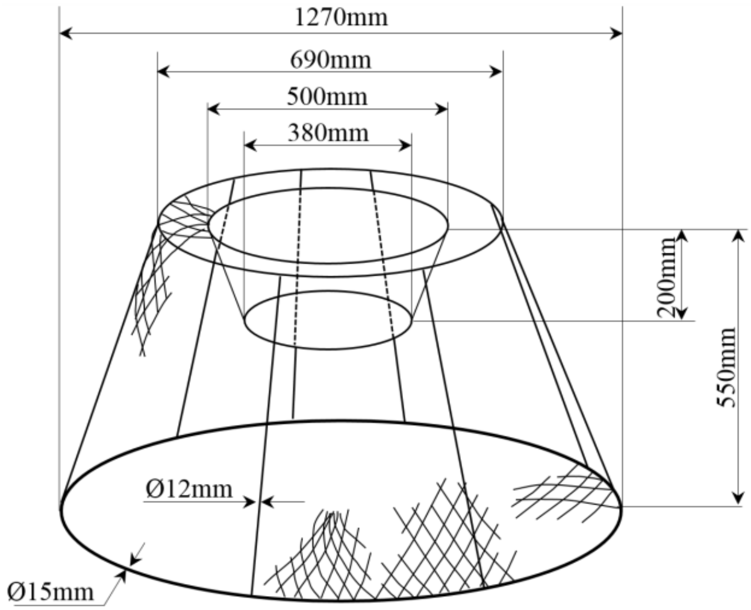

Figure 5.1. Line drawing of the conical snow crab pots used in this experiment.

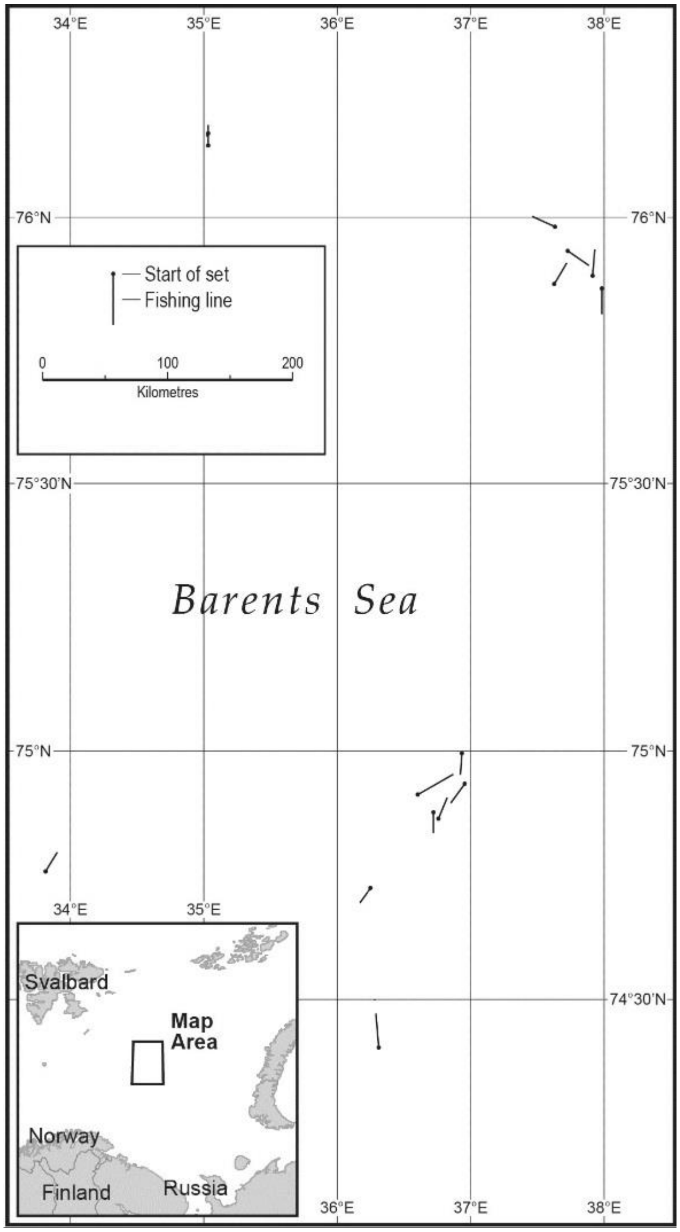

Figure 5.2. Map of the study site, located in international waters along the Norwegian continental shelf.

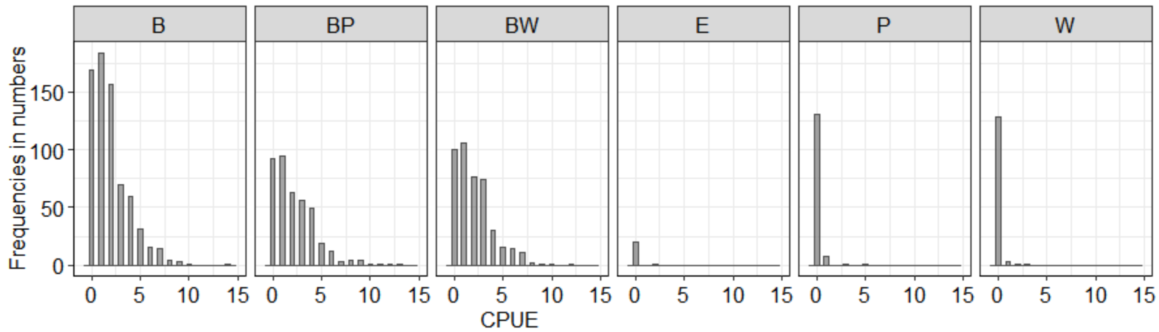

Figure 5.3. Frequency plots of CPUE of legal-sized crab for the different treatments. B represents the control pot; BP represents the purple light pot; BW represents the white light pot; E represents the empty pot (nothing inside); P represents the unbaited purple light pot; and W represents unbaited white light pot.

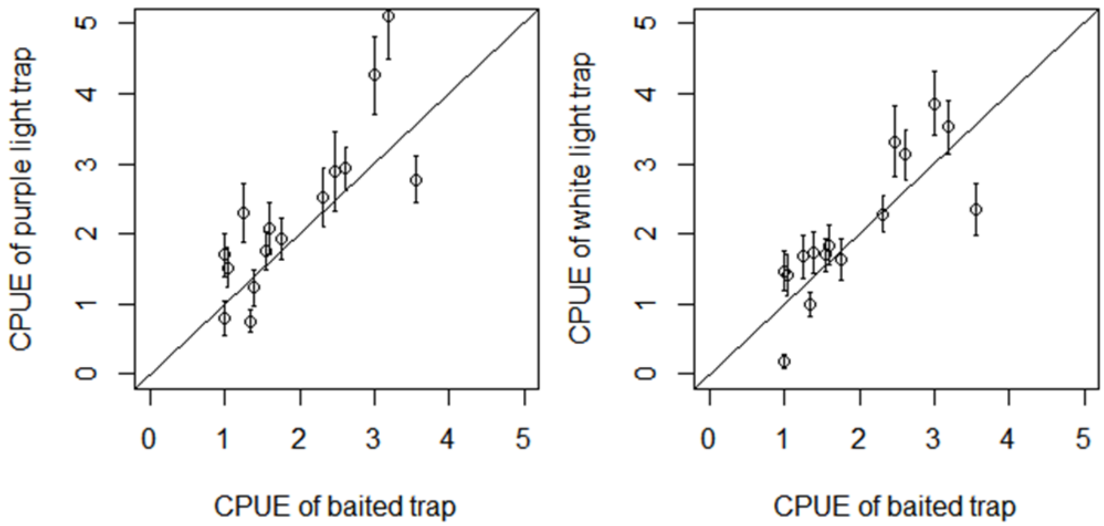

Figure 5.4. Comparison of CPUE of legal-sized crab for 15 fleets of pots. The left panel represents a comparison between the control pot and the purple light pot. The right panel represents a comparison between control pot and the white light pot. CPUE of the control pot is plotted on the x-axis, and CPUE of the experimental pot is plotted on the y-axis. Each point represents the mean from one fleet. Vertical bars denote the standard errors. The solid 1:1 lines show the same CPUE between control pot and experimental pots (either purple light pot or white light pot). Points above the 1:1 line indicates the experimental pot captured more than control pot in the same fleet, and vice versa.

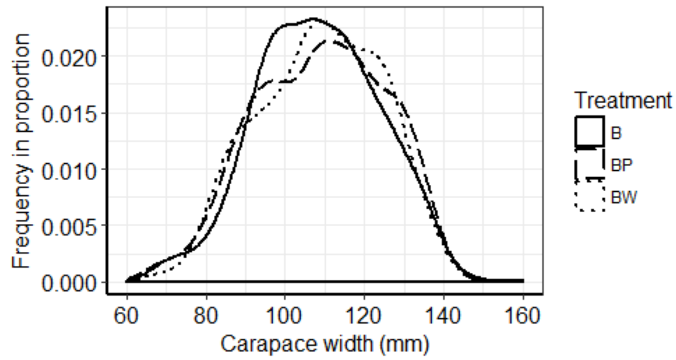

Figure 5.5. Carapace width (CW) frequency distribution of male crab captured by different pot treatments.

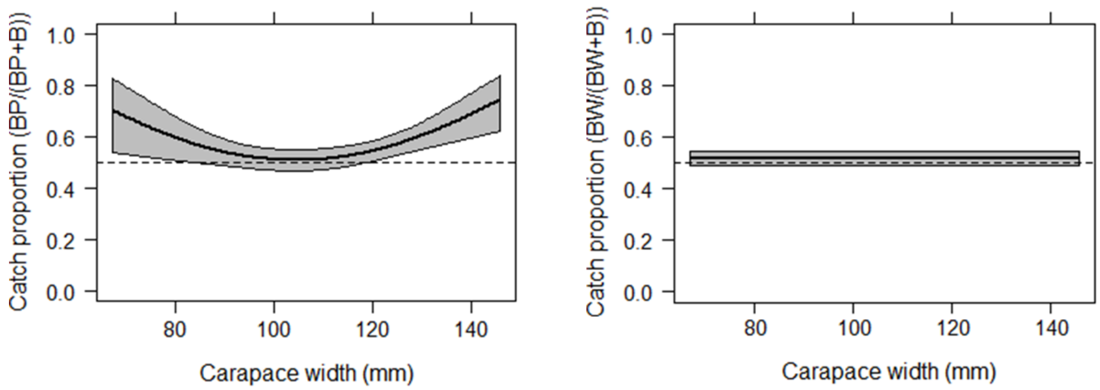

Figure 5.6. A GLMM comparison of the proportion of crab captured at each size class caught in different treatments. Left panel represents the catch proportion of the purple light pot vs. the control pot, while the right panel represents the catch proportion of the white light pot vs. the control pot. B is the control pot. BP is the purple light pot, and BW is the white light pot. A value of 0.5 indicates that catch was the same between the experimental and control pots (no size-based selectivity). For example, a value of 0.25 indicates that at the specific length class, 25% of crab were captured by the experimental and 75% of crab were captured by control pots. The solid bold lines show the modelled means, while the grey area are the 95% confidence interval.

Table 5.1. Parameter estimates, fit statistics, and variation from the random effect of a GLMM model for legal-sized snow crab using fleetID as a random factor (*n* = 15). Number of pots were 1839. SE is the standard error of the mean and SD is the standard deviation. BP is the purple light pot; BW is the white light pot; E is the empty pot (no bait, no light); P is the unbaited purple light pot; W is the unbaited white light pot.

Treatment	**Estimate**	**SE**	**z-value**	**95%CI**	***p*-value**
(Intercept)	0.62	0.11	5.40	1.48-2.32	<0.001
BP	0.11	0.06	2.01	1.00-1.24	0.044
BW	0.02	0.05	0.42	0.92-1.14	0.677
E	-2.22	0.72	-3.09	0.03-0.44	0.002
W	-3.30	0.36	-9.18	0.02-0.07	<0.001
P	-2.68	0.28	-9.73	0.04-0.12	<0.001
Random effect			**Variable**	**SD**	**Variance**
FleetID			Intercept	0.35	0.13

Table 5.2. Parameter estimates, fit statistics, and variation from the random effect of a GLMM model for sublegal-sized snow crab using fleetID as a random factor (n = 15). Number of pots were 1543. SE is the standard error of the mean and SD is the standard deviation. BP is the purple light pot; BW is the white light pot. Because of negligible sublegal-sized crab caught by the empty pot, unbaited purple light pot, and unbaited white light pot, these treatments were excluded from the model.

Treatment	**Estimate**	**SE**	**z-value**	**95%CI**	***p*-value**
Intercept	-3.39	0.64	-5.28	0.01-0.12	<0.001
BP	-0.13	0.26	-0.50	0.52-1.47	0.62
BW	0.16	0.24	0.66	0.73-1.89	0.51
Random effect			**Variable**	**SD**	**Variance**
FleetID			Intercept	2.11	4.44

Table 5.3. Parameter estimates, fit statistics, and variation from the random effect of a GLMM model comparing the CPUE of snow crab for the different pot treatments by different catch densities, SE is standard error of the mean and SD is standard deviation.

Treatment	**Estimate**	**SE**	**z-value**	**95%CI**	***p-value***
Average CPUE ≤ 2					
Intercept	0.35	0.10	3.59	1.17-1.72	<0.001
BP	0.09	0.08	1.09	0.93-1.28	0.278
BW	0.01	0.08	0.17	0.87-1.19	0.866
Random effect			**Variable**	**SD**	**Variance**
FleetID			Intercept	0.25	0.06
Average CPUE > 2					
Intercept	1.02	0.07	15.14	2.44-3.18	<0.001
BP	0.22	0.07	3.16	1.09-1.44	0.002
BW	0.14	0.07	2.04	1.01-1.32	0.042
Random effect			**Variable**	**SD**	**Variance**
FleetID			Intercept	0.12	0.02

Table 5.4. Summary of all bycatch species caught during the experiment. B represents the control pot; BP represents the purple light pot; and BW represents the white light pot. Values shown are percent of individual per pot and total number of pots in brackets for the different treatments.

Categories	**B (708)**	**BP(400)**	**BW(428)**
Wolffish (*Anarhichas sp.*)	3.1	0.6	0.6
Dover sole (*Microstomus pacificus*)	1.1	0.7	0.6
Atlantic cod (*Gadus morhua*)	0.1	0.1	0.0

Chapter 6. Application of luminescent netting to improve the catchability of snow crab traps

6.1. Abstract

In this study, we investigated luminescent netting as a means to improve the catch rates of snow crab. A benchtop laboratory experiment was conducted to investigate the intensity and duration of luminescence using time-lapse photography. We exposed experimental traps to five different treatments of ultraviolet (UV) light to excite the luminescent fibers in the netting. Our results showed that luminescent netting can be effectively activated to emit light, and that the resulting intensity and duration of luminescence emitted over time depends on the initial duration of UV exposure and the source of light. A fishing experiment was subsequently conducted to compare the catch rate of traditional and luminescent traps, and determine how soak time affected catch rate. We found that the catch per unit effort (CPUE; measured as number of crab per trap) was significantly higher in luminescent traps compared to identical traps with non-luminescent netting, representing a 17% increase in the legal-sized crab catch rate, with no significant difference detected for sublegal-sized animals. Our results indicate that luminescent netting can significantly increase catch rates of snow crab, but this increase is relative to soak time. The CPUE was significantly higher in luminescent traps fished for relatively short soak times (55% increase), but when soak times were longer, ~8 d, CPUE was not significantly different.

Keywords

luminescent netting, light intensity, snow crab, catch comparison, trap fishery

6.2. Introduction

For more than five decades, the snow crab (*Chionoecetes opilio*) fishery has provided a significant source of income for coastal communities in Canada's most eastern province, Newfoundland and Labrador (Davis, 2015). In 2017, approximately 33,584 metric tonnes of snow crab was landed, corresponding to $325 million CND, representing the highest landed value of marine product in the province (DFA, 2017). However, the resource has shown signs of decline in recent years, resulting in a reduction in the Total Allowable Catch (TAC) and dockside landings over the past 10 years. The overall quota decreased 43% from 51,582 tonnes in 2014 to only 29,390 tonnes in 2018 (DFO, 2014; 2018). Additional challenges facing the snow crab fishery include: 1) reduced abundance levels due to environmental change and disease (Marcogliese, 2008; Wassmann et al., 2011; Mullowney et al., 2014); 2) interaction with mobile shrimp trawling (Nguyen et al., 2014); 3) effects of underwater noise from seismic exploration (Morris et al., 2018); 4) potential interaction with marine mammals (Benjamins et al., 2012); 5) suspension of Marine Stewardship Council certification (MSC, 2018); and 6) increases in operating cost (Davis, 2015).

In response to these challenges, improvements in fishing efficiency through increased catch rate and reduced operating costs (e.g., less bait, fuel, labour) are currently being considered as methods to maintain the economic viability of fishing enterprises. To date, several studies have been undertaken to improve the catchability and selectivity of traps, including modifications to trap shape (Cyr and Sainte-Marie, 1995; Hébert et al., 2001; Sainte-marie and Turcotte, 2015), bait type and amount (Cyr and Sainte-Marie, 1995; Grant and Hiscock, 2009), escape mechanisms (Winger and Walsh, 2007; 2011), and underwater lights (Nguyen et al., 2017; Nguyen and Winger, 2019). As a commercially important species, regulations are enforced to maintain a sustainable fishery, including input controls (e.g., fishing capacity, vessel usage, fishing effort), output controls (e.g., total allowable catch), technical measures (e.g., trap characteristics and minimum landing size) (DFO, 2017), and a new regulation to reduce the amount of floating rope on the water surface to reduce negative encounters with North Atlantic right whales (DFO, 2018).

Previous studies have shown that snow crab exhibit positive responses to artificial light, resulting in increased catch rates when baited traps are equipped with low-powered LED lights (Nguyen et al., 2017, Nguyen and Winger, 2019). In at least one case, the economic performance of using LED lights in traps has been evaluated, with an estimated profit of up to $1,100 CDN per ton of quota per fishing vessel annually (Nguyen and Winger, 2018a). However, the use of LED lights in baited traps are not without their challenges. Investment in LED lights requires initial capital costs and the regular replacement of batteries during the lifetime of the lights. Economic profit depends on a variety of factors, such as input costs (e.g., fuel, bait, labour), output value (e.g., crab price), and the amount of quota allocated, making it difficult to confidently predict the period of time until fishing enterprises achieve a return on investment (Nguyen and Winger, 2018a). Finally, purchasing and equipping every trap with an LED light is certain to produce ecological costs. Possible negative effects include increased marine litter and CO_2 emissions associated with the production of plastics (Nguyen and Winger, 2018b).

The authors estimated that a total of 265 tonnes of plastic would be needed, emitting 1,589.8 tonnes of CO_2, to produce 1.2 million LED lights for the snow crab fishery in Newfoundland and Labrador (Nguyen and Winger, 2018b).

A potential alternative to LED lights is luminescent netting. Euronete Company (Maia, Portugal) recently introduced a novel polyethylene netting (EuroGlow™) containing luminescent fibers. The fibers absorb ultraviolet (UV) radiation when exposed to sunlight, exciting the particles which then emit light which is visible to the human eye. This study investigated the potential application of this luminescent netting for the snow crab fishery. We conducted a benchtop laboratory experiment to investigate the intensity and duration of luminescence using time-lapsed photography, followed by a fishing experiment to compare the catch rate of traditional and luminescent traps and how they are affected by different soak times. Results are compared to recent research using LED lights and discussed in relation to the possible application to commercial fishing operations.

6.3. Methods and Materials

6.3.1. Laboratory Experiment

A benchtop laboratory experiment was conducted at the Fisheries and Marine Institute (Memorial University of Newfoundland, St. John’s, NL, CA) between April and August 2018. A small experimental room was designed and built to hold a luminescent trap, with dimensions of 2 m long x 2 m wide x 2 m high. Black plastic sheets were used to cover all sides of the room, preventing light from entering or exiting. Photos taken by a

Canon Rebel T5i DSLR camera were used to capture the light intensity of the trap. The trap was placed 0.5 m away from the camera equipped with an EF-S18-55 mm 1:3.5 lens. Through USB connection, the camera was programmed using EOS Utility ver. 28.0 software by Canon with the use of a laptop. The camera was set to ISO 1600 for maximum light detection in dark settings, and the shutter speed was set to 15 seconds to allow enough light into the camera. The camera was set to manual focus in order to ensure focused images in dark lighting. The EOS Utility software was used to program the camera to take one picture every 10 minutes for at least 6 hours.

Ultraviolet lights (UV Flood 36, ADJ Group) were mounted inside the room for the purpose of “charging” the experimental traps. A total of 4 lighting units were used, each containing 12 individual 3-Watt diodes (4x12x3=144 watts total). The wavelength of the UV light varied between 395 - 400 nm, according to manufacturer specifications. Each lighting unit had dimensions of 300 mm long x 235 mm wide x 115 mm high, with a weight of 2.2 kg. The UV lights were suspended near the ceiling of the room, orientated toward the trap, spaced between 0.8 and 1.2 m away from the trap. See Figure 6.1 for a schematic drawing of the experimental setup.

Four experimental treatments were conducted with the use of the UV lights. Traps were exposed to the UV light for either 1 s, 1 min, 5 min, or 10 min, and then photographed in the dark for 6 h to document the change in light intensity over time. In between trials, the trap was left covered in the dark for at least 12 hours to ensure no residual light from the previous trials remained. A fifth experimental treatment was undertaken using natural sunlight. The weather on experimental days was sunny with scattered clouds and a high UV index (Weather, 2018). The trap was placed in direct sunlight for 10 min, and then immediately returned to the experimental room to begin the photographing process. Figure 6.2 shows the experimental trap following charging. Eight replicates were repeated for each treatment. Baseline photos (e.g., experimental room with no trap and no UV light) were also taken in order to identify the baseline level of illumination in the room. A total of 1,680 photos were successfully taken and analyzed during the experiment (1,600 experimental photos, and 80 baseline photos).

In order to quantify the light intensity within each photo, the electronic images were sequentially uploaded into open source *ImageJ* software v.1.8.0_112 to be analyzed for their "mean gray value", which is commonly used to analyze light intensity (Selinummi et al., 2005; Collins, 2007; Vrekoussis et al., 2009; Ristivojević et al., 2017). The mean gray value in an image is considered a measurement of the light intensity within the image, based on the red, green, blue (RGB) model (Hunt, 2004). Mean Gray Value is the sum of the gray values of all the pixels divided by the number of pixels. For RGB images, the mean is calculated by converting each pixel to grayscale using the formula gray=0.299red+0.587green+0.114blue (Hunt, 2004; Seletchi and Duliu, 2007). Using *ImageJ* software, the mean gray value of each image was obtained by selecting *set measurements* with area and mean gray value selected.

6.3.2. Fishing Experiment

A comparative fishing experiment was undertaken between April and June 2018 in two locations: Harbour Breton and Hermitage, off the south coast of Newfoundland, Canada, during the annual commercial snow crab fishery. The depth at the sampling sites ranged from 140 to 182 m. Experimental and control (traditional) traps were deployed from three different snow crab vessels in both inshore and offshore areas (Table 6.1; Figure 6.3). A total of 20 experimental traps and 20 control traps were used per vessel. All of the traps were new and identical in every respect. The only difference was that the experimental traps had luminescent fibers woven into their netting. A summary of experimental information is shown in Table 6.1. Each trap was baited with a 1.36 kg (3 lbs.) combination of frozen Atlantic herring (*Clupea harengus*) and squid (*Illex illecebrosus*).

To ensure the luminescent traps were fully charged, the traps were deployed between 7:10 am and 11:00 am, which was after sunrise (Timeanddate, 2018), allowing sufficient exposure to UV radiation. Both trap types (experimental and control) were randomly located within a fleet for comparative purposes. Each fleet consisted of 20 traps. Each trap was spaced at intervals of 45 m along the fleet. A total of eight fleets of gear were deployed and retrieved during the course of study. Fishing practices were similar to the traditional fishing habits of the snow crab fishery. The traps were soaked one day (~24 h) in the inshore sampling sites and 8 days in the offshore sampling sites (~191 h). For each retrieved trap, the number of crab caught was counted, catch per unit effort (CPUE) was noted, and legal versus sublegal was determined. For short soak times, we randomly selected a few traps to compare size selectivity between experimental and control traps. Traps were randomly selected from each treatment and from each fleet to measure the carapace width (CW) of all crab in that trap using Vernier calipers to the nearest mm. A total of 370 crab were measured for CW during the fishing experiment. Legal-sized crab (≥ 95 mm CW) were retained for commercial purposes, and sublegal-sized crab (< 95 mm CW) were immediately returned alive to the ocean after sampling. Offshore fishing practices precluded our ability to get as detailed measurements of snow crab CWs.

6.3.3. Statistical Analysis

For the laboratory experiment, the relationship between mean gray value (light intensity) and time decreased exponentially, and the data was fit with a log-linear model:

$$y(t)= Ce^{kt} \qquad (1)$$

where y is light intensity at the time t. C and k are constants, and obtained from the model. k is usually a negative value because light intensity decreases with time. Differences among treatments was determined by a likelihood ratio test ($p < 0.05$; *anova* function in R statistical software version 3.5.0 (R core team, 2018). If significantly different, a post-hoc test was conducted to determine differences among treatments using a general linear hypothesis test-Tukey all-pair comparison (*glht* function in the *multicomp* package).

For the fishing experiment, a generalized linear mixed-effect model (GLMM) was used to estimate the effect of trap treatment on CPUE. Analyses were conducted for both soak time groups via the *glmmadmb* function based on package *glmmADMB*. We used a Poisson distribution of the response variable because it was non-normal (i.e. count data), and a mixed effect model where traps were nested within fleet, and fleets were nested within a vessel. The fitted model showed indications of overdispersion, which was determined from the quasipoisson dispersion parameter being greater than 1 (3.63 for legal-sized crab and 7.05 for sublegal-sized crab), thus the negative binomial distribution was used. Zeroinflation was not significant and therefore dropped. All assumptions of GLMM were met with regard to homogeneity of variance, normal distribution of errors, and independence of errors. The fitted model was built as following:

```
model= glmmadmb(CPUE~Treatment +(1|Vessel/IDfleet),
family="nbinom", zeroInflation=F, data = dat)
```

A comparison of the catch proportion retained at each CW length class by luminescent and control traps for short soak times was also analyzed using GLMM with catch proportion as a response variable, length class as the explanatory variable (fixed effect), the fleet number (ID) as a random effect, and subsample ratio as an offset, following the methods suggested by Holst and Revill (2009). In this procedure, polynomial GLMM was used to fit curves for the expected proportions of catch length using the `glmmPQL` function from the `MASS` package. We began by using higher-order polynomials (i.e., cubic, quadratic, linear, or constant) to fit the proportions at each length class retained in the experiment traps to those retained by experimental traps and control trap, followed by subsequent reductions until all terms were significant ($p < 0.05$), with removal of one term at each step to determine the best-fit model (Holst and Revill, 2009).

6.4. Results

6.4.1. Laboratory Experiment

Measures of light intensity ranged between 1.52 and 60.30 (pixel), while light intensity of the background (empty experimental room) was 0.28 (pixel). This means the trap still had low light intensity after 6 h, which varied around 1.52 (pixel) for all charge treatments. The likelihood ratio test indicated that charging treatment significantly affected the duration of light intensity ($F = 22.48$; $p < 0.001$). Subsequently all-pair post-hoc analysis showed significant differences between each treatment, except for 5 min UV versus 1 min UV, 10 min UV, and 10 min sunlight and 1 min UV versus 10 min sunlight (Table 6.2). The relationship between light intensity and time post charge for the different charging treatment is shown in Figure 6.4. Variability of light intensity between time series within treatment was low, thus the 95% confident intervals along the regression lines were narrow (Figure 6.4).

Charging time significantly affected the light intensity and duration of luminescence, of which traps exposed to UV light for longer periods, produced higher intensity. Initial light intensity (i.e., C value of the model) for the 1 s, 1 min, 5 min, 10 min treatments, were 21.77, 33.63, 37.41, and 49.46, respectively (Table 6.3). Each UV treatment resulted in similarly shaped decreasing, exponential curves that converged toward 0 light intensity at approximately 100 min (Figure 6.4). Based on an evaluation of the confidence intervals, the 1 s treatment was significantly lower than all other treatments until they converge at 100 min. The intermediate treatments (1 and 5 min), had very similar values of light intensity throughout, but 5 min had a slightly larger initial charge. The 10 min UV treatment was higher throughout the first 100 min.

The sunlight treatment had a less severe, decreasing relationship over time. The initial light intensity level was the lowest of all treatments, was equivalent to the intermediate treatments (1 and 5 min) at 25 min duration, equivalent to the longest UV treatment (10 min) at 48 min, and had the longest duration of all treatments reaching 0 at approximately 215 min. This relationship was explained in the model by having the lowest initial intensity, C =18.995, and the longest duration due to the highest k value (Table 6.3).

6.4.2. Fishing Experiment

For all data combined, the model output predicted that the luminescent trap caught 17% more legal-sized crab on average than control traps (p = 0.04) (Table 6.4). The modelled catch rate of legal-sized crab was 9.20 for the experimental trap and 7.86 for the control trap (95% CI: 3.37 - 18.34). There were no statistically significant differences in CPUE of sublegal-sized crab between the experimental and control traps (p = 0.82) (Table 6.4). The modelled catch rate of sublegal-sized crab was 1.30, and 1.25 for the experimental and control traps (95% CI: 0.25 - 6.25), respectively.

Results indicated that the effect of luminescent trap on CPUE was dependent on the soak time. The model output predicted that the luminescent trap had a 55.0% higher catch rate of legal-sized crab than the control traps (p = 0.001) with shorter soak times (Table

6.5). At longer soak times, catch rate was not significantly different (p = 0.61). The modelled catch rate at short soak times for legal-sized crab was 6.5 for the experimental trap and 4.2 for the control trap (95%CI: 2.39-7.3; Table 6.5). For longer soak times, catch rate was 25.8 for the experimental trap and 26.8 for the control (95%CI: 21.96-32.76; Table 6.5). Figure 6.5 illustrates the CPUE of both legal and sublegal-sized crab captured using the experimental and control traps for each soak time.

The frequency distribution of CW for crab captured in the control and experimental traps are illustrated in Figure 6.6. CW ranged from 51 to 140 mm for the different treatments (ranged: 51-135mm for control traps and 64 - 140mm for experimental traps). Figure 6.7 illustrates length frequencies and a constant model GLMM that was the best fit for snow crab captured using control and experimental traps at short soak times. Results showed that there was no difference in size selectivity between the luminescent trap and control trap for short soak times.

6.5. Discussion

Our results showed that luminescent netting can be effectively activated to emit light, and that the resulting intensity and duration of luminescence emitted, depends on the initial duration of UV exposure and the source of light. Assuming the traps used in our fishing experiment performed similar to those in the laboratory, we would have expected the visibility of the traps to decay rapidly. Thus, we speculate that emission from the luminescent netting were likely too low to elicit increased ingress rate of snow crab into the traps after the first initial hours (i.e., ranged from 16.75 to 44.55). Our CPUE data appears to corroborate this hypothesis, given that significant differences were only detected during the shorter soak times at the inshore fishing locations. This suggests that the positive benefits of luminescent netting shrink with increasing soak time, and at some point the trap will function similar to a traditional trap, relying solely on attraction by bait. The opposite has been shown for low-powered LED lights that can last as long as 12.5 days. Nguyen et al. (2017) and Nguyen and Winger (2019) both reported that longer soak times disproportionately benefited baited traps that were illuminated with LED lights compared to identical traps with bait alone. They speculated that bait plays a pivotal role in the first days of soaking, but as the bait odor begins to deplete, traps with LED light tend to perform better than their unilluminated counterparts because they continue to attract crab irrespective of the bait.

Our fishing experiment demonstrated that luminescent traps were more effective at harvesting snow crab than traditional traps, with an increase of 17% for legal-sized crab compared to traditional traps with standard polyethylene netting. These findings document the first known empirical evidence on the positive attributes of luminescent netting/twine in fishing operations. To our knowledge, all previous evaluations of luminescent technologies have yielded negative or inconclusive results (e.g. Glass et al., 1993; Stone and Bublitz, 1996; Werner et al., 2006). Although our findings are encouraging, we suggest caution in interpreting the results. We recognize that the experimental replicates of each vessel and the number of fishing trips were relatively low in our fishing experiment. Pooled data indicated a positive effect of the luminescent trap on catch rate of snow crab, however variation in CPUE between vessels was large. Given the number of remaining unanswered questions, we recommend a larger and more comprehensive study to investigate the effectiveness of luminescent traps in different environments, seasons, soak times, and fishing operations.

Using light as a stimulus to attract and accumulate animals has existed for thousands of years, ranging from simple torches to sophisticated artificial illumination systems both above and below water (reviewed by Nguyen and Winger, 2018b). However, the mechanism that explains the behavioural response of animals to artificial light is not fully understood in many cases. A simple explanation is that animals are simply attracted to the light (Ben-Yami, 1976). However, in some cases the mechanism may be more complicated. For example, evidence suggests that Atlantic cod are not necessarily attracted to artificial light, but instead can be enticed to enter a trap in pursuit of prey, which are themselves attracted by the light (Humborstad et al. 2018; Utne-Palm et al., 2018). In the case of snow crab, much remains unknown about how and why light increases the CPUE of traps. Recent work by Nguyen and Winger (2019) reported that the location and orientation of a light is not important. These results suggested that 'how' the trap is illuminated is immaterial to snow crab. The authors speculated then, that whatever the light illuminates (e.g., the trap, the seafloor, or even conspecifics), is less important than the light itself. These findings lend support for the hypothesis that snow crab simply find white LED light to be a novel stimulus in a dark and barren landscape. In other words, simply the presence of the light, and not what the light illuminates, appears to be important.

Artificial light is known to attract some species, but in other cases, it can deter and cause animals to move away from fishing gear, reducing the incidental capture of non-target species. For instance, attaching LED lights to gillnets reduced bycatch of green turtle (*Chelonia mydas*) by over 60%, and cormorants (*Phalacrocorax bougainvillii*) by 85% (Ortiz et al., 2016; Mangel et al., 2018). Similar results were also found in set nets, which retained no loggerhead turtles (*Caretta caretta*) when deployed with LED lights (Virgili et al., 2018). Additonal fishing experiments are required in order to document that non-targetted species do not experience increased vulnerability to capture in luminescent traps, campared to traditional traps.

Vison is very important in predator avoidance, food location, and prey capture for many marine species including invertebrates such as snow crab (Frank et al., 2012). We hypothesize that the light emitted by the luminescent netting in this study was visible to snow crab, explaining the increase in CPUE observed. Much is understood about the minimum light intensity threshold for species such as mantis shrimp, squid (*Todarodes pacificus*), mackerel (*Scomber japonicas*), loggerhead turtles (*Caretta caretta*), sea bass (*Dicentrarchus labrax*), and northern krill (*Meganyctiphanes norvegica*) (Cronin et al., 2001; Marchesan et al., 2005; Wang et al., 2007; Matsui et al., 2016; Utne-Palm et al., 2018). To our knowledge there is very little known about how snow crab see and perceive light, as well as the structure, function, or evolution of the eye. Nguyen et al. (2017) demonstrated that crab had positive phototaxis behaviour in response to white (wavelength of 456 nm) and blue (wavelength of 464 nm) LED lights, but the optimal light intensity for attracting snow crab was not measured. This suggests an opportunity for future research on these mechanisms.

In conclusion, this study evaluated an innovative luminescent netting for potential application in a snow crab fishery in eastern Canada. We found that, as expected, the luminescent trap emitted light in a dark room over a period of several hours, with the resulting intensity and duration of luminescence dependent on the duration of UV exposure and source of light.

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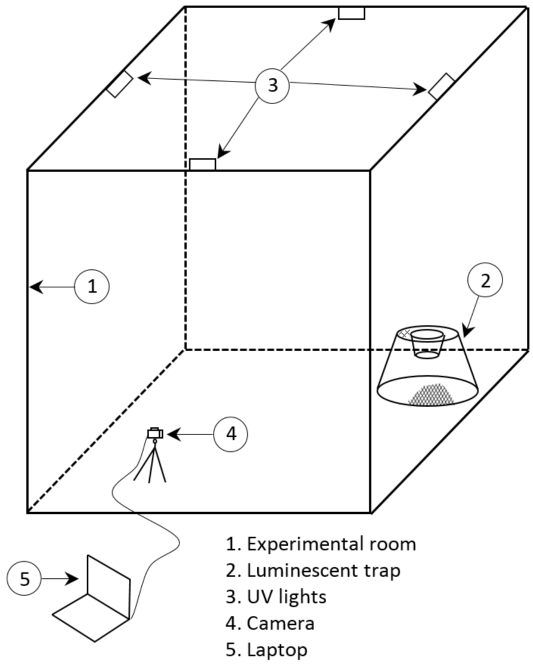

Figure 6.1. Schematic drawing of the laboratory setup for filming traps in the dark.

Figure 6.2. Photograph of an experimental luminescent trap in the dark.

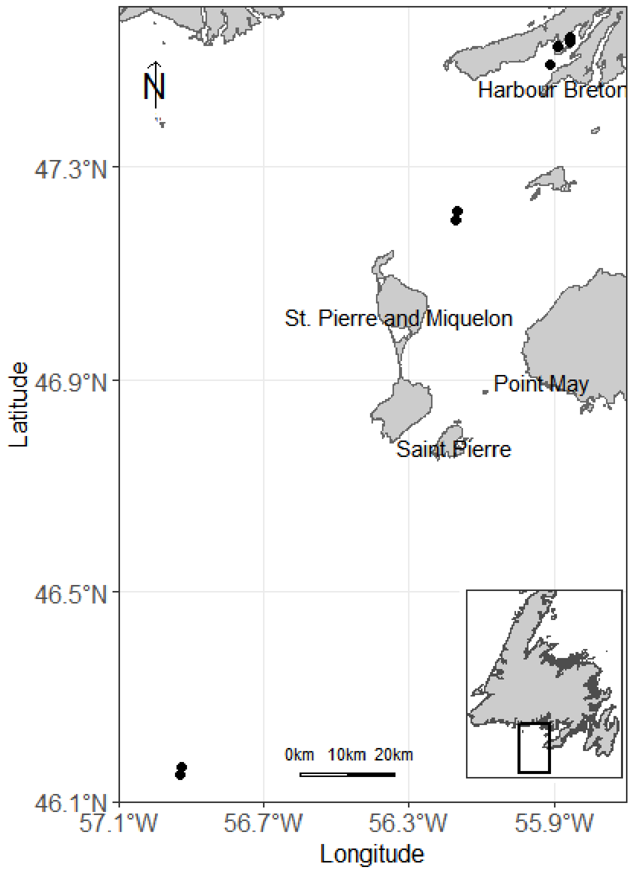

Figure 6.3. Location of sampling sites in the south coast of Newfoundland. The rectangle on the bottom-right of the figure indicates the sampling site, and the black dots indicate the location of an individual fleet of traps that was deployed during the study.

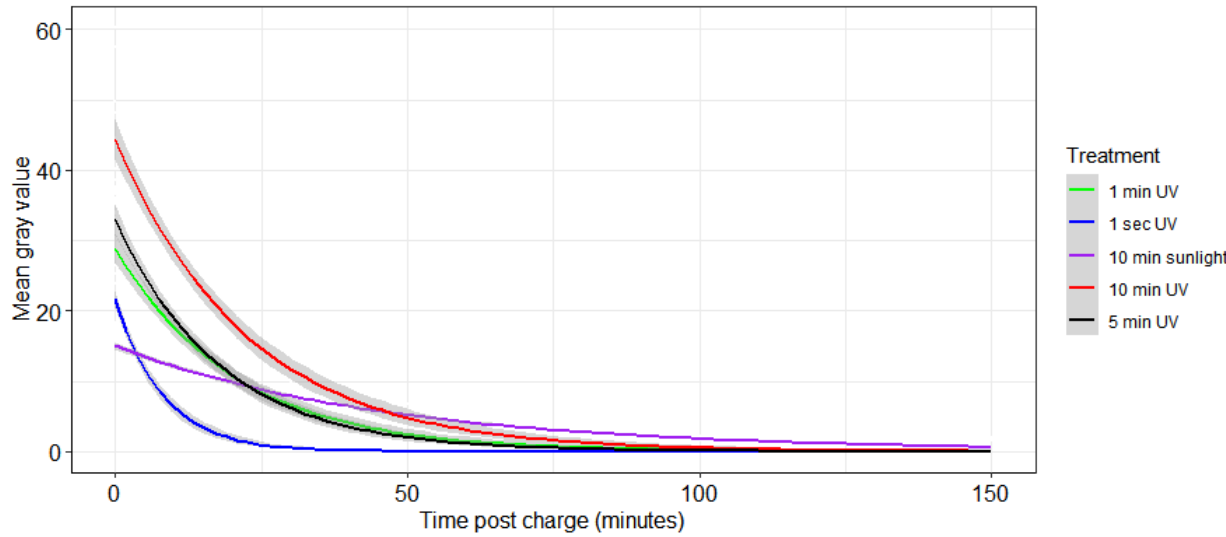

Figure 6.4. Relationship between light intensity (mean gray value) and time post charge for the different charge treatments. Shaded areas represent 95% confidence intervals.

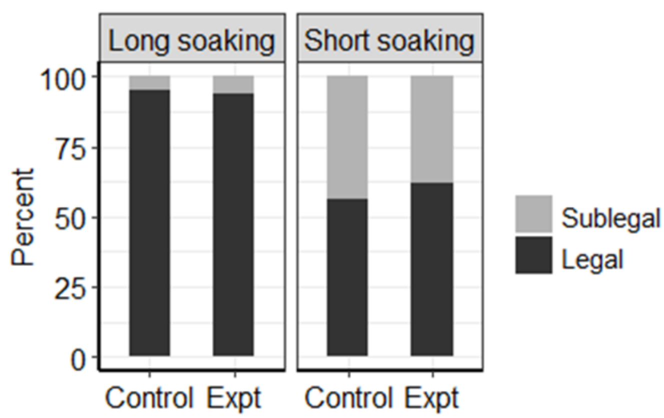

Figure 6.5. The proportion of legal and sublegal-sized crab captured by the control and experimental (Exp.) traps at different soaking levels.

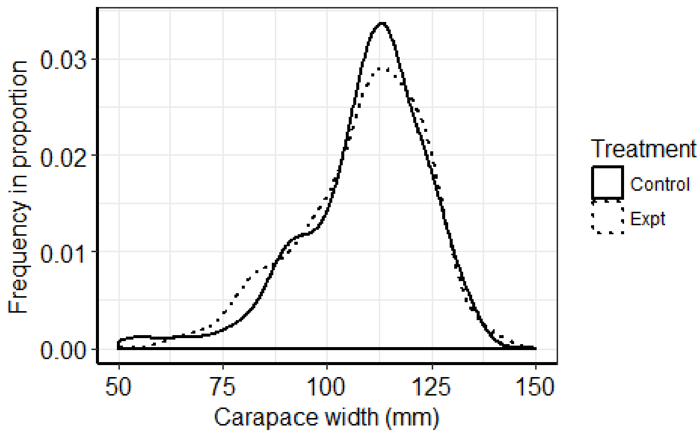

Figure 6.6. CW frequency distribution of male crab captured by the control and experimental (Expt.) traps.

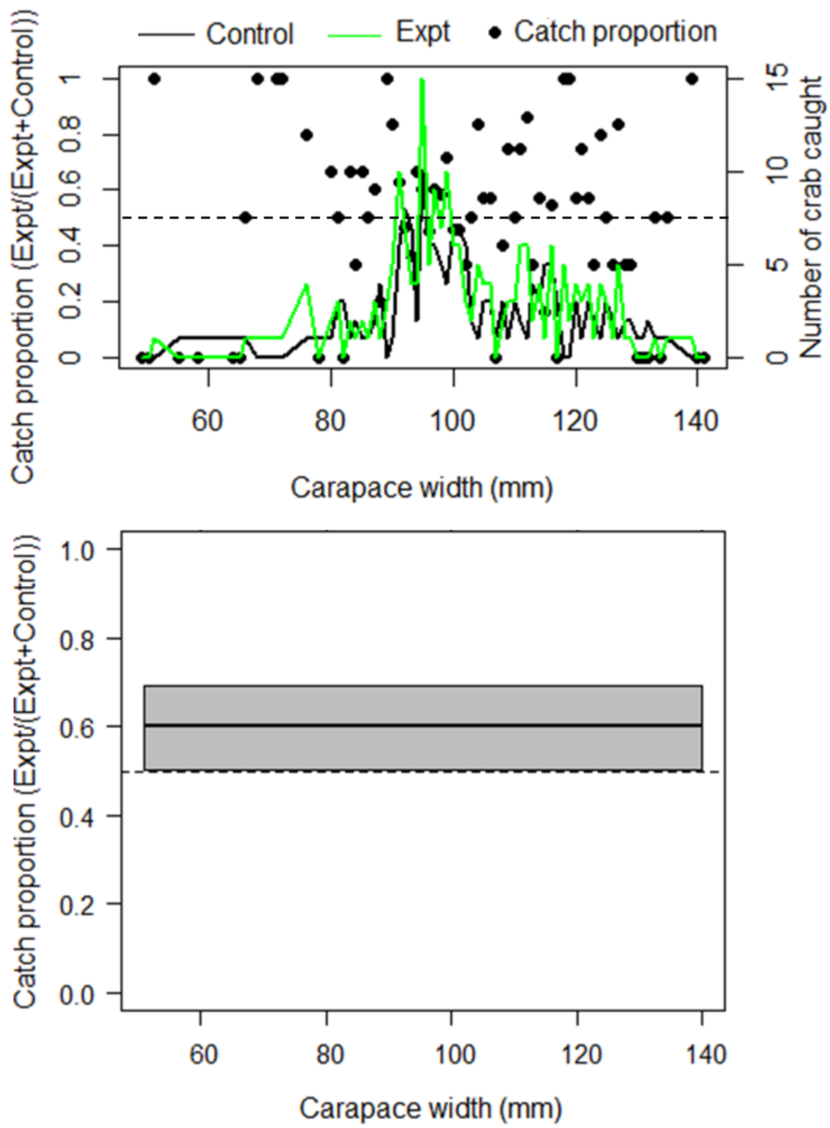

Figure 6.7. Pooled length frequency curves (top panel) and observed proportion for snow crab caught by luminescent traps and control traps. Expt is the experimental trap. GLMM-modeled proportions of the number of crab in each length class. The horizontal dot line at 0.5 indicates an even split between glow in the dark trap and control trap. Lower values indicate that fewer crab at a given length were caught in the glow in the dark traps than in the control traps, and vice versa. While the thick black line represents the modeled means, the gray shaded areas indicate the 95% confident regions.

Table 6.1. Summary details for the comparative fishing experiment. Expt is experimental trap, Ctr is control (traditional) trap.

Vessel name	Vessel length (m)	Location	Fishing site	Fleet deployment	Expt trap	Ctr trap
F/V Trusty	12.0	Harbour Breton	Inshore	4	20	20
F/V Paula Charlene	11.9	Hermitage	Inshore	2	20	20
F/V Another Girl	10.4	Harbour Breton	Offshore	2	20	20

Table 6.2. Pairwise post-hoc comparison of the different experimental treatments using Tukey's HSD method.

Treatment comparison	Estimate	t-value	95%CI	p-value
1 s UV vs.1 min UV	-0.24	-5.94	-0.35-(-0.13)	< 0.001
1 s UV vs. 5 min UV	0.27	6.73	0.16-0.38	< 0.001
1 s UV vs. 10 min UV	0.37	9.11	0.26-0.48	< 0.001
1 s UV vs.10 min sunlight	0.22	5.45	0.11-0.33	< 0.001
1 min UV vs. 5 min UV	0.03	0.79	-0.08-0.14	0.93
1 min UV vs. 10 min UV	0.13	3.17	0.02-0.24	0.01
1 min UV vs. 10 min sunlight	-0.02	-0.49	-0.13-0.09	0.99
5 min UV vs. 10 min UV	-0.10	-2.38	-0.21-0.01	0.12
5 min UV vs. 10 min sunlight	0.05	1.28	-0.06-0.16	0.70
10 min UV vs. 10 min sunlight	0.15	3.66	0.04-0.26	0.002

Table 6.3. Parameters of a log-linear model for different treatments. C and k are the constants represented in equation (1).

Treatment	C	k	t-value	p-value	R^2
1 s UV	21.777	-0.129	0.555	*39.22*	<0.001
1 min UV	33.631	-0.115	0.926	*36.32*	<0.001
5 min UV	37.421	-0.121	0.930	40.24	<0.001
10 min UV	49.446	-0.072	1.145	43.19	<0.001
10 min sunlight	18.955	-0.052	0.5786	32.76	<0.001

Table 6.4. GLMM estimated regression parameters of catch comparison for all data combined.

Fixed effects	**Estimate**	**SE**	**z-value**	**p-value**
Legal-sized crab				
Intercept	2.06	0.43	4.77	<0.001
Experimental trap	0.16	0.08	2.04	0.04
Random factor			**Variance**	**SD**
FleetID			0.50	0.71
Vessel			0.34	0.58
Subegal-sized crab				
Intercept	0.22	0.82	0.27	0.79
Experimental trap	0.04	0.17	0.22	0.82
Random factor			**Variable**	**SD**
FleetID			0.84	0.92
Vessel			1.55	1.25

Table 6.5. GLMM estimated regression parameters of catch comparison of legal-sized crab for different soak times.

Fixed effects	**Estimate**	**SE**	**z-value**	**p-value**
Short soak time				
Intercept	1.43	0.29	5.01	<0.001
Experimental trap	0.44	0.13	3.28	0.001
Random factor			**Variance**	**SD**
FleetID			0.42	0.65
Vessel			<0.001	0.01
Long soak time				
Intercept	3.29	0.10	32.24	<0.001
Experimental trap	-0.04	0.08	-0.51	0.61
Random factor			**Variable**	**SD**
FleetID			0.02	0.12
Vessel			<0.001	0.01

Chapter 7. Summary and Synthesis

In this thesis, I examined the effectiveness of artificial light at improving the catch rate of snow crab traps. The central aim was to enhance the catching performance of a commonly used trap design to contribute to the development of a more profitable, sustainable, and efficient snow crab fishery. This thesis documents the behaviour of snow crab in response to various light sources under laboratory and field conditions. First, I began with a literature review of vision in aquatic marine species and their behaviour in response to artificial light, as well as the application of fishing lights in commercial industrialized fisheries (Chapter 2). Second, I investigated the behaviour and catch rates of snow crab in response to different low-powered LED lights under laboratory and field conditions (Chapter 3). I then examined the effect of installing underwater LED lights in different locations and orientations inside baited traps (Chapter 4). After that, I compared the catch rate of baited and illuminated traps in the Barents Sea during different fishing seasons (Chapter 5). Finally, I examined whether luminescent netting could absorb UV from the different light sources, the resulting duration of intensity, and its application to commercial fishing conditions (Chapter 6). The following sections are an integrated account of the results and conclusions from these five research-based chapters. I also include a discussion on the limitations of the approaches used and future research directions.

7.1. Fish Vision and the Use of Artificial Light in Commercial Fishing Applications

Vision is an important sensory input in the life of many marine animals. Understanding visual characteristics of animals is a necessary step in understanding the capture process and interactions between fish and fishing gear. As many species depend on vision as a sensory means of interaction, further understanding about visual capabilities is warranted when evaluating the performance of fishing gears. The literature review in Chapter 2 showed that there are different eye structures among fish, shrimp, crab, and sea turtles. Functional morphology varies widely across species, producing differences in sensitivity to different wavelengths of light as well as behavioural responses toward light. Each species has an optimal wavelength (i.e., colour) and intensity level where they prefer and aggregate. However, some marine species are able to see at both bright and dim light situations, which has been attributed to the large number of rods and cones (Woodhead, 1966; McFarland, 1986). In addition, 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). Some pelagic fish species can see distances beyond 50 feet (15.2m) under optimal conditions (Woodhead, 1966; McFarland, 1986).

The use of artificial light for attracting and catching animals is a common practice around the world and has been regarded as one of the most advanced, efficient, and successful methods for capturing purposes. Using artificial light in fishing operations as a stimulus source is an advanced technique to attract and aggregate fish and eventually capture them using various fishing gear such as hooks, gill nets, purse seines, beach seines, cast nets or other means that have evolved over thousands of years (Ben-Yami, 1976). 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. As the global demand for seafood products continues to increase, more regulations that aim to protect fishing grounds and maintain sustainable fisheries continue to emerge (Okpala et al., 2017). Chapter 2 demonstrated that the use of artificial light in commercial fishing operations appears to produce both benefits and costs (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. In my judgement, the use of artificial light in commercial industrialized fishing operations is expected to continue growing, particularly with the advent of LED technology and luminescent netting. With this, comes the requisite discussion about ecological/financial trade-offs. Chapter 2 provides a helpful overview of the positive and negative effects that scientists, government, fishermen, and society must consider.

7.2. Improving Catch Rates of Snow Crab Traps Using LED Lights

The findings from Chapter 3, Chapter 4, and Chapter 5 demonstrate the advantages of using low-powered LED lights to improve the catch rate of baited traps. I found that traps equipped with an LED light tended to exhibit higher CPUE compared to identical traps without lights. This was validated across multiple years and locations. However, my results showed that snow crab behaviour in response to LED light varied across different colours and conditions (laboratory or field environment) (Chapter 3). Past investigations on crustaceans are consistent with this conclusion, i.e., mantis shrimp (*Odontodactylus scyllarus*, see Marshall et al., 1996). This result is also similar with squid and other commercial species such as European seabass (*Dicentrarchus labrax*), common grey mullet (*Mugil cephalus*), gilthead seabream (*Sparus auratus*) and striped bream (*Lithognathus mormyrus*) (Marchesan et al., 2005; An et al., 2009).

However, some of my results are not consistent across my experiments. The 2016 fishing experiment conducted in Newfoundland and Labrador demonstrated that both white and purple LED lights increased CPUE of crab compared to control traps, with white light outperforming purple light (Chapter 3). In contrast, the results were opposite in the Barents Sea (Chapter 5), with purple light outperforming white light. In addition, I found that the efficiency of the LED lights was associated with population density (Chapter 5). This suggests that LED lights do not affect the availability of crab, they simply increase the vulnerability of crab in the vicinity of the trap. In other words, LED lights motivated crab to enter pots, but did not appear to attract crab from large distances. This finding is consistent with previous research in which the catch of conical traps was positively correlated with bait weight, but the trap numeric yield would not increase when animal abundance was low (Cyr and Sainte-Marie, 1995). For stationary fishing gear like traps, fishing performance is associated with immersion time (Hébert et al., 2001). Chapter 3 and Chapter 5 demonstrated that CPUE increased with increased soak time, however longer soak times provided greater benefits for the illuminated the traps than baited traps.

My research shows that ‘how’ the LED lights are installed into traps is less important than the light itself, as the results showed there were no differences in CPUE among light position and orientation treatments, while each light treatment produced more crab than the control traps (Chapter 4). Thus, subtle changes in light positioning does not appear to be important. This contrasts with recent work on the west coast of the USA where ocean shrimp are captured by bottom trawls. Attaching LED lights along the fishing line of the trawl significantly reduced a variety of bycatch, while switching the LED light to the headrope had no effect on bycatch reduction (Hannah et al., 2015; Lomeli et al., 2018a; 2018b). These differences highlight that much is unknown regarding the mechanisms determining animal behaviour in response to artificial light, and that there is available room for further research.

Taken together, these Chapters suggest that increasing the catch rates of traps through the use of LED lights could be highly beneficial for the commercial fishing industry. For fishing enterprises, using LED lights to increase CPUE of snow crab traps permits the opportunity to catch individual quotas with greater efficiency. This means potentially fewer days on the water and the possibility of reduced variable cost, thereby improving the financial viability of thousands of small owner-operated businesses. Several studies have already demonstrated the economic benefits of using artificial light in other fisheries (Matsushita et al., 2012; O’Neill et al., 2014; An et al., 2017). These studies have shown that a key challenge in adopting artificial lights is the financial burden of the initial capital investment. Higher catch rates would, however balance this additional cost, with fishing enterprises eventually achieving a return on investment and thereafter increased profit.

7.3. An Alternative to LED Lights – Luminescent Netting

Chapter 6 demonstrated that traps equipped with luminescent netting exhibited increased CPUE, suggesting it could be a possible substitute for more expensive products, such as LED lights. These findings are novel, and to my knowledge have not been previously reported. I found that the light intensity of the luminescent netting decreased exponentially over time. Therefore, luminescent traps could improve catch rates of snow crab over short durations, resulting in luminescent traps catching more crab than the control traps when soak times are short (i.e., 24 hours), with decreasing benefits when traps are soaked for longer periods. Interestingly, I found that luminescent traps exposed to natural sunlight produced a lower initial intensity, but they provided longer light emission compared to traps charged with UV lights. This chapter suggests the potential application of luminescent netting as a method to improve the catch rate of the existing trap design in the snow crab fishery. This could have several advantages over LED lights, including lower capital investment, suitability for small-scale fisheries, convenient deployment, less labour requirement during setting/hauling, and reduced environmental impact (i.e., no batteries or plastic production).

7.4. Limitations of My Approach

I wish to recognize that my thesis is not without limitations. Several major limitations in experimental design and data collection were identified throughout this thesis. For this reason, the results should be considered preliminary in some cases and interpreted with caution.

The first limitation relates to my literature review of fish vision (Chapter 2). Knowing the structure and function of the eye can help inform researchers on the likely response of animals to light. Unfortunately, Chapter 2 reviewed almost nothing about crustacean eyes including snow crab, despite its significant economic value to the east coast of Canada and the Barents Sea. For this reason, I recommend the preparation of an annotated bibliography of all literature related to decapod crab vision, snow crab eye dissection (i.e., gross morphology using scanning electron microscopy (SEM), light microscope dissections, and histological dissections), and analysis of the light absorption characteristics (called microspectrophotometry) of pigments located in the eye's photoreceptors. A second limitation of this Chapter relates to artificial light in commercial industrialized fisheries. It was my effort to synthesize all reports, research projects, and scientific papers with different languages and published sources. Although I have tried to review all available literature, I could not review literature without English in the text or abstract. Therefore, perhaps I missed some important research or findings that was reported and published in other languages such as Russian, Japanese, Korean, French, and Chinese. This limitation may limit our knowledge about the global application of underwater light.

There were limitations related to my sampling methods as well. All field experiments were conducted onboard commercial fishing vessels. Although skippers and crews were very kind and cooperative, some variables could not be controlled, and produced some biases that might affect my conclusions. For example, although quantity and type of bait, trap and fleet intervals were standardized and identified within a vessel, these factors still varied across the fishing vessels. In addition, bait was kept in a perforated plastic jar for experiments in Chapter 3, while it was directly hung in the entrance of the trap using a snap shackle for experiments in Chapter 4 and Chapter 6. Whereas, bait bags made of polyethylene netting were used in Chapter 5. In addition, traps were dropped and retrieved haphazardly depending on the weather (Chapter 3, Chapter 4, and Chapter 6). For this reason, if further studies are undertaken, it is recommended to standardize soak times, sample sizes of each treatment, and fishing techniques. This will reduce variability, improve statistical inference, create better estimates, and create an understanding as to how traps with artificial light actually perform compared to traditional traps.

Small sample sizes in some experiments are another limitation of my thesis. Most experiments were deployed with an adequate number of replicates, i.e., Chapter 4, Chapter 5, and the laboratory experiment of Chapter 3 and 6, but I recognize that Field Experiment II in Chapter 3 and the field experiment in Chapter 6 had limited replicates. This produced large standard errors and variation throughout my results. In cases where uncertainty was noted, it always mentioned and documented for the reader.

This thesis has not been designed to assess the negative effect of artificial light on ecosystem and environment. Potential for negative trade-offs may exist in situations where underwater light is used, especially the challenge of marine litter. For example, just roughly speaking, in order to equip approximately 4.6 million traps around the province of Newfoundland and Labrador with a single low-powered LED light (57.6 g), this would constitute placing 265 tonnes of plastic in the ocean. Some of this plastic will be lost when traps are unintentionally lost at sea. 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.

The exact mechanism behind the effect of artificial light on snow crab behaviour remains unknown at the present time. Many marine species are known to be attracted to artificial light, but variation in behavioural response can be high and in many cases it remains difficult to predict behaviour patterns (Ben-Yami, 1976). A common understanding is that animals are simply attracted to the light (Ben-Yami, 1976). However, for other species the mechanism could be more complicated. In some cases, fish appear to be attracted to the light to feed on prey which are themselves attracted by the light (Ben-Yami, 1976; Marchesan et al., 2005; Bryhn et al., 2014; Utne-Palm et al., 2018). It could also be possible that lights better enable animals to see structure or refuge in an otherwise barren landscape. Or perhaps underwater lights help individual animals identify conspecifics already inside a baited pot, thereby encouraging entry through social facilitation (Winger et al., 2016). Or perhaps underwater lights simply help crab detect pot entrances. Furthermore, the percent of crab that actually entered the trap when approaching the trap was not measured and remains unclear. Substantial studies have demonstrated that numerous fish were observed to make unsuccessful entry attempts when approaching the entrance of a trap (Bryhn et al., 2014; Meintzer et al., 2018). More detailed studies, including the use of underwater cameras, are recommended to better understand the behaviour of snow crab and further improve the effectiveness of using lights as a supplemental stimuli for fishing gears.

7.5. Recommendations for Further Research

How to use underwater lights to improve the efficiency and selectivity of fishing gear remains a key research agenda. As part of this thesis, several gaps and obstacles in existing knowledge were identified. For this reason, I offer the following list of research questions for further investigation in order to support sustainable development of the snow crab fishery in the North Atlantic, in particular Newfoundland and Labrador and the Barents Sea.

Crab vision and behaviour in response to artificial light:

1) Determine the spectral absorption of the pigments located in the photoreceptors of the snow crab eye. This task is important because finding the ideal light colour to attract snow crab is probably best achieved by studying the pigments in the eye itself, rather than trial and error. This technique has been successfully used for other marine species, i.e., Japanese flying squid (*Todarodes pacificus*), shrimp (*Haptosquilla trispinosa*), and fish (Sillman et al., 1990; Cronin et al., 2001; Frank et al., 2012; Matsui et al., 2016).
2) The lack of knowledge on the structure, function, or evolution of the eye of the snow crab makes it difficult to understand functional explanations for how and

why snow crab respond to underwater light and colour. Therefore, I recommend that the eye of snow crab be thoroughly documented, including gross morphology using scanning electron microscopy (SEM), light microscope dissections, and histological dissections.

3) Investigate the behaviour of snow crab in response to underwater light *in situ*. Use of an underwater camera capable of observing crab in deep/dark waters will help to identify the mechanism behind increased CPUE of illuminated traps.
4) Conduct underwater camera observations to evaluate snow crab behaviour in response to artificial light, and estimate the light effectiveness area, and likelihood of a crab encountering the light.

Increase catch rate:

5) My research has demonstrated that artificial light improves the catch rate of traps, however other novel (yet untested) stimuli may still exist. Several studies have documented that animals produce sound when feeding, and that this sound attracts other animals in the vicinity. I recommend additional research on the feeding sounds of snow crab, both in the laboratory and the field, to determine if this sound can be used to attract snow crab.
6) Expand the field experiment in Chapter 6 to evaluate the effect of luminescent traps on the catch rate of snow crab. This would involve instrumentation capable of "seeing in the dark" – what intensity level is necessary to attract snow crab?

7) Evaluate factors affecting the catch rate of snow crab with low-powered lights. This includes optimal light intensity, optimal soak time, and distance between traps.

Extend the application of artificial light to other fisheries:

8) Studies have demonstrated that traps equipped with LED lights exhibit increased CPUE for Atlantic cod (Bryhn et al., 2014; Humborstad et al., 2018). This work was conducted in Sweden and Norway, respectively. Given the recent rise of cod potting in Newfoundland and Labrador (Meintzer et al., 2018), I recommend research to determine if artificial light could be helpful in improving CPUE for fishing enterprises in this province.
9) Studies have also demonstrated that artificial lights can be used to reduce the bycatch of finfish while targeting ocean shrimp off the coast of Oregon, USA (Hannah et al., 2015; Lomeli et al., 2018a). Could these results be transferrable to trawl fisheries in eastern Canada? I recommend a study to investigate the effectiveness of underwater lights at reducing capelin bycatch in the Northern shrimp trawl fishery off Newfoundland and Labrador.

Technology improvement:

10) Development of new underwater light technologies that could improve chromatic performance, longer operational batteries or rechargeable batteries, and biodegradable plastic should be encouraged. This could improve affordability for fishing enterprises with reduced environmental impact.

11) The luminescent netting tested in this thesis contained a certain percentage of luminescent fibers. Could additional fibers be added, and if so, how might this affect the cost of production and fishing performance at sea?

Economic analysis:

12) I recommend an economic analysis (e.g., business case) be conducted on the use of artificial light by fishing enterprises targeting snow crab in eastern Canada and the Barents Sea. This will help individual companies make informed decisions about whether the capital investment is right for their business.

7.6. Conclusions

This thesis examined the effectiveness of using artificial light to improve the catch rate of baited traps in eastern Canada and the Barents Sea. I conducted both laboratory and field experiments under different contexts and in different environments. The research is both novel and innovative. To the best of my knowledge, this is the first scientific investigation conducted on the behaviour of snow crab in response to artificial light, as well as using artificial light in commercial snow crab fishing operations. The results indicate that equipping baited traps with artificial light can significantly improve the catch rate. These are promising and encouraging results. For fishing enterprises, using artificial light to increase the catch rate of snow crab traps permits the opportunity to catch individual quotas with greater efficiency. This means potentially fewer days on the water and the possibility of reduced variable costs, thereby improving the financial viability of thousands of small owner-operated businesses.

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