Visual Modeling Approach to Assess Fishing Gear Efficiency and Visual Capacity of Snow Crab (*Chionoecetes opilio*): A Case Study on Luminescent-netting Pots in Commercial Fisheries

by

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A thesis submitted to the

School of Graduate Studies in Partial Fulfillment of the Requirements for the

degree of

Master of Science in Fisheries Science and Technology

School of Fisheries

Fisheries and Marine Institute

Memorial University of Newfoundland

November 2023

St. John's Newfoundland and Labrador

This thesis is dedicated to my dad, Calvin Frank,

the inspiration for my work ethic, intellectual curiosity, and love of the sea.

Abstract

This thesis explored the visual capabilities of snow crab (*Chionoecetes opilio*) and their interactions with luminescent-netting pots to better understand the role of light intensity during capture. I compared three experimental luminescent-netting pots with increasing brightness to the traditional non-luminescent pots used in the Newfoundland and Labrador snow crab fishery. First, I developed a visual model for snow crab by characterizing their visual parameters, the emitted pot light, and environmental factors. I found that the distance that snow crab can see the light from the pots at 200 meter depth (fishing grounds) depends primarily on the solar angle (height of the sun) and the time elapsed after deployment. I then performed field trials, comparing the catch per unit effort (CPUE; number of crab per pot) and size-selectivity (size-based capture) between each pot treatment. Results showed that the lowest light level pot performed better in comparison to other treatments when considering a balance between commercial, management, and environmental concerns, catching more large crab and fewer small crab. In conclusion, this thesis describes how snow crab vision and pot light intensity effect luminescent-netting pot effectiveness and that increasing the light in luminescent-netting pots does not lead to an improved approach.

General Summary

This thesis explored the visual capabilities of snow crab and the effectiveness of luminescent-netting pots in the Newfoundland and Labrador commercial snow crab fishery. I compared three luminescent-netting pots with varying brightness levels to the traditional non-luminescent pot. I then developed a visual model using environmental and biological factors to predict how well snow crab see the pots. Next, I assessed the performance of each pot with field trials. Results showed that the dimmest experimental pots caught slightly fewer legal crab (carapace width ≥ 95 mm) but significantly fewer sub-legal crab (carapace width < 95 mm) than traditional pots. Brighter pots either showed a negative (increased capture of sub-legal snow crab) or non-significant catch differences. This research provides insights into snow crab visual ecology and highlights the potential for manipulating size-based catch rates with light.

Acknowledgements

I have infinite gratitude to my advisor Dr. Shannon Bayse for giving me a chance to prove my abilities. I had an extensive background in the fisheries world but no quantitative experience. Like my lab mates, I had a unique path leading up to this position that many advisors would have ignored. With the unwavering and sometimes unrelenting help of Dr. Bayse, I navigated my way through the modeling and data analysis world. Throughout my time in three different universities, I have witnessed many graduate students who had very little to virtually no access to or help from their advisors; I am appreciative of the environment that Dr. Bayse has fostered, i.e., we all were in our offices roughly 40 hours per week, including Dr. Bayse. That approach was partially influenced by the work ethic and attentiveness the Centre for Sustainable Aquatic Resources (CSAR) department head, Dr. Paul Winger, exhibited each week. Although I knew how important it is to have a solid background in science and networking for my career endeavors, Dr. Paul Winger made me realize how important it is to foster networking relationships for myself and everyone I work with. Dr. Winger's strong family commitment has also left a mark on me as a scientist; he is highly dedicated to his work but balances that with a strong dedication to his family, a dynamic that I often see out of balance when people are passionate about their careers. I am also grateful to all of the CSAR staff and researchers who keep our department running; our department has a group of highly capable people ready to solve hands-on problems, including some of my own, with a plethora of knowledge and experience.

I would also like to thank my lab mates and my Marine Institute grad student cohort for being a great group of researchers to problem-solve with or, just as often, procrastinate with. I am grateful for my labmates (Vang, Sidney, Tomas, Meghan, Rioghnach, and Cameron), who always made time to talk when I needed to vent or laugh. Thanks to Vang, Sidney, Meghan, and Rioghnach for helping me in the field so that I could collect my data.

The Marine Institute (MI) administrators were a fantastic group for which I have so much respect. Through my time as a seminar coordinator, a part-time employee at the MI gym, and a confused graduate student, I received unending support and advice from MI staff; Jennifer Howell, Angie Clarke, Sarah Hiscock, Sonia Ho, and so many others have taken so much time out of their busy schedules to help myself and other graduate students, and for that, I am forever grateful and inspired to be patient and supportive of those that could use my help.

In and out of the university, my friends have helped give me a solid foundation in Newfoundland, 7,000 km from home. In that respect, and at the risk of forgetting someone important, a special thanks to Katja Kochvar, Raul Belenguer, Laura Lozano, Forrest Fractal, Amy Wilson, Abe Solberg, Megan Wiley, and Ana Belen Yanez Suarez for being the kindest friends during my time here in Newfoundland.

Thanks to the Parsons family (Craig, Colleen, Colin, and Corey) and their assistance and flexibility in helping me gather the data I needed for my thesis. Even though at times it was confusing, two to three Colins onboard every trip, they were instrumental in the project, and I hope to run into the crew sometime outside of fisheries. Their boat, the *F/V Four Seas*, had a fifth “C” onboard for two seasons, and I hope to repay the favor in the future.

My financial support came from the Centre for Canadian Fisheries Innovation (CCFI), Ocean Frontier Institute (OFI) Module H.3, SnowMAP, and SINTEF. SnowMAP provided the funds of the netting. SINTEF provided my initial salary, and CCFI funded most of my research and some of my salary. OFI provided most of the funding for my stipend and a portion of my research.

Finally, special thanks to my family for their unconditional support through both my work and academic careers. Their dedication to our family is the only reason I could have made it this far, and I don’t take it lightly. Thanks to my mother (Terra), my father and his wife (Calvin and Charlotte), my brothers (Jesse, Jordan, Cole, Trevor, Terrin, Raven, and Zayden), and all 100 or so of my favorite aunts, uncles, grandparents, and cousins who were always there for me one way or another.

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Abbreviations and Symbols

Abbreviations

AMO = Atlantic Multi-Decadal Oscillation
BBL = Benthic Boundary Layer
BIC = Bayesian Information Criteria
CI = Confidence Interval
CMA = Crab Management Area
CPUE = Catch Per Unit Effort
CW = Carapace Width
DFO = Fisheries and Oceans Canada
DOM = Dissolved Organic Matter
GLMM = Generalized Linear-Mixed Model
IQ = Individual Quota
NAFO = Northwest Atlantic Fisheries Organization
TAC = Total Allowable Catch
MP = Megapixel

Symbols

q = Photons
I = Relative Intensity
D = Facet diameter
R = Local radius of curvature of the eye
$\Delta\phi$ = Interommatidial angle
O = Height of pot (smallest dimension of pot)
Φ = Photon flux ($q \cdot s^{-1}$)
L = Irradiance ($q \cdot s^{-1}\ m^{-2}$)
Ω = Solid angle (sr)
A = Area (m^2)
K = Diffuse attenuation coefficient (m^{-1})
P = Proportion of glowing twine to empty space in pot area (from side view)
d = Distance between snow crab eye and pot (m)
f = Photosensitivity function
C = Michelson contrast
α = Power
S = Shape

Indices

t = time (initiation of decay)
g = glowing pot
b = background
sc = snow crab eye

Co-authorship Statement

CRediT author statement (Contributor Roles Taxonomy)

Chapter 2

I intend to submit this chapter to the journal *Fishes* under the Special Issue entitled "Advances in Crab Fisheries."

Colin Frank: Conceptualization, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Shannon Bayse**: Conceptualization, Methodology, Validation, Formal analysis, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Pierre-Paul Bitton**: Conceptualization, Methodology, Validation, Formal analysis, Resources. **Rioghnach Steiner**: Investigation.

Chapter 3

Published in *Aquaculture and Fisheries* (In Press).

https://doi.org/10.1016/j.aaf.2023.08.001

Colin Frank: Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Shannon Bayse**: Conceptualization, Methodology, Validation, Formal analysis, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Chapter 1. General Introduction

The most economically important fishery in the Newfoundland and Labrador province of Canada is the commercial snow crab (*Chionoecetes opilio*) fishery. In 2021, it boasted $883 million of a $1.64 billion seafood sector in a province long heralded for its prominent fishing industry and culture (Davis, 2015; FFA, 2021). This has not always been the case, as the region was home to a large Atlantic cod (*Gadus morhua*) fishery that gave Newfoundland and Labrador this reputation. The economic potential of the cod fishery fueled an expansion throughout the 1960s and ‘70s, from small inshore fisheries to large offshore enterprises, helping the province compete with seafood markets on a global scale (Davis & Korneski, 2012). However, the infamous decimation of the cod stock throughout the 1980s and early ’90s left an entire province reeling. The cod moratorium in 1992 was a devastating and sobering response to the state of the economically essential groundfish stocks. Starting *tabula rasa* was not an option for many for economic, family, or cultural reasons, so a scramble for another fishery ensued (Davis, 2015). Several smaller, less profitable fisheries were used as supplemental income for local fishers until, to oversimplify a complex and tumultuous decade, snow crab took front and center in the following years. Davis and Korneski (2012) and Davis (2015) recount how Newfoundland came to rely on the cod fishery, its eventual collapse, and the rise of the inshore and offshore snow crab fisheries.

Since its inception as the most prominent fishery in Atlantic Canada in 2004 (Pinfold, 2006), the snow crab fishery in Newfoundland has experienced a cyclical trend in exploitable biomass, increasing and decreasing for several years. This trend is strongly tied to bottom water temperature, which fluctuates on a large scale, according to the Atlantic multi-decadal oscillation (AMO), a phasic atmospheric phenomenon that strongly influences sea surface temperatures in the North Atlantic (DFO, 2022; Mullowney et al., 2014). Periods of warm water temperature result in low survival for post-settlement recruits. The warm water causes a reduction in exploitable biomass, observed after 7-10 years when the impacted recruits are legal-sized (Boudreau et al., 2011). This relationship helps scientists predict snow crab population trends in the coming years and how that might affect management decisions, such as the annual total allowable catch (TAC) (DFO, 2022; Mullowney et al., 2020). Today, exploitable snow crab biomass is in good standing, allowing managers to increase the overall TAC by 8.4% to 54,727 tonnes in 2023 (DFO, 2023). This positive trend is met with some caution as coastal Newfoundland waters have been warmer recently, leading to an expectation from scientists of a downward trend in the coming years (DFO, 2022).

Fisheries and Oceans Canada (DFO) is the Canadian government department responsible for the policies surrounding the Newfoundland snow crab fishery. It employs a suite of management tools in the Newfoundland and Labrador snow crab fishery to help keep a sustainable population. The fishery is managed within Northwest Atlantic Fisheries Organization (NAFO) divisions, sub-divisions, and crab management areas (CMA), allowing for spatial quota allocation and local area openings and closures (DFO, 2022). Effort controls fall in line with other "responsible fisheries" and consist of pot limits, individual quotas (IQ), trip limits, and seasonal openings (DFO, 2022; Pope, 2002). Commercial fishers can retain only hard-shell males with a carapace width (CW) of 95 mm or greater. Small males (CW < 95 mm), softshell males, and all females are less desirable in the seafood market and are discarded at sea to help maintain a sustainable snow crab population (Conan & Comeau, 1986; DFO, 2022; Sainte-Marie et al., 1995). Minimum mesh size requirements (135 mm) aid in size selectivity for larger snow crab, reducing incidental discard mortality of smaller crab. Females reach maturity and terminal molt at smaller sizes (47-95 mm) than males (50-150 mm), which helps improve size selectivity for larger males (Elner & Beninger, 1992).

The Newfoundland snow crab fishery, like most pot fisheries, has little negative environmental impact when compared to other fisheries around the world (Petetta et al., 2021; Suuronen et al., 2012; Ziegler et al., 2021). Commercial pot fishing, compared to trawling, generally requires less fuel use as a passive fishery, has less impact on the seafloor, allows for better selectivity for target species, and results in increased survival of discarded bycatch (Parker et al., 2018; Suuronen et al., 2012). For these reasons, commercial pot fishing is often considered an environmentally responsible alternative to many other commercial fisheries (Petetta et al., 2021; Suuronen et al., 2012).

Problems in the fishery exist and can be more difficult to observe and measure than bycatch or fuel use; ghost fishing, whale entanglements, and inefficient bait sourcing are the most significant problems plaguing many commercial pot fisheries. Ghost gear can cause an auto-baiting scenario where animals are trapped in pots, eventually die, and rebait the pot when decomposing, attracting more animals (Lively & Good, 2019; Maselko et al., 2013; Thomsen et al., 2010). Whale entanglements are at the forefront of problems in the Newfoundland snow crab fishery as the endangered North Atlantic Right Whales are expected to expand their territory further within Newfoundland waters (Durette-Morin et al., 2022) along with the already commonly entangled Humpback whales (Benjamins et al., 2012; SAI Global, 2018). Additionally, squid (*Illex spp.*) is commonly used as bait in the Newfoundland snow crab fishery and many other passive gear fisheries. Industrial trawlers with large resource requirements are often necessary to supply the demand for bait across passive gear fisheries, with the commercial snow crab fisheries being no exception (Araya-Schmidt et al., 2019; Cerbule et al., 2023; Driscoll & Chan, 2022).

Management, researchers, and industry are searching for solutions to each problem. To help mitigate ghost fishing, biodegradable twine was implemented in the Newfoundland snow crab fishery in 2013 (Winger et al., 2015). The biodegradable twine either replaces the industry standard twine in a section of the pot or can be used to attach escape devices. When the twine is submerged for an extended period, it degrades, creating a large hole and allowing the trapped crab to escape. Whale entanglements are still an issue in pot fisheries, but there are significant international efforts to track problematic fisheries and reduce the likelihood of entanglement (Lebon & Kelly, 2019; Myers et al., 2019). Like whale entanglements, the baiting system in pot fisheries is still a largely unresolved issue (Driscoll & Chan, 2022). However, recent explorations into alternative baits, such as repurposed fish processing waste and other potentially more sustainable bait sources, for snow crab fisheries have promising results and may help increase overall sustainability (Araya-Schmidt et al., 2019; Cerbule et al., 2023; Zhou, 2021).

The Newfoundland and Labrador snow crab fishery also struggles with maintaining sustainable snow crab populations (Mullowney et al., 2021a). The highly selective nature of the fishery can result in low reproductive health of the population if fishing mortality is too high (Baker et al., 2022; Hebert et al., 2001). The fishery aims to reduce the bycatch of non-legal snow crab, helping improve stock health and reproductive potential with lower numbers of discards and, therefore, lower discard mortality (DFO, 2022; Mullowney et al., 2021a). Improving the catch efficiency of pots, i.e., catching a higher proportion of target crab to bycatch, would help mitigate this problem and result in a healthier and more sustainable fishery (Zhou & Kruse, 2000). Scientists and managers highlight the need for increased catch efficiency for the health of snow crab populations (DFO, 2022; Murawski, 2005) while the industry wants the same, but for economic feasibility within a volatile market (Anders et al., 2023; Pinfold, 2006).

With fluctuating market prices for snow crab and increasing prices for the resources and gear required to operate commercial fishing vessels (i.e., bait, fuel, pots, etc.), it is difficult to maintain economic sustainability as a fisher in commercial snow crab fisheries (Cerbule et al., 2023; Murray & Ings, 2015; Pinfold, 2006). New innovative gear technologies are being tested to help increase catch rates and reduce the fuel and bait needed to catch IQs (e.g., Cerbule et al., 2021; Nguyen et al., 2017). Higher catch rates of target-sized snow crab would increase the gap between expenditures and profit, allowing snow crab fishers to alleviate financial risk during difficult years and maximize profit during times of high exploitable biomass. Incidentally, reducing the amount of fuel and bait required to harvest the same amount of snow crab would substantially decrease the carbon footprint of the fishery, both directly from the fuel needed for the snow crab fishery and indirectly from the fuel required to catch bait for the fishery (Bayse et al., 2021). Increased catch rates would also allow fishers to fill their IQs earlier in the season before the summer months, when softshell snow crab are most active (DFO, 2022; Mullowney et al., 2021a), thereby reducing the amount of softshell snow crab bycatch and presumed fishing mortality.

There are several methods by which researchers and industry attempt to increase catch rates in snow crab fisheries, using alternative baits, improving pot designs, and, most recently, the use of light. Light in fisheries is not new, dating back centuries from when coastal peoples used beach fires to attract fish to shallow waters, where they would surround and drive the fish onto the beach (Arimoto et al., 2010; Yami, 1976). With scientific and technological advances, light use has become more specialized in its application, adjusting the color, intensity, and pattern to attract or deter animals in fisheries (Nguyen & Winger, 2019a). In Newfoundland, researchers incorporated green LED lights into pots designed for the flatfish fishery. They found that when bait and LED lights were present, there was a 70% increase in snow crab bycatch compared to baited pots without lights (Murphy, 2014). This finding eventually fueled interest in using various forms of light to increase catch rates in snow crab fisheries in Newfoundland, Alaska, and the Barents Sea (e.g., Cerbule et al., 2021; Nguyen et al., 2017, 2019; pers. comm. Dr. Noëlle Yochum, NOAA).

In a commercial setting, there is a considerable effort and cost in using LED lights per pot, making the technology less attractive to commercial snow crab fishers. In recent years, approximately 4-6 million pots have been used annually in the Newfoundland and Labrador snow crab fishery (Mullowney et al., 2021). While some CMAs have a limit of 1200 pots per license, in the 3K inshore 3A area, each license is allowed 150-300 pots (Dawe et al., 2021); at $65 per LED system (Nguyen et al., 2019), the total additional cost per vessel in this area would be $9,750 -$19,500. However, Euronete created a product called Euroglow, a netting in which phosphorescent fibers are woven within standard polyethylene twine. This netting is fitted onto a snow crab pot, requiring no additional effort from the fishers and a small extra cost per pot ($10 CAD in 2019; Nguyen et al., 2020). Following the same exercise above, at $10 per pot, the total additional cost per vessel to purchase luminescent-netting would be $1,500-$3,000, saving fishers $8,250-$16,500 for the initial implementation of the gear compared to LEDs. Unlike LED lights, the light emitted from the phosphorescent twine rapidly diminishes to a dim green, only visible in dark environments. Regardless of this limitation, the luminescent pots increased catch rates by 55% with one-day soak times in the first luminescent pot study (Nguyen et al., 2019) and 21.6% with six-day soak times in the second study (Nguyen et al., 2020). There are cheaper LED options available with some research on their effectiveness within the fishery, e.g., FishTekMarine PotLights used by Cerbule et al. (2021). However, the battery requirements and maintenance of the lights are still a significant issue within the potential commercial-scale application of the technology; new or newly charged batteries need to replace old batteries, increasing operation time, cost-effectiveness, energy requirements, and potential for pollution.

Light use in the underwater environment requires careful consideration to ensure minimal behavioral disruption within the local ecosystem while also achieving the goals of the fishery. Using artificial light in fishing gear manipulates the behavior of animals using their visual system, whether to attract or deter the animal, increasing catch rates or decreasing bycatch (Arimoto et al., 2010; Yami, 1976). Complex behaviors are also possible where an increase in catch rates of an animal is from following its prey, which is attracted to the light (Humborstad et al., 2018), or better behavioral flexibility when using visual cues rather than chemical cues (Stiansen et al., 2010). The behavioral changes that artificial light may induce on intended and unintended species could be difficult to observe or interpret and should be approached responsibly (Blackmore et al., 2021). Low-powered LEDs and phosphorescent light in snow crab fisheries are examples of limiting light intensity while attempting to increase catch rates.

To promote responsible practices in fisheries, scientists can assess the potential impact of light on marine life by considering factors such as the intensity of illumination in the area and its duration. This approach enables scientists to utilize more efficient lighting systems that allow for wavelength, intensity, and pattern adjustments so as to not produce more light than is necessary while still achieving the desired results, i.e., increased catch rates, decreased bycatch, etc. These modifications could help fishers influence specific species' behavior while minimizing adverse effects on others (Blackmore et al., 2021).

The visual capabilities of marine animals has generated a lot of research over recent decades (Herring et al., 1990; Land & Nilsson, 2012; Nicol, 1989). Researchers can develop models that facilitate the interpretation and prediction of animal behavior by determining or reasonably estimating key visual parameters like acuity, optokinetic response, and spectral sensitivities (Bitton et al., 2017). Such modeling efforts have been undertaken for many types of animals, such as fish, birds, frogs, and insects, to understand better how they interact with their environment (Bitton et al., 2017; Nilsson et al., 2014; Willink et al., 2014). Visual modeling has also been applied to fishing gear bycatch mitigation for seabirds (Cocking et al., 2008) and the perception of towed fishing gear in respect to fish (Kim & Wardle, 1998). Applying visual modeling techniques to study snow crab vision in the context of luminescent-netting pots could provide valuable insights into the mechanisms behind increased catch rates and inform future research on gear design. However, a visual model does not necessarily answer if and why animals are affected by artificial light; this hypothesis would ideally be tested using resource-prohibitive high-resolution spatial data or camera technology (see section 4.2.4). Without such technology, researchers can leverage the knowledge gained from a visual model, combined with catch rates and size-selectivity data, to improve the efficiency of snow crab harvesting, increase catch rates, or minimize environmental disturbances caused by fishing activities.

To my knowledge, this study is the first to use a visual modeling approach to investigate fishing gear efficiency concerning crustaceans. Similarly, this is the first study to measure and estimate the visual parameters of snow crab. Using visual modeling, I predict the distance and duration in which snow crab can see three treatments of luminescent-netting pots, each with different light intensities, through visual modeling. “Distance” is the furthest distance that snow crab can see the light from the pots and “duration” is the length of time the light is visible at different distances. I incorporate water quality, time of day, and turbidity to highlight the ever-changing conditions that govern visibility in the underwater environment. I then test the fishing gears in a commercial snow crab fishery setting, modeling target male, undersized male, and softshell male catch rates and the size-selectivity of each treatment.

Chapter 2. Snow crab (*Chionoecetes opilio*) vision: the sighting distance and duration of luminescent-netting pots

2.1 Abstract

This thesis chapter investigates the visual capabilities of snow crab (*Chionoecetes opilio*) in relation to their interactions with luminescent-netting pots used in commercial snow crab fisheries. Light from snow crab pots can increase catch per unit effort, but there is little known about what motivates or attracts snow crab to enter pots with lights at higher rates. In this study, I begin answering this question by determining the sighting distance (maximum visible distance) and duration (time visible after deployment) of luminescent pots. To achieve this, I characterized the light emitted from the pots, determined the abiotic factors that influence vision in the ocean, and estimated the visual capabilities of snow crab, including acuity, contrast sensitivity, and spectral sensitivity. Based on these visual capabilities and the abiotic factors of the fishing environment, I modeled the photon flux and Michelson contrast ratio of the pots in snow crab eyes. Results indicate the distance that snow crab can see the light from the pots at a 200 meter depth, depends primarily on the solar angle (height of the sun) and the time elapsed after deployment. The light intensity from the phosphorescent twine decays exponentially, significantly reducing the distance that the gear is visible to snow crab over time. These findings provide important insights into the visual ecology of snow crab and can inform the development of more effective fishing gears that improve catch efficiency and promote sustainability. This study is the first to describe the visual ecology of snow crab, an internationally important fisheries species.

2.2 Introduction

The commercial snow crab fishery is Newfoundland and Labrador's most economically important fishery, bringing over $883 million to the province in a $1.64 billion industry sector (FFA, 2021). However, as Mullowney et al. (2021a) attest, sustainably managing the fishery does not come without substantial difficulties. The bycatch of animals other than snow crab is not a significant issue in this fishery, so management focuses on minimizing non-marketable snow crab (soft-shell, undersized, and female), all of which must be discarded at sea (DFO, 2022). The Newfoundland snow crab fishery currently uses gear (pots) that is designed to be size-selective, minimizing the catch of female and undersized male snow crab by controlling mesh size (DFO, 2022). Thus, small individuals can escape through the mesh while the larger crab are unable to and are retained. However, the bycatch of soft-shell snow crab, too large to escape through the mesh, can only be mitigated through effort controls, such as area and fishery closures. Reducing soft-shell snow crab bycatch is essential, as it can sometimes comprise more than 50% of the total catch, while 15-20% is generally needed to close an area to fishing (DFO, 2022; Mullowney et al., 2021a). Discarding snow crab contributes to fishing mortality and harms the snow crab population by reducing current and future spawning stock biomass and, in effect, recruitment (DFO, 2022). Reducing the total bycatch and discards while maintaining comparable landings would help fishers and would assist management in maintaining sustainability (Nguyen and Winger, 2019a).

Although regulating mesh size proves to be effective at removing female and undersized snow crab (carapace width, CW < 95 mm), the average soak time in the Newfoundland and Labrador snow crab fishery is three to five days (Mullowney et al., 2020), while the optimal soak time allowing undersized snow crab to escape is around nine days (Olsen et al., 2019a).

Controlling soak time from a management perspective is challenging to enforce. The disjunction between optimal soak time for the fishery and optimal soak time for undersized crab escapement highlights the need for an additional gear design if the fishery wishes to improve catch efficiency by increasing catch per unit effort (CPUE) and decreasing bycatch.

The governing body that manages snow crab fisheries in Newfoundland and Labrador, Fisheries and Oceans Canada (DFO), employs a proactive strategy to minimize bycatch of soft-shell snow crab by starting the fishing season in the spring when the soft-shell snow crab catch-to-target ratio is at its lowest (DFO, 2022). This timeline allows researchers and the industry to help minimize soft-shell catches by improving catch efficiency. However, individual quotas are often not met until summer, when the soft-shell catch ratio increases (Mullowney et al., 2021a). Increasing the CPUE may fill individual quotas before soft-shell catches dramatically increase. Additionally, a higher CPUE potentially reduces fishing time at sea, cutting fuel costs, carbon footprints, and opportunities for work-related injuries (Nguyen et al., 2017).

There have been many attempts to create a more efficient pot in global snow crab fisheries (e.g., Cerbule et al., 2022; Olsen et al., 2019b; Winger & Walsh, 2011). Most new pot designs focus on changing the shape, the escape opening size/shape, or the entrance of the pot (e.g., Cerbule et al., 2022; Olsen et al., 2019b; Anders et al., 2023). Recently, changes employed the use of light in conjunction with bait to create an additional form of positive taxis (Nguyen et al., 2017, 2019) in theory. Positive and negative taxis are the stimulation of an organism and their subsequent behavior towards that stimulation, positive meaning to attract and negative meaning to repulse. Fishers have historically used bait (squid, fish, etc.) as the means to attract crab to pots, initiating a dynamic behavior between chemotaxis and rheotaxis, or attraction through chemical means and against the current, respectively (Weissburg & Zimmer-Faust, 1994; Zimmer-Faust et al., 1995). In the case of chemotaxis, crab are only attracted to the pot if they initially come into contact with the chemicals (bait plume), which is subject to ocean currents and diminishes over time and distance (Weissburg & Zimmer-Faust, 1994). When another form of positive taxis is used, such as light or sound (phototaxis or phonotaxis), an even dispersion of stimuli is projected from the pot in all directions, potentially attracting crab without being subject to currents (Nguyen & Winger, 2019a). Thus far, the two forms of light explored in the snow crab fishery are light-emitting diodes (LEDs) and phosphorescence (Nguyen et al., 2017, 2019), both light forms proved to increase CPUE. LEDs are currently too expensive to use on a commercial scale due to the combination of the cost of the lights, the batteries, and the replacement of lost components while fishing. Replacing dead or dying batteries with new or newly charged batteries also adds to the fishing time and may increase marine litter. Conversely, purchasing phosphorescent netting for a pot is cheaper than purchasing and maintaining LEDs for industry-standard netting, and it recharges within minutes of sunlight exposure (Nguyen et al., 2019). In those regions where sunlight is seasonally limited (e.g., Alaska and Norway), there is the option to quickly charge the netting using ultra-violet (UV) lights (Nguyen et al., 2019). However, using UV lights does add to the cost and complications of using luminescent-netting pots.

Recent advances in phosphorescent technology have led to various applications in the last two decades (Anesh et al., 2014). Historically, sulfide-based phosphorescence was the most common source of industrial glowing material. It is known to be a low-intensity and quickly dissipating light source, severely limiting its potential. However, in 1996, Europium and Dysprosium (Eu^{2+} and Dy^{3+}) rare-earth element doped strontium aluminate emerged as a glowing contender that widely expanded the possible use of luminous material. The new phosphorescent material is roughly ten times brighter and lasts fifty times longer than commercial sulfur-based phosphorescence (Matsuzawa et al., 1996). Using UV light, Fouzar et al. (2021) found that the charge time of strontium aluminate, depending on its exact composition is generally less than 10 seconds and decreases with cold temperatures, with greater than 90% of a full charge within milliseconds of UV exposure when at 14 °C. Other elements can be used with strontium aluminate with varying degrees of light intensity and decay (Fouzar et al., 2021; Rojas-Hernandez et al., 2018).

In this study, I use pots with strontium aluminate-based phosphorescent twine (often referred to as luminescent pots), as they are currently the most economically feasible method of using light commercially. The drawback to using phosphorescence in pots is when removed from a high-intensity light source (UV, sunlight), the emitted light intensity exponentially decreases, as opposed to the long-lasting LEDs (Nguyen et al., 2019). My goal in this study is to understand the visual abilities of snow crab and how they perceive luminescent pots in commercially relevant depths, water qualities, and distances. Once the limitations of the gear is known, in respect to snow crab vision, the efficiency can be maximized to (i.e., choose the best pot) to increase CPUE or catch efficiency.

To understand how snow crab may see luminescent pots, it is important to understand how abiotic factors influence vision in the ocean: depth, water quality, distance from the object, ambient light, and and phosphorescent duration (light intensity over time). Fortunately, these are all well-studied variables of which we can make reasonable assumptions and develop ranges for each (Aas et al., 2013; Cronin et al., 2014; Jerlov, 1968). However, it is also important to understand the visual capabilities of snow crab (acuity, spectral sensitivity, and contrast threshold), and no studies, to my knowledge, that provide such information. This data deficit does not make it impossible to make predictions because there have been many vision studies on different species of crustaceans (Caves et al., 2016; Cronin & Forward, 1988; Cronin et al., 2014).

In this study, I aim to understand the visual capabilities of snow crab, in general, and concerning luminescent pots. To understand those interactions and capabilities, I (1) characterize the light emitted from the phosphorescent material in the pots (intensity and decay); (2) determine the abiotic characteristics of the relevant fishing environment (ambient light, water quality, depth, and turbidity); (3) determine the likely visual abilities of snow crab (acuity, contrast sensitivity, and spectral sensitivity); and (4) model the photon flux and Michelson contrast ratio of luminescent pots in snow crab eyes given the results from objectives 1-3.

2.3 Materials and methods

2.3.1 Experiment setup and data collection

I used three different intensities of luminescent netting, each manufactured by Euronete (Euronete company, Maia, Portugal). All three treatment types (2-strand, 4-strand, and 6-strand) had a different number of phosphorescent fibers woven in with standard polyethylene strands. The first and dimmest treatment has only two glowing strands and is also the only netting that is commercially available for snow crab pots. The second and third treatments are woven with four and six glowing strands, respectively. All pots were Japanese-style conical pots with a bottom diameter of 102 cm, top diameter of 55.5 cm, height of 44 cm, and mesh size of 135 mm.

To determine the spectral irradiance from the twine, I glued twine from each treatment to individual cardboard discs (radii = 5.0 cm) in a tight spiral pattern to create 100% coverage on each disc. There were five replicates per treatment, and each replicate's light was measured three times. Discs were placed in a sunlit environment for at least one hour before measurements were taken. They were quickly taken to a dark room one disc at a time and placed in a fixed location. Next, I used the Ocean Optics QE Pro spectrometer (Ocean Insight, Orlando, FL, USA) to measure the relative and absolute irradiance of the glowing twine across the visible spectrum (400 – 700 nm). The QE Pro spectrometer is designed for low light applications because of its minimized noise (signal to noise ratio 1000:1), high optical resolution (~1.2nm), and wide range of wavelengths (~185-1100nm). Relative irradiance is the measure of power across the electromagnetic spectrum and can be helpful when comparing the light intensity of different sources or when interested in the spectral curve of an object or light-source. Absolute irradiance is more challenging to obtain and is the measure of the number of photons emitted at each wavelength from an object or light-source, thoroughly describing its spectral characteristics. The cosign corrector CC-3-UV-S was used for absolute irradiance measurements, and the spectrometer was calibrated using the Ocean Optics DH-3P-CAL. While relative irradiance measurements were taken for all treatments, absolute irradiance was only taken for the brightest treatment, 6-strand. It was extrapolated for 2- and 4-strand treatments using the results from the relative irradiance measurements. If the relative irradiance of the 4-strand is 50% of the 6-strand, then the absolute irradiance of the 6-strand would be multiplied by 0.50 and assumed to be the absolute irradiance of the 4-strand. I used five replicates of 6-strand twine to measure the decay rate by taking relative irradiance measurements with 5 min integration times for 60 min. Because the phosphorescent twine is the same material in each treatment, I assumed the decay rate of 2- and 4-strand treatments were the same as the 6-strand treatment given that they are composed of the same materials; the decay rate is influenced by the composition and temperature of the material and not the quantity of material. After taking light measurements, the distance between the disk and the receiver was measured and recorded.

2.3.2 Light data analysis

I first collected the data from the spectrometer using OceanView software, a product of Ocean Insight. The spectral data were then analyzed using R software (R Core Team, 2022) and pavo, a spectral analysis package (Maia et al., 2019). The absolute brightness of the 6-strand treatment was initially measured in $\mu W/cm^2/nm$ with a 5 min integration time but was converted to photons/m^2/nm/s by using (((irradiance x 10^{-6}) x 10^4) / 300) x wavelength x 5.05 x 10^{15} (Johnsen, 2012). Relative irradiance measurements from each replicate were averaged. From the relative irradiance measurements, absolute values were then calculated for the two other treatments, 4- and 2-strand. Correction factors for the distance from the receiver to the disc were implemented using SACALC 3.14 software (Whitcher, 2012) (settings in Appendix A).

The light decay was modeled using a standard power law decay function (Eq. 1) previously used in strontium aluminate studies (Eftimov et al., 2021; Fouzar et al., 2021). Parameters were fitted to the measured decay data using a negative log-likelihood function and the *optim()* function. Because phosphorescent material performance is temperature dependent, and measurements were taken at room temperature (~21 °C), adjustments to the decay function and the initial intensity were implemented to match the fishing location (see below) temperatures 0 – 2 °C (Deyoung & Sanderson, 1995). I modeled the effect of temperature (*t*) on the initial intensity (*I*), the shape (*S*), and the power (α) parameters at 0 °C using extrapolated data from Fouzar et al. (2021, Fig. 7b) (Appendix B).

$$I_t = S \cdot t^{-\alpha} \quad (1)$$

2.3.3 Ambient light intensity and the spectral curve

In this study, I used the Jerlov water quality classification system (Jerlov, 1968), first described for oceanic water and then expanded to productive coastal waters. The system describes the irradiance transmissibility of different water types. The water types are in order from clear to turbid: Jerlov I, IA, IB, II, III, 1C, 3C, 5C, 7C, and 9C (Solonenko & Mobley, 2015). The snow crab fishery that takes place in Conception Bay, Newfoundland and Labrador, Canada, was used as an example location for measurements (Lat: 47.5850, Long: -53.2134). Water quality estimates in this region range between Jerlov I and 1C waters (Pepin et al., 2017; Solonenko & Mobley, 2015). Therefore, I used Jerlov I, III, and 1C water qualities to predict the scattering and absorption properties of coastal and oceanic Newfoundland waters. Ambient light values (horizontal radiance) for Jerlov water types I and III at 200 m (109 fms) deep were used from published data (Nilsson et al., 2014) and converted into irradiance by multiplying by pi (Johnsen, 2012; Santon et al., 2020). The spectral curve for Jerlov type I waters at 200 m was estimated from measurements by Johnsen et al. (2004). However, spectral curves for Jerlov type III and 1C waters are not known and were instead estimated using diffuse attenuation coefficients (Solonenko & Mobley, 2015) and surface light data derived from SMARTS v2.9.5 Fortran code (Gueymard, 2019) (settings in Appendix A). All ambient light measurements were taken at the equivalent of 14:00 on April 18, 2022 (solar angle ≈ 55.5°), near solar noon with clear skies, a typical start date of the local fishery. To model how the time of day affects the snow crab's ability to see the luminescent pots, I determined the proportion of light available beyond solar noon according to the solar angle at each hour before sunset (14:00-20:00) and adjusted the ambient light accordingly (Johnsen, 2012). The models do not account for the constantly changing solar angle; the viewing time of the pots would be longer than the models predict when the sun is setting and shorter when rising.

2.3.4 Spectral sensitivity

To my knowledge, the spectral sensitivity of snow crab has not been documented. However, most crabs have a single visual pigment in rhabdoms 1-7, which follows a standard sensitivity distribution with a maximum between 473 nm (blue) and 515 nm (green) (Cronin & Forward, 1988). Although many shallow-water crustaceans have a rhabdom eight that can detect UV light, this area of research is lacking. In this study, I assume snow crab are monochromatic and do not differentiate color. When focusing on crabs more closely related to snow crab or have similar life histories, a sensitivity of roughly 495 nm is the most likely maximum spectral sensitivity of snow crab (Cronin & Forward, 1988; Marshall et al., 1999; Marshall et al., 2003). Following recommendations from previous research (Cronin & Forward, 1988; Dawis, 1981), I chose to model the snow crab spectral sensitivity to a general sensitivity function for vitamin A_1-based visual pigments, Dartnall's nomogram (Dartnall, 1953). To incorporate Dartnall's nomogram, a by-hand measuring tool, into the model, I used a polynomial function (Eq. 2) to describe snow crab spectral sensitivity (Dawis, 1981). The function describes the log absorption coefficient (B) per wavelength (λ) using peak absorption of vitamin A_1-based visual pigments (L_{max}) and the estimated snow crab spectral shift in peak absorption (λ_{max}).

$$B(\lambda) = \sum_{k=1}^{8} b_k [\left(\frac{L_{max}}{\lambda}\right) - \left(\frac{L_{max}}{\lambda_{max}}\right)]^k \quad (2)$$

L_{max} = 502 nm (for Dartnall's nomogram)
b_1 = -0.0106836
b_2 = -28.28
b_3 = 148.133
b_4 = -498.627
b_5 = -1457.94

$b_6 = 127994.4$
$b_7 = -789.371$
$b_8 = -60749.2$
$\lambda_{max} = 495$nm
$B(\lambda) = \log_{10}$ (absorption coefficient per wavelength)

2.3.5 Contrast sensitivity (Michelson contrast)

I used a Michelson contrast sensitivity function to determine if snow crab could distinguish the phosphorescent twine from ambient light (Eq. 9). I chose to use Michelson contrast because it is more appropriate when modeling vision of patterns within an object, as the light from around the patterns can obscure the image (Cronin et al., 2014). I also chose a range of minimum contrast thresholds (high = 0.10, medium = 0.15, low = 0.20) in which snow crab could likely distinguish the phosphorescent light from ambient light. I selected a threshold range because the contrast sensitivity of snow crab is unknown. However, based on research studying the contrast sensitivities of decapods, this range (0.10 to 0.20) is an appropriate approximation for a low-light environment (Drerup and How, 2021). The Michelson contrast ratio ranges from 0 to 1. The further the contrast value is from 0, the more likely the object is visible, with the minimum contrast threshold being the point at first detection. Contrast thresholds are not a static number and vary with ambient light and temperature (Douglas & Hawryshyn, 1990), which is especially important when considering animals that migrate between shallow and deep water. However, I only consider a single range because I assume a static fishing environment at 200 m.

2.3.6 Acuity

To estimate snow crab visual acuity, I removed the left and right eyes from three commercially legal adult male snow crab (CW ≥ 95 mm) during the Newfoundland commercial fishing season. I did not sample soft, female, or undersized male snow crab because they are bycatch and must be discarded at sea (DFO, 2022). I immediately placed the eyes in 10% neutral buffered formalin. I took images of the eyes under a dissecting microscope and measured interommatidial distance, roughly the diameter of each facet, with ImageJ software (Schneider et al., 2012). I selected seven locations across the eye for measurements due to varying facet sizes: forward distal, forward middle, forward proximal, middle middle, middle proximal, rear distal, and rear middle (Figure 2.1A). Distal and proximal are named according to the eyestalk's attachment site. Fifteen measurements were taken per location per eye and were averaged across individuals. Using ImageJ, circles were fitted to the images to determine local area curvature (Baldwin-Fergus et al., 2015; Caves et al., 2016). Using Equation 3, I determined the distance that the light from the pot may fall on a single ommatidium, becoming a point source of light and becoming more complex than the model allows. I determined the limitations of the model (before an object becomes a point source) by determining the interommatidial angles in all seven regions of the snow crab eye; to achieve this, I divided the interommatidial distance ($\Delta\phi$) by the radius of the local area curvature of the eye (R). Next, I divided the smallest measurement of the commercial pot (height = O = 440 mm) and solved for the distance (d). This method results in a best-case scenario and may slightly overestimate visual acuity. However, it is an acceptable alternative for acuity estimation without additional physiological studies determining snow crab eyes' focal length, acceptance angles, and presence or absence of neural pooling (Feller et al., 2021; Nilsson & Ro, 1994). Lastly, I used the R package AcuityView (Caves & Johnsen, 2018) to help visualize the spatial resolution of snow crab when viewing a luminescent pot from several distances. A photograph of the 6-strand pot was taken using a 12MP camera and was resized to a resolution of 2048 x 2048 pixels for processing. Only the highest acuity estimate was used when predicting the resolution of the pots.

$$\Delta\o = D/R = O/d \text{ (Land \& Nilsson, 2012)} \tag{3}$$

2.3.7 Light from the pot area

To estimate the total light from the pot, I added the light from the twine to the horizontal ambient light from the space between the twine. I achieved this by using ImageJ to quantify the proportion of the pot area composed of twine when viewed horizontally(P). I multiplied the phosphorescent twine measurements (L_{gt}) by the proportion of twine coverage in Eq. 4. Then, I applied diffuse attenuation coefficients per wavelength per meter (e^{-Kd}) to estimate light loss due to scattering and absorption for each water type (Solonenko & Mobley, 2015). The space between the twine (1 - P) was then multiplied by the background irradiance (L_{bz}) (Eq. 5), known as veiling light (Partridge, 1990), and added to Eq. 4 as the total irradiance from the pot area (Johnsen, 2012; Santon, 2020).

$$L_{gt} \times e^{-Kd} \times P \tag{4}$$

$$L_{bz} \times (1 - P) \tag{5}$$

2.3.8 Solid angle

I account for the size and distance of the pot by converting it to a solid angle. Solid angles, measured in steradians, are dimensionless units that I included in the model to adjust for the apparent decrease in the size of the pot to the surrounding environment. By definition, solid angle of the pot decreases exponentially as the distance from the snow crab eye increases and vice versa (Johnsen, 2012). The solid angle (Ω_g) is equal to the area of the pot as seen from the side (A_g) divided by the distance squared (d^2) from the snow crab eye to the pot (Eq. 6).

$$\Omega_g = \frac{A_g}{d^2} \tag{6}$$

2.3.9 Photon flux

Combining the measurements from equations 1-2 and 4-6, along with the area of the snow crab eye in m^2 (A_{sc}), and the sensitivity function (f), I modeled the total photon flux(Φ), that is, the amount of light reaching the retina of a snow crab (Eq. 7). Using the same values and equations, I modeled the background photon flux (Eq. 8). I used both photon flux measurements, Φ_{gt} and Φ_{bz}, to determine the Michelson contrast (C) (Eq. 9).

$$\Phi_{gt} = \left(\left(L_{gt} \times e^{-Kd} \times P \right) + \left(L_{bz} \times (1 - P) \right) \right) \times \Omega_g \times A_{sc} \times f \tag{7}$$

$$\Phi_{bz} = \left(L_b \times (1 - P) \right) \times \Omega_g \times A_{sc} \times f \tag{8}$$

$$C = \frac{\Phi_{gt} - \Phi_{bz}}{\Phi_{gt} + \Phi_{bz}} \tag{9}$$

2.3.10 Turbidity in the benthic boundary layer

I estimated the impact of benthic boundary layer (BBL) turbidity on the visual models in Jerlov type III waters, as it most accurately represents coastal Newfoundland (Pepin et al., 2017). To estimate the effect of turbidity, I maintained the ambient light level value at a solar angle of 8.6° and changed diffuse attenuation coefficients (K in Eq. 7) from the phosphorescent twine to match turbid waters (Jerlov 3C = medium turbidity, Jerlov 9C = high turbidity). In effect, the ambient light level is maintained, but the light from the pot does not travel as far in moments or areas of increased turbidity in the BBL.

2.4 Results

2.4.1 Phosphorescent twine characteristics

The visible spectrum in all three treatment groups follows the same distribution and peaks at 523 nm (green). Light intensity at this wavelength jumps 2.3-fold from 2-strand to 4-strand twine, while it only increases an additional 1.8-fold from 4-strand to 6-strand twine, totaling about a 4.2-fold increase in intensity from 2-strand to 6-strand twine (Figure 2.2).

Photon emission of 6-strand twine in 21 °C totaled 2.7×10^{13} q/m^2/s across all wavelengths, between 400 – 700 nm, and binned to 1 nm. When I apply the absolute intensity of the 6-strand to the relative measurements of 4-strand and 2-strand twine, I obtain 1.5×10^{13} q/m^2/s, and 6.4×10^{12} q/m^2/s, respectively. The peak wavelength in the absolute intensity measurement was the same as the relative measurements (523 nm). At the peak wavelength, 6-, 4-, and 2-strand light emission was 3.7×10^{11}, 2.1×10^{11}, and 9.6×10^{10} q/m^2/s (Figure 2.3).

The decay model changes dramatically according to temperature. At room temperature (about 21 °C), S and α equal 1.06 and 1.16. At 0 °C, S and α are 0.55 and 0.83. The initial intensity of light emitted by the pots at 0 °C is 55% that of the light emitted at 21 °C (Figure 2.4A) but decays slower (Figure 2.4B). Models are asymptotical and never reach zero.

2.4.2 Snow crab acuity measurements

Acuity results vary across the snow crab eye, with the greatest resolution in the forward-facing and middle parts of the eye (Table 2.1). The distal portions of the eye had the worst acuity as there was more curvature in these measured locations. Although the rear-facing ommatidia had the largest facets, acuity was moderate because the curvature is slight. The AcuityViewproduced images (Figure 2.5) illustrate the limitations of snow crab acuity as blurry light sources begin to dissipate and blend with the background using the highest acuity values.

2.4.3 Contrast of phosphorescent light in different water types

The models estimate that light from all three phosphorescent pot treatments is not distinguishable from ambient light to snow crab at 200 m in clear oceanic water during the minimum solar zenith. However, in coastal waters (Jerlov III and 1C), the light from the luminescent pots becomes increasingly visible as the number of phosphorescent strands within the twine increases (Figure 2.6). Turbidity models from Jerlov III waters show that increased turbidity affects the sighting distance (distance that the light from the pot is visible) more than it does the decay (Figure 2.7), changing the y-intercept (distance) while the x-intercept (time) remains relatively unchanged. Lastly, the time-adjusted models show that as the solar angle decreases in the evening (28.6° to 8.6°; 18:00 to 20:00NT), the distance the light from the pot is visible increases by 5x (5 m to 25 m) and the duration that it is visible increases by about 10x (4 min to 40 min) (Figure 2.8).

2.5 Discussion

2.5.1 Main factors influencing visibility of light from luminescent-netting

The results from this study show that one of the main factors that influences visibility of luminescent pots is the amount of ambient light at depth, which is under constant change, influenced mainly by the solar angle, but is also dependent on water column absorption and scattering properties (Sathyendranath & Platt, 1990; Solonenko & Mobley, 2015). This is all in relation to deployment time, as pot light intensity rapidly decrease once set. However, cloud coverage, wave height and periodicity, suspended sediment, plankton layers, phytoplankton concentration, and anthropogenic light all contribute to an ever-changing underwater light environment (Loew & McFarland, 1990; Nicol, 1989; Sathyendranath & Platt, 1990). The results help us better understand the prominence of solar irradiation at 200 m and its potential on the diurnal behavior of the animals that live in this environment. Though the light at these depths is only a fraction of the solar irradiance at the surface, there is enough light to mask low-intensity light throughout much of the day.

2.5.2 Temperature and its effect on phosphorescent twine

The cold waters of Newfoundland and Labrador reduce the efficiency of strontium aluminate, minimizing the initial intensity by nearly half while only slightly decreasing the decay rate compared to phosphorescent material at room temperature. Studies suggest that the most efficient temperature for strontium aluminate's phosphorescence is 65 °C, which reduces when colder or warmer (Fouzar et al., 2021). The decay function's temperature component would benefit by taking measurements described in the methods (Section 2.3.1) at cold temperatures rather than using extrapolated parameter values from other studies. The parameter values for this decay function deviated from previous studies on strontium aluminate, likely due to mixing the compound within a polymer matrix affecting its absorption and emission properties. Strontium aluminate and polymer composites have significantly reduced light intensity and slower decay rates (Ge et al., 2012; Mishra et al., 2009). Regardless of the accuracy of the cold decay rate, from past studies on phosphorescent material, the same trend would hold, reduced and prolonged light emission compared to the room temperature measurements (Fouzar et al., 2021).

2.5.3 Sustainability of strontium aluminate activators

In terms of material sustainability, factors need to be considered when considering the substances being used within the luminescent-netting. Although strontium aluminate ($SrAl_2O_4$) alone is not composed of uncommon elements, it is only a host material, and an activator is needed to produce long-lasting phosphorescence. Activators can either be rare-earth elements or transition metals, but the most commonly studied in conjunction with strontium aluminate is the activator element Europium (Eu^{2+}) and the co-activator element Dysprosium (Dy^{3+}) (Rojas-Hernandez et al., 2018). These elements are often scarce, and the energy requirements for processing can be high, often leading to high production costs (Chiatti et al., 2021; Rojas-Hernandez et al., 2018). Without knowing the exact activator or co-activator elements used in the luminescent-netting product or the amount of elements needed to create the product, I cannot presume to know the sustainability of the product itself. I can say, however, that this is an active field of study, with new processes being created to improve production and material efficiency (Chiatti et al., 2021; Huang et al., 2023; Yang et al., 2023).

2.5.4 Visibility of luminescent-netting in different conditions

The only commercially available luminescent pot, with the 2-strand twine netting, is hardly visible to snow crab in Newfoundland-type waters (Jerlov III) during peak sunlight hours, significantly limiting the potential benefits of the light emission during this time. The sighting distance is drastically diminished in the evening (20:00; solar angle = 8.6°) when medium or heavy turbidity is simulated in the BBL currents, reaching a maximum of 5 to 10 m and lasting just beyond 30 minutes from initial pot deployment (Figure 2.7). Pots may be deployed after the minimum solar zenith (about mid-day) to increase the contrast between the pots and the ambient light. Setting the pots at dusk would take advantage of the dramatic decrease in ambient light levels while emitting a significant amount of phosphorescent light in later hours, maximizing the contrast between the two light sources. Another way to further increase the contrast is to charge pots using UV lights on the boat before a night deployment. However, I cannot say a higher contrast would catch more crab without knowing why snow crab enter lit pots at higher rates. To the contrary, research performed by our lab suggests that the 4-strand pots outperform the 6-strand pots with a 12% increase in adult male snow crab catch (See Chapter 3), lending to the idea that the attraction of light may be more nuanced than brighter means better.

2.5.5 Snow crab visual characteristics and their environment

Acuity measurements suggest that beyond 27.4 m in the front-facing middle portion of the eye (Table 2.1), the light from luminescent pots will fall on a single ommatidium and become a point source of light. These results show that snow crab have relatively high acuity compared to other crustaceans, likely enabled by their larger size, allowing them to carry large compound eyes. With large compound eyes, snow crab can have large facets for low-light sensitivity and a small interommatidial angle for higher resolution. The model does not go beyond 30 m because point sources of light require additional complexities that are not within the bounds of these models. With that in mind, if a pot were visible beyond this maximum distance as a point source, its visibility would decrease dramatically with increasing distance as the ambient light began taking more space within the single ommatidium. Each ommatidium acts to sample a region of space for average brightness rather than complexity (Cronin et al., 2014). With decreasing brightness in a single ommatidium, the phosphorescent light would eventually be discounted as noise during neural processing (Cronin et al., 2014). The perceived brightness, or radiance, of a light-source is generally conserved in the air or in a vacuum until it becomes a point source, at which it becomes dimmer according to the inverse square law (intensity = 1 / distance^2). Underwater, the inverse square law is compounded by light scattering and absorption (Johnsen, 2012). When crabs enter a defensive "sitting" position, their eyes are generally situated within the orbital space (Figure 2.1B, 2.9, 2.10) to protect them from damage or to appear less conspicuous by tucking in both legs and eyes (Burrows & Horridge, 1968; Su & Lim, 2015). Juvenile snow crab and tanner crab (*Chionoecetes bairdi*) fully or partially bury themselves as a primary defensive response to predators, likely retracting their eyes to remain inconspicuous (Conan et al., 1996; Ottmar et al., 2022). Crabs can still visualize and react to their environment when their eyes are in the orbital space, though many of their ommatidia face either the ground or the body wall. In this position, the dorsal-facing part of the eyes is composed of large ommatidia (Figure 2.10), commonly seen in benthic and pelagic crustaceans with predators or prey that approach from above. The large facets increase light sensitivity for better spotting silhouettes against dim downwelling light (Cronin et al., 2014; Hiller-Adams & Case, 1988). The interommatidial angle is slightly larger in the dorsal-facing part of the eye, reducing the resolving power compared to the forward and middle sections. The increased light sensitivity in the dorsal-facing part of the eye when in a defensive, sitting, or buried position is likely a tactic to scan above for the silhouettes of predators while remaining inconspicuous. In this position, the ability of snow crab to see luminescent-netting pots is likely poor, owing in part to the fewer number of ommatidia scanning the horizon and the increased terrain obstruction when positioned low to the seafloor.

When the eye is not situated in the orbital space, it is elevated; the distal portion is dorsal, and the proximal portion is ventral. As described in this thesis, the front is still front-facing (anteromedial), and the rear is still rear-facing (posterolateral), but both are scanning the horizon instead of facing forward and dorsal. In the elevated position, the distal area of the eye has a thin set of ommatidia with poor resolution that may view directly above. The small interommatidial angle in the middle section of the eye falls in line with other crustaceans that need better vertical spatial resolution, where they can scan the horizon for predators near the seafloor while also looking for their next meal, a potential mate, or see point-source bioluminescence from a greater distance (Cronin et al., 2014; Hiller-Adams & Case, 1988; Nalbach, 1990). This characteristic can be compared to the fiddler crab, *Gelasimus vomeris*, which also lives in a flat environment. Fiddler crabs respond to any object above the horizon as a potential threat, as might snow crab (Smolka & Hemmi, 2009). Above the horizon, fiddler crabs are wary of birds, while snow crab are preyed upon by large fish and marine mammals (DFO, 2022; Mullowney et al., 2014). Snow crab have most of their ommatidia focused on the horizon for better spotting conspecifics and food, while ommatidia facing above spot predators and those below help determine distance of benthic structures or other animals (Smolka & Hemmi, 2009). These areas also have smaller facets compared to the posterolateral area and likely come at the cost of reduced light sensitivity. Because most of the ommatidia are focused on the horizon, and acuity slightly increases from the mediolateral to posterolateral parts of the eye, snow crab can likely see pots the best, with or without light, directly in front of them. However, the increased facet size in the posterolateral sections of the eye allows for greater light sensitivity and may improve the likelihood of snow crab seeing dimly lit pots or other objects from the side. This peripheral light sensitivity is analogous to human vision when a dim object, such as a star, is only visible while focused away from it; the densely packed cones in the *fovea centralis* (focal point on the retina) are not as light-sensitive as the rods in the periphery, allowing human peripheral vision to be better at seeing dim objects in low-light conditions (Tuten & Harmening, 2021).

Supporting these acuity results is the pseudopupil shape (Figures 2.9, 2.10). The pseudopupil in compound eyes appears as if a pupil follows the viewer as they move. The pseudopupil, however, is an illusion where the viewer observes the absence of a reflection (black and pupil-like) from the ommatidia that absorb light from the viewer's position. The perceived size of the pseudopupil is indicative of acuity in that region of the eye from that viewing angle; in general, the larger the pseudopupil, the greater the acuity. The pseudopupil of snow crab is largest across the center and is rectangle-shaped, several dozen ommatidia wide, stretching from the distal to the proximal end of the eye (Figure 2.9). As the viewer orients from the front to the rear-facing portion of the snow crab eye, the rectangular pseudopupil follows without changing shape until near the edges of the ommatidia (personal observations). When the viewer orients from a proximal or distal position, there is only a thin pseudopupil around the edges of the eye. The large pseudopupil of snow crab supports the idea that they have relatively high acuity for compound eyes. The vertical orientation of the large pseudopupil also reinforces the discussion above about the possible vertical resolving power of snow crab.

The distal portion of the eye appears to have screening pigments that fade dorsoventrally (Figure 2.9), as seen in fiddler crabs (Zeil & Hemmi, 2006), suggesting that these screening pigments protect their eyes from stray light. These screening pigments could also allow for a degree of color discrimination in the dorsal part of the eye.

2.5.6 Knowledge gaps

Although small males and females were not sampled in this study, it is reasonable to assume that their eyes are also smaller and, therefore, their acuity is worse (Schweikert et al., 2022). Smaller eyes of the same crustacean species have larger interommatidial angles, leading to worse spatial resolution and distance vision (Hiller-Adams & Case, 1988; Schweikert et al., 2022). Given this information, we can assume that luminescent pots may be visible further for larger snow crab, especially during the initial deployment when light intensity and contrast are at their highest. This assumption is considered in Chapter 3, where size selectivity results were found in luminescent pots.

To my knowledge, this is one of the first published studies on the physical characteristics of snow crab eyes (see Meyers et al., 2022) and the first that estimates their visual capacity. Because of this lack of information on snow crab vision, I must either make assumptions or ignore factors that may affect the models. Additional research that would help inform the understanding of snow crab vision would include but is not limited to understanding the presence or degree of size/sex dependence on visual characteristics, temporal summation, neural superposition, screening pigments, polarization vision, opsin characterization and spectral sensitivity, contrast sensitivity, and dark- vs. light-adapted characteristics. Knowing how snow crab use posturing and eye movement to view their environment would also be beneficial.

Future research into contrast sensitivity could also help us understand how snow crab perceive traditional pots. Because traditional pots have orange, red, or black twine and are 200 m deep in the ocean, pots are likely prominent silhouettes to snow crab during the day, as they would appear dark black against the ambient light. The brighter the ambient light, the higher the contrast of the pots. Thus, at 200 m, snow crab likely use their vision to assist in the capture process during daylight hours with traditional pots. At night, bioluminescent animals may interact with or be near the pot and aid in the capture process. However, in the absence of bioluminescent animals, the crab's other senses are likely used in capture at night. Perhaps luminescent-netting pots increase the visual-system-associated fishing effort from daylight hours to day and night. In that respect, if smaller snow crab are more risk-averse and forage at night more often (Cote et al., 2018), they may encounter luminescent-netting pots more frequently than traditional pots. Conversely, studies show that adult male snow crab move a greater distance than juvenile males and females, increasing their likelihood of encountering and interacting with the light from luminescent-netting pots (Cote et al., 2018; Florko et al., 2021; Maynard & Robichaud, 1986). These are all speculations on snow crab's visual ecology and behavior but could be clarified with additional research into their visual capabilities.

2.5.7 Future applications of visual models within fisheries

The models in this study could predict how other animals perceive their environment, luminescent pots, and other light sources. Parameter values and the model itself would need to be adjusted according to life history (depth, diurnal movement, etc.), typical environment, viewing angle, spectral sensitivity, contrast threshold, light-source size, and acuity. Depending on the species and location, additional factors may be needed. However, this information would help us understand the potential impact on behavior that the light technology could have on non-target animals in the vicinity, particularly at night or in darker environments. This approach provides a path forward in gear innovation while being cognizant of the possible effects on the local environment.

2.6 Tables

Table 2.1 Adult male (carapace width ≥ 95mm) snow crab inter-ommatidial measurements with standard deviations and corresponding acuity-related derivations: D = Distal, M = Middle, P = Proximal. R = Radius of curvature, Δø = Interommatidial angle, U = maximum sighting distance of luminescent pots.

Eyes (n=6)	**Front D.**	**Front M.**	**Front P.**	**Mid D.**	**Mid M.**	**Mid P.**	**Rear D.**	**Rear M.**
Mean (mm)	0.057	0.061	0.060	0.067	0.071	0.059	0.076	0.076
SD (mm)	0.004	0.003	0.003	0.003	0.003	0.004	0.004	0.005
R (mm)	1.2	3.8	2.2	1.5	3.7	1.1	1.2	2.8
Δø (rad)	0.048	0.016	0.027	0.045	0.019	0.054	0.063	0.027
U (m)	9.2	27.4	16.2	9.9	23.1	8.2	7.0	16.3

2.7 Figures

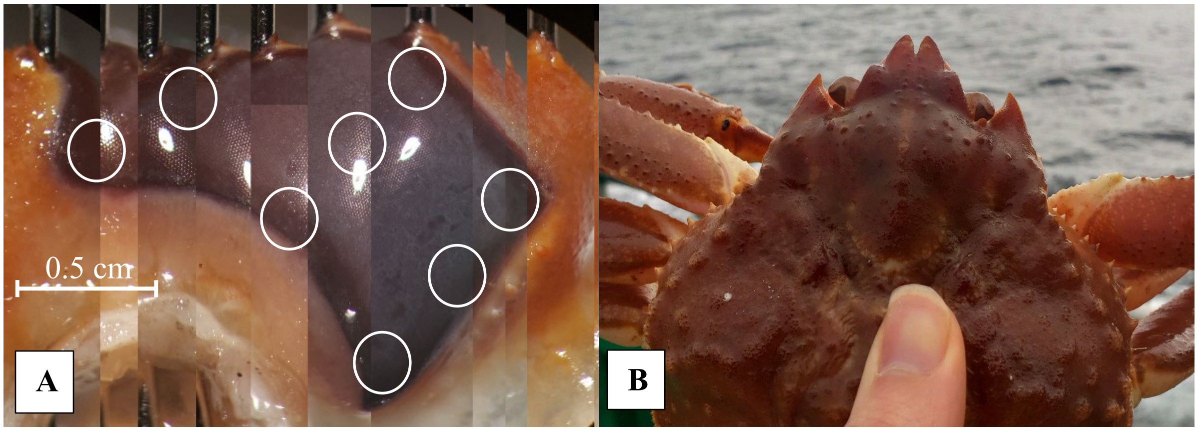

Figure 2.1 A) A composited picture of a snow crab eye under a dissecting microscope. White circles indicate acuity measurement locations. The area on the right is front-facing on a live snow crab, and the left is rear-facing. The bottom is proximal, and the top is distal. B) The rear ommatidia wrap around the back of the eye and face dorsally when the eyestalks are positioned against the body wall, as in the picture, but are facing posterolaterally on the horizon when eyestalks are in the elevated position.

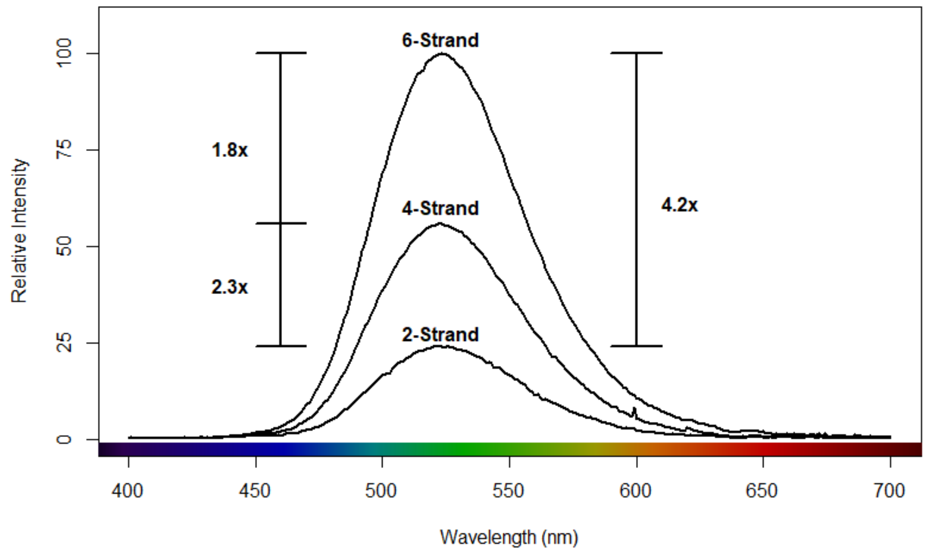

Figure 2.2 Spectral characteristics and the relative light intensities of each treatment (6-, 4-, and 2-strand). All strands peak at 523 nm (green).

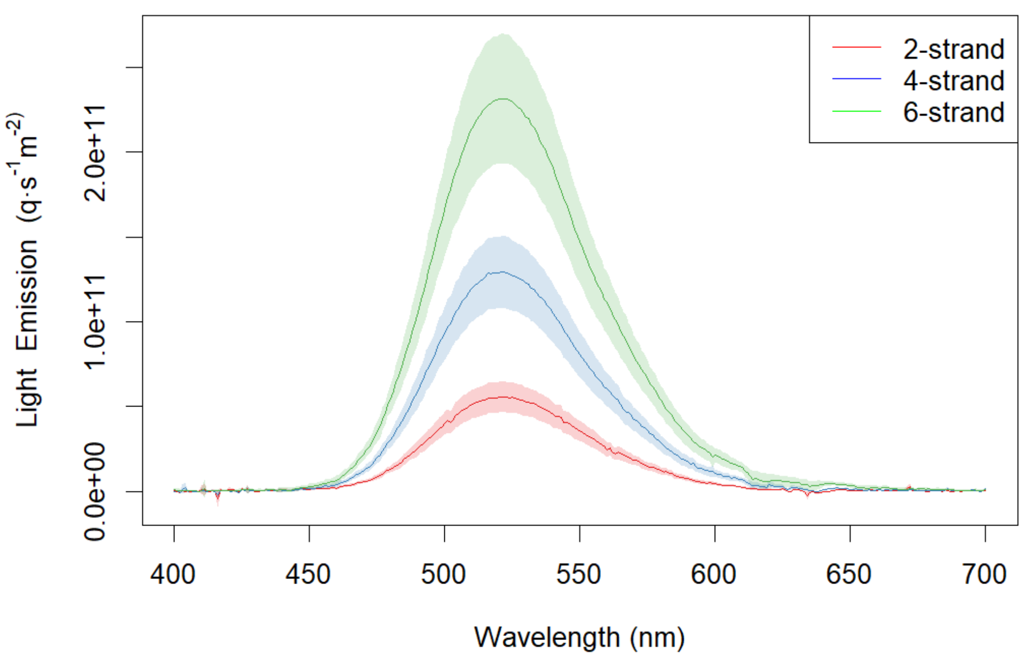

Figure 2.3 Absolute intensity measurements of the 6-strand phosphorescent twine and the extrapolated 4-strand and 2-strand measurements according to relative intensity measurements.

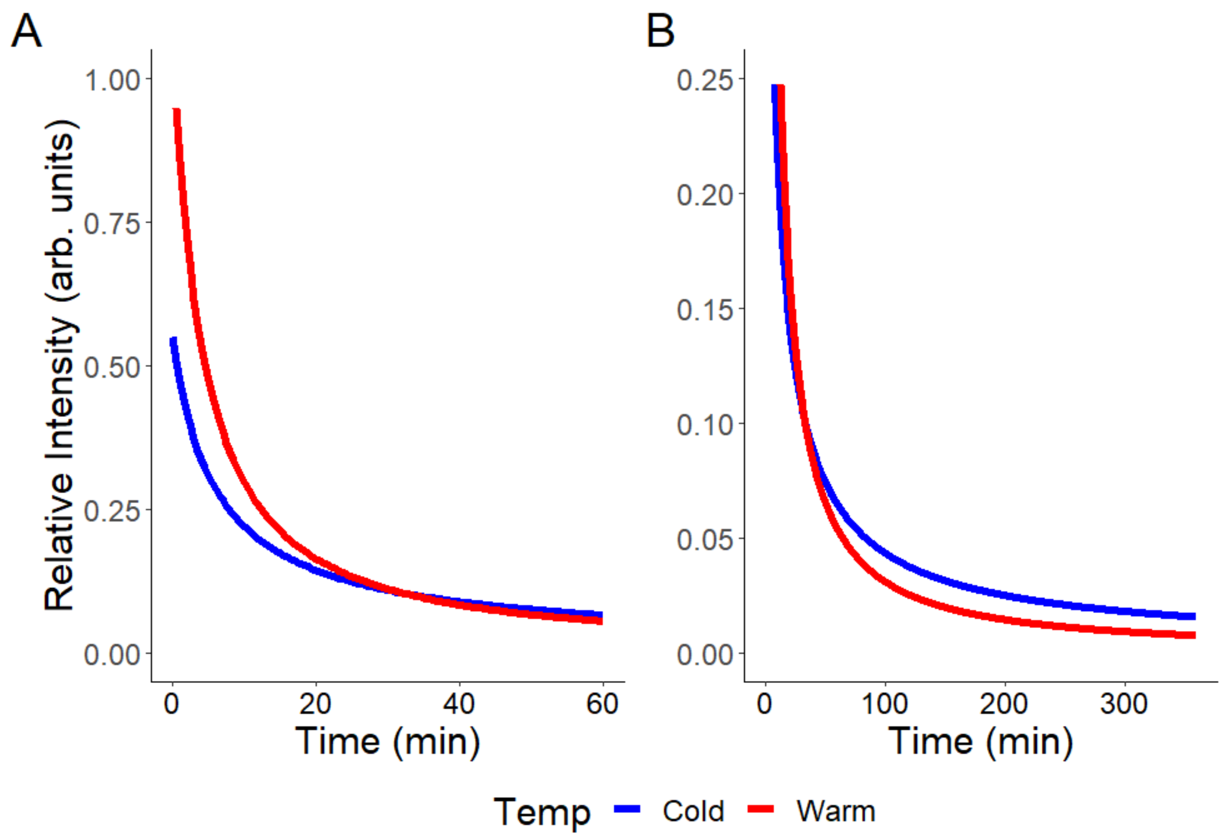

Figure 2.4 The measured decay rate of the phosphorescent twine at 21°C (red) and the estimated decay rate at 0°C (blue). A) One-hour projections highlighting the initial intensities and B) six-hour projections focusing on the long decay. Units are relative to the maximum intensity at 21°C.

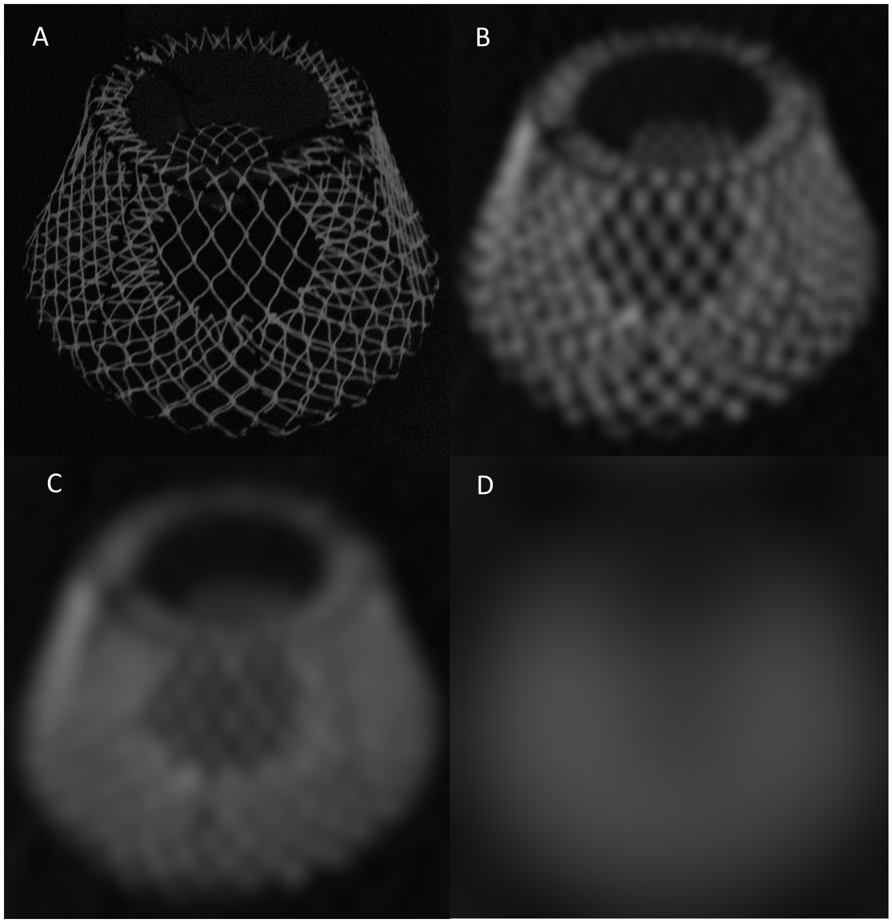

Figure 2.5 A monochromatic picture of a 6-strand luminescent-netting pot in a dark environment simulating the acuity of A) the human eye at 1 meter, B) the estimated snow crab spatial resolution of the luminescent pot at 1 meter, C) 2 meters, and D) 10 meters. Figures created with the AcuityView package in R.

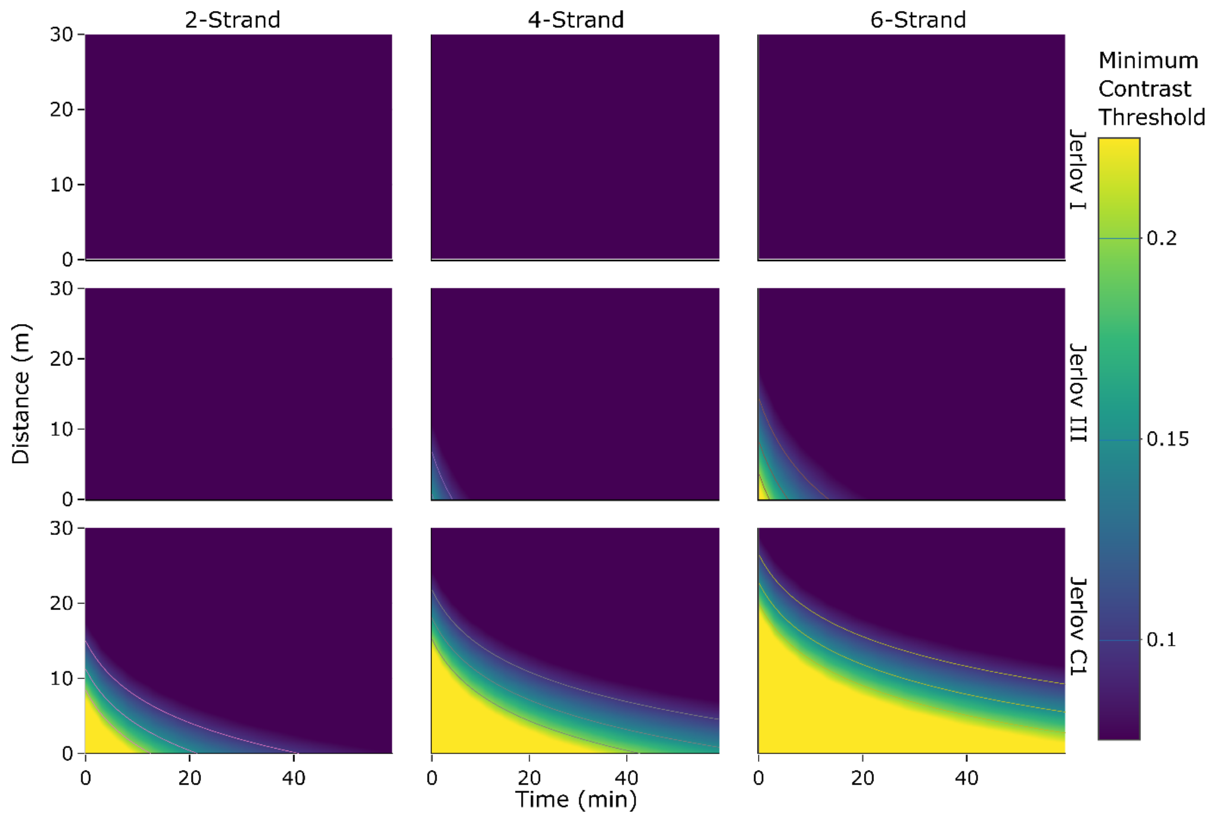

Figure 2.6 Snow crab visual contrast plots for each luminescent pot treatment (columns) and three water types (rows). Models are set at solar noon on April 18, 2022 in Conception Bay, NL. The y-axis is the distance from the pot to the eye of a snow crab, and the x-axis is the time from pot deployment when light emission intensity begins to decay. Colors indicate Michelson contrast values: yellow = visible, green and light blue = possibly visible, dark blue = not visible.

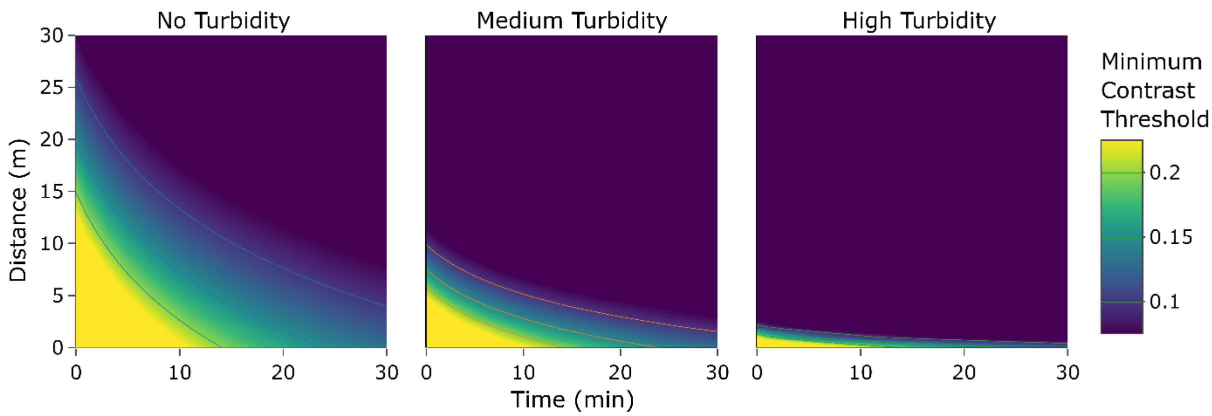

Figure 2.7 Snow crab visual contrast plots 2-strand pots in three benthic boundary layer turbidity scenarios. Each scenario is simulated at 20:00 (NT), Conception Bay, NL, on April 18, 2022. Models are all set within Jerlov III waters. Colors indicate Michelson contrast values: yellow = visible, green and light blue = possibly visible, dark blue = not visible.

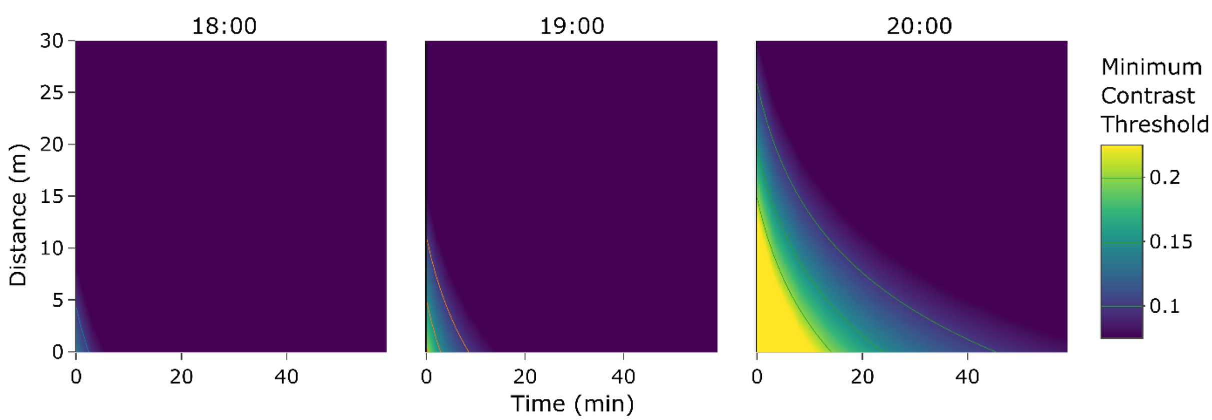

Figure 2.8 Snow crab visual contrast plots for 2-strand luminescent pots at three different times (solar angle): 18:00 NT (28.6°), 19:00 NT (18.6°), and 20:00 NT (8.6°), Conception Bay, NL April 18, 2022. Models are all within Jerlov III waters. Colors indicate Michelson contrast values: yellow = visible, green and light blue = possibly visible, dark blue = not visible.

Figure 2.9 Snow crab pseudopupil. Images are from the eye’s forward and ventral facing areas when in the orbital space. They are anteromedial to anterolateral facing when elevated, scanning the horizon. The pseudopupil is vertical when the eyes are elevated.

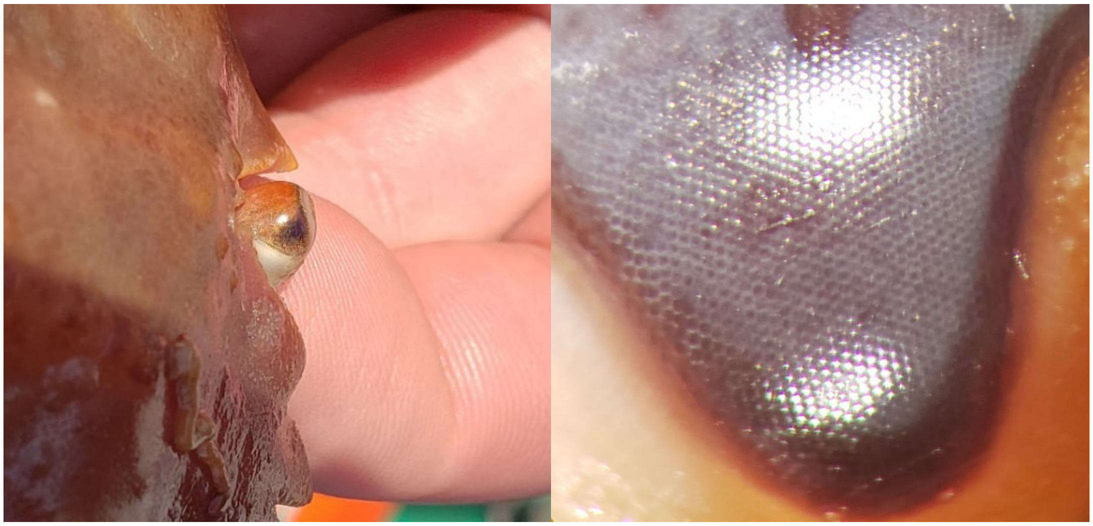

Figure 2.10 Image on the left is a snow crab pseudopupil from the eye's dorsal facing area when the eye is in the orbital space, scanning above. It is posterolateral facing when elevated, scanning the horizon. Image on the right is of the same location on the eye but was taken at 50x magnification under a dissecting microscope, showing the large ommatidial facets.

Chapter 3. The effect of variable light intensity in luminescent-netting pots on the catch of snow crab (*Chionoecetes opilio*).

3.1 Abstract

The use of light in pots has been shown to increase snow crab catch rates in eastern Canada and the Barents Sea, where better fishing efficiency could result in less fuel consumption and financial and ecological benefits. However, some light characteristics necessary for maximizing efficiency have yet to be researched. The purpose of this chapter was to determine if there is a change in catch per unit effort (CPUE; number of snow crab per pot) and size selectivity of snow crab with varying light intensity. Three types of experimental luminescent-netting pots were used, each type with a different level of light intensity via the number of phosphorescent strands woven into the pot netting (either 2-, 4-, or 6-strands) and were compared to the traditional pot used in the fishery. There were mixed results among treatments, with the 2-strand pot catching significantly fewer small snow crab (carapace width, CW < 103 mm) and significantly more large snow crab (CW ≥ 103 mm) than the traditional pots, but overall, had a lower CPUE for legal and sub-legal sized males (14.8 and 3.1 per pot, respectively) than the traditional pot (16.1 and 5.5 per pot, respectively) when considering all size classes. Compared to the traditional pot, the 4-strand pot caught more legal and sub-legal (CPUE of 18.8 and 8.0 per pot, respectively) snow crab in terms of CPUE but caught fewer commercial snow crab from 103-116 mm CW. The highest intensity pots (6-strand) showed no significant difference in CPUE or size selectivity compared to the traditional. Conversely, the 2-strand pot showed decreases in juvenile crab catch and increases in the catch of the most valuable size classes observed, which are attractive results to fisheries managers and harvesters, respectfully. These

results and a large price increase suggest that higher light-intensity pots are unattractive for commercial fishery.

3.2 Introduction

Researchers and fishers are currently testing new fishing gear technologies to increase catch efficiency and catch rates in snow crab (*Chionoecetes opilio*) pot fisheries (e.g., Cerbule et al., 2021; Nguyen et al., 2019a; Olsen et al., 2019b). The Newfoundland and Labrador snow crab fishery is the highest-valued fishery in the region (valued at over $600 million CAD in 2022; DFO 2023 data cited from Baker et al. 2022) and is comprised of several fleet sectors and approximately 2,300 license holders (DFO, 2022). The fishery targets large males (carapace width (CW > 95 mm), and typical bycatch includes undersize males, soft-shell crab, and rarely females, which are about half the size of males. Increasing catch rates (catch per unit effort; CPUE) and catch efficiency (increasing the catch proportion of legal snow crab to bycatch) could reduce fishing time at sea, bait wastage, carbon footprints, opportunities for work-related injuries, and costs associated with being on the water (e.g., fuel) (Nguyen & Winger, 2019a). There are also potential benefits for snow crab stocks. Because the Newfoundland and Labrador snow crab fishery is based on individual quotas (DFO, 2022), expediting the catch helps fishers avoid fishing into summer months when the catch ratio of the undesirable and unmarketable soft-shell snow crab increases (DFO, 2022). Soft-shell snow crab has very little muscle tissue and instead has replaced the tissue with water (Mullowney et al., 2021a). For this reason, there is no market for soft-shell snow crab, and all soft-shell crab must be discarded at sea, potentially incurring discard mortality. Harvesting snow crab quota more quickly could reduce the catch of soft-shell snow crab, reducing discards and discard mortality. Considering the economic importance of the Newfoundland and Labrador snow crab fishery (Davis, 2015), it would be prudent to explore options such as these to help the industry become more profitable while at the same time reducing bycatch and fishing mortality.

Among new fishing gear technology tested for snow crab is the use of light in conjunction with bait, taking advantage of snow crab's visual system, which until recently has been largely ignored. Nguyen et al. (2017) found that white LED lights in snow crab pots significantly increased the CPUE of snow crab by 77.0%. To continue exploring the use of light as an attractant, Nguyen et al. (2019; 2020) began using pots with luminescent (specifically phosphorescent) netting and found that CPUE of legal-sized snow crab increased by 55.0% and 21.6%, respectively, for the two studies. Luminescent-netting pots have twine composed of two types of strands: standard polyethylene and phosphorescent polyethylene. The phosphorescent strands passively charge with brief exposure to sunlight, eliminating waste from using battery-powered LEDs and adopting a renewable charging solution. The costs of luminescent netting pots have ranged from marginally higher ($10 CAD more per pot; Nguyen et al., 2020) to the same price (pers. Comm. Jerry Williams, ESL Marine Supplies Ltd., St. John's, NL, CA) as traditional pots. Hence, luminescent pots are much more economically feasible on a commercial scale than battery-powered LEDs, which require purchasing of the LED lights along with either new or rechargeable batteries (~$20-$75 CAD) (pers. Comm. Dr. Paul Winger, Centre for Sustainable Aquatic Resources, St. John's, NL, CA).

The mechanism behind the increase in snow crab CPUE while using light is unknown. Potential mechanisms may include, but are not limited to, a positive phototactic response to light stimuli (Yami, 1976), prey attraction toward the light (Humborstad et al., 2018), and behavioral changes based on initial attraction to the pot (Stiansen et al., 2010). Studying the catch rates and size-selectivity of fishing gear with different light intensities could aid in understanding the mechanism behind the capture of snow crab using light. Additionally, increased light could further improve catch efficiency. Thus, the first goal of this study was to determine if there is a correlation between the catch rates of snow crab and varying light intensity of luminescent-netting pots among legal-sized males, sub-legal males, soft-shell males, and females. The second goal is to determine whether the light intensity of luminescent-netting pots affects the size-selectivity of snow crab. Understanding the influence of light intensity will provide some of the first steps in understanding the mechanism of light-influenced capture in snow crab and the limitations of the new fishing gear.

3.3 Materials and methods

3.3.1 Gear description

The study design used three types of luminescent-netting pots (experimental) and the typically used commercial pot (traditional). All pots were Japanese-style conical pots with a bottom diameter of 102 cm, top diameter of 55.5 cm, height of 44 cm, and mesh twine is constructed of polyethylene and mesh size is nominally 135 mm. Mesh is stretched over the shape of the pot, providing irregular mesh shapes and sizes, which is dependent on the location of the pot (Olsen et al. 2019b). Experimental pots were identical to the traditional pots, except they had varying numbers of luminescent fiber strands woven in with non-luminescent green twine, and traditional pots use all orange twine (Euroglow netting from Euronete Company, Maia, Portugal) (Figure 3.1). Neither non-luminescent color, green nor orange, is known to provide differing catch rates (Nguyen et al., 2020). The 2-strand pot was previously used in the local fishery and research (Nguyen et al., 2019, 2020). The other two experimental pots had either 4 or 6 luminescent fibers. The brightest treatment, 6-strand, is 4.2 x more intense (2.7×10^{13} photons/m^2/s) than the 2-strand treatment (6.4×10^{12} photons/m^2/s), and the 4-strand pots are 2.3 x more intense (1.5×10^{13} photons/m^2/s) than the 2-strand (See Section 2.4.1). Each treatment has the same spectral profile, with a peak wavelength at 523 nm (green; Figure 2.2), and decreases in intensity exponentially when removed from a high-intensity light source, such as solar or ultra-violet (Figure 2.4). Orange plastic bait jars filled with 0.9 kg of northern shortfin squid (*Illex illecebrosus*) were used in all pots. Squid was thawed and cut into smaller pieces before jars were filled.

3.3.2 Field data collection

Fieldwork was carried out during the 2021 and 2022 commercial seasons in Conception Bay, NL, Canada (Figure 3.2). All work was done aboard the inshore *F/V Four Seas*. Sampling occurred during normal commercial fishing operations. In 2021, 5 longlines (fleets) were deployed with 50 pots each (250 pots total) per trip. In 2022, 4 fleets were deployed with 62 to 64 pots each per trip (250 pots total). All pots were spaced at approximately 46 m intervals on each fleet. I carried out two trips in 2021 and four in 2022, totaling six trips and 1500 pots fished. Each fleet had alternating treatment groups of 10 pots to provide a buffer zone between treatments for snow crab that may be affected by adjacent pots (Bayse & Grant, 2020) (Figure 3.3). Pots that appeared to have flipped over, shifted through current or tidal action, unintentionally deviated from the design, contained a fallen bait jar, or were otherwise fishing differently than normal were excluded from the data analysis.

During haulback, pots were emptied one at a time onto a sorting table, and snow crab were either counted or placed in a bin for carapace width (CW) measurements. On the first trip, the effort was directed toward CW measurements because only one researcher was available to take samples. Pots were selected opportunistically, according to the speed of measurements taken, which was approximately 6-7 pots per fleet. Where there were fewer crab, more pots were sampled, and vice versa. At least one pot per treatment group was selected for CW measurements in each fleet. On trips 2 through 6, CW measurements were taken similarly, but an additional researcher was present to track counts of snow crab in every pot. Counts in each pot were separated into four categories: legal (male, CW ≥ 95mm), sub-legal (male, CW < 95mm), soft shell (male), and female. The commercial fishing crew counted sub-legal, female, and soft-shell snow crab and relayed that information to research personnel at their side. Vernier calipers were used to take CW measurements to the nearest mm. Due to the vessel only fishing during fair weather days, soak times varied between 4 and 8 days at the captain's discretion.

3.3.3 Data Analysis

3.3.3.1 CPUE

All statistical analyses were performed in the R environment (R Core Team, 2022). I used a general linearized mixed model (GLMM) approach (Bolker et al., 2009) to model CPUE (number of snow crab per pot) with the *lme4* package (Bates et al., 2015). Negative binomial distributions were used because there was evidence of overdispersion when using a Poisson distribution. Models were tested for overdispersion and zero-inflation using the R package DHARMa (Hartig, 2022). Because I measured catch as a function of effort and fleet fishing duration varied, I included "soak time" as an offset. To account for variation in and among trips and fleets, I modeled each as nested random effects, adjusting the model intercept to incorporate variation in catch rates from fleet to fleet and trip to trip. Year was included as a fixed effect because it only had two levels and could not be included as a random effect since the models did not properly converge. Model selection to determine the best model among candidate models, using all variable combinations, was made using the Bayesian information criterion (BIC;

Schwarz, 1978) with the BICtab function from the *bbmle* package (Bolker & R Development Core Team, 2022). The model with the lowest BIC was determined to be the best-fit model. Separate models following Eq. (1) were fit for the CPUE of legal size, sub-legal size, and soft-shell snow crab. CPUE is the *k*th observation in the *j*th Fleet, nested in the *i*th Trip.

(1)

$$CPUE_{ijk} \sim \text{NB}\ (\mu_{ijk}, \theta)$$

$$var = \mu_{ijk}\ (1 + \mu^2_{ijk}/\theta)$$

$$\log(\mu_{ijk}) = \alpha_{ijk} + \beta_1(\text{Treatment}_{2.\text{Strand}}) + \beta_2(\text{Treatment}_{4.\text{Strand}}) + \beta_3(\text{Treatment}_{6.\text{Strand}}) + Trip_i + Fleet_{ij}$$

$$Trip_i \sim \text{N}(\mu_{Trip}, \sigma^2_{Trip})$$

$$Fleet_{ij} \sim \text{N}(\mu_{Fleet}, \sigma^2_{Fleet})$$

Post-hoc analyses were performed with a Tukey test within the glht function from the *multcomp* package (Hothorn et al., 2008), comparing CPUE between pot treatments. Models were then bootstrapped with 1000 iterations to infer 95% confidence intervals using the bootMer function from the *lme4* package (Bates et al., 2015). Due to four separate treatments being tested simultaneously, I ran a power analysis on the CPUE models to validate the results following the methods of Kratzer et al (2021).

3.3.3.2 Size Selectivity

Size-selectivity data were analyzed using the unpaired method in the *selfisher* package, given that the study design did not perfectly pair each treatment (Brooks et al., 2022). Catch comparisons were made with three separate binomial models of unpaired data: 2-strand to traditional, 4-strand to traditional, and 6-strand to traditional. Catch comparisons were modeled as proportions (experimental / experimental + traditional) caught per mm carapace width, as described in Holst and Revill (2009). To account for sampling effort, I up-scaled the data by dividing the number of snow crab measured by the proportion of snow crab caught per treatment per fleet (Aquaprojects Inc., 1995; Blackmore et al., 2023). I used a B-spline on the dependent variable (CW) to allow model flexibility and avoid polynomial fitting issues (Venables & Dichmont, 2004). Low-order polynomials (1-4 degrees) and knots within the spline were adjusted to find the best combination for model flexibility while maintaining simplicity; five models were tested per treatment, each with increasing complexity. Model comparisons were then made using BIC to determine the best fit. The best-fit models Eqs. (2-4) were then double bootstrapped with 1000 iterations for confidence intervals (CIs) estimates using the bootSel function from *selfisher*. Double bootstrapping considers variation from within and between fleets, eliminating the need to use fleet as a random effect (Brooks et al., 2022; Miller, 1993). Interpretation of size selectivity models considers that if a retention of 0.6 is observed at a specific CW, then 60% of the snow crab caught at that CW were caught with the experimental gear, and 40% were caught with the traditional. If model CIs encompass the 0.5 line, then there was no difference between the experimental and traditional gear retention at the specific CW.

Best fit models for each treatment group are as follows:

$$P[\text{logit}(2\text{-}strand/2\text{-}strand + traditional)] = a + \text{s}(CW, knots = 3, degree=4) + \varepsilon \qquad (2)$$

$$P[\text{logit}(4\text{-}strand/4\text{-}strand + traditional)] = a + \text{s}(CW, knots = 3, degree=3) + \varepsilon \qquad (3)$$

$$P[\text{logit}(6\text{-}strand/6\text{-}strand + traditional)] = a + \text{s}(CW, knots = 3, degree=4) + \varepsilon \qquad (4)$$

where *P* is probability, *a* is the model intercept, *s* is the spline function, and *ε* is the error term. Within the spline function, degree indicates the degree (cubic or quartic) of the piecewise polynomials, and knots indicates the number of internal knots in the spline.

3.4 Results

3.4.1 CPUE

Of the 1336 pots counted, 1154 were included in the final analysis: 247 traditional, 230 2-strand, 342 4-strand, and 335 6-strand. Pots were distributed among 21 fleets, five trips, and two years. Raw counts, which includes those crab sampled for size-selectivity, are seen in Table 3.1. Depths ranged from about 180 to 245 meters but most fishing took place between 200 and 220 meters. The sampling began in April 2021 and 2022 and ended in April in year one and May in year two.

Predictions from the final CPUE models for legal and sub-legal-sized snow crab can be seen in Figure 3.4. Similarly, for both legal and sub-legal models, the best-fit models included only the variable treatment (Table 3.2). The maximal models, which included Year, had a slightly higher BIC (Δ BIC 0.1) than those without year for legal snow crab and a moderately higher BIC (Δ BIC 4.9) for sub-legal snow crab. Thus, the more parsimonious model, which did not include Year, was chosen as the best model. For legal-size snow crab, only the 4-strand pots had a significantly higher CPUE (18.8) than the traditional (16.1), a 16.8% increase (Table 3.3). The 2-strand pot caught significantly fewer snow crab per pot (14.8) than the traditional, an 8.0% decrease. The 6-strand pot CPUE (16.8) was not significantly different from the traditional, showing a 4.3% increase. This trend was consistent for all trips where CPUE was measured. Sub-legal males followed the same trend with a lower CPUE in the 2-strand treatment (3.1;

43.6% decrease), higher CPUE in the 4-strand (8.0; 45.5% increase), and no difference in the 6-strand (5.1; 7.3% decrease) when compared to the traditional (5.5) (Figure 3.4). Post-hoc Tukey tests for legal and sub-legal snow crab can be seen in Table 3.4 and 3.5, respectively.

The null model for the soft-shell CPUE analysis had the best fit (Δ BIC 13.9 lower than the nearest model). Low catch amounts of soft-shell snow crab led to a posthoc investigation into the power of that analysis to confirm if no treatment effect was a reasonable conclusion. Power analysis followed the methods described in Kratzer et al. (2021), where the model was run through a created data set of 240 fleets; this was combined from 24 simulated data sets, each with 10 fleets and repeated 3000 times, recording the proportion of times a likelihood ratio test was significant. The analysis shows that 59 fleets (compared to the 21 fleets in the study) would have been needed to have a reasonable power of 0.8 (Cohen, 1992) (Figure 3.5) indicating that the soft-shell snow crab model does not have enough data for analysis. Likewise, only seven females were captured throughout the two-year study and were not considered for further analysis. Legal and sub-legal snow crab power analyses were performed in the same manner and had a power of 1.0 within 10 fleets, well below the 21 fleets that we used in the study, providing confidence in the size of my dataset for analysis.

3.4.2 Size Selectivity

All 180 pots sampled for CW measurements were used in the size-selectivity analyses. One fleet was missing a 2-strand pot section (10 pots); therefore, one traditional pot section was not used in the 2-strand size-selectivity analysis. Each fleet must have at least one experimental and traditional treatment to analyze the size-selectivity data; one traditional pot section, and therefore one fleet, was excluded in the 2-strand analysis because the fleet was missing a 2-

strand sample. The number of pots by treatment is shown in Table 3.1. Some outliers were excluded from the analysis due to low sample sizes ($n < 20$ per length class, 1 mm) and totaled 3.9% of snow crab measured, resulting in a CW range of 83 to 123 mm.

The 2-strand pots caught significantly fewer sub-legal snow crab than the traditional ones (Figure 3.6). In addition, the 2-strand treatment caught significantly fewer small legal male crab (95 mm ≤ CW ≤ 98 mm) but caught more large legal snow crab (CW ≥ 103 mm). The opposite trend occurred between the 4-strand and traditional pots (Figure 3.6), with more snow crab being caught between the CW measurements of 87 mm and 99 mm and fewer caught between 103 mm and 117 mm. There was no difference in size selectivity across all sizes between the 6-strand and traditional pots (Figure 3.6).

3.5 Discussion

3.5.1 Overall trends

This study shows evidence that varying light intensity of luminescent-netting pots affects the capture of snow crab. The mechanism behind the change in snow crab capture is unknown and may simply be a difference in contrast from pot light to ambient light or an increase in the duration or distance of luminescent-netting pot visibility. Although the increase in legal-sized snow crab CPUE from the 4-strand pots, when compared to the traditional, was not overwhelming (16%; Table 3.3), it was observed across each trip. Contradicting previous research (Nguyen et al., 2019; 2020), the 2-strand luminescent-netting pots had a lower CPUE for legal-sized snow crab when compared to traditional pots, though large snow crab were caught significantly more at sizes > 103 mm and generally increased from ~100 mm to the largest-sized snow crab observed in the study. These differences could be due to several factors that were different between studies, including the number of snow crab measured (the current study had three times as many measured snow crab compared to previous studies), local snow crab density, or pot saturation. For example, crab behavior may change with population density. Increased density or decreased resources may increase risk-taking behavior, either to compete for resources or because an increase in conspecifics reduces the chance of mortality through predation (Gruber et al., 2019; Matassa et al., 2016). Given that capture rates of crab can be affected by intimidation from crab within pots (Miller, 1978), it is feasible that during times of increased density or decreased resources, snow crab will change risk-taking behaviors and approach or enter the pots with less apprehension. Similarly, if pots reach a saturation point (current catch amount reduces potential for incurring additional catch; Miller, 1990), these behaviors could affect crab catch rates. These unknown factors may have affected the results presented in the current study or studies by Nguyen et al. (2019, 2020) by having some effect on snow capture in a way not directly related to light (or light amount) in pots.

3.5.2 Pros and cons of the 2-strand (dimmest) treatment

The 2-strand pots caught significantly fewer sub-legal (CW < 95 mm) snow crab compared to the traditional while simultaneously catching more large (CW > 103 mm) snow crab, with a legal to sub-legal CPUE ratio of about 5:1 for 2-strand pots and 3:1 for traditional pots (Table 3.3). Though some legal-sized snow crab (95 mm–100 mm CW) size classes had lower retention and a slight, but significant, reduction in CPUE was observed when compared to the traditional. The reason that the CPUE analysis shows a decrease in snow crab for the 2-strand and the size selectivity analysis showed both an increase and a decrease is explained by crab sizes observed in the study. Sub-legal crab results matched for both analyses; the CPUE and size selectivity analyses showed that sub-legal snow crab were caught less often by the 2-strand pot. However, size selectivity results for legal-sized crab is more complicated, showing a decrease (95-98 mm), no difference (99-102 mm), and an increase (>103 mm) for the 2-strand pot in comparison to the traditional pot. The traditional pot capturing more (or no difference) snow crab at 99-102 mm size classes, representing the most observed sizes, is driving the reduction in CPUE despite an increase in large-size class catches. Regardless, a pot that catches fewer sub-legal and more large-sized snow crab would benefit industry and conservation concerns. Of note, these results are contrary to previous findings for snow crab size selectivity with luminescent-netting pots, where no retention differences were observed across size classes (Nguyen et al., 2019; 2020), and sub-legals had a slight, but significant, increase in CPUE in Nguyen et al. (2020).

3.5.3 Pros and cons of increasing light intensity

Despite some signals of increased catches of legal-sized snow crab in the 4-strand treatment, increased catches of sub-legal snow crab would dissuade harvesters from adopting the drastic price increase per pot for brighter luminescent-twine pots. A similar conclusion could be expected for the 6-strand, which showed no difference in catches. Although the 2-strand pot is available commercially, the other experimental pots were custom-made for this project and are not readily available for purchase. As mentioned in the introduction, the price increase per pot has ranged from \$0 to \$10 for 2-strand pots, and the estimated price increase for 4-strand and 6-strand pots would be about \$30 and \$50, respectively; at current gear prices, 4-strand and 6-strand pots would have a 40% and 67% price increase.

3.5.4 Speculating the reason for different results between light intensities

Why the size-selectivity trend from the 2-strand treatment did not continue for 4-strand and 6-strand pots is unclear. Because the 4-strand pots are significantly brighter than the 2-strand pots (2.3x) and the distance that the light reaches is greater, which could allow for more snow crab in the vicinity to be exposed to the light and provides an opportunity for them to find the pot outside of the bait plume. Given that the brighter pots (4- and 6-strand) have a greater light radius, they may be attracting a more (or less) representative subset of the local population compared to those attracted through bait alone. A more representative subset would indicate that snow crab attracted to the light is not size-dependent. If a less representative subset of the population in the immediate vicinity were being caught, then that would indicate that catch efficiency based on light attraction, or attraction outside of bait, is size-dependent. Larger snow crab can likely see the luminescent-netting pots from further away (Schweikert et al., 2022; See Chapter 2), which would explain why more large snow crab and fewer small snow crab were caught in the 2-strand pots compared to the traditional. This effect would entirely depend on the density and stratification of the snow crab population in the vicinity. Also, there may be a threshold for positive phototaxis in snow crab, where increased light beyond that threshold provides either no phototactic response or a negative response, explaining why the 6-strand pots did not differ from the traditional in size-selectivity or CPUE. These interactions may also change spatially and temporally depending on where and when the snow crab is relative to the location of the pot, given that the intensity of the luminescent-netting is time dependent.

3.5.5 Speculating the mechanism of capture when adding light to pots

Stiensen et al. (2010) found that when red king crab (*Paralithodes camtschaticus*) approached pots from within the bait plume, they generally had very little behavioral flexibility. Crab commonly tried to find the bait without going around the pot or higher than the bait position, resulting in a lower likelihood of capture. However, when red king crab approached the pot from outside the bait plume, they had greater behavioral flexibility when interacting with the pot, resulting in a higher likelihood of capture. If this behavior holds for snow crab, as might be expected considering they both opportunistic feeders (Falk-Petersen et al., 2011; Wieczorek & Hooper, 1995), then there is potential that when snow crab are initially attracted to the pot from the luminescent twine (if that is the mechanism) and not in the bait plume, the behavioral flexibility could drive higher catch rates. This behavior would help explain why light has been associated with increased CPUE, whether through LED lights, regardless of light location (Nguyen & Winger 2019b), or phosphorescence. It could also explain why the 4-strand outperformed the 2-strand in total catch and legal-sized CPUE, as crab could potentially see brighter pots from further away and for a longer duration. Although this theory does not seem to hold for the 6-strand pot, the behavioral complexity of snow crab concerning their visual ecology is unknown. For example, the initial brightness of the 6-strand pot may invoke a degree of negative phototaxis in some snow crab, causing the treatment to fish the same as the traditional pot once the initial intensity subsides.

3.5.6 Ecosystem effects and gear limitations

The use of light in the aquatic environment, particularly in the deep sea (> 200 m), does not come without its ecological, behavioral, and ethical questions (Bayse et al., 2021;

Mullowney et al., 2021b; Zapata et al., 2019). Fortunately, when it comes to luminescent-netting pots, the twine is relatively dim and likely loses much of its intensity before hitting the seafloor. After five minutes without charge, the pots emit under half the initial light intensity. After one hour, light emissions are less than five percent of the initial intensity and are too dim to distinguish from the ambient light at 200 m depths in daytime Newfoundland waters (Sections 2.4.5, 2.5; Figure 2.6). In addition to light decay, light intensity drops drastically with distance in the aquatic environment, especially near the coast, where the water's scattering and absorption properties are generally greater as compared to the open ocean (Aas et al., 2013). Results from Chapter 2 indicate that even the brightest pot (6-strand) is outshined by the ambient light at 200 m in pure oceanic water or Jerlov type I water. In clear coastal water, Jerlov type C1, where chlorophyll and dissolved organic matter (DOM) are at higher concentrations, less sunlight reaches 200 m by two orders of magnitude (Nilsson et al., 2014; Pettersson et al., 1951). In these environments, the light emitted from the luminescent-netting snow crab pot may be seen within several meters for a relatively short period because the contrast ratio of the pot intensity and ambient light is higher (Section 2.4.5; Figure 2.6). In addition to the biological and physical factors that influence light scattering and absorption in the pelagic environment, these pots are resting on the seafloor, where visibility may again be impacted by terrain, sessile animals, and suspended substrate (Figure 2.7) (Johnsen et al., 2012).

Harvesters could artificially charge the pots with high-intensity UV lamps and set them at night, providing much more contrast in the deep ocean when the ambient light is several orders of magnitude dimmer (Clarke & Wertheim, 1956; Johnsen et al., 2004; Kampa, 1970). The aforementioned limitations still exist, and light emission from the pots decreases exponentially, likely minimizing any sustained ecological disruption that may occur. Even in these conditions, light is not foreign to deep-sea creatures as roughly 80% of animals deeper than 200 meters are thought to bioluminesce (Davis et al., 2014; Martini & Haddock, 2017), and 20-41% of benthic animals may bioluminesce (Johnsen et al., 2012; Martini et al., 2019). However, general concerns about adding artificial light to the marine environment are valid, and any ecological disruption from new and old fishing gears should be further studied in all environments and fisheries where artificial light is used (Nguyen & Winger, 2019a).

In addition to the limitations of the ecological impact that luminescent-netting pots have, are limitations of the technology's effectiveness. Because the amount of light emitted from luminescent-netting pots reduce exponentially, pots need to be deployed near snow crab populations to result in higher CPUE and snow crab interaction. After a short time (~5-20 minutes) in Newfoundland and Labrador waters, snow crab within a meter would be unable to distinguish the light from the luminescent-netting pot from ambient side-welling light (Sections 2.4.5, 2.5; Figure 2.6). If snow crab density is low or commercial fishers do not deploy pots within the immediate vicinity of snow crab, then there is a low likelihood that snow crab will interact with the gear before the phosphorescence has been effectively exhausted. Once the light is exhausted, luminescent-netting pots are likely equally effective as traditional pots, resulting in an inverse relationship between soak time and the proportional difference in CPUE from luminescent-netting pots to traditional pots.

In this study, there was a 7-day soak average, suggesting a high likelihood of difficult overall catch rate discernibility, as experimental pot lights diminish rapidly after deployment, and pots continue to fish well beyond that time. The shortest soak time was in 2022, at four days, which yielded the largest and most consistent improvement in legal-sized snow crab CPUE in year two, with all experimental pots outperforming the traditional: 2-strand (7% increase), 4-

strand (43% increase) and 6-strand (18% increase). Future work should consider further investigations into soak time effects on capturing snow crab with luminescent-netting pots, though this is challenging in a commercial environment.

3.5.7 Conclusion

This study found that CPUE and size-selectivity can be manipulated in the Newfoundland snow crab fishery using light. However, the results were mixed and showed a slight CPUE decrease in the 2-strand treatment. The 44% CPUE bycatch reduction of sub-legal-sized snow crab counters the slight decrease of legal-sized crab within the 2-strand treatment. The 2-strand pots show some potential when it comes to size selectivity for the fishery and could help foster snow crab fishery sustainability, provided that the observed trends hold. Based on these results, the 2-strand luminescent-netting is worth the $10 price increase per pot for both the sustainability of the fishery, the decrease in the catch of sub-legal and small legal crab, and the increase in the catch rates of large legal snow crab. There should be some reservation in wholly adopting this to be true, as the 4- and 6-strand treatments did not show the same trend in size-selectivity. To sustainably increase the CPUE of snow crab in Newfoundland and Labrador's most economically important fishery, more research should be done on the complex dynamics of snow crab capture (behavioral interactions with the pot, size-dependent catch efficiency, behavior post-capture, etc.) when adding light to pots. Future research on snow crab fishing technologies, reliant on comparing catch rates (light, sound, etc.), should incorporate short, medium, and long soak times to help researchers understand the nuances of how newer gears affect the catch over time.

3.6 Tables

Table 3.1 Number of crab, pots, and fleets used for CPUE and size selectivity analyses.

Treatment	CPUE			Size selectivity		
	Crab (#)	Pots (#)	Fleets (#)	Crab (#)	Pots (#)	Fleets (#)
Traditional	5816	247	21	846	35	26
2-strand	4428	230	21	860	42	25
4-strand	9686	342	21	1568	49	26
6-strand	7904	335	21	1532	54	26

Table 3.2 Legal, sub-legal, soft-shell snow crab models and ΔBIC values. ΔBIC values are differences in BIC scores from the best-fitting model. df = degrees of freedom or number of model parameters. Random effects are in parentheses.

Legal models	ΔBIC	df
CPUE~Pot treatment+(Trip/Fleet)	0	7
CPUE~Pot treatment+Year+(Trip/Fleet)	0.1	8
CPUE~Pot treatment + Fleet	2.6	6
CPUE~1 + (Trip/Fleet)	56.2	4
CPUE~Pot treatment+(Trip)	221.4	6
CPUE~Pot treatment	646.9	5
Sub-legal models	**ΔBIC**	**df**
CPUE~Pot treatment+(Trip/Fleet)	0	7
CPUE~Pot treatment+Year+(Trip/Fleet)	4.9	8
CPUE~Pot treatment + Fleet	10.2	6
CPUE~Pot treatment+(Trip)	48.1	6
CPUE~1 + (Trip/Fleet)	260.1	4
CPUE~Pot treatment	378.2	5
Soft-shell models	**ΔBIC**	**df**
CPUE~1 + (Trip/Fleet)	0	4
CPUE~Pot treatment + Fleet	13.9	6
CPUE~Pot treatment+(Trip/Fleet)	17.1	7
CPUE~Pot treatment+Year+(Trip/Fleet)	20.5	8
CPUE~Pot treatment+(Trip)	172.8	6
CPUE~Pot treatment	317.6	5

Table 3.3 CPUE of snow crab per size-class and treatment type and a ratio of legal to sub-legal catch. Percentages within parentheses indicate difference from traditional CPUE. * indicates significance ($p < 0.05$).

Size-class	Traditional	2-strand	4-strand	6-strand
Legal	16.1	14.8* (-8%)	18.8* (+16%)	16.8 (+4%)
Sub-legal	5.5	3.1* (-44%)	8.0* (+46%)	5.1 (-8%)
Ratio	2.9	4.8	2.6	3.3

Table 3.4 Legal model post-hoc Tukey test. * indicates significance (p-value < 0.05).

Treatment	Estimate	Std. error	z-value	p-value
2-strand – traditional	-0.08424	0.03022	-2.788	0.0271*
4.Strand – traditional	0.1514	0.02678	5.654	<0.001*
6.Strand – traditional	0.03829	0.02709	1.414	0.4892
4-strand – 2-strand	0.23564	0.02762	8.531	<0.001*
6-strand – 2-strand	0.12253	0.02807	4.366	<0.001*
6-strand – 4-strand	-0.1131	0.02431	-4.652	<0.001*

Table 3.5 Sub-legal model post-hoc Tukey test. * indicates significance (p-value < 0.05).

Treatment	Estimate	Std. error	z-value	p-value
2-strand – traditional	-0.57229	0.0614	-9.32	<1e-04*
4-strand – traditional	0.38131	0.04895	7.789	<1e-04*
6-strand – traditional	-0.0803	0.05127	-1.566	0.395
4-strand – 2-strand	0.9536	0.05602	17.022	<1e-04*
6-strand – 2-strand	0.49199	0.05831	8.438	<1e-04*
6-strand – 4-strand	-0.46161	0.04527	-10.197	<1e-04*

3.7 Figures

Figure 3.1 Image on the left is a luminescent-netting snow crab pot used in the Newfoundland and Labrador snow crab fishery. Image on the right is a close view of the netting (6-strand) of a stack of the same pots.

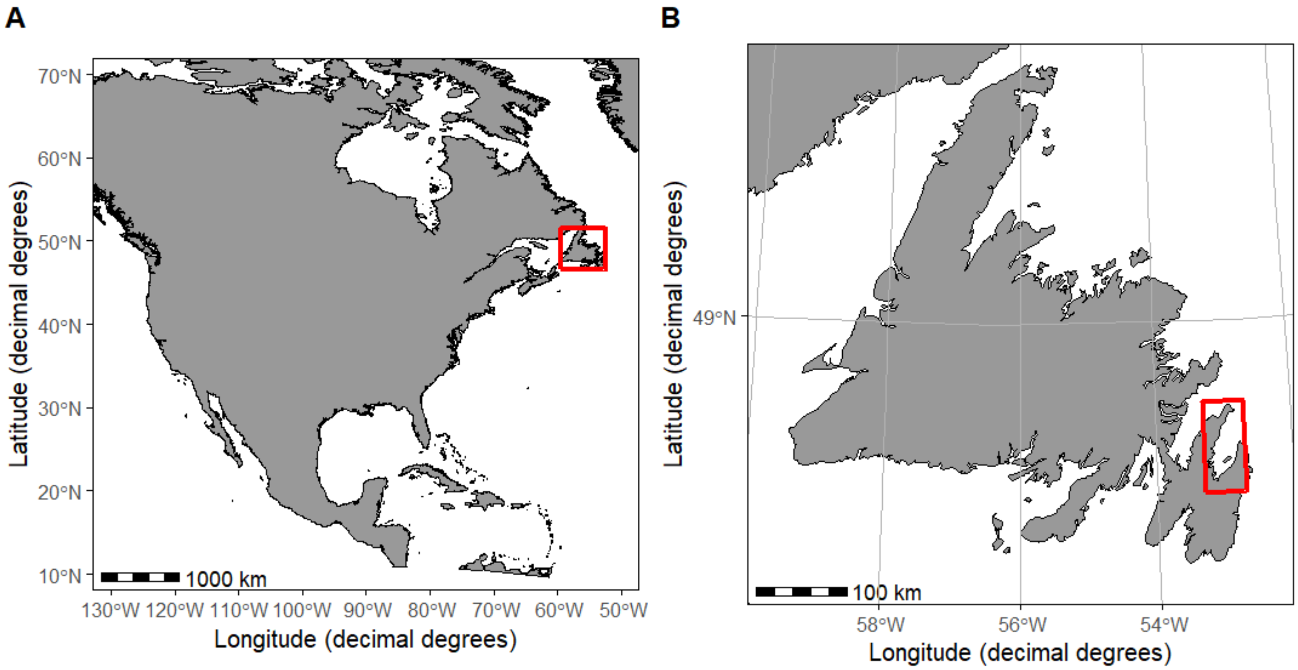

Figure 3.2 Map of North America, rectangle highlighting Newfoundland (A) and a map of Newfoundland, rectangle highlighting the study area in Conception Bay (B).

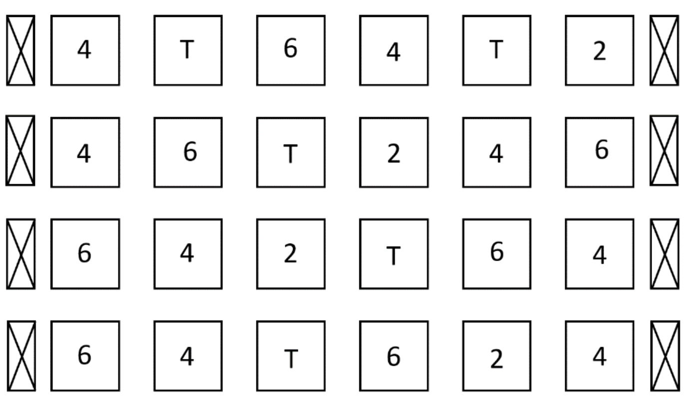

Figure 3.3 An example of the study design treatment blocks in year two. Each row is separate fleet in a trip. Year one used five fleets with five treatment blocks, otherwise was setup in the

same manner. Boxes with an “X” indicate those pots that did not follow the study design (i.e., additional pots beyond the 60 per fleet; 4 pot treatment blocks were not counted in the analyis) or dragged along the seafloor, common among pots on the end of a fleet. T = 10 traditional pots, 2 = 10 2-strand pots, 4 = 10 4-strand pots, 6 = 10 6-strand pots.

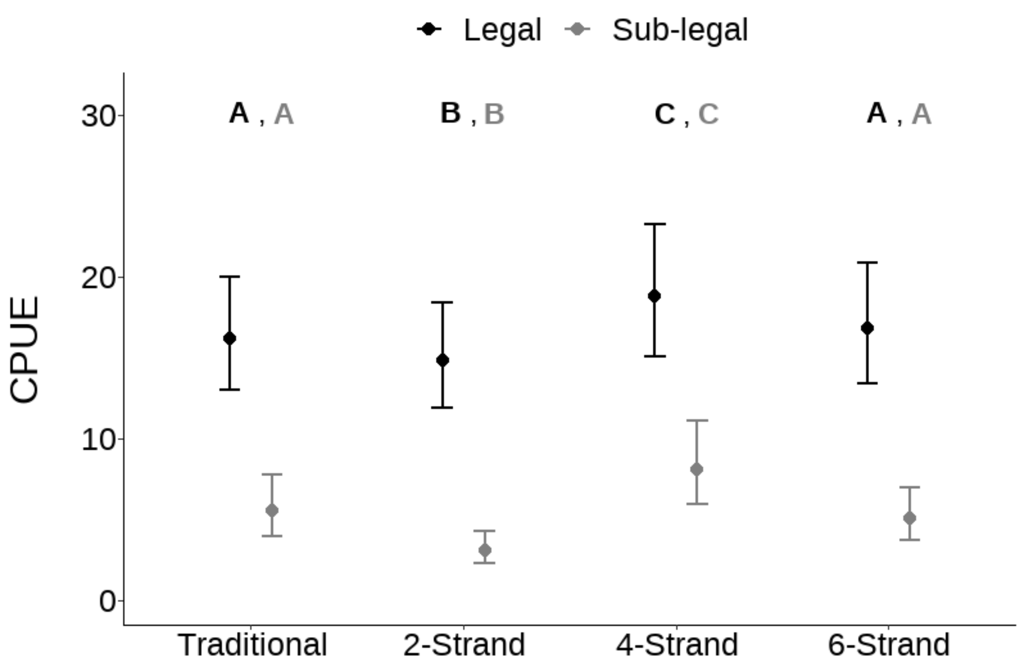

Figure 3.4 Results from separate catch per unit effort (CPUE; number of snow crab per pot) models of legal snow crab (CW ≥ 95 mm; black) and sub-legal snow crab (CW < 95 mm; gray) with 1000 bootstrapped 95% confidence intervals for each treatment; traditional commercial pot (traditional), pot with two phosphorescent strands (2-strand), four phosphorescent strands (4-strand), and six phosphorescent strands (6-strand). Different letters indicate significant differences between treatments, the letter to the left (black) is for legal-sized snow crab and to the right (gray) for sub-legal snow crab, different letters indicate significantly different results.

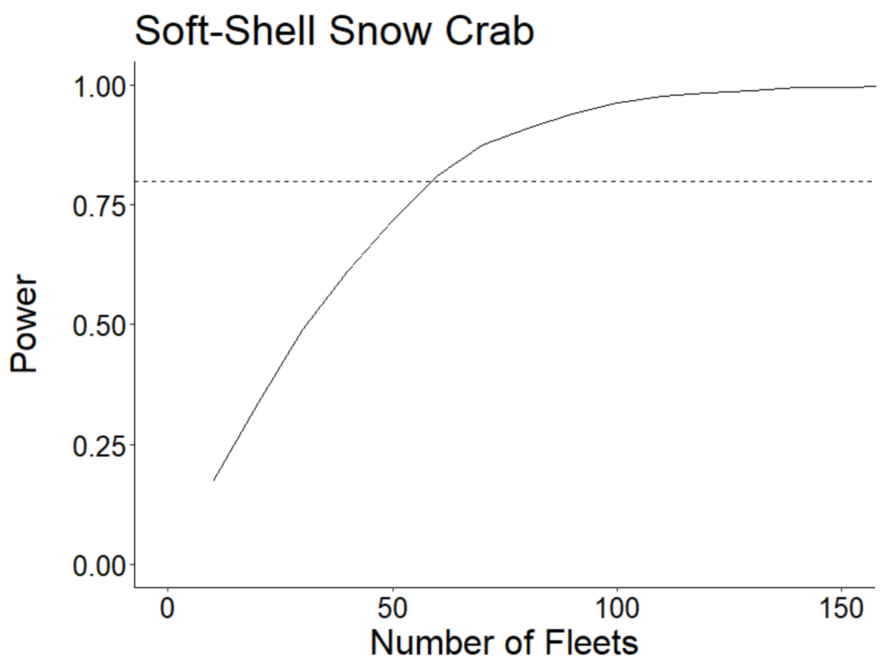

Figure 3.5 Power analysis of the number of fleets that would be required for soft-shell snow crab CPUE model confidence (Power > 0.8, horizontal dashed line).

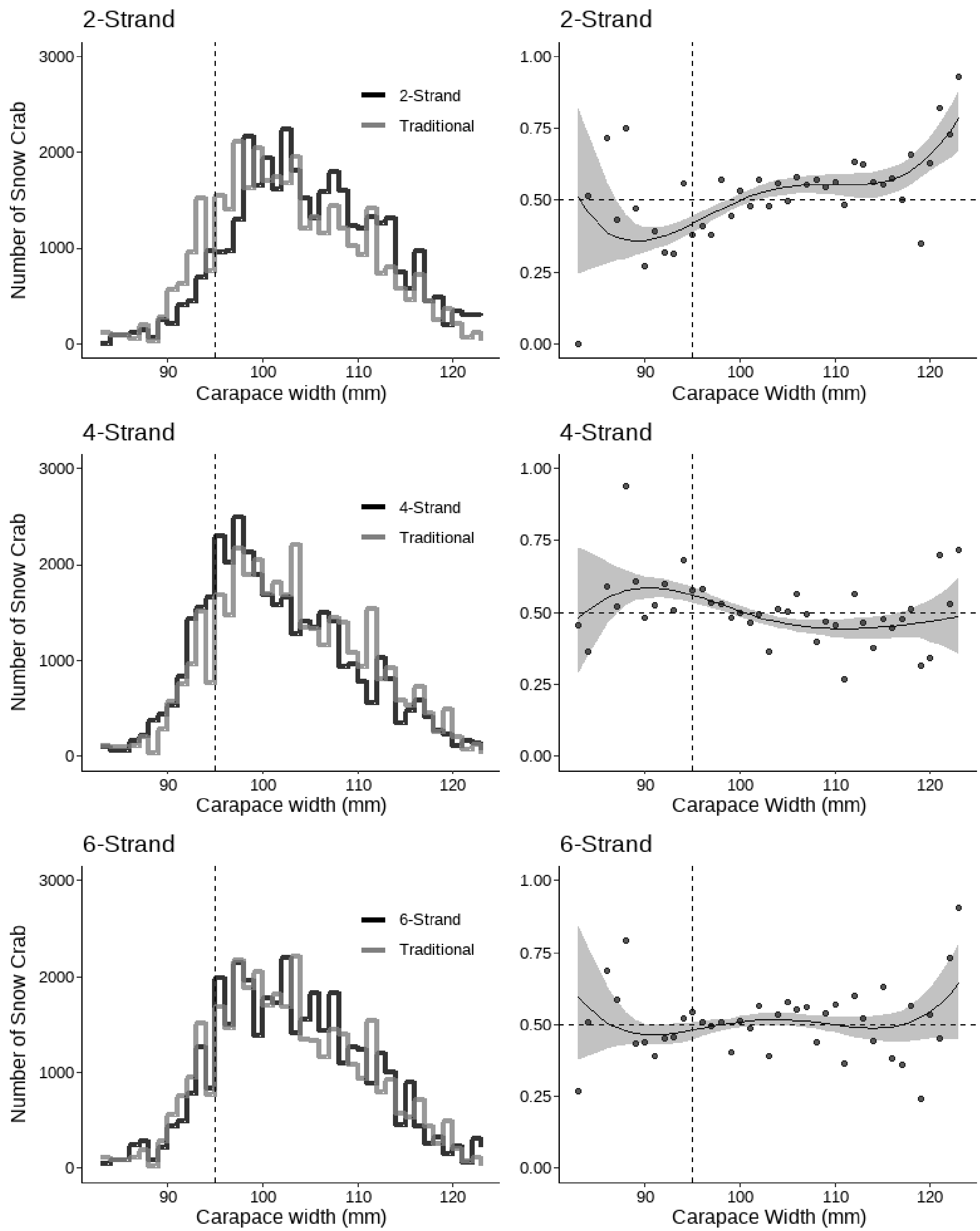

Figure 3.6 Size selectivity plots comparing the catch sizes (carapace widths, CW) of snow crab per experimental treatments (2-, 4-, and 6-strand luminescent pots) compared to the traditional pot that is typically fished in the fishery. The plots on the left depict the length frequency

distribution of CWs between experimental (black lines) and traditional (gray lines) pots. The plots on the right are the modeled proportions of experimental to traditional catches by CW with 1000 double bootstrapped 95% confidence intervals in grey. Model proportions are on the y-axis. The horizontal dashed line indicates catch differences between the experimental (> 0.5) or the traditional (< 0.5). The dashed vertical line indicates the minimum commercially legal size of snow crab (95 mm).

Chapter 4. General Discussion and Conclusions

4.1 Synthesis

The results in Chapter 2 highlight the importance of studying animal vision, particularly in the advent of increasing light use in fishing gear (Nguyen & Winger, 2019a). I show the sighting distance over time of luminescent-netting pots for snow crab at different times of the day (solar angles). At a solar angle of 8.6° above the horizon (20:00 NT; Conception Bay, NL, Canada; April 18, 2022), light from the 2-strand luminescent-netting pot is visible for up to 43 min and from a distance of up to 25 m at initial deployment (Figure 2.8). During this study, pots were not dropped later than 15:00, when the light from the 2-strand pot was not visible to snow crab. However, the 4- and 6-strand treatments are visible during this time, potentially increasing their initial detection range and the pot's overall visibility over the entire soak time. The increase in visibility time of the light from the 4-strand and 6-strand treatments would explain why they both had a higher catch rate than the 2-strand treatment in legal and sub-legal snow crab (Figure 3.4). This does not explain why the 2-strand treatment caught fewer crab than the traditional pot nor why the 6-strand treatment had no significant difference from the traditional pot.

Directly related to the solar angle and ambient light availability is the season and the latitude where the snow crab are being fished. Higher latitudes (Alaska and the Barents Sea) have a smaller peak in solar angle (Johnsen, 2012), reducing the light availability during solar noon at the surface and in the ocean, increasing the likelihood that luminescent-netting pots are visible during the day. This is also true for seasons where there is a decrease in daylight time and solar elevation. If the light is visible for longer, the time that light potentially influences snow crab behavior will increase in higher latitudes compared to lower latitudes and darker seasons to lighter seasons. This extended light visibility could explain the larger catch rate increase in

Cerbule et al. (2021) compared to the results in Chapter 3 and other studies in Atlantic Canada (Nguyen & Winger, 2019b; Nguyen et al., 2017; 2020).

Increased visibility time may have also influenced the size-selectivity results. Crustacean eyes grow in size by adding ommatidia to the edges of the eye as part of the molting process (Cronin & Jinks, 2001). Because I found that the largest ommatidial facets are on the rear margin of the snow crab eye, it is reasonable to assume that larger crab have better light sensitivity due to the additional large facets. Larger snow crab also likely have more ommatidia scanning the horizon and larger rhabdoms, increasing light sensitivity and visual acuity (Hiller-Adams & Case, 1985; 1988). These differences in stages of development and size would help explain why this study using the 2-strand pots captured significantly more large snow crab (CW $\geq$ 103 mm) than small ones (CW $\leq$ 98mm), as the light from the 2-strand pots would be visible earlier for large crab. This hypothesis does not explain why the 2-strand pots caught significantly fewer legal and sub-legal crab than the traditional pots.

In contrast, increasing turbidity could drastically reduce visibility distance and is a factor that should warrant more attention in future studies on light use in fisheries. Light use in fishing gears are likely extremely limited in areas with increased turbidity near the seafloor (Figure 2.7). The turbidity model would be valuable to help inform the suitability of light use in pots for snow crab in areas with elevated turbidity. Harvesters in areas with moderate turbidity may wish to increase the light intensity of fishing gear to compensate for the decreased visibility. Fishing in areas with high turbidity may result in negligible benefits when using light. As seen in Figure 2.7, high turbidity reduces the distance that snow crab can see pots from up to 26 m to 1-2 m at initial deployment. These results could also help inform researchers and harvesters in other fisheries that use light in turbid environments, i.e., trawling in soft-bottom substrate (Lomeli et al., 2020). This relationship could explain differences in light effectiveness from season to season or location to location in previous snow crab light studies. If one season or location has increased turbidity, the significance of the effects of light within fishing gears would likely reduce. This relationship is particularly important when comparing studies where turbidity in the BBL is unknown (Nguyen et al., 2017; Nguyen & Winger, 2019b; Nguyen et al., 2019; Nguyen et al., 2020; Cerbule et al., 2021) and may explain why the change in catch rates in this study were weaker than those of other studies.

Light sources of different sizes and intensities could be used in the models to predict snow crab vision on the seafloor. However, the model would need to be more complicated with higher-intensity light sources, as the halo effect would need to be incorporated into the model. The halo effect is seen when a light source has higher intensity, many of the photons will scatter, angling out from the object and then scattering back towards the viewer, making the light source look larger and obscuring the edges (Cronin et al., 2014). Depending on the intensity, the light could be viewed further as it would become a point-source at a greater distance (See Section 2.5) but would appear dimmer as photons are spread over a greater area. This could explain why relatively small LEDs, such as Electralume LED lights (Lingren-Pitman, Pompano Beach, FL), are effective at increasing catch rates of snow crab (Nguyen et al., 2017; 2019). Karlsen et al. (2021) measured the equivalent of 10-strand luminescent-netting from Euronete and compared it to Electralume lights; with 5x more phosphorescent strands than the 2-strand netting, they found that the LEDs were four orders of magnitude brighter than their initial luminescent-netting measurements. However, these lights are also about 50x smaller in a 2-dimensional area than a snow crab pot, making them more challenging to see with poor acuity unless there is considerable light scattering to make the lights appear larger. There is a balance between the size and intensity of the light source in terms of the effective area where snow crab and other animals could see it against background light.

The 2-strand pots showed the greatest promise of the treatments tested and would be attractive to management and harvesters, even with a slight reduction in the CPUE of legal-size snow crab. Considering that the 2-strand pots caught significantly more large snow crab than traditional pots, there may be some compensation with crab weight; using intermediate and old-adult size-weight regressions from the Gulf of St. Lawrence snow crab (Hebert et al., 2002), the 2-strand pots caught significantly more crab with a weight of about 0.42 kg (CW = 103 mm) to the maximum sizes of 0.73 kg (CW = 124 mm) and fewer legal-sized crab between 0.34 kg (CW = 95 mm) and 0.36 kg (CW = 98 mm). Because quotas are weight-based, and CPUE does not account for weight, the slight reduction in CPUE may be offset by the weight of the crab being caught.

4.2 Limitations of approach

4.2.1 Luminance measurements and predictions

In this thesis, I do not predict the intensity of the pots compared to ambient light into the night because the assumptions of light intensity of both the ambient light and the pot light are too numerous to predict far in time or at very low intensities (i.e., decay rate, initial intensity, ambient light levels at night, etc.). Confidence in night predictions could be achieved if ambient light intensity were measured at 200 m depth in Conception Bay, NL. Likewise, I could make longer predictions if the intensity and decay rate of the luminescent-netting was measured at 0° C. As discussed in Section 2.5, the decay function I used is an extrapolation from a single study comparing decay rates of strontium aluminate in different temperatures (Fouzar et al., 2021).

That study measured decay rates from 11 temperatures, ranging from 14.21 °C to 90.85 °C. I extrapolated their results to 0 °C using a generalized additive model and adjusted those values based on the proportional difference of the results at 21 °C (Appendix B). To validate my results, I also extrapolated a separate parameter from the same study, initial intensity, which matched the decay function I developed and provided some validity to the approach. I could not use the exact values from the paper because the strontium aluminate has been mixed with polyethylene, affecting the phosphorescent properties (Ge et al., 2012; Mishra et al., 2009; Yan et al., 2012). The accuracy of the decay rate, especially over a long period, would benefit from repeating the methods from Section 2.3.1 near 0 °C. That said, I would still expect similar results to what I used in Figure 2.4, a drastically reduced initial intensity followed by a slower decay rate (Fouzar et al., 2021).

Due to the 300-second (5-minute) integration time used to measure the number of photons emitted from the phosphorescent twine, the absolute intensity per second represents the average number of photons detected within this period. To achieve higher resolution, a shorter integration time would be necessary. Reducing the integration time comes with a trade-off, as it would compromise the ability to measure very low intensities. It is important to note that the longer integration used in this study time makes it challenging to compare my results with other studies utilizing luminescent-netting, as it impacts the intensity readings but not the decay function. This difference would not be a problem if the light decay were linear; however, because the decay rate is exponential, inequal integration times of the same light source will create somewhat different results.

For instance, Karlsen et al. (2021) utilized the same type of netting, albeit brighter, but analyzed the luminance with a 10-second integration time over a 10-minute duration, providing their results with better resolution within that timeframe. In contrast, I opted to take a single measurement after 5 minutes of photon capture to achieve greater accuracy for low-intensity light. The 2-strand treatment had 5x fewer glowing strands compared to Karlsen et al. (2021), and consequently, it is presumed to be much dimmer. Nevertheless, due to the 5-minute integration time, measurements could be comfortably taken for up to an hour, even when light levels may have been indistinguishable from noise with a shorter integration time.

4.2.2 Acuity estimates

Acuity was estimated using local radius curvature measurements from a 2-dimensional image of snow crab eyes. However, the eye is 3-dimensional, and more accurate measurements would entail an average of local radii from multiple angles. Acuity is likely slightly overestimated in some regions and underestimated in others because of this measurement technique.

I may also be overestimating acuity because there are many adaptations that crustaceans could have to their dim environment, including spatial summation (neural pooling) and temporal summation (Caves et al., 2016; Warrant, 1999). Snow crab likely have apposition eyes (Meyers et al., 2022), which often exhibit neural pooling to increase light sensitivity. Neural pooling is when information from multiple adjacent ommatidia provide information as a single summation, increasing sensitivity but decreasing resolution (Warrant, 1999). Snow crab may also have a high degree of temporal summation. Temporal summation is an increase in integration time for visual signals, where ommatidia absorb photons for a period of time before sending a signal (Caves et al., 2016). This buffering allows more photon collection and stronger signals where there is light. High temporal summation reduces temporal resolution but not necessarily acuity. However, even a slight movement of the crab or its environment would decrease acuity in this situation (Warrant, 1999). These characteristics would be helpful in some deepwater species where light is limited but have trade-offs that limit vision in other aspects, e.g., high temporal summation reduces the likelihood of seeing flashing bioluminescence or moving objects (Warrant, 1999). Because there are no studies on the visual capacity of snow crab, I cannot be sure whether either of these traits is present or absent. Future research into the visual capacity of snow crab would greatly benefit from additional anatomical and physiological eye studies.

4.2.3 Reduced light sensitivity in damaged eyes

Crustaceans removed rapidly from darker environments (i.e., deep water) have shown signs of severe damage to their visual components (Meyer-Rochow, 2001). Before being discarded in commercial snow crab fisheries, sub-legal male, female, and softshell male crab are exposed to intense light and often higher temperatures, significantly increasing their risk of eye damage (Kashiwagi et al., 1997). Damage to the eyes can cause behavioral changes that reduce survival and reproductive success (Meyer-Rochow, 1994; Meyer-Rochow, 2001). The damage would also reduce the snow crab's ability to detect the dim light from luminescent-netting pots, meaning that those crab that had not been previously discarded may see the light from a greater distance. Those crab that are removed from deeper, and thus darker, environments would be the most at risk for potentially irreversible light-induced damage (Gaten, 1998; Herring et al., 1999) even if only exposed to sunlight for less than 1 min (Frank et al., 2012).

4.2.4 Fieldwork study design

Work was performed quickly during commercial fishing operations, which caused a significant amount of lost data; lost pots were often replaced by the incorrect treatment, and data was removed from analysis for deviating from the study design. One of the most effective ways to analyze snow crab behavior around experimental and traditional pots is by using a drop camera from a research vessel to evaluate successful entrance rates, the direction that crab approach the pot, and escape behavior. If snow crab entrance rates increase significantly in luminescent-netting pots, then as discussed in Chapter 3, pots that initially attract crab with light may allow for greater behavioral flexibility and eventual capture. If crab approach luminescent-netting pots opposite the bait plume or from more directions than the traditional pots, then an increase in catch rates would suggest that light is the mode of attraction for some crab rather than bait. Lastly, if there are fewer escape attempts and successes in pots with light, it would suggest that light increases catch rates by reducing escape. The costs associated with working from a research vessel in this capacity would require significant resources not available for this thesis project but would be valuable for future studies on snow crab behavior around light.

4.3 Conclusion

The international economic importance of the snow crab fishery, particularly in Newfoundland and Labrador, warrants the pursuit of gear innovation, attempting to increase catch efficiency or catch rates and reduce energy and resource consumption. This thesis shows that both catch rates and catch efficiency can be manipulated (positively and negatively) using luminescent-netting pots. However, more research must be performed to determine the mechanism behind the change in catch rates and size-selectivity of these pots if we want to maximize the potential of light in the snow crab fishery. I show that the 2-strand luminescent-netting pot balances increased catch efficiency with a low risk of light pollution. Future work on light use in fisheries should consider the visual ecology aspect of fishing gear to limit or proceed with light use efficiently and responsibly.

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Appendices

Appendix A: software settings

SACALC 3.14 software settings

Source Dimensions: source radius: r1 = 50, source thickness: t1 = 0

Detector Dimensions: detector radius: r2 = 1.95, detector thickness: t2 = 0

Detector-source displacement: displacement: d = 0, displacement: c = each recorded distance from detector to disc

Rotational angles: x = 0, y = 0, z = 0

Source emissions: 2π source, Emissions = 1E7

SMARTS v2.9.5 code settings

Location: Port de Grave, NL (47.585, -53.213)

Date: 4/18/2022 (first day of fishing season)

Time: 12:00

Angle of surface: Horizontal (not tilted: tangent to earth's surface)

Solar zenith: 44.71

CO_2: 412.0ppm (measurement as of 4/18/2022)

Aerosol: S&F maritime (Shettle & Fenn, 1979)

Turbidity: TAU5 (aerosol optical depth at 500nm, t5) = 0.084 (default)

Appendix B: decay function extrapolation

Fitted parameter values for 21 °C from luminescent-netting (composited material):

$S = 1.06$ $\alpha = 1.16$

Modeled parameter values for 21 °C from raw strontium aluminate:

$S = 0.029$ $\alpha = 0.166$

Ratios to back transform raw 0 °C results to the composited material:

$S = 1.06 / 0.029 = 36.6$ $\alpha = 1.16 / 0.166 = 6.99$

Extrapolated parameter values for 0 °C from raw strontium aluminate:

$S = 0.015$ $\alpha = 0.119$

Extrapolated parameter values for 0 °C from the composited material:

$S = 0.015 \times 36.6 = 0.55$ $\alpha = 0.119 \times 6.99 = 0.83$

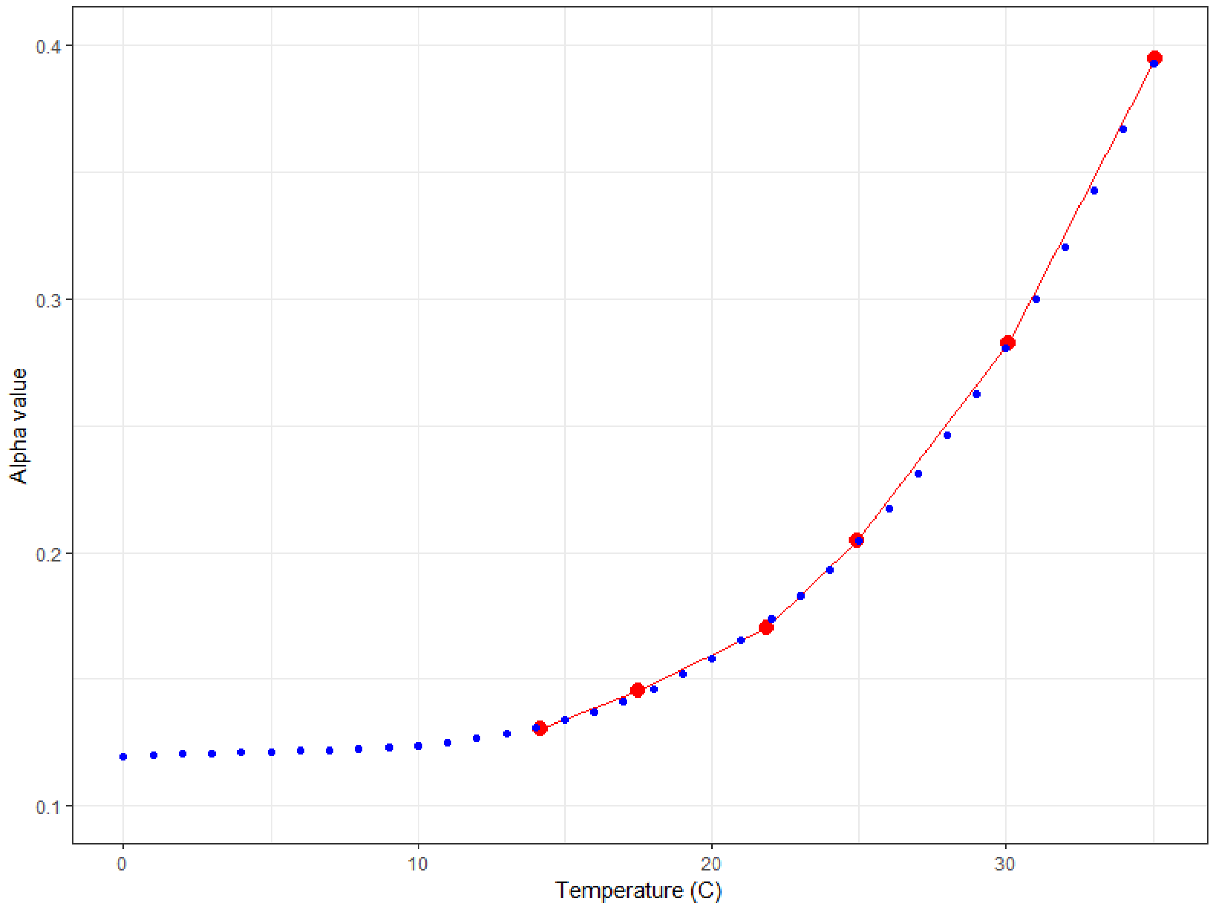

Figure B1 Extrapolated results for the power parameter within the decay function for strontium aluminate. Red points are raw data points from Fouzar et al. (2021, Fig. 7b). Blue points are predicted parameter values (Temp = 0 °C, $\alpha = 0.119$).