Evaluating the suitability and performance of entanglement mitigation devices for fixed gear fisheries in Atlantic Canada

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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

Fisheries Science and Technology

School of Fisheries

Fisheries and Marine Institute of the Memorial University of Newfoundland

November 2024

St. John's Newfoundland and Labrador

ABSTRACT

Entanglement in fishing gear is inhibiting the recovery of North Atlantic right whales (*Eubalaena glacialis*). Low breaking-strength (LBS) modifications have the potential to reduce severity of entanglements. The first part of this thesis aims to assess if LBS components have sufficient strength to withstand conditions in the Newfoundland and Labrador snow crab (*Chionoecetes opilio*) fishery by documenting tensions while hauling. Results showed that tension regularly exceeded the 771 kgf LBS threshold when hauling traps, suggesting that they are not suitable for this fishery. The second part involved assessing time-tension line cutters (TTLCs), a double-threshold (time and tension) entanglement mitigation device. Due to their use of hydraulic fluid and the known effect of temperature on its viscosity, a controlled laboratory experiment reflecting the conditions of Atlantic fisheries was conducted to evaluate the effect of temperature on time to cut (TTC). Results revealed that for every unit increase in temperature (1°C), time to cut was reduced by 0.759 min. Additionally, extreme TTC values at the lowest temperature tested showed further development and testing are needed. This thesis presents several novel methods and findings with direct application to one of Canada's most economically important fisheries and the innovation of entanglement mitigation devices.

GENERAL SUMMARY

North Atlantic right whales (NARWs) are nearing extinction. Their survival is threatened by human-caused mortality, notably, entanglement in fixed fishing gear, including those targeting lobster and snow crab. Mitigation and prevention methods are being developed collaboratively between harvesters, researchers, and conservation groups to reduce harm to NARW. Mitigation methods aim to reduce the risk of mortality and serious injury and include the integration of components with a reduced breaking strength, meant to break and release whales when they pull on the lines. My research measured line tensions in the Newfoundland snow crab fishery and evaluated the performance of an innovative mitigation device, meant to release when tension is sustained for a pre-determined amount of time, through a series of experiments. My results will help inform decisions regarding the implementation of these devices in fisheries, and illuminate considerations for further refinement, research and testing protocols of this device.

ACKNOWLEDGEMENTS

I would like to thank Dr. Paul Winger for his valuable guidance, support, and effort to share knowledge. I am very grateful for his actions that made possible the funding and the existence of this thesis. Thank you to Dr. Ed Trippel for being a valuable member of my supervisory committee and for his valuable assistance, advice, and reviews. Thank you also to Dr. Sean Brillant for not only being a part of my supervisory committee, but for going above and beyond to make me feel included in his team. I am grateful for his valuable and profound knowledge of North Atlantic fisheries, North Atlantic right whales, entanglement mitigation, and entanglement prevention. Getting to work with him, and everyone at the Canadian Wildlife Federation in Halifax has been a joy and a privilege. I have truly learned so much from my visits, workshops, conferences, and meetings with them.

Thank you to everyone at CSAR that has been a helping hand and a friendly face whenever I needed it: Mark Santos, George Legge, Craig Hollett, Melissa Rideout, Shannon Bayse, Vang Nguyen, and Tomas Araya-Schmidt. Thank you to Sidney Andrade and Jackson Yang for their support with data analysis when needed. Thank you to Lindsee Clark for her tremendous support in the field and outside as well. I am thankful that this project has brought you onto my path. Thank you also to Meghan Donovan, Jill Conway, and Liam McGregor for their continuous help with material sourcing, procedure development, trials and more.

Thanks to John Cross for his contribution to the angle correction protocol used in the second chapter of this thesis. Thank you also to Hannah Drake, Kirklen Johnson, Elizabeth Vézina, Krystyna Urbancic, Rhyl Frith, Alexandra Mayette, Alexandra Cole, Dr. Shiva Javdan, and Ryan Mahoney for their technical support, help with preparations, experimental design, data analysis, and more. Thanks to the crew of the *F/V Island Voyager*.

Thank you to my fellow graduate students for the great company, help and distraction when needed. And finally, thank you to my parents and my sister who have supported me wholeheartedly these past two years. Your interest in my work, your acceptance of my constant state of stress, and your continuous words of encouragement have truly played an enormous part in the completion of this thesis. Thank you also to all my friends who have truly kept me sane throughout this journey.

This work was funded by Fisheries and Oceans Canada through the Whalesafe Gear Adoption Fund.

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LIST OF ABBREVIATIONS AND SYMBOLS

ANOVA	Analysis of variance
BWC	Blue Water Concepts Inc.
DFO	Fisheries and Oceans Canada
kgf	Kilogram-Force (1kgf= 9.80665 Newtons)
lbf	Pound-Force (1lbf= 4.448222 Newtons)
LBS	Low-breaking strength
NARW	North Atlantic right whale
NL	Newfoundland and Labrador
NOAA	National Oceanic and Atmospheric Administration
TTC	Time to cut
TTLC	Time-tension line cutter
UME	Unexpected Mortality Event

CO-AUTHORSHIP STATEMENT

I, Geneviève Peck, the author of this thesis contributed to experimental design, and data collection and I was the main executioner of the interpretation, data analysis, prepared figures and tables, as well as the manuscripts for all material presented in this thesis. Dr. Paul Winger is responsible for funding and material acquisition for the experiments and contributed significantly to research proposals, experimental designs, discussions of ideas, and provided editorial reviews of all chapters. Dr. Sean Brillant and Dr. Ed Trippel were members of my supervisory committee. Dr. Tomas Araya-Schmidt assisted with analysis for Chapter 2. Krystyna Urbancic and Dr. Sean Brillant aided with material acquisition and contributed to the experimental design and protocol development of Chapter 3.

Dr. Tomas Araya-Schmidt and Dr. Paul Winger are second and third authors for Chapter 2, respectively.

Krystyna Urbancic, Dr. Sean Brillant, and Dr. Paul Winger are second, third, and fourth authors for Chapter 3, respectively.

A version of Chapter 2 has been published in the journal *Fishes*, and is available at: https://doi.org/10.3390/fishes9050154

It is expected that Chapter 3 will be submitted as a separate manuscript to a scientific journal.

CHAPTER 1: INTRODUCTION AND OVERVIEW

1.1 Trap Fisheries and Cetacean Interactions

Accidental mortality of cetaceans in fishing gear is well documented worldwide (Hofman, 1990; Read, 2006). Cetacean populations are largely threatened by lethal interactions with anthropogenic activities, such as entanglement in fishing gear (Reeves et al., 2003) and vessel strikes (Clapham et al., 1999; Thomas et al., 2016). Some cetacean populations, like larger populations, are less likely to be seriously impacted, while in other cases, removals exceed the rate of population increase; notably, in smaller populations (Clapham et al., 1999; Read, 2008; Tulloch et al., 2020).

When investigating large whale entanglements off the west coast of the U.S., from 1982-2017, Saez et al. (2021) identified a shift in the type of gear involved in large whale entanglements starting in 2000. Prior to 2000, in 140 confirmed reports, gillnets were the primary type of gear identified in entanglement reports (71%; 99) while baited traps were identified in only 2% (3) of cases. After 2000, in 289 confirmed reports, baited traps had become the most common gear type in entanglements reports (32%; 92) and entanglements in gillnets being less common (16%; 45). The authors hypothesized that the change was due to regulatory changes in gillnet fisheries during those years, as well as improved trap gear marking making identification easier. Additionally, the percent of “unknown” fishing gear in entanglement reports increased from 26% prior to 2000 to 52% after, likely attributable to the increase in trap gear entanglement since nets have discernable characteristics that are easily identifiable, while trap gear entanglements may leave only rope which cannot be attributed to any specific type of gear (Saez et al., 2021).

Fixed fishing gear (gill nets and trap fisheries) is a known major concern for large whale entanglement on the east coast of Canada and the U.S. (Johnson et al., 2005). Johnson et al. (2005) found that where gear could be identified, entanglement of North Atlantic right whales (NARWs) (*Eubalaena glacialis*) in that region are most often attributed to baited traps. While studies of this kind offer valuable insight in entanglement trends and patterns, there are biases that are important to consider. Mainly, the analysis of entangling gear retrieved from whales is dependent on the whale being sighted, either alive or deceased, and the successful retrieval and identification of the gear which can both be challenging due to factors like lack of identifying features on the gear, weather, and location of the whale (Saez et al., 2021).

For decades now, the primary cause of death globally for certain cetacean species is bycatch and gear entanglement (Knowlton and Kraus, 2001; van der Hoop et al., 2013) and the problem persists (NOAA, 2024c). Due to the growing incidence and severity of entanglement of endangered NARWs in baited trap fisheries on the east coast of Canada and the U.S. (van der Hoop et al., 2013), the Monterey Bay Aquarium Seafood Watch program has put snow crab (*Chionoecetes opilio*) and American lobster (*Homarus americanus*) fished in the NARW's range on the "red list", signaling to consumers that they should avoid consuming this seafood for now because of the high risk it poses to the environment (Monterey Bay Aquarium Seafood Watch, 2022abc). This includes the Newfoundland and Labrador (NL) snow crab and lobster fisheries. While this assessment has been criticized (i.e., Alam, 2022; Blank, 2022; Moore and Sharpless, 2022;), it does highlight the importance of social license within the seafood industry. Indeed, concerns about the moral, social, and environmental implications of fishery and aquaculture products are becoming more widespread among customers (Del Giudice et al., 2018; Panda et al., 2020), resulting in the demand for products with sustainability certifications to rise (Peiró-

Signes et al., 2022). Additionally, The U.S. Marine Mammal Protection Act (MMPA) is banning seafood imports from nations who don’t comply with U.S. by-catch standards for marine mammals by 2026 (Natural Resources Defense Council, 2023). As the United States is the primary market for Canadian seafood and accounts for 83% of NL snow crab exports (Government of Newfoundland and Labrador, 2023), the need to establish sustainable fishing methods in Canadian fisheries and find ways to harvest seafood without causing harm to marine mammals is crucial and urgent (Government of Canada, 2023; Natural Resources Defense Council, 2023).

1.2 Entanglement of North Atlantic Right Whales

Perhaps one of the most high-profile topics within marine mammal interactions with fisheries is the North Atlantic right whale and the baited trap fisheries along the east coast of the U.S. and Canada (e.g., Kraus, 1990; Caswell et al., 1999; Knowlton et al., 2012; Sharp et al., 2019). NARWs are one of the most endangered whales in the world, with a current population estimate of 372 (+11/-12) individuals and under 70 calving mothers (Linden, 2024). Entanglement in fishing gear and vessel strike have been barriers to their recovery (Kraus, 1990; Caswell et al., 1999; Moore et al., 2021). While vessel strikes are seemingly more lethal (Figure 1.4), whales killed by vessel strikes are more likely to die nearly instantaneously and be sighted or drift ashore than whales dying due to entanglement since these whales are usually entangled longer, leading to poor body conditions and loss of blubber causing the carcasses to sink (Moore et al., 2004; van der Hoop et al., 2013). Pace et al., 2021 found that observed carcasses represented only one third (36%) of estimated NARW mortality between 1990 and 2017 with entanglements being most likely to be underreported. Additionally, sub-lethal entanglements cause stress, and injuries that lead to decreased physical conditions, debilitation, foraging disruption, hemorrhage, reduced reproductive success and more (Cassoff et al., 2011; Moore and van der Hoop, 2012; van der Hoop et al., 2016; van der Hoop et al., 2017; Moore 2023), making entanglement the biggest threat to NARW recovery and survival (Sharp et al., 2019; Moore et al., 2021; Pettis and Hamilton, 2024).

While entanglements of NARW off the east coast of Canada and the U.S. have been documented since the 1990s (Kraus et al., 1990; Caswell et al., 1999; Knowlton et al., 2005), incidence of severe and lethal cases has increased in recent decades due to i) the expansion and growth of fisheries, ii) the shift from predominantly groundfish trawl fisheries to mainly non-tended, passive crustacean fisheries (stationary gear where a rope connects traps on the seafloor to a buoy on the surface and left unattended for extended periods of time), and iii) changing oceanographic conditions favoring a northward shift in food resources (Worm and Myers, 2003; Johnson et al., 2005; Anderson et al., 2008; Greene et al., 2013; Knowlton et al., 2016; Meyer-Gutbrod et al., 2018; Sharp et al., 2019; Sorochan et al., 2019). Together, these factors have increased the spatial and temporal overlap of migrating NARWs with various fisheries along the east coast of Canada and the U.S. Anthropogenic causes have been known to be the main factor inhibiting NARW recovery for decades (Kraus, 1990; Caswell et al., 1999). Between 1980 and 2017, over 1,500 interactions have been documented involving 86.1% of the population with some individuals having been entangled as many as eight times (Knowlton et al., 2012).

Entanglement is not only a significant cause of mortality, but sublethal injuries and stress linked to entanglement events also have negative effects on NARWs' health, reproduction, and overall species recovery (Roland et al., 2016; van der Hoop et al., 2016; Fauquier et al., 2020; Knowlton et al., 2022). NARW calving intervals for individual females have been increasing in the last decade and individuals are less likely to calve (Roland et al., 2016; Fauquier et al., 2020; Knowlton et al., 2022; Stewart et al., 2022). Additionally, following an entanglement, whales can carry fishing gear for months and up to a year (van der Hoop et al., 2017), which causes significant energy expenditures due to drag (van der Hoop et al., 2016) as well as long lasting effects even after disentanglement (van der Hoop et al., 2017). NARW entanglement events involve most commonly the head region (Johnson et al., 2005; Cassoff et al., 2011), with lines sometimes wrapping fully around the rostrum, resulting in restricted opening of the mouth and impeding feeding (Moore and van der Hoop, 2012). Painful injuries from entanglements can also inhibit the whale's ability to swim, leading to slow, painful deaths (Moore et al., 2006; Cassoff et al., 2011). All these factors are further inhabiting NARW recovery (Moore, 2023).

Ocean warming in recent years has already led to a shift in distribution of the copepod *Calanus finmarchicus* (Greene et al., 2013; Meyer-Gutbrod et al., 2018; Sorochan et al., 2019), the main food source of the NARW (Kann and Wishner, 1995), and ultimately led to a shift in their Canadian feeding grounds from the Bay of Fundy (BoF) to the Gulf of St-Lawrence (GSL) from 2015 forward (Meyer-Gutbrod et al., 2015; Simard et al., 2019; Sorochan et al., 2019). This unexpected shift northward into a heavy vessel traffic area led to a rapid increase in mortality from anthropogenic causes (Daoust et al., 2017; Bourque et al., 2020). Research shows that as waters continue to warm, the distribution of these copepods will likely continue to move northwards (Reygondeau and Beaugrand, 2011; Grieve et al., 2017; Freer et al., 2022) and will impact NARWs, either forcing them to alter their foraging grounds to follow *C. finmarchicus* northward, or change main prey species (Greene, 2016; Davis et al., 2017; Grieve et al., 2017), as well as other aspects of their biology related to prey abundance (e.g. calving success (Meyer-Gutbrod et al., 2015)). Indeed, seasonal conditions for the success and survival of *C.*

finmarchicus at Arctic latitudes have emerged in recent decades (Freer et al., 2022). Specifically, the Greenland, Labrador, and Southern Barents Seas are predicted to be increasingly favourable for *C. finmarchicus* due to an earlier sea ice retreat (Freer et al., 2022).

North Atlantic right whales were listed as endangered in 1973 under the U.S. Endangered Species Act (ESA) (National Marine Fisheries Service, 2015) and in 2005 under Schedule I, Part 2 of the Canadian Species at Risk Act (SARA) (Brown et al., 2009). Measures and regulations that have been implemented in the U.S. and Canada to mitigate and reduce entanglements have been insufficient and unsuccessful in decreasing lethal entanglements of NARWs (Kraus et al., 2005; Knowlton et al., 2012; van der Hoop et al., 2013; Pace et al., 2014; McDonald et al., 2016; Sharp et al., 2019).

1.3 History of Large Whale Entanglements in Newfoundland

Historically, there have been numerous records of large whale entanglements in fixed gear fisheries in NL, specifically humpback (*Megaptera novaeangliae*) and minke whales (*Balaenoptera acutorostrata*) (Perkins and Beamish, 1979; Lien et al., 1986; Ledwell et al., 2024). Almost 600 whale entanglements (humpback, minke and fin) were reported between 1969 and 1986 (Lien et al., 1986; Hofman, 1990) and since 1979, there have been 2,288 large whale entanglements reported in NL, consisting mainly of humpback whales (2,019) followed by minke whales (164) (Ledwell et al., 2024). Research suggests entanglement events prior to 1992 in NL were correlated with the movement of capelin (*Mallotus villosus*), becoming more frequent when they are abundant inshore, as whales follow them there where the incidence of fishing gear is higher than in offshore areas (Perkins and Beamish, 1979; Whitehead and

Carscadden, 1985). The subsequent expansion of the snow crab fishery led to increased numbers of fixed (untended) fishing gears in the offshore region, leading to an increase in the reporting of entanglements in offshore waters (Benjamin et al., 2011). These offshore entanglements have primarily involved baited traps (snow crab and whelk (*Buccinum undatum*)) (Benjamin et al., 2011; Ledwell et al., 2024) whereas cod traps, cod gillnets and Atlantic salmon (*Salmo salar*) gill nets were the most common entangling gears prior to 1992 (Benjamin et al., 2011).

In the last five years (2019 to 2023) there have been 97 documented large whale entanglements in NL, 77 of which were humpback whales (Ledwell et al., 2020, 2021, 2022, 2023, 2024). Considering these numbers are based exclusively on opportunistic sightings, large whale entanglements in Newfoundland and Labrador may be more common than what is reported. Additionally, estimated yearly NARW mortality rates are vastly underestimated when using observed carcass counts (Pace et al., 2021), demonstrating that many carcasses are never found and therefore, many entanglements and mortalities go unseen.

1.4 Newfoundland and Labrador Snow Crab Fishery

In Newfoundland and Labrador, where Atlantic cod (*Gadus morhua)* was the principal source of income for the majority of fishing households and the engine of economic growth for many rural areas, many were left jobless and countless more were indirectly impacted when the fishery closed following the 1992 moratorium in the area (Bavington, 2011). Impacts were catastrophic for local economies, harvesters, and the fishing industry (Steele et al., 1992; Rose, 2007; Bavington et al., 2011). The dramatic decrease in abundance of Atlantic cod resulted in significant ecosystem changes favoring lower-trophic level species which led to fisheries transitioning to the suddenly more abundant crustaceans like crab, shrimp, and lobster (Worm and Myers, 2003; Anderson et al., 2008). Today, lobster and snow crab are the most economically profitable fisheries in Canada with landings of $1.8 billion and $1.4 billion, respectively in 2022 (DFO, 2023b). For NL specifically, the rapid growth in population of shellfish species following the moratorium (Worm and Myers, 2003; Anderson et al., 2008; Davis, 2015), coupled with the increase in economic value of snow crab resulted in this fishery surpassing the cod fishery as the most profitable in the history of the province (Bavington, 2011) and the NL snow crab fishery contributing the greatest supply of the species worldwide for thirty years (Mullowney et al., 2024). Snow crab still remains the most commercially important species for NL with $757 million in landings (49,971 tonnes) and $761 million in exports (25,565 tonnes) in 2022 (Figure 1.1) (DFO, 2023b; Government of Newfoundland and Labrador, 2023).

Snow crab is a stenothermal species with a circumpolar distribution (Sainte-Marie et al., 2005; Dawe et al., 2012; Mullowney et al., 2023). Due to strong sexual size dimorphism in the species, the fishery is designed for a sex-exclusive harvest of males only (Sainte-Marie et al., 2008; DFO, 2019b; Mullowney et al., 2024), allowing females to escape since males are significantly larger than females at maturity (Sainte-Marie et al., 1995; Sainte-Marie et al. 1996). The NL snow crab season opens in early April and generally ends between mid-June to late July (DFO, 2019b). The fishery has inshore and offshore fleets with two vessel categories: <40’ and 40’ – 89’11” vessels (DFO, 2019b). Typically, larger vessels go offshore, and fishing trips are multiple days rather than going back to shore every night like the inshore vessels. Snow crab harvesters in the province fish using baited, top-entry, conical, “Japanese style” traps arranged in fleets (also referred to as trawls or long-lines) (Figs. 1.2 and 1.3) (DFO, 2019b). The number of traps per fleet is not regulated, however there are trap limits per enterprise (includes a fishing harvester (head), their registered vessels and their commercial licenses) (DFO, 2019b; DFO, 2024b). Typically, harvesters will string 25 to 100 traps together to form a fleet, the amount depending on the size of their vessels or simply their preference (Derek Day, personal communication, Portugal Cove, NL). Traps are typically set for several days depending on the weather, catch rates, regions, and harvesters (Nguyen and Winger, 2019).

Trap fisheries are generally considered to have less environmental impacts compared to many other types of active fishing gears (MacDonald et al., 1996; Jennings and Kaiser, 1998; Chuenpagdee et al., 2003), especially concerning discards, seabed interaction, size selectivity, and catch quality (Suuronen et al., 2012; Kopp et al., 2020). However, this does mean that there are no conservation issues associated with trap gears. Common issues related to this type of gear include lost gear and ghost fishing, capture of non-target species, discard mortality, as well as incidental megafauna interactions (Chuenpagdee et al., 2003; Johnson et al., 2005; Thomsen et al., 2010; Uhlmann and Broadhurst, 2015). In the last decade, due to an increased overlap between human activities and North Atlantic right whales, there is a growing concern over mortality and serious injuries from entanglement in fixed gear (traps and nets) resulting in a rapid population decline (Moore and van der Hoop, 2012). This issue, however, is far from new, it has been known to researchers and ongoing for years (Kraus, 1990; Caswell et al., 1999; Knowlton and Kraus, 2001).

With around 2,250 license holders in the province (DFO, 2023a), this means several thousand traps are deployed in NL waters at the same time. As a result, the number of vertical buoy lines in the water column at any one time around the island could be over ten thousand, representing a significant risk of entanglement for whales (Johnson et al., 2005; Moore, 2019).

1.5 Whalesafe Gear Adoption Fund

Over a 4 year period between 2015 and 2019, an unprecedented number of NARW were found dead or entangled in fishing gear in Canada (Davies and Brillant, 2019; DFO, 2021b). This prompted the creation of a number of protection measures by the Canadian government, including the Whalesafe Gear Adoption Fund which supported the purchase, development and testing of innovative fishing gears that aim to prevent or alleviate whale entanglement (DFO, 2021a). The fund provided nearly $20 million to 34 projects across Atlantic Canada during 2021-2023 (DFO, 2023c). The results were presented at a symposium in Moncton, NB in the fall of 2023, including presentations and posters on gear trials in various fisheries using low breaking strength (LBS) devices (e.g., Côté, 2023; Giffin, 2023; Skripsky et al., 2023; Winger and Peck, 2023) and on-demand fishing (e.g., Stevenson, 2023; Vézina, 2023). See summary report prepared by Fisheries and Oceans Canada (DFO, 2023d). Based on the results of these trials, DFO is currently developing the Canadian Whalesafe Fishing Gear Strategy (DFO, 2024a). Consultations are currently ongoing through the fall of 2024. DFO recognizes that a “one size fits all” approach will not be suitable, and that a range of existing and emerging gear innovation options will be required for Canada’s fisheries (DFO, 2024a). When finalized, the strategy will outline a five-year plan to review Canadian fisheries for their respective whale interaction and entanglement challenges, and to identify safe and effective gear innovation options and implementation timelines, including next steps, milestones, and progress indicators individualized to the diverse fishing conditions throughout Canada (DFO, 2024a).

1.6 Whalesafe Fishing Gear

Whalesafe fishing gear can be divided into two categories: entanglement prevention and entanglement mitigation. Preventive gear aims to eliminate entanglement risk by removing untended buoy lines in the water column while fishing by using “on-demand” systems with stowed ropes or lift bags and acoustic systems to retrieve traps (Myers et al., 2019; DFO 2024a). Mitigative gear is designed to reduce the risk of serious injury and mortality if entanglement occurs by reducing the length and severity of entanglement (Knowlton et al., 2018)

Knowlton et al., 2016 analyzed 132 different ropes retrieved from 70 entanglements of right, humpback, fin, and minke whales between 1994-2010 on the east coast of Canada and the U.S. For each case, the breaking strength of the ropes, injury severity and entanglement duration were estimated. Amongst other important results, the authors found that ropes with a higher breaking strength were linked to more severe injuries in whales, that longer entanglements led to increased injury severity, and that broad adoption of ropes with breaking strengths of ≤1,700 lbf (771 kgf) could reduce the number of life-threatening entanglements for large whales by at least 72% assuming they could withstand loads while fishing. These results prompted Canada and the U.S. to adopt a ≤1,700 lbf (771 kgf) threshold for LBS gear (DFO, 2024a; NOAA, 2024b). However, the authors also stated some important factors that should be considered when developing gear with reduced breaking strength to ensure their efficacy; they should have adequate strength to be able to withstand normal fishing forces to avoid unintentional breakage while hauling which can result in gear loss, they should be durable and have a sufficient operational lifespan, they should be effective for whale entanglement mitigation, and finally, they should be practical for fisheries allowing harvesters to use them without significant additional cost or effort. These four components (strength, durability, effectiveness, and practicality) should be considered and assessed when evaluating the suitability of LBS components for fisheries.

Low-breaking strength (LBS) components are tools for entanglement mitigation with a breaking strength of 1,700 lbf or lower, based on Knowlton et al. (2016). They are meant to be inserted in buoy lines and designed to break under extreme tension (i.e. when a whale becomes entangled) to prevent prolonged entanglement or drag and reduce the risk of serious injury or mortality (DFO, 2024a; NOAA, 2024b). However, they should also be strong enough to withstand typical loads in fisheries, durable, practical, and effective for entanglement mitigation, which isn't necessarily true even if they have a low breaking strength (Moore, 2019). LBS components come in many shapes to be compatible with different fisheries. There are plastic links, plastic swivels, breakaway links with weak stitching, weak rope inserts, and sleeves (NOAA, 2024b). When NOAA tests LBS components, the inserts must have an average breaking strength within 10 % of 1,700 lbf through 10 consecutive tests on a calibrated rope-breaking machine to be approved for use in the U.S. (NOAA, 2024b).

1.7 Research Objectives

This thesis aims to evaluate and to advise on the use and development of whale entanglement mitigation methods for baited trap fisheries in Atlantic Canada.

Chapter 2 documents an at-sea study conducted aboard the *F/V Island Voyager* in the fall of 2022. The main objective was to measure tension while hauling in the Newfoundland inshore commercial snow crab fishery to assess the suitability of LBS components as well as evaluate factors that affect the tension. Loads while fishing have never been measured in this fishery an due to the significant depths fished and the unique gear configuration (i.e., large numbers of traps per fleet), loads may be significant and may exceed the limits of LBS components. If tension exceeds 1,700 lbf, while hauling and LBS gear is used, it will break during fishing operations and may result in gear loss. Breakage of LBS components while fishing represents risks of endangering the safety of harvesters on deck, the creation of ghost gear and ensuing environmental repercussions, and loss of profit and time. Such repercussions highlight the importance of ensuring the suitability of LBS components and evaluating whether they are strong enough to sustain loads in fisheries before they are utilized. Measuring tension directly while fishing to detect the maximum loads experienced while hauling and comparing it to the LBS gear threshold should reveal if such components can be inserted in buoy lines while fishing without the risk of unintentional breakage.

Three treatments were deployed: traditional baited traps (TB); traditional unbaited traps (TU); and traditional traps without the polyethylene mesh netting (frames only) (W) to evaluate the effect of various trap components (catch and mesh) on tension while hauling, as well as document how tension may be affected by environmental conditions (wind and sea state). The following hypotheses were evaluated:

H0: Tension while hauling is independent of trap type (TB=TU=W).

H1: Tension while hauling differs for at least one trap type (TB≠TU≠W).

and:

H0: Tension while hauling is independent of wind conditions.

H1: Tension while hauling is dependent of wind conditions.

and:

H0: Tension while hauling is independent of sea state.

H1: Tension while hauling is dependent of sea state.

Overall, the research presented in this chapter is expected to inform decision makers and engineers on considerations that should be made when developing entanglement mitigation measures for this fishery. Additionally, the tension data collected can inform other research endeavors or gear engineering for similar fisheries globally by providing tension data for the retrieval of baited fleets of traps and investigating the role of different environmental conditions and components of traps in the creation of tension while hauling.

Chapter 3 documents a controlled benchtop laboratory study to evaluate the performance of a type of double threshold device called a time tension line cutter (TTLC). These devices are also inserted in buoy lines and designed to sever the line when sufficient tension is applied for a designated amount of time using a hydraulic piston system. This mechanism was developed in order to allow harvesters to safely retrieve their gear without risk of breakage in heavier fisheries with loads exceeding 1,700 lbf while hauling. Based on prior studies and the use of an oil-like hydraulic fluid within TTLCs, we hypothesized that the viscosity and time to cut (TTC), would be temperature dependent. The purpose of the study was to measure the effect of temperature on the device and evaluate if it affects its suitability for North Atlantic fisheries and performance as an entanglement mitigation device.

H0: Time to cut is independent of temperature.

H1: Time to cut is dependent of temperature.

How temperature affects the TTC of TTLCs must be evaluated in order to avoid TTCs outside a reasonable expected range. If TTCs are lower than the bottom limit of the range, TTLCs may sever lines while hauling which would be a safety concern for harvesters on deck, and may results in lost gear, posing further economic and environmental risks. If the TTCs are over the higher limit of the reasonable range, they may prolong entanglement and suffering, therefore increasing the risk of serious injury and mortality of entangled whales, i.e., they would not be practical nor have conservation benefits. This is why the effect of factors like temperature on their functioning must be properly understood so that they may be adjusted prior to fishery integration. Overall, this research aims to gain information on the functioning of TTLCs and identify areas where the mechanism could be improved or refined to better fit into fisheries while ensuring harvester safety and entanglement mitigation.

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1.9 Figures

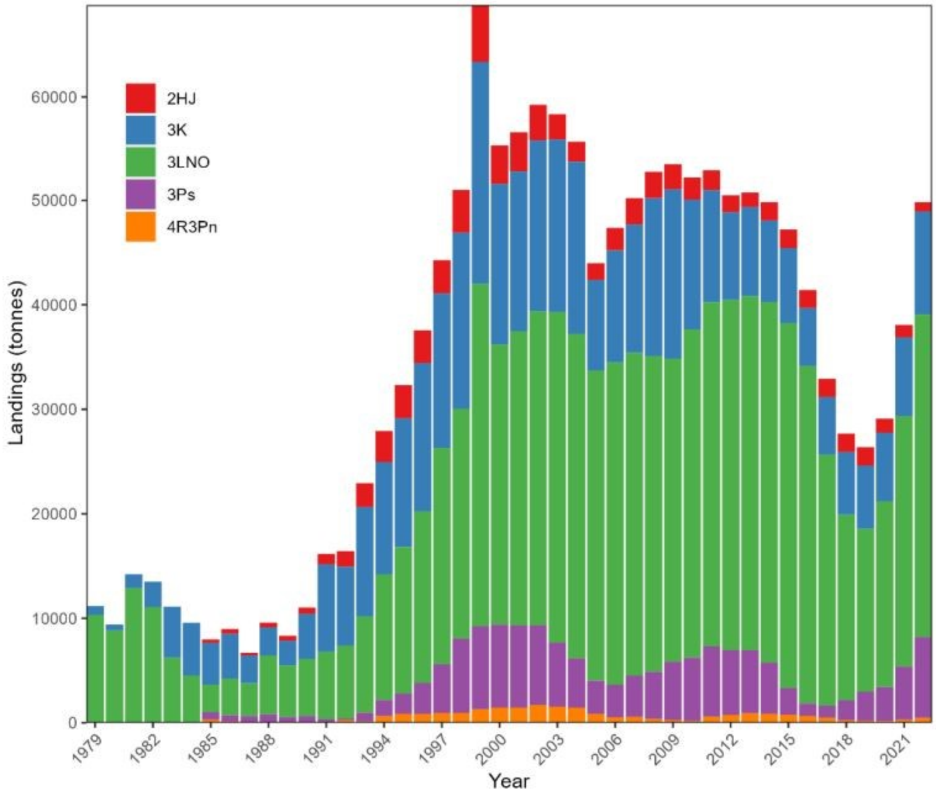

Figure 1.1 Annual landings of snow crab in Newfoundland and Labrador by NAFO Division (3LNO = 3LNO Offshore + 3L Inshore) from 1979 to 2022 (DFO, 2023a).

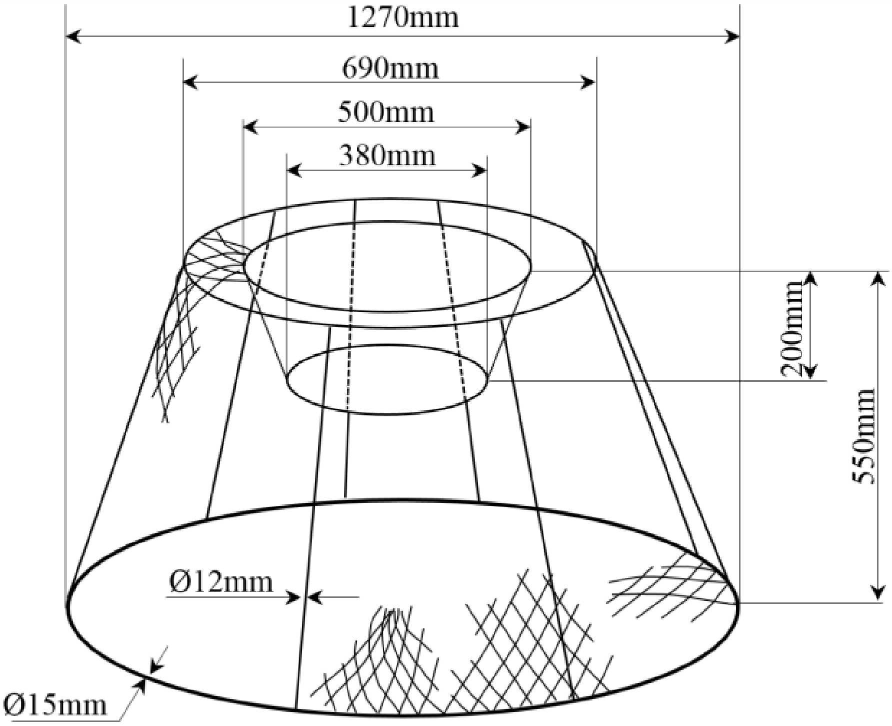

Figure 1.2 Line drawing of the conical snow crab pots used in this experiment (Nguyen, 2019).

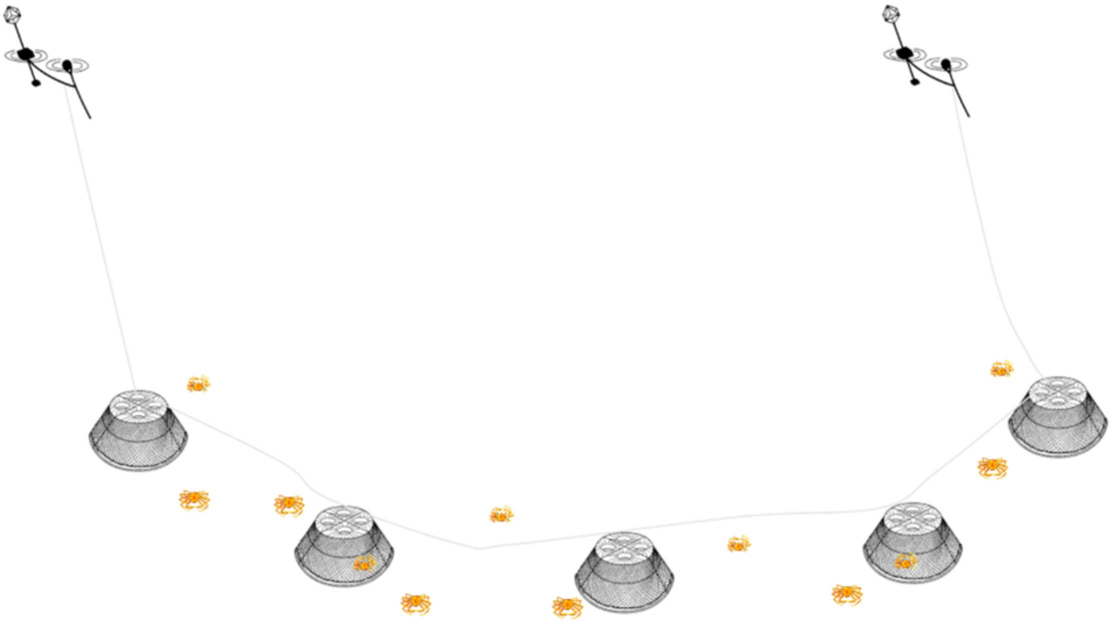

Figure 1.3 Diagram of Newfoundland snow crab fleet configuration demonstrating two highflyers and two buoys at the surface of the water on each end, attached by buoy lines to the traps that are connected to each other with a main line. Number of traps per fleet varies (Peck et al., 2024).

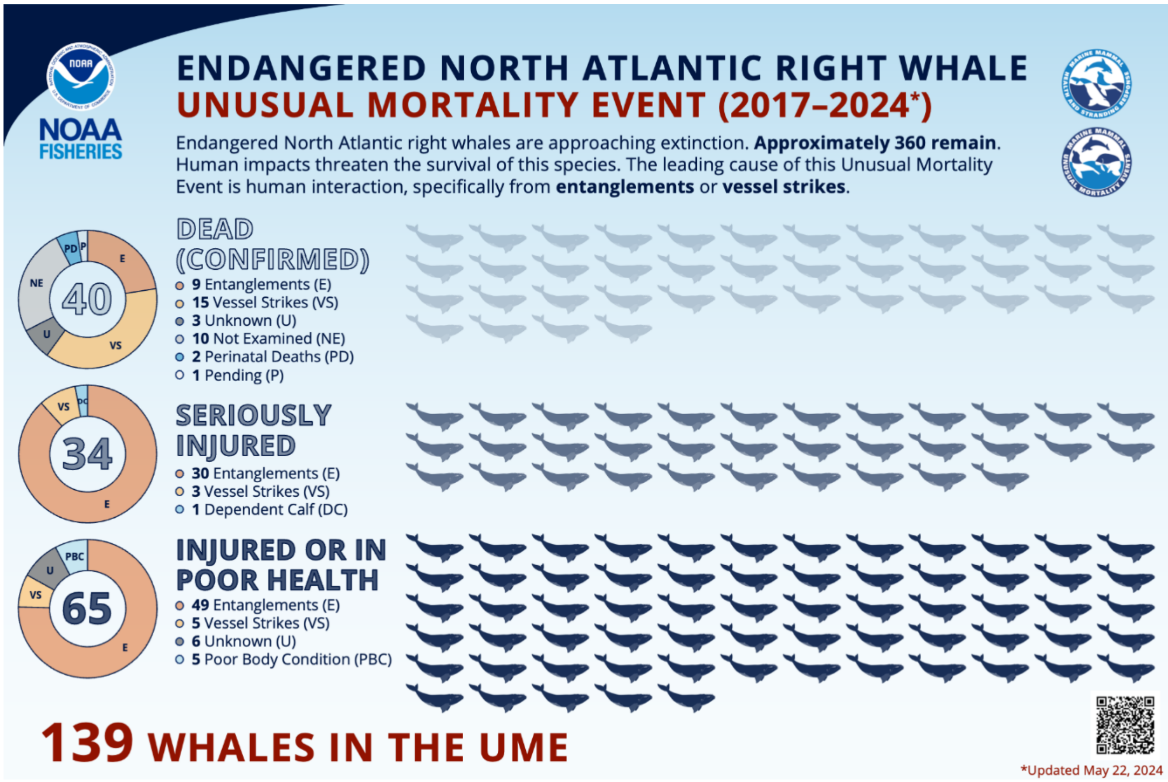

Figure 1.4 Infographic of North Atlantic right whales impacted by the ongoing Unusual Mortality Event (UME) since 2017. Data includes confirmed dead, injured, and sick individuals. Individuals are only counted once in the UME. A serious injury designation is attributed when a whale was alive at its last sighting, but injuries are severe enough that it is likely to die from those injuries. Pie graphs show the different causes of mortality, serious injury and morbidity (NOAA, 2024a).

Chapter 2: Hauling Snow Crab Traps in Eastern Canada: A Study Documenting Tension in Ropes

A version of this manuscript has been published in the journal *Fishes*, and is available at:

https://www.mdpi.com/2410-3888/9/5/154

Peck G, Araya-Schmidt T, Winger PD. 2024. Hauling Snow Crab Traps in Eastern Canada: A Study Documenting Tension in Ropes. *Fishes*. 9(5), 154. https://doi.org/10.3390/fishes9050154

2.1 Abstract

Entanglement in commercial fishing gear is one of the main factors inhibiting the recovery of critically endangered North Atlantic right whales. Installing low-breaking-strength (LBS) components in the buoy lines and main lines of stationary fishing gear may be a viable solution for some fisheries. But is it an effective solution for deep-water trap fisheries? This study quantified in-line rope tensions observed during fishing operations for snow crab (*Chionoecetes opilio*) in Newfoundland and Labrador, Canada. We conducted a controlled fishing experiment in which we documented the loads experienced while hauling fleets of traps. The results showed that several factors contributed to the loads observed, including the components of the traps, the presence of crab, and environmental conditions such as wind direction and wave height. According to the statistical models, the maximum tension from the estimated marginal means was 477.53 kgf in the buoy line and 987.99 kgf in the main line (line between traps) for the baited hauls, which exceeds the breaking strength of the proposed low-breaking-strength components. Our results suggest that LBS components are not a viable solution for this deep-water fishery.

2.2 Introduction

North Atlantic right whales (NARWs) are one of the most endangered whale species on Earth, with an estimated population of around 356 (+7/−10) individuals and fewer than 70 calving mothers (Pettis et al., 2023). Entanglement in commercial fishing gear is one of the main causes of mortality for NARWs and a major factor inhibiting the recovery of this species (Myers et al., 2019; Pace et al., 2021). Evidence indicates that any vertical line rising into the water column poses a significant entanglement risk for large whales (Moore, 2019), with trap/pot gear used in the lobster and crab fisheries posing the greatest risk (Myers et al. 2019, Johnson et al., 2005). The rate of entanglement for NARWs increased between 1980 and 2009, in part due to innovation and the adoption of ropes with higher tensile strength in many fisheries (Knowlton et al., 2012; Knowlton et al., 2016). Despite years of focused regulation and management efforts in the United States, there has been no decrease in the frequency or severity of entanglements (Knowlton et al., 2012; Pace et al., 2014; Henry et al., 2019; Pettis et al., 2023).

Alternative equipment (termed "whalesafe" gear) to reduce the amount and strength of vertical ropes in the water column have been developed for the fishing industry (Moore, 2019; NOAA, 2023). Whalesafe fishing gear aims to either prevent entanglement by reducing the amount of rope in the water column or alleviate entanglement by incorporating "weak" components in fishing gear to reduce the severity and duration of these events, improving the odds of survival for entangled whales. These "weak" components, also referred to as low-breaking-strength (LBS) components, are designed to break when they experience a set amount of tension. Examples include plastic links, plastic swivels, weak ropes, weak sleeves, and break-away links (NOAA, 2023). In most cases, these components are designed to fail at 1,700 lbf (771 kgf) +10% of tension based on Knowlton et al. (2016). Although not designed to prevent entanglements, these components should fail when an entangled whale exerts sufficient force to break the LBS component, thereby separating itself from a portion of the fishing gear, reducing the risk of serious injury and mortality due to entanglement (Knowlton et al., 2018). Ideally, these components can be used in fisheries where loads remain under the breaking strength of LBS components.

The Government of Canada recently announced plans to implement whalesafe fishing gear in non-tended, commercial fixed-gear fisheries in Atlantic Canada and Quebec to mitigate entanglements, starting with the voluntary use of such gear in 2024. While shallow inshore fisheries are likely to operate within the preferred 1,700 lbf (771 kgf) breaking strength, e.g., (Willse et al., 2022), additional research is necessary to evaluate the suitability of LBS components for offshore fisheries that experience heavy loads and use large-diameter rope to compensate for the significant tension. One of Canada's deepest and heaviest fisheries is the snow crab (*Chionoecetes opilio*) fishery off the coast of Newfoundland and Labrador (NL), Canada's easternmost province. With a landed value of nearly CAD 624 million in 2021 (DFO, 2022), snow crab is a significant economic contributor to the province. A barrier to the implementation and adoption of LBS components in this fishery is the unintended breakage and loss of gear during hauling procedures. The fishery is known for its significant depth (>300 m) and high number of traps per haul (Mullowney, 2020). Trap limits increase with vessel size (DFO, 2024), with smaller coastal vessels typically setting 25 traps in a fleet, and larger offshore vessels typically setting 100 and up to 200 traps in a fleet. The in-line tension in the buoy lines (rope connecting the surface buoy to the first trap) and main lines (or ground rope; rope in between traps) is expected to be high during hauling procedures owing to the thick ropes commonly used by harvesters to haul these fishing systems.

This study quantifies the in-line rope tensions observed during fishing operations for snow crab in Newfoundland and Labrador. We conducted a controlled fishing experiment in which we documented, with high precision, the loads experienced while hauling fleets of traps. We investigated several factors that contribute to hauling loads with the aim of determining whether LBS components are suitable for this fishery. This research aims to address significant knowledge gaps regarding LBS technology and the NL snow crab fishery in order to help make evidence-based decisions regarding the best path forward to reduce human-caused mortality of

NARWs while ensuring that the fishery remains sustainable. This research gathers crucial data that can inform decisions, as well as to provide lessons that may be useful in similar fisheries that require solutions for entanglement mitigation in order to protect fisheries, harvesters, and economies.

2.3 Materials and Methods

Study Site

A comparative fishing experiment was conducted in Conception Bay, Newfoundland and Labrador (Figure 2.1), aboard the fishing vessel *FV Island Voyager* (18 m length) between 26 October and 6 November 2022. Fleets of traps were set in a very small area to ensure substrate of the sea floor and water depth was similar to allow for comparison between trap types. The water depth at the study site ranged from 269 to 289 m and the substrate type was mud. Traps were set and hauled on 15 separate days. Environmental conditions during hauling were recorded, with wind speeds varying between 9 and 56 km/h and wave height varying between 1.0 and 4.5 m.

Fishing Gear

The traps used were the standard conical design with 140 mm stretched mesh, a bottom ring diameter of 133 cm, a volume of 2.1 m^3, and a top plastic entrance cone. The trap frame, which accounts for most of the weight, is ~12.5 kg (Brown et al., 2024). Three experimental treatments were evaluated (Figure 2.2) in order to identify how trap components contribute to loads while hauling:

1. W - frames only (no netting, cone, or bait);

2. TU - traditional traps unbaited;
3. TB - traditional traps baited with squid.

For each treatment, the traps were arranged in a fleet of fifty traps, 33 m apart and attached to a 1,617 m long, 16 mm diameter 3-strand polypropylene main line. No anchors were used. Two buoy lines of 402 m long of the same rope as the main line (16 mm diameter 3-strand polypropylene) were attached to buoys and high flyers on either side (Figure 2.3). Each fleet consisted of a single treatment (trap type). Fleets containing treatments 1 and 2 were deployed and hauled multiple times every day (weather permitting), while treatment 3 (baited traps) was deployed and hauled once per day to allow them to soak for at least 24 h, allowing enough time for crabs to enter the pots. The vessel was placed in neutral while hauling the gear, allowing it to stay over top of the gear during hauling. Catches were released immediately after sampling.

A wireless load cell, Euroload ELT24 (accuracy within ±1% of applied load), was calibrated and installed above the hauler (Figure 2.4) to measure the tension while hauling. Data were transmitted to a laptop computer on the bridge of the vessel in real time at a rate of 90 measurements per minute. Two images of the hauler and rope angle were taken per haul before the traps came aboard: one near the beginning of the haul, after the buoy, and another just before the first trap. These images were used to measure the angle of the buoy line in relation to the load cell (Figure 2.4). The average of all angles was 4.4° (0.08 rad), representing a decrease of 0.3% for the actual tension from the measured tension. A difference of 0.3% is well under 5% and was not deemed significant, indicating that the load cell was in-line, requiring no correction of the observed loads.

Statistical Analysis

All analyses were performed using R statistical software (version 4.2.1) (R Core Team, 2022). The response variable was maximum tension (kgf). To estimate the rope breaking strength required in the buoy lines and in the main line, two maximum tension values were extracted for each haul: the maximum tension before the first trap came aboard (buoy line; Phase A), and the maximum tension after the first trap came aboard (main line; Phase B).

The explanatory variables in the data exploration included “Treatment” (i.e., W, TU, or TB), “Depth”, “Wind Speed”, “Wind Direction”, and “Wave Height” and the random variable was “Haul” (i.e., haul 1 to haul 63). However, “Wind Speed” and “Wave Height” were highly correlated; therefore, “Wind Speed” was discarded from the model selection procedure (i.e., “Wave Height” was deemed to have a larger effect on the maximum tension). Two Gaussian generalized linear mixed-effect models (GLMMs) were fitted using the glmmTMB package (Brooks et al., 2017), one for Phase A and one for Phase B. A model selection procedure was followed, where the model with the lowest correction to Akaike’s information criterion (AICc) (Akaike, 1974) was identified and selected using the AICctab function in the bbmle package (Bolker, 2020). Model fit was assessed with a residual investigation, quantile–quantile plot, and dispersion test in the DHARMa package (residual diagnostics for hierarchical (multi-level/mixed) regression models) (Hartig, 2021). The model’s estimated marginal means for Phase A and Phase B were calculated with their respective 95% confidence intervals (CI) using the function emmeans from the emmeans package in R (Lenth, 2019).

2.4 Results

A total of 63 hauls were conducted during the experiment: 24 hauls for the fleet containing the frames only (W), 22 hauls for the fleet containing traditional unbaited traps (TU), and 17 hauls for the fleet containing traditional baited traps (TBs). The average weight of catch for the baited traps was 20.48 kg per trap and 1024.00 kg per fleet. The total time to haul the fleets was 43.7 min and 44.4 min, on average, for the W and TU fleets, respectively. By comparison, the treatment with baited traps (TBs) typically took longer (56.4 min on average) to allow time for the crew to empty the catch in all 50 traps after they came aboard. In Phase A, the maximum tension observed for the W fleet ranged between 21.04 and 448.2 kgf, between 16.24 and 814.60 kgf for the TU fleet, and between 16.61 and 917.46 kgf for the TB fleet. For Phase B, the observed maximum tension values were higher, ranging between 355.51 and 566.56 kgf for the W fleet, between 546.67 and 773.49 kgf for the TU fleet, and between 837.73 and 1,203.72 kgf for the TB fleet.

Figure 2.5 provides an example of the typical loads observed during the hauling of a fleet of baited snow crab traps. Phase A begins when the high flyer is taken aboard and the harvester inserts the rope into the hauler (time = 0). As the buoy line is drawn aboard the vessel, the tension increases, initially slowly as the slack rope is collected, and then more rapidly as traps begin to lift off the seabed towards the surface. This phase lasts, on average, 5.2 min. Phase B begins when the first trap is hauled aboard the vessel. At this point, the buoy line is completely onboard. The subsequent 45–55 min demonstrate the common hauling procedure until all traps are hauled. The variance in the tension over time (rising and falling) is largely determined by harvester behaviour. The speed of the hauler is dynamically manipulated by the crew using a hydraulic system. Typically, the operator increases the hauling speed (and resulting tension) between traps until the next trap breaks the water surface, at which point the operator slows the hauler (reducing tension) so the trap can be safely brought onboard. Once the trap is aboard, the hauler is accelerated (increasing tension) until the next trap breaks the water surface. The sequence repeats itself until all traps are brought aboard the vessel.

Statistical Model – Phase A

The lowest AICc GLMM model for Phase A included "Treatment" and "Wave Height" as explanatory variables and "Haul" as the random variable. When assessed for fit, quantile-quantile plot showed a straight line with non-significant deviation and uniform distribution (similar to quantile-quantile Normal plot), no patterns between residuals and model predictions and no over or under dispersion were detected. The result from the model indicated that the maximum tension was significantly reduced by 151.08 kgf (CI: 27.63–274.98 kgf) (*p*-value = 0.017) and by 212.26 kgf (CI: 90.99–333.53 kgf) (*p*-value = 0.005) for the TU and W fleets, respectively, when compared to the TB fleet (Table 2.1, Figure 2.6). Wave height was shown to be not statistically significant (*p*-value = 0.055). Estimated marginal means from the model indicated that the maximum tension for the TB fleet was 477.53 kgf (CI: 382.84–572.21 kgf), while the TU and W fleets produced maximum tensions of 326.44 kg (CI: 243.95–408.94 kgf) and 265.27 kgf (CI: 186.26–344.27 kgf), respectively, averaged over wave height variable.

Statistical Model – Phase B

For Phase B, the model with the lowest AICc included "Treatment", "Wind Direction", and "Wave Height" as explanatory variables and "Haul" as the random variable. When assessed for fit, quantile-quantile plot showed a straight line with non-significant deviation and uniform distribution (similar to quantile-quantile Normal plot), no patterns between residuals and model predictions and no over or under dispersion were detected. Similar to Phase A, hauling the TU fleet significantly reduced the maximum tension by 280.19 kgf (CI: 239.91–320.48 kgf) (*p*-value

< 0.0001) and hauling the W fleet significantly reduced the maximum tension by 525.71 kgf (CI: 486.41–565.01 kgf) (*p*-value < 0.0001) when compared to the TB fleet (Table 2.2, Figure 2.7). Wave height was statistically significant (*p*-value < 0.0001), and the model indicated that for every one unit increase in wave height (i.e., 1 m), the maximum tension increased by 42.35 kgf, averaged over trap treatment. Relative to an East wind direction, the North and South wind directions significantly increased the maximum tension by 129.81 kgf (*p*-value = 0.016) and by 91.52 kgf (*p*-value = 0.041), respectively, averaged over trap treatment. The remainder of the wind directions were not statistically significant when compared to the East wind direction (Table 2.2). Estimated marginal means from the model indicated that the maximum tension for the TB fleet was 987.99 kgf (CI: 954.72–1021.26 kgf), the maximum tension for the TU fleet was 680.60 kgf (CI: 651.61–709.58 kgf), and the maximum tension for the W fleet was 433.93 kgf (CI: 406.17–461.69 kgf), averaged over wave height and wind direction variables.

2.5 Discussion

This study measured tension in the inshore snow crab fishery in Newfoundland for the first time. We evaluated the tension in both the buoy lines (Phase A) and main lines (Phase B). The maximum tension across all three treatments in Phase A was lower than in Phase B, likely due to the lower number of traps that were elevated from the sea floor in Phase A.

Our results showed that the components of the traps contribute to the loads experienced. The addition of both netting and catch increased the tensions observed. According to the estimated marginal means from Phase A, traps with mesh (TU) had an increase in tension when hauling of 23.06% compared to frames only (W) and traps with catch (TB) showed a 46.28% increase in tension when hauling compared to traps without (TU). We attribute this increased load to increased hydrodynamic drag as the traps are lifted through the water column. Since crab are close to neutral buoyancy, drag forces are much more significant in water than the effect of gravitational force (i.e., weight) (Martinez, 1998; Fraser, 2006). Traps with netting had more drag than frames alone because of the additional contact area, and the mesh at the bottom of traps with catch were completely covered with crab, which also increased the area interacting with water and, therefore, the drag. Additionally, factors such as the number of traps per trawl have been shown to add significant tension while hauling due to the drag of traps on the seafloor increasing with the number of traps (Willse et al., 2022).

Environmental conditions (water depth, wind direction, wind speed, and wave height) were recorded during the experiment. Although water depth has been shown to increase load when harvesting lobster in the Gulf of Maine (Willse et al., 2022), this was not detected in our results. We attribute this to the limited range of depths in our study design. Wave height was shown to have no effect in Phase A, but increased tension significantly in Phase B. Willse et al. (2022) observed that loads when hauling are likely to increase in inclement weather. Our observations showed this only to be true for the main line connecting traps.

The authors recognize that there were limitations to the study. Principally, tension was measured across a limited range of depths and so the effect of depth on tension was not statistically detectable. The snow crab fishery encompasses depths of 50 to 600 m (DFO, 2015) but focuses mostly on depths of 200 to 400 m where legal-size males are more abundant (Dawe and Colbourne, 2002; Mullowney et al., 2018). While this experiment was conducted within the depth interval most commonly fished, further research should aim to capture a wider variety of depths to evaluate the relation between depth and tension in this fishery. The length of the fleets was not a varying factor in this study. Another study identified a drag effect increase with a greater number of traps in an inshore fleet (Willse et al., 2022); therefore, additional research on tension when hauling fleets of varying lengths should be conducted in this fishery.

The loads documented in this study significantly exceed the breaking strength of LBS components when hauling baited traps and even during a few unbaited traps hauls. Our results suggest that the use of LBS components would be an unwise gear modification for deep-water fisheries such as the snow crab fishery in eastern Canada since if at any point the tension surpasses the threshold of the LBS components while it is on the line, the component would break, and this would result in the loss of fishing equipment and likely ghost gear as depths are too great for grappling. Ghost gear not only poses a risk of entanglement and monetary loss for harvesters, but it also has the potential to have serious repercussions on the ecosystem due to the continuous capture of animals (Cerbule et al., 2023). LBS breakage also represents a safety risk for harvesters as it has been known to fly backwards out of the hauler after breakage as the energy (tension on the rope) in the system is released. Furthermore, evidence suggests that the entanglement severity was not reduced in areas where LBS components were used (Pace et al., 2014; Moore, 2019); however, the LBS components used at the time were inserted next to the surface buoy rather than lower in the buoy line where conservation benefits could be greater, and so much research remains to be conducted on them to assess their efficacy. Additionally, intact LBS inserts have been found on dead entangled whales, failure to release was not attributed to a specific cause but could have been due to a multitude of factors such as improper configuration, defective design, or insufficient strain at the site of insertion (Sharp et al., 2019). The above findings emphasize the need for further research and assessment of the value of LBS gear for large whale conservation before implementation is considered. There is also a need for future studies investigating where on the buoy line tension exceeds LBS thresholds and whether there is a location where LBS components could be placed without the risk of breakage while still having the potential to mitigate entanglements. Since LBS components are only placed on a small section of the buoy line, there is a chance they could be inserted at a point where tension isn't yet high while hauling however, there needs to be a careful balance between considerations for harvester safety and considerations for conservation. Additionally, with the diversity of the fishing industry and the many factors that affect tension, said location would most likely be different for most fisheries and possibly even each fleet. Nonetheless, the results obtained from this research should be considered for further studies and for the implementation of LBS components in this fishery and similar deep fisheries. Without considering the results obtained from this study and conducting thorough research, the adoption of LBS components has the potential to create serious environmental repercussions and negative impacts on harvesters and the province's economy.

In conclusion, this study involved a controlled fishing experiment in which we documented the loads experienced while hauling fleets of snow crab traps in eastern Canada. The results showed that several factors contributed to the loads observed, including the components of the traps and the presence of crab, as well as environmental conditions such as wind and wave height. The maximum tensions observed significantly exceeded the LBS threshold. Our results suggest that current LBS components are likely not a viable solution for this fishery on the basis of potential human safety risks, gear loss, and ecosystem impacts, however, an assessment of tension throughout the buoy line could highlight a "safe", low tension locations for LBS to be placed if one exists.

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2.7 Tables

Table 2.1. Generalized linear mixed model (GLMM) estimates, standard error, z value and p-value for hauling of Phase A (buoy line).

Phase A Model	Estimate	Standard error	Z Value	*p*-value
Intercept	363.89	81.08	4.488	<0.0001
Treatment: TU	-151.08	62.99	-2.399	0.016461
Treatment: W	-212.26	61.88	-3.430	0.000603
Wave height	47.41	24.74	1.916	0.055335

Table 2.2. Generalized linear mixed model (GLMM) estimates, standard error, Z value and p-value for hauling of Phase B (main line).

Phase B Model	Estimate	Standard error	Z Value	*p*-value
Intercept	834.812	51.339	16.261	<0.0001
Treatment: TU	-280.194	20.555	-13.631	<0.0001
Treatment: W	-525.712	20.052	-26.217	<0.0001
Wave Height	42.351	9.386	4.512	<0.0001
Wind direction: North	129.808	53.680	2.418	0.0156
Wind direction: North East	69.335	44.391	1.562	0.1183
Wind direction: North West	52.598	39.152	1.343	0.1791
Wind direction: South	91.517	44.803	2.043	0.0411
Wind direction: South West	9.345	40.226	-0.227	0.8206
Wind direction: West	42.351	9.386	0.232	0.8136

2.8 Figures

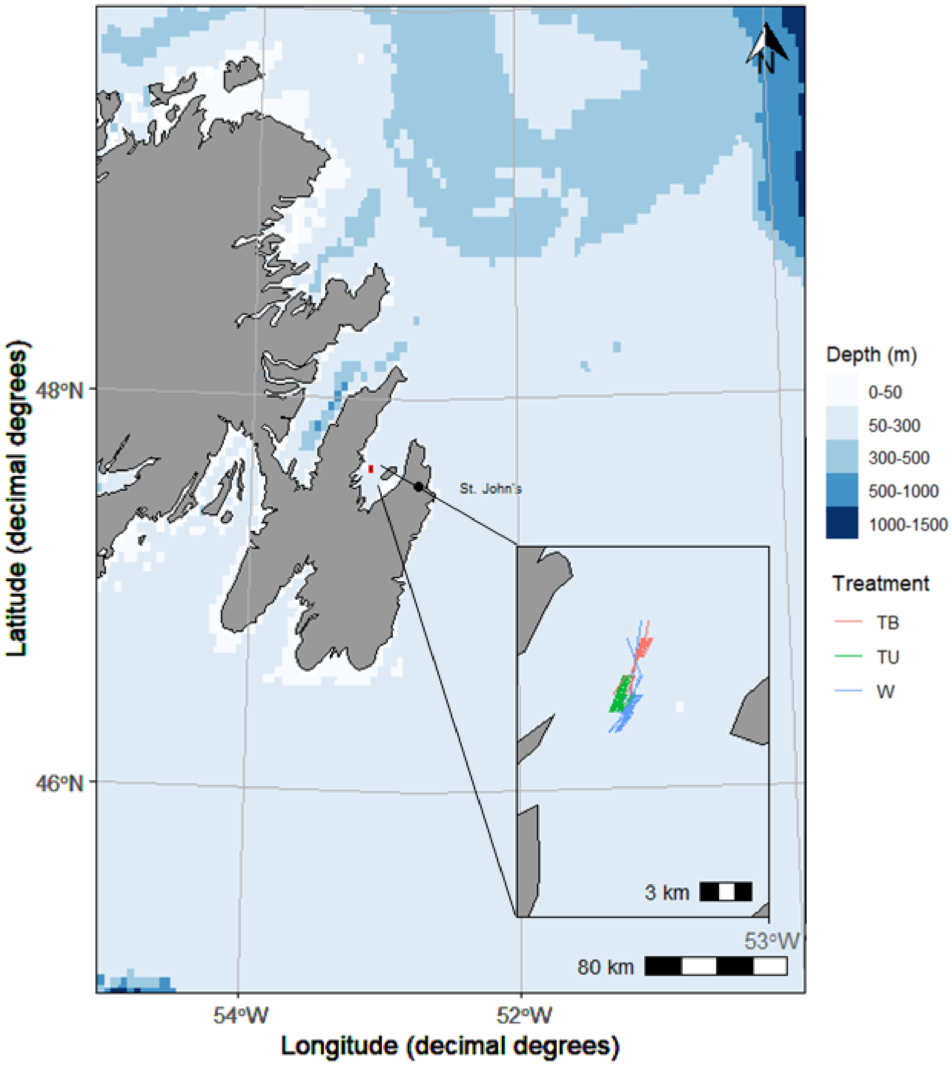

Figure 2.1. Map of the fishing area located in Conception Bay, Newfoundland and Labrador, Canada with an inset map of the fleets of traps deployed during the experiment coloured by treatment. Map was created using the ggOceanMaps package and ggOceanMapsData packages in R (Vihtakari, 2022). Arctic polar stereographic projection was used.

Figure 2.2. Picture of the two different types of traps used in the experiment. a) Frames only: traditional conical traps with mesh and entrance cone removed and b) unaltered traditional conical crab traps.

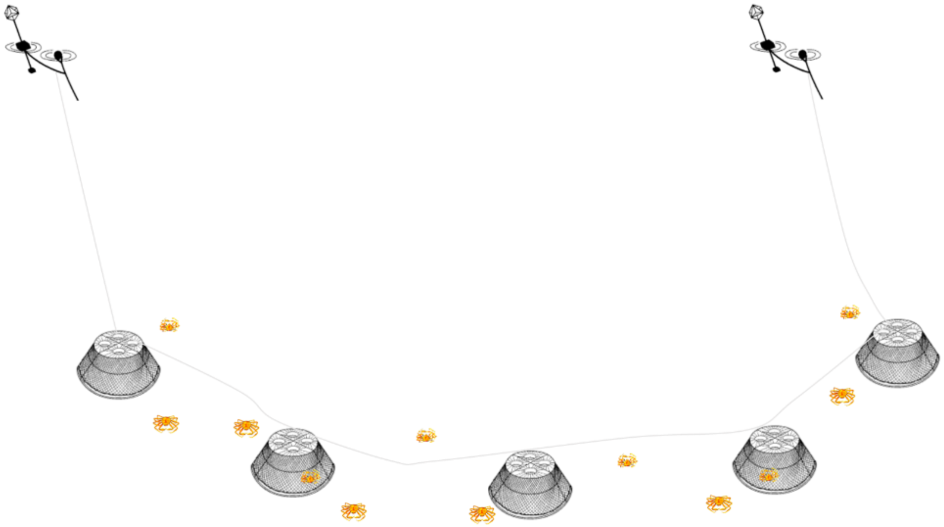

Figure 2.3. Diagram of fleet configuration demonstrating two high flyers and two buoys at the surface of the water attached to the two buoy lines of 402 meters, with a total of 50 traps per fleet.

Figure 2.4. Picture of the Euroload load-cell (ELT24) installed above the hauler aboard the *FV Island Voyager* fishing vessel during the experiment.

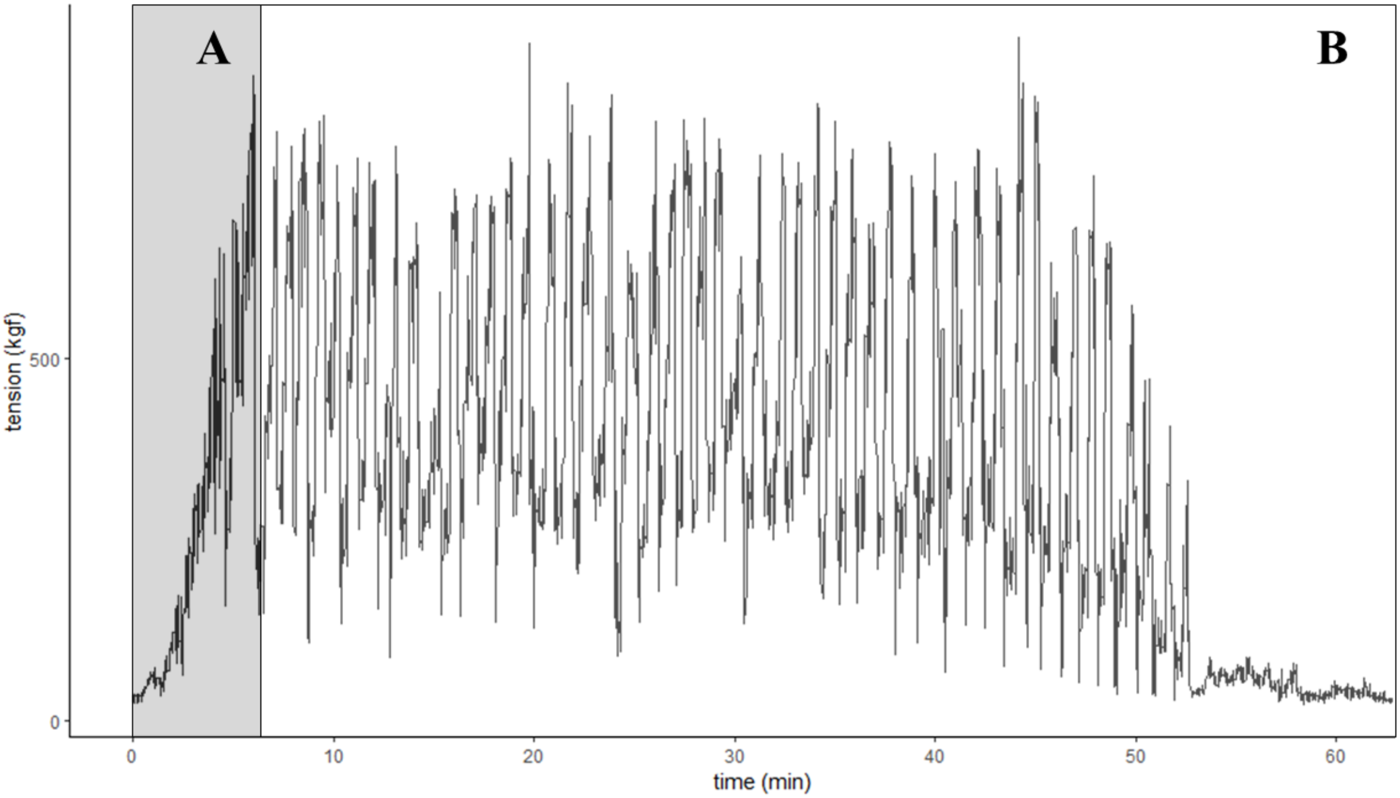

Figure 2.5. Representation of the tension in kgf through time in minutes of a typical haul of baited traditional traps (TB) with Phase A (shaded) and Phase B illustrated. Phase A is the healing of the buoy line beginning when the high flyer is taken aboard and the harvester inserts the rope into the hauler (time = 0) until just before the first trap comes aboard. LBS components would be inserted within this phase (in the buoy line). Phase B is the hauling of the main line, beginning when the first trap is aboard the vessel until the end of the haul. The visually identifiable fifty peaks are the points at which each of the fifty traps are brought aboard.

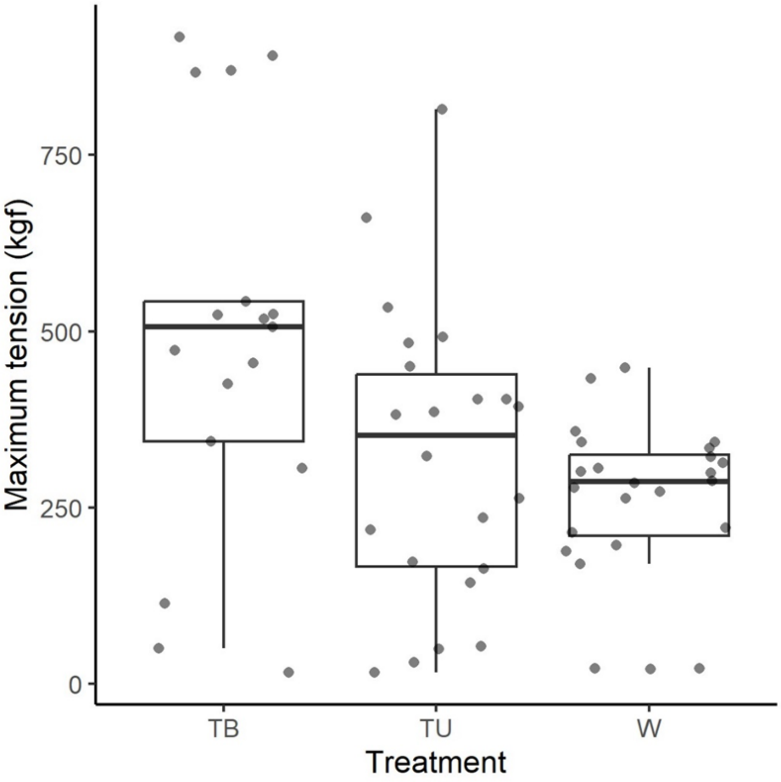

Figure 2.6. Box plot for the maximum tension per haul (kgf) during Phase A for all 3 treatments; frames only (W), traditional unbaited traps (TU), and traditional baited traps (TB). The bottom of the box represents the 25th quartile (Q1), the horizontal bar in the middle represents the median (Q2), the top of the box represents the 75th quartile (Q3). Dots show the observed values.

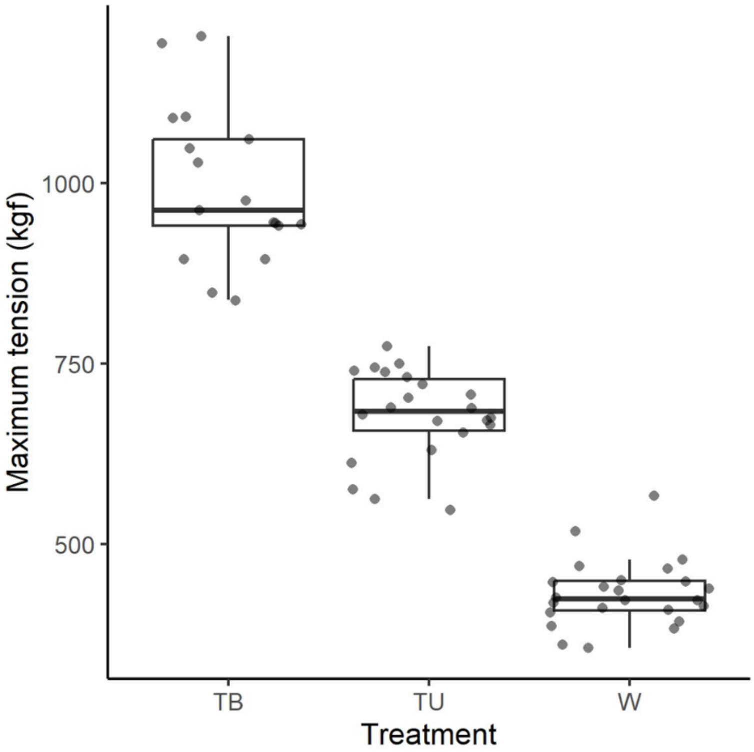

Figure 2.7. Box plot for the maximum tension per haul (kgf) during Phase B for all 3 treatments; frames only (W), traditional unbaited traps (TU), and traditional baited traps (TB). The bottom of the box represents the 25th quartile (Q1), the horizontal bar in the middle represents the median (Q2), the top of the box represents the 75th quartile (Q3). Dots show the observed values.

Chapter 3: Effect of Temperature on Cut Time of Time-Tension Line Cutters

3.1 Abstract

Entanglement in fishing gear is one of the primary threats inhibiting the recovery of critically endangered North Atlantic right whales (NARWs). To alleviate the severity of these entanglements, Fisheries and Oceans Canada (DFO) is promoting the voluntary adoption of low breaking strength modifications (LBS) for use in Atlantic Canadian fixed-gear fisheries. LBS components are required to break at 1,700 lbf (771 kgf) +10%, which raises safety and economic concerns for deep fisheries utilizing heavy equipment, such as commercial snow crab fisheries in Atlantic Canada, where loads regularly exceed 1,700 lbf (771 kgf). An alternative to LBS is time-tension line cutters (TTLCs). These devices allow harvesters to haul their gear at full strength They operate using hydraulic pistons that are calibrated to cut a buoy line after a set duration of constant load. This duration can be set to be longer than the normal haul time, allowing harvesters to haul gear at high tensions without risk of gear loss, whereas it would cut the line under the prolonged load applied by an entangled whale. This study evaluated the effect of temperature on cut time through a series of controlled experiments that reflect the conditions of the NL snow crab fishery using Blue Water Concepts Inc. TTTLCs. Results showed that the time to cut was significantly reduced by 0.759 min (CI: 0.571 – 0.947 min) for every unit increase in temperature (1°C) over the range of 4°C to 21°C which means that TTLCs may need to be calibrated according to temperature or manufacturers may need to develop temperature-cut timetables to ensure predictability of cut time at bottom temperature.

3.2 Introduction

North Atlantic right whales (NARWs) are one of the most endangered species of whales on earth (Kraus et al., 2005) and they are experiencing a recent rapid decline in population size which is caused mainly by entanglements and vessel strikes (Sharp et al., 2019; Henry et al., 2020; Knowlton et al., 2022; Pirotta et al., 2023). Injuries and stress resulting from entanglements specifically, have long lasting negative effects on NARWs' health and reproduction (Stewart et al., 2021; Knowlton et al., 2022; Reed et al., 2024). With severe entanglement injuries having increased since 2013, resulting in disproportionately higher mortality rates for females with calves (Linden et al., 2023), the population has been unable to recover (Knowlton et al., 2016, Linden et al., 2023).

With rapid technological developments in the fishing industry, the substitution of traditional gears for synthetic materials, which have a lower cost, improved durability, and increased breaking strength, and the expansion of fishing grounds to areas overlapping with the NARW range (Lien et al., 1986; Knowlton et al., 2016; Do and Armstrong, 2023), risks to NARW are not declining soon unless changes are implemented in fisheries. There continues to be an urgent need to amplify efforts to address sources of human caused mortality and serious injury to NARWs (Knowlton et al., 2022). Solutions to date include the use of i) low breaking strength (LBS) components in vertical buoy lines (Knowlton et al., 2016; NOAA, 2023b), ii) ropeless or on-demand technology (Baumgartner et al., 2019; Myers et al., 2019), and iii) time-area closures (Leaper and Calderan, 2018; Knowlton et al., 2022). Although eliminating buoy lines from the water column (i.e., on-demand systems) is the only sure way to decrease the risk of entanglement while fishing (Leaper and Calderan, 2018; Moore et al., 2021), some concerns associated with gear marking requirements, cost, and interoperability remain to be addressed prior to their implementation across all regions and fisheries (DFO, 2023; Cosensus Building Institute, 2024). Some limitations specifically are interoperability of the geolocation systems and cost per unit (Baumgartner et al., 2019; Alkire, 2022; Galvez et al., 2023). Alternatively, if unable to remove or reduce the risk of entanglement itself, there is an urgent need to at least minimize their severity. Low breaking strength (LBS) insertions are a mitigation method utilizing reduced breaking strength components and are currently being tested and utilized in some fixed gear fisheries in the US and Canada (NOAA, 2023a; DFO, 2024). These components are required to have a breaking strength of 1,700 lbf (771 kgf) + 10% that is presumed to enable whales to free themselves from the gear or reduce the amount of gear carried by entangled whales (Knowlton et al., 2016). However, the low breaking strength of these components may not work in deep water fisheries as they are currently conducted because of the extreme loads experienced, which are compensated for with the use of ropes with greater breaking strengths. Recent at sea observations have shown that hauling snow crab traps in eastern Newfoundland regularly and repeatedly generated tensions greater than 1,700 lbf (771 kgf) during hauling, suggesting that a different solution is needed (see Chapter 2, Peck et al., 2024).

Time tension line cutters (TTLCs) are a technology currently under development for use in deeper, heavy fisheries where LBS components are unsuitable and on-demand gear isn’t quite adapted to yet. They are a double-threshold device inserted in buoy lines (endlines above traps) that account for both time and tension, using a hydraulic piston system, spring, and cutting blade. TTLCs use a ‘bight loop’ system so they can be inserted on lines without cutting them and they can be repositioned easily. Inside a thick plastic casing, the hydraulic piston is kept from compressing inside the unit by the spring, but when a compressive force is applied, the piston forces fluid through a small hole and the top of the housing moves towards the base. The spring establishes the minimum cut threshold, and the time component dictates how long the tension must be sustained on the device before the fluid moves from one side to the other of the piston, at which point, the blade is exposed through the opening at the top of the housing and the endline is cut, allowing harvesters to retrieve gear at heavy loads without the risk of gear loss. When the compressive force is removed, the mechanism starts to reset, and the blade slowly retracts until it is back to its original position. A laminar flow restrictor is also encased within the system to manage the pressure so that at higher tensions, the fluid doesn't move faster, and the line isn't cut significantly quicker than the intended cut time. (Pickett, 2009; Justia Patents, 2020) (Figure 3.1). This hydraulic system aims for practicality, avoiding the use of batteries and electronics that would require regular maintenance and/or recharging. TTLCs allow harvesters to retrieve their gear at full strength (within the time limit) but they could also reduce the risk of serious injury to entangled whales by separating the buoy line from the trap (or traps), provided that a whale could sustain sufficient tension for sufficient time (Baldwin and Picket, 2009; Pickett, 2009). A previous version of the BWC TTLCs were tested by Picket et al. (2009), these older units differ from the new ones because they were tensional units in which the line was tied to both ends of the shell and the mechanism was activated by tensional separation force, while the new ones use a "bight-loop" system and need a compressive force to engage the mechanism instead (Justia Patents, 2005). Due to the use of an oil-like hydraulic fluid, it is hypothesized that, as with the previous version of TTLCs, a change in viscosity caused by a change in temperature will in turn, alter the speed of fluid movement within the unit (i.e., time to cut) (Pickett, 2009). We intended to evaluate if or how time to cut (TTC) may be affected in the newer version of these TTLCs. We aimed to identify or evaluate that effect through a series of temperature-controlled experiments that reflect the conditions of commercial fisheries in Atlantic Canada. These experiments represent the first time this version of TTLC is tested and assessed for implementation and will demonstrate whether they are a suitable LBS solution for harvesters. If TTLCs are suitable for these fisheries, their use could reduce the severity of entanglement injury to NARWs, without gear loss or implications to harvester safety.

3.3 Materials and Methods

Time Tension Line Cutters

The time tension line cutters (TTLCs) used in these trials were black plastic units with a length of 34 cm and a diameter 9.5 cm purchased from Blue Water Concepts Inc. (BWC), based in Eliot, Maine in the U.S., and were received in January 2023. BWC TTLCs are a type of compressive force rope severing device. The rope severing device includes a plastic housing composed of a base and a top that have grooves on either side to accommodate a rope inserted into the device, and a blade fixed within the top housing (Figure 3.2). Upon application of a compressive force to the unit, the top moves toward the base, and the blade is partially exposed through an opening in the top to sever a rope attached to the device (Justia Patents, 2020). Their mechanism also includes a laminal flow restrictor that works by relieving the pressure between both valves, in a similar way that a scuba tank pressure regulator would work, to ensure the device doesn’t cut significantly quicker than intended when subjected to higher tensions (Justia Patents, 2020). It also has a dump valve that engages once the unit is compressed enough and the distance between the blade and the rope is close to none. When engaged, it causes the final distance, before complete compression of the unit, to happen rapidly and briskly, a sort of “point of no return”, and aims to swiftly cut the rope in its entirety and avoids instances where the rope is merely nicked or cut halfway. TTLCs are fully enclosed and factory calibrated so they cannot be adjusted by the user. When in use, TTLCs are meant to be inserted in buoy lines, with one device per line, ideally between the mid-point and the first trap but preferably immediately before the first trap (bottom of the buoy line) to facilitate the passage through the hauler. Upon purchase, the manufacturer stated that these specific units are set to sever ropes between 10-20 minutes of constant 1,700lbs (771kfg) tension. A total of ten (n=10) TTLCs were randomly selected to be tested from the 200 units purchased.

Chilling The Units

The units tested at 4°C and 12°C were chilled prior to trials by being submerged in a double walled plastic tank inside a smaller plastic bin filled with 70 liters of fresh water attached to an ActiveAqua AACH10HP water chiller (Figure 3.3) by 1 inch (2.5 cm) vinyl tubes wrapped in foam pipe insulation for at least 24 hours before each pull. Water was circulated between the tank and the chiller by a Little Giant PondWorks statuary fountain pump model PES-80-PW.

Time to Cut Trials

Trials measuring the time to cut (TTC) were conducted at the Fisheries and Marine Institute of the Memorial University of Newfoundland. Individual units were tested using a Constant Rate of Traverse (CRT) Tensile Test Machine (see Winger et al., 2015 for description) and an HRS-10K hermetically sealed stainless steel load cell from Load Cell Central, based in Milan, Pennsylvania, U.S., with a 4,536 kg capacity. The load cell was calibrated prior to trials and calibration was verified each day before testing. Segments of 16 mm 3-strand polypropylene rope were precut and tucked 3 times on each end to create loops so they could be attached to the arms of the tensile machine with clevises. Ropes were kept dry, as per International Organization for Standardization (ISO) testing procedures (International Organization for Standardization, 2019), and inserted in the devices immediately before testing. Each of the 10 TTLC units was tested once at each of the 3 temperatures. First at 4°C, then at 12°C, and finally at 21°C, an order which was chosen randomly. All tests of the same temperature (n=10) were completed before starting the next round of testing for logistical reasons. See Tables 3.1 to 3.3 for details. None of the units had been used prior to these trials. A new blade was installed in the units after each cut. After being kept at testing temperature for a minimum of 24 hours, TTLCs were then loaded onto the machine and a static load of 1,700 lbf (771 kgf) was applied. Temperature while testing was room temperature (21°C). As tension decreases when the rope compresses the cylinders and the gap closes, the load was adjusted to the upper 10% threshold allowance (1,870 lbf) every minute to ensure it stayed consistent throughout the trials. A timer was started when tension reached 1,700 lbf (771 kgf) and stopped as soon as the rope was cut all the way through. For the 21°C trials, TTLCs were left on a benchtop at room temperature for at least 24 hours before being tested again following the above procedure.

Statistical Analysis

All analyses were performed using R statistical Software (version 4.3.3) (R Development Core Team, 2022). The response variable was time to cut (TTC) in minutes, with temperature as an explanatory variable. Due to the high degree of variability between units, we included individual units (ttlc_sn) as a random effect.

Levene's test was conducted to check equality of variance between groups (temperature). A Gaussian Generalized Linear Mixed-effect Models (GLMM) was fitted using the glmmTMB package (Brooks et al., 2017). A model selection procedure, where the model with the lowest correction to Akaike's information criterion (AICc) (Aikaike, 1974) was identified and selected using the AICctab function in the bbmle package (Bolker and R Development Core Team, 2020). Model fit was assessed with a residual investigation, quantile-quantile plot and dispersion test in the DHARMa package (residual diagnostics for hierarchical (multi-level/mixed) regression models) (Hartig, 2021). The model's estimated marginal means were calculated with their respective 95% confidence intervals (CI) using the function emmeans from the emmeans package in R (Lenth, 2019).

3.4 Results

A total of 10 tests were conducted at each of the 3 different temperature treatments for a total of 30 tests. The resulting time to cut (TTC) was between 9 and 38 min at 4°C, between 7 and 19 min at 12°C, and between 4 and 15 min at room temperature (21°C). The hypothesis that that variance was equal between groups was rejected (p-value: 0.0228).

The lowest AICc GLMM model included "Temperature" as the explanatory variable and "Unit Serial Number" as the random variable. When assessed for fit, quantile-quantile plot showed a straight line with non-significant deviation and uniform distribution (similar to quantile-quantile Normal plot), no patterns between residuals and model predictions and no over or under dispersion were detected. The results from the model indicated that the TTC was significantly reduced by 0.759 min (CI: 0.571 – 0.947 min) (p-value: <0.0001) for every unit increase in temperature (1°C) (Table 3.4, Figure 3.4). Estimated marginal means from the model indicated that TTC at 4°C was 21.46 min (CI: 17.93 – 25.0 min), while at 12°C and 21°C, TTC was 15.39 min (CI: 12.26 – 18.5 min) and 8.55 min (CI: 4.99 – 12.1 min), respectively.

Between unit variability in the sensitivity to temperature was also observed. Figure 3.5 shows the variability in TTC between units at the same temperature for all three tested temperatures and the variable effect of temperature on individual units. Standard deviation for the 10 units tested was 8.7 min at 4°C, 4.0 min at 12°C and 3.3 min at 21°C.

3.5 Discussion

This study represents the first temperature testing of these compression TTLCs from BWC. We measured the TTC of the randomly selected devices at 3 different temperatures.

The results show that as water temperature lowers, the resulting TTC increases. These results corroborate our hypothesis that the viscosity of the hydraulic fluid, and resulting performance, of the TTLCs is affected by water temperature. This finding is consistent with Baldwin and Landino (2007) which compared TTC at 40°F (4.4°C) and room temperature (21°C) and found that TTC at 4.4°C was double TTC at room temperature. As a result, we recommend that when applying the technology to different fisheries, knowledge of the water temperature near the seafloor would be beneficial so appropriate adjustment to the units could be conducted by the manufacturer prior to purchase to ensure the units do not deviate greatly from intended TTC as lower TTCs are a concern for harvester safety and gear loss and higher TTCs are a concern for entangled whales.

The results also demonstrated that the variability differed between temperatures, showing that not all units responded in the same extent when temperature changed. This could be due to the nature of the hydraulic fluid inside the units. While our knowledge of the fluid is limited as it is protected by trade secret (Ben Brickett, personal communication, Eliot, Maine, U.S.), we do know from conversations with BWC that it is an oil-like fluid with non-Newtonian properties, and it may not always be completely homogeneous when the unit is received from the manufacturer. If that is the case, as it is pushed through the piston for the first few times, its movement speed may vary depending on the viscosity of the fluid going through at any given moment. Since the TTC varies the most at 4°C and those tests were conducted first, it could be because the fluid was not completely mixed at that time. BWC tests every device before it is sent out however, it is unknown how many pulls would be needed to properly mix the fluid if that is the case. Further, whether the fluid remains mixed after cutting and if units being left idle for extended periods of time causes the fluid to separate again also remains to be assessed. Additionally, this variation could be dependent on the temperature at which the units were tested by the manufacturer. Ideally, the manufacturer should produce units that are able to consistently cut at a desired time (+10%), at a specific temperature (i.e., bottom temperature of a specific fishery).

Over half of the TTLCs tested at room temperature had a TTC outside of what was specified by the manufacturer upon purchase which was between 10 and 20 minutes. Additionally, the TTC at 4°C was as low as 9 minutes and as high as 38 minutes. These two extremes are a concern as the unit cutting prematurely could result in gear loss, and an overdue cut could prolong whale suffering in the event of an entanglement and thus, these deviating values are a concern for integration of these devices in fisheries. In previous studies, the main factor explaining the inconsistency of the units was attributed to blades becoming dull or damaged after a number of pulls (Baldwin and Picket, 2009) however, our protocol eliminated this source of bias.

In the case of U.S., fisheries, for LBS gear to be approved, approval standards state that the breaking strength must be within 10% of 1,700 lbs (771 kgf) (NOAA, 2023b). While TTLCs are a double threshold device, it could be assumed that TTC should also be within a certain range in order to obtain approval. However, they differ from other LBS gear types in the way that they are reusable; when the threshold is exceeded, the line is cut, but the device itself does not break, as other components do. Therefore, unlike other LBS components which are destructible, a TTLC unit can be repeatedly tested rather than requiring multiple separate units to be tested as per NOAA's current testing protocol (2023b). This type of testing remains to be done to assess the consistency of a single unit over several trials. Nonetheless, units marketed as having the same TTC should be within a reasonable range of that TTC to ensure reliability, harvester safety and, reduction of prolonged suffering and serious injury or mortality to entangled whales.

Furthermore, TTC at temperatures similar to seawater near the seafloor (4°C) was over 20 minutes for 6 of the units and over 25 minutes for 4, with the highest time being 38 minutes. It is unknown if an entangled NARW could maintain a of tension over 1,700 lbf (771 kgf) on the line for that long. Evidently, as with other LBS components, the conservation benefits of TTLCs need to be assessed before they are approved. The risk when implementing LBS components is not only that they may not mitigate entanglements, but that they also pose a risk for harvester safety and they have the potential of creating lost fishing gear which poses a threat to many marine animals (Unger et al., 2016; Wilcox et al., 2015; Werner et al., 2016) including cetaceans (Baulch and Perry, 2012; Kühn et al., 2015), amongst numerous other negative environmental repercussions (Brown and Macfadyen, 2007; NOAA, 2015; Wilcox et al., 2016; Werner et al., 2016). This concern is evident as some TTLCs trialed had a concerningly low TTC. As a result, a harvester may not have time to retrieve their gear before the line is cut before the time at which it is expected to. For conservation purposes, there may be a need for a maximum time threshold at which TTLCs are required to cut in order to ensure entanglement mortality and injury risk reduction, and a minimum to avoid gear loss and ensure harvester safety. Typically, harvesters in deeper fisheries would require between 5-15 minutes to haul the buoy line (surface buoy to first trap) completely. If the units can be tuned to cut at a specific time for a requested temperature, as mentioned above, this concern could be eliminated. A laminal flow restrictor is contained within the TTLCs, as mentioned above, nonetheless, the effect of tension on TTC should be investigated before adoption to ensure the laminar flow restrictor functions as intended and the TTC is not significantly reduced at high tension as tension regularly exceeds 1,700 lbf (771 kgf) in some fisheries where the devices could be utilized (Peck et al., 2024).

While TTLCs were not kept at temperature during testing, we do not expect that this had a major effect on results due to the thick plastic casing surrounding the piston and hydraulic fluid. Keeping TTLCs at temperature while attached to the tensile strength machine was considered during protocol development but ultimately, precise methods were logistically unfeasible. We recognize this may have introduced a small (but standardized) bias in TTLC performance.

Additionally, this study only utilized one rope size throughout the experiment which was chosen based on what is commonly used in heavier gear fisheries (Peck et al., 2024). Rope size could be a factor affecting TTC since it represents a greater distance for the blade to travel in order to sever it completely. However, the TTLC’s dump valve (described in material and methods above) may eliminate this concern and mean that changing rope size would not affect

TTC, if tension and time are the same throughout, since the valve should dump and completely cut the rope in the same amount of time however, it could be taken into consideration for further testing.

Finally, this experiment did not investigate considerations associated with the installation or utilization of TTLCs in fisheries. Past research has identified a few concerns from harvesters related to the safety and ease of use of the devices. In a study by Stoni (2021), harvesters identified that the TTLC going through the block and hauler was their main concern, followed by safety. The hauler is a hydraulically or electronically powered piece of equipment that includes a sheave and a swiveled pulley block, the fishing line is placed over the block then gripped around the sheave which pulls it from the sea. The narrow space in which the rope fits over the block and within the sheave is not accommodating to bigger equipment such as TTLCs and removing the rope from the hauler while hauling is a safety concern for crew members. Additionally, a pilot study by Baldwin and Pickett (2009) collected feedback from harvesters after using TTLCs and highlighted a concern that the units sink when deployed, resulting in the TTLCs and attached lines interacting with the bottom which increases the risk of them becoming lodged, especially on hard substrates where the TTLC can roll easily, making retrieval more difficult. Suggestions included making the unit square rather than round to minimize rolling or adding some kind of flotation component to avoid contact with the bottom completely. In the most recent version of the BWC TTLC, there is a small twine attached to one end which can be weaved into buoy lines to prevent slippage but none of the other aforementioned concerns seem to have been addressed. While some of these may be due to unfamiliarity of harvesters with the device and could be dissipated after prolonged regular usage, as they become accustomed to the TTLCs and adjust to their presence on the lines, ease of usage and harvester safety are crucial factors for any and all

LBS gear that is being considered for implementation, highlighting the need for at sea trials of the devices.

In conclusion, this study documented the engineering performance of TTLCs in a controlled benchtop study. TTC was measured across several temperature treatments, ranging from room temperature to low temperatures expected near the seafloor. The results revealed extreme high and low values at the lowest temperature tested (4°C). The cause of which being still unclear and possibly related to the procedure. The testing procedure was developed in accordance with the NOAA (2023b) testing protocol for approved inserts, however, due to the unique case TTLC represents as far as LBS components go, an individualized testing protocol should be developed for further testing of the device based on these results. This research provided preliminary steps towards that goal.

These results suggest the manufacturer should continue to improve this technology to narrow the range of TTC between units with the same or similar calibration and, if possible, standardize their sensitivity to temperature. If unable to, the units could also be tested to create a table of cut time ranges according to temperature available at purchase so harvesters can choose their units according to their needs. If these changes are able to be made, we recommend that TTLCs should then be further tested in a controlled environment to re-evaluate performance and reliability, followed by at sea trials to determine the suitability and functionality of the technology while fishing. The device’s ability to survive in deep harsh environments with repeatable performance, fishability, and ease of use should especially be investigated with ample trials. Finally, modification to prevent tampering and ensure the use of the device can be easily enforced will be crucial before they are approved and implemented. Overall, while some adjustments remain to be made, these TTLCs seem to be sturdy, utilize advanced technology, and have many factory-adjustable parameters that show great potential for success once refined.

While this technology shows promise for integration in fisheries where traditional LBS inserts are not suitable, they are simply a mitigation method and do not prevent or reduce the risk of entanglement. They could, however, provide a temporary solution until prevention methods are developed. Ultimately, preventing entanglement by removing ropes in the water column is the most effective way to reduce interactions with whales and fisheries and promote NARW recovery (Leaper and Calderan, 2018; Moore et al., 2021).

3.6 References

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3.7 Tables

Table 3.1. Details of the TTLCs evaluated at 4ºC in the controlled laboratory study.

Unit No.	Serial No	Date Tested	Temperature Treatment
1	03326	11-Apr	4ºC
2	03383	12-Apr	4ºC
3	03140	12-Apr	4ºC
4	03162	12-Apr	4ºC
5	03382	15-Apr	4ºC
6	03177	15-Apr	4ºC
7	03213	15-Apr	4ºC
8	03160	15-Apr	4ºC
9	03028	15-Apr	4ºC
10	03221	16-Apr	4ºC

Table 3.2. Details of the TTLCs evaluated at 11ºC in the controlled laboratory study.

Unit No.	Serial No	Date Tested	Temperature Treatment
1	03326	22-Apr	11ºC
2	03383	22-Apr	11ºC
3	03140	24-Apr	11ºC
4	03162	24-Apr	11ºC
5	03382	24-Apr	11ºC
6	03177	24-Apr	11ºC
7	03213	25-Apr	11ºC
8	03160	25-Apr	11ºC
9	03028	25-Apr	11ºC
10	03221	25-Apr	11ºC

Table 3.3. Details of the TTLCs evaluated at 21ºC in the controlled laboratory study.

Unit No.	Serial No	Date Tested	Temperature Treatment
1	03326	25-Apr	21ºC
2	03383	25-Apr	21ºC
3	03140	25-Apr	21ºC
4	03162	25-Apr	21ºC
5	03382	25-Apr	21ºC
6	03177	25-Apr	21ºC
7	03213	26-Apr	21ºC
8	03160	26-Apr	21ºC
9	03028	26-Apr	21ºC
10	03221	26-Apr	21ºC

Table 3.4. Generalized linear mixed model (GLMM) estimates, standard error, z value and p-value for hauling of Phase A (down rope).

Model	Estimate	Standard error	Z Value	*p*-value
Intercept	24.49700	1.92631	12.717	<0.0001
Temperature	-0.75922	0.09591	-7.916	<0.0001

3.8 Figures

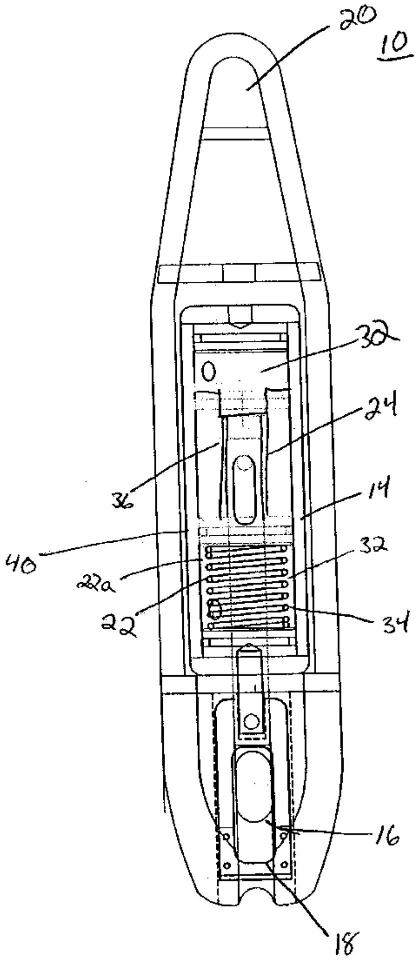

Figure 3.1 Annotated image of the inner workings of a Blue Water Concepts Inc. TTLC (10). TTLC patent drawing of the mechanical components of the TTLC. The Flow is initiated by compressing the spring (32) and driving hydraulic fluid through the restrictive orifice (36, 24), and into the secondary fluid reservoir (32). This advances the blade (16) into the line and cuts it. This specific image is showing a tensional separation unit however, manufacturer states that for the compressional units (used in this study), the forces within the cylinder were reversed but everything internally remained the same (Justia Patents, 2005; Pickett, 2009).

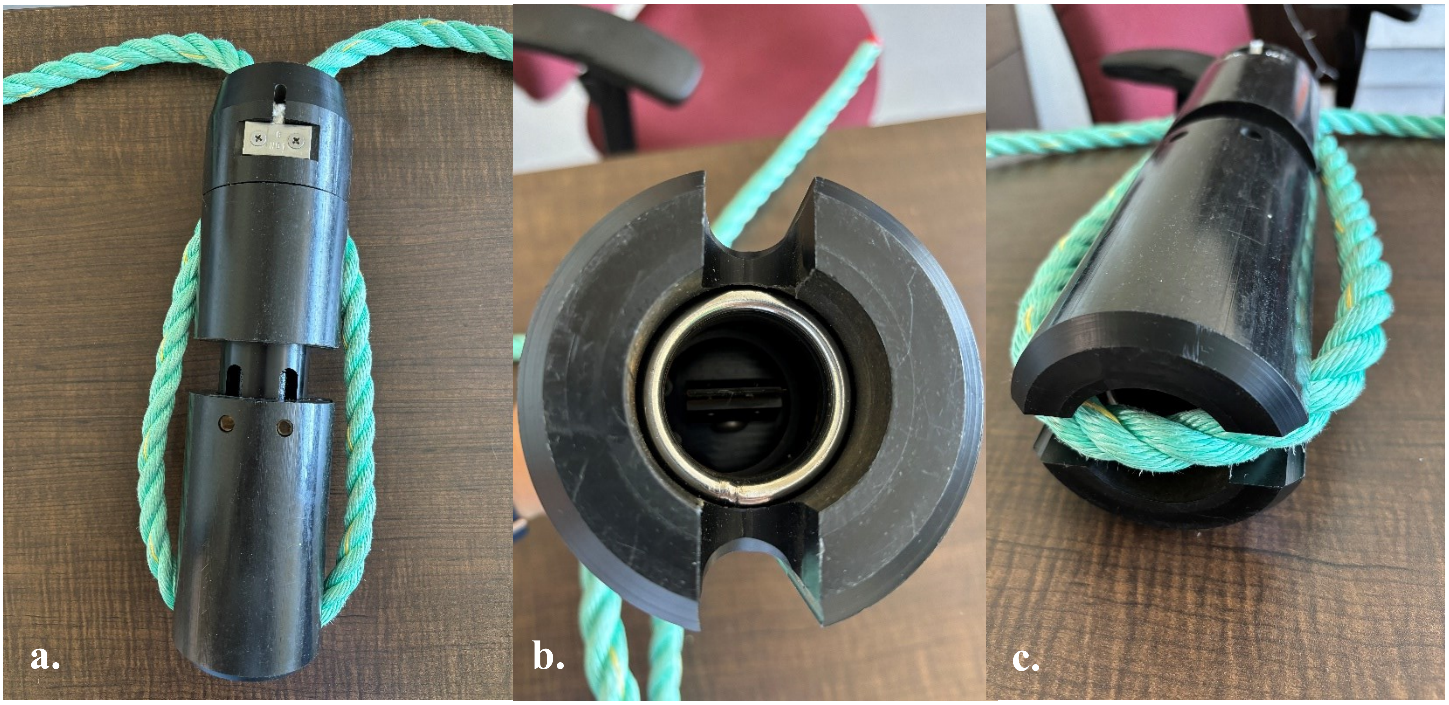

Figure 3.2 Photographs of a TTLC: a. Shows the unit attached to a rope, showing how the rope inserts through the top and loops around the unit. b. Shows the top of a TTLC without rope. The blade within the black casing and grooves on either side where the rope is held in place are visible. c. Shows the top of the unit again with the rope in place within the grooves. The blade is under the rope.

Figure 3.3. ActiveAqua AACH10HP water chiller used to chill a tank of water containing TTLCs to 4°C and 12°C.

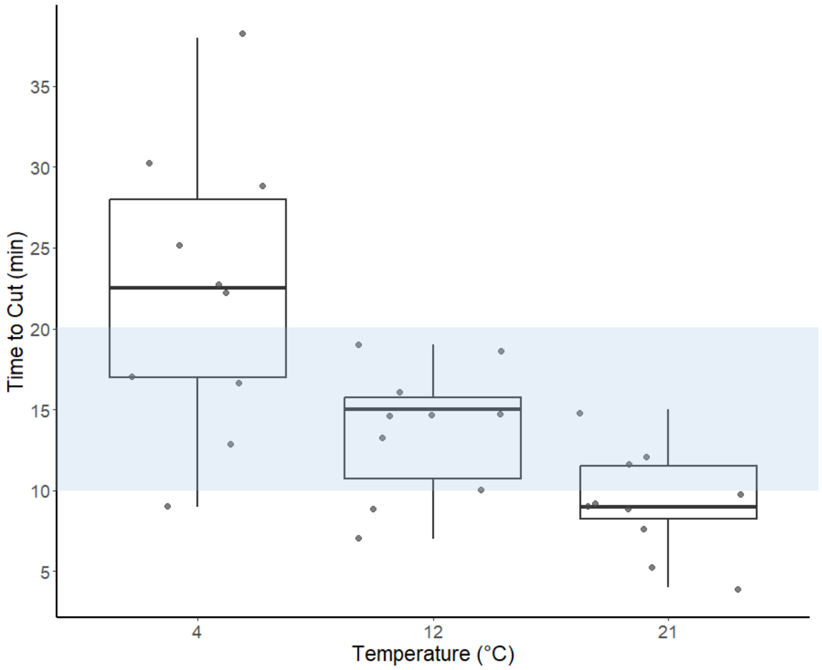

Figure 3.4. Box plot for the time to cut (min) at 4°C, 12°C and 21°C. The bottom of the box represents the 25th quartile (Q1), the horizontal bar in the middle represents the median (Q2), the top of the box represents the 75th quartile (Q3). Dots show the observed values. Shaded area represents range of cut times of the units specified by manufacturer.

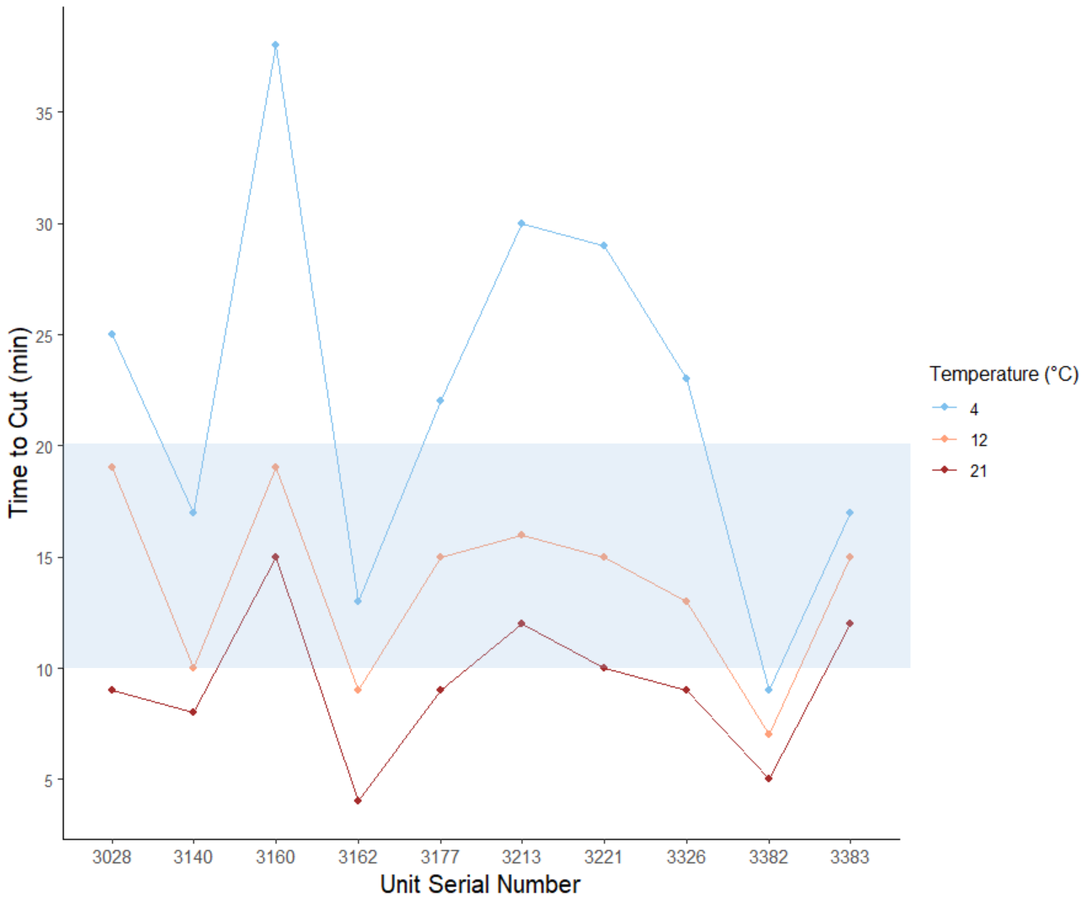

Figure 3.5. Connected scatter plot of the time to cut in minutes of the ten TTLC units tested at 4°C (blue), 12°C (orange) and 21°C (red). Shaded area represents range of cut times of the units specified by manufacturer.

CHAPTER 4: SUMMARY

4.1 Summary remarks

The research presented in this thesis is intended to contribute to the development of entanglement mitigation devices for fixed gear fisheries. Chapter 1 provides an introduction and overview of the species, fishery, and emerging challenges. Chapter 2 provides tension data collected in the Newfoundland snow crab fishery, with insights into the factors contributing to tension and knowledge necessary for decision making concerning LBS devices in this fishery. The study indicated that tension was significantly higher for traps with catch compared to traps without catch and traps without catch or mesh. Tension in the first part of hauling (before the first trap) is lower than tension after the first trap however, when hauling traps with catch, tension exceeds breaking strength of LBS components. It is recommended that additional experiments be undertaken to increase sample size and repeat in different conditions to identify effect of depth, sea conditions, rate of hauling, number of traps per trawl, and wind speed on tension while hauling.

Chapter 3 documents an experiment that evaluated the performance of time-tension line cutters (TTLCs) in different temperatures as a step in the assessment of their suitability for integration in fisheries. Results showed that in colder temperatures, TTLCs take longer to engage and cut, however, we found the effect of temperature to be highly variable from unit to unit. This study documents the first trials of these types of TTLCs to evaluate consistency and the effect of temperature in controlled conditions. Though these devices offer the potential for harvesters to be an adequate entanglement mitigation device for fisheries where tension while hauling exceeds 1,700lbs (771kg) and on-demand systems cannot be implemented currently. It is recommended that the further research and development be undertaken for TTLCs to ensure reliability, durability, and effectiveness before implementation. Specific suggestions for the manufacturer include standardizing the time to cut to ensure it is within the threshold for approved devices, fine tuning mechanism to ensure higher tension does not affect time to cut, to reduce or predict effect of temperature on time to cut, and to reduce variability between units. Specific suggestions for future studies include increasing the number of repetitions per unit, sea trials to assess performance in actual conditions, season long sea trials to assess durability of units. Together, these two experiments are intended to contribute to the implementation of entanglement mitigation methods and the development of LBS devices.

4.2 Limitations of Approach

Several limitations in experimental design and circumstances were encountered during these studies. For this reason, the results should be considered preliminary and interpreted with caution.

The experiment described in Chapter 2 was performed during day trips aboard a smaller vessel that would remain docked when weather conditions were too severe. This meant a small range of environmental conditions were experienced during the experiment and thus, has limited our ability to properly identify the effects of such factors, or lack thereof, on tension. Additionally, baited traps needed to soak for extended periods of time to fish, while wire traps and unbaited traps could be hauled repeatedly, multiple times a day, this resulted in the number times each treatment was hauled being unequal, with baited traps being hauled the least number of times, producing a smaller sample size than intended. If further studies are undertaken, it is recommended to increase the sample size, deploy traps in a wide range of depths and environmental conditions to better asses their effect on tension.

The experiment described in Chapter 3 used a tensile test machine equipped with a hydraulic ram. To ensure the load remained at 1,700lbf (771kgf) +10%, the operator had to regularly adjust the position of the clamps. In attempt to control variation, the test protocol integrated an adjustment of the position of the clamps to bring the tension back up to 1,700lbf (771kgf) +10% every minute. However, both the stretching of the rope, and compression of the TTLC caused loosening, resulting in a non-linear drop in tension. The operator dynamically compensated by regularly adjusting the hydraulic machinery to prevent dipping below 1,700lbf (771kgf). Ideally, future experiments assessing TTLCs using constant tension should be performed using a tensile tester machine that adjusts itself to maintain a set tension automatically. Furthermore, the machine used in this experiment had to clevises on either end as means of attachment, therefore, the rope and TTLC was attached to the machine by creating two loops on each end and tucking it 3 times. This however, meant that as loads on the system increased, the tucks were adjusting, slipping, and stretching slightly as they settled which could have increased TTC as it would have decreased tension for some length of time before it was adjusted back up manually. Nonetheless, since all tests were performed on the same machine in the same manner and all ropes were tucked 3 times, this shouldn't affect the comparison of TTC within and between temperatures tested but may have some impacts of the overall TTCs. It is suggested that further testing be conducted using manual capstan grips, commonly used for testing high capacity ropes, where both ends of the rope is wrapped around capstans and are secured in place by clamps using pneumatic pressure. Additionally, the water chiller utilized in this experiment was borrowed from the Center for Aquaculture and Seafood Development (CASD) at the Fisheries and Marine Institute. The water chiller was chosen out of convenience, proximity, and since it incurred no additional expense. The chiller used was not industrial, and the lowest temperature setting was 3°C, however given the size of the water tank used, 4°C is the lowest temperature the water reached and therefore, was chosen for the lower value of our temperature range. Although this temperature is representative for some snow crab fisheries in Atlantic Canada, it is also far from bottom temperatures experienced in other areas (e.g., the Grand Banks of Newfoundland) (Cyr et al., 2022). In order to properly assess the TTC of a unit in real fishing conditions, after having been at depth for an extended period of time, further trials should be conducted at temperatures closer to bottom temperatures of fisheries in which it would be integrated, using industrial chillers with that capacity. Due to time constraints, each unit was only tested once at every temperature. Further trials should perform repeated testing per unit at each temperature to assess if TTC stays constant. Also due to time constraints, the effect of rope size and tension on TTC were not tested however, they have the potential to affect it and should be integrated in future research.

4.3 Conclusions

With rising concern over the survival of endangered NARWs due to entanglement in fixed fishing gear, many mitigation and prevention methods are being considered for implementation including LBS components. This thesis documents the first time tension was measured in the NL snow crab fishery and the first controlled laboratory experiment testing performance and temperature sensitivity of these TTLCs. The results presented throughout this work provide valuable information regarding concerns and considerations towards the integration and development of LBS gear. This thesis also provides insight on previously unknown tension while hauling in Newfoundland’s most valuable fishery. Major findings from this work include that tension while hauling exceeds the 1,700 lbf (771 kgf) +10%, threshold, indicating that single threshold LBS components are not an adequate solution for this fishery. TTLCs tested had a variance in TTC exceeding acceptable threshold of approved gear, and lower temperatures resulted in significantly higher TTC, demonstrating that this technology requires further development and testing before it may be approved and implemented. Although I recognize the limitations of the above studies, the results are valuable and contribute to the development of entanglement mitigation technology and informing decisions concerning their implementations.

4.4 References

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