Evaluating the effects of North Atlantic right whale (*Eubalaena glacialis*) fishery closures on entanglement risk of other large whales from the southern Gulf of St. Lawrence snow crab (*Chionoecetes opilio*) fishery

By

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TABLE OF CONTENTS

ABSTRACT

Since 2018, time-area closures have been implemented in Atlantic Canda to reduce entanglements of North Atlantic right whales (NARW) in fixed-gear fisheries, particularly the Gulf of St. Lawrence (GoSL) snow crab fishery. Other large baleen whale species also occur in GoSL and face similar risks of entanglement. These include endangered blue whales, fin whales (special concern), and humpback whales, the second most commonly entangled baleen whale in Atlantic Canada, and other studies have shown the rate of entanglement for these whales in the GoSL are vastly underestimated. The goal of this study was to estimate the risk of entanglement in snow crab gear for these other species, and to quantitatively evaluate the potential change in risk due to the NARW time-area closures. Distributions for each species were based on annual sightings (2015-2022) using a location uncertainty model and combined with snow crab logbook data to estimate entanglement risk. The average risk of entanglement for blue, fin, and humpback whales was estimated for the years prior to the implementation of fisheries management measures (2015-2017) and compared to the entanglement risk estimate for each year with time-area closures (2018-2022) to identify the change. The results showed ranges in annual change in risk of -50.76 to -9.04% for blue whales, -70.70 to 6.21% for fin whales, -73.51 to 34.56% for humpback whales, where negative values indicate a decrease. Monthly results show some risk reduction from certain management measures, but an increase as an unintended consequence from others. This study provides important information on the effects of fisheries management measures on non-target whale species.

Keywords: Fisheries management measures, entanglement, snow crab fishery, blue whale, fin whale, humpback whale, conservation, non-target species

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LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF APPENDICES

LIST OF ABBREVIATIONS

ANOVA – Analysis of variance

BoF – Bay of Fundy

CFA – Crab Fishing Area

DFO – Department of Fisheries and Oceans

GoSL – Gulf of St Lawrence

MICS – Mingan Islands Cetacean Society

MMON – Marine Mammal Observation Network

NA – No answer

NARW – North Atlantic right whale

NARWC – North Atlantic Right Whale Consortium

SARA – Species at Risk Act

SNK – Student-Newman-Keuls

WGS – World Geodetic System

XMAR – DFO Maritimes Whale Sightings Database

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To the whales for being themselves and wonders in the ocean. Having the experience of working with them on the water and on my computer has brought me joy and sadness, but overall, I am so happy that I could learn more about them every day. And I am thankful to all the whale people for inspiring me to stay in this field.

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Chapter 1: Introduction

1.1 North Atlantic Right Whales

The North Atlantic right whale (NARW), *Eubalaena glacialis,* is an endangered species under the *Species at Risk Act* (SARA) in Canada since 2005 (DFO 2020a). This baleen whale is large, mostly black, lacks a dorsal fin, and is very rotund due to its thick layer of blubber (DFO 2020a). Their range is from Florida to Newfoundland and Labrador and can be observed seldomly in other areas of the North Atlantic (DFO 2020a). The NARW population was heavily impacted by the whaling industry since it was the “right” whale to hunt, so a moratorium was implemented in 1935 to prevent this species from going extinct (DFO 2020a). Their population slowly bounced back; however, today NARW face threats from entanglement in fishing gear and vessel strikes (DFO 2020a; Davies & Brillant 2019). There are approximately 350 individuals left and even without the influence of whaling there is a trend of a decreasing population due to these threats in addition to low reproductive rate (DFO 2020a; Hayes et al. 2023; Linden 2023). Their potential biological removal is below one (Van der Hoop et al. 2012; Hayes et al. 2023), meaning that no individuals can be removed to attain a sustainable population (NOAA 2021).

Historically, NARW would migrate north from their breeding grounds in the southern United States to feed primarily in the Gulf of Maine and Bay of Fundy (BoF) during the summer months (DFO 2020a). As climate change progresses, the oceans are warming; one of the impacts of this is species range shift. Copepods more specially *Calanus finmarchicus* are NARW’s primary source of food (Meyer-Gutbrod et al. 2018; DFO 2020a). As a result of climate change, these copepods have decreased in the Gulf of Maine (Meyer-Gutbrod et al. 2018; DFO 2020a). As a result, in 2010, NARW were not observed as frequently in their primary feeding habitat (Davies et al. 2019). In 2015, it was shown that the NARW range had shifted to the Gulf of St. Lawrence (GoSL) (DFO 2020a; Davies et al. 2019; Pettis et al. 2020). Although the risk of entanglement in fishing gear and vessel strikes to whales were known by the Canadian government, no management measures had been implemented until 2017 in the GoSL (Davies & Brillant 2019). This shift in range coincided with an increase in mortality of NARW (DFO 2020a). In 2017, the first mass mortality event resulted in 12 NARW deaths in the GoSL due to entanglements in fixed fishing gear and vessel strikes (DFO 2020a). Then, a second mass mortality event occurred in 2019 with 9 NARW deaths in the GoSL (DFO 2020a). In all, the NARW population is continuing to face anthropogenic related deaths; however, the Department of Fisheries and Oceans Canada (DFO) has since implemented management measures to mitigate these threats.

1.2 Snow Crab Fishery

Snow crab (*Chionoecetes* opilio) is a species of cold-water crustaceans that go through a moulting phase every year. Fish harvesters are only allowed to harvest males once they have a carapace width of 95mm (Hébert et al. 2020). The southern GoSL which boarders Quebec, New Brunswick, Nova Scotia, and Prince Edward Island is one of the areas where this fishery takes place (Figure 1.1). Fishing takes place between a depth of 20-200 fathoms and is separated into four Crab Fishing Areas (CFA): 12, 12E, 12F, and 19 (Hébert et al. 2020). The fishing season for CFA 12, 12E, and 12F starts near the end of April or early May, when the ice melts) until mid-July and July through August for CFA 19 (Hébert et al. 2020). This Canadian fishery which started in the mid-1960s (Hébert et al. 2020) is economically important with a revenue valued at 1.3 billion CAD in 2021 for all of Atlantic Canada which includes Quebec, Nova Scotia, New Brunswick, Prince Edward Island, and Newfoundland (DFO 2022c).

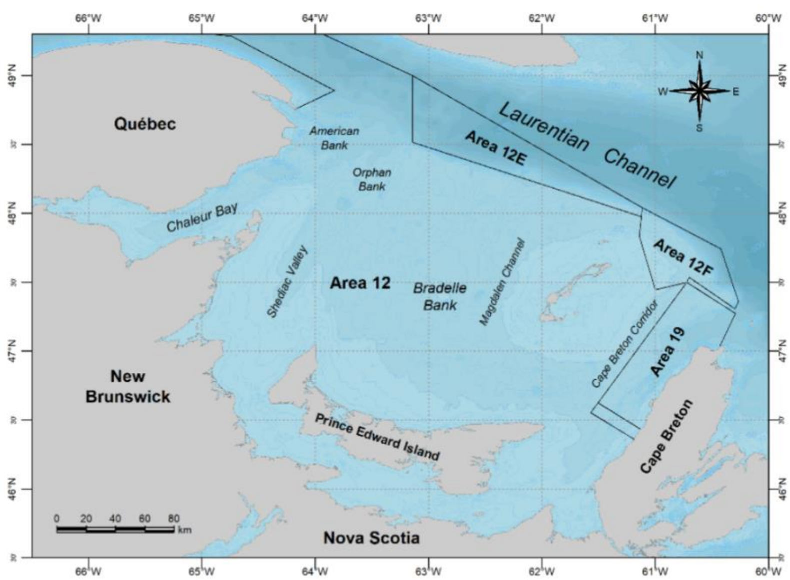

Figure 1.1: Map of the southern GoSL with the delineation of the four Crab Fishing Areas: 12, 12E, 12F, and 19

This fishery is quota based which means fishers can only catch the amount of snow crab that is allocated to them (Hébert et al. 2020). The annual total allowable catch is determined by DFO since the stock can vary each year. This total quota is then divided amongst fish harvesters based on their allocations. As seen in Figure 1.2, the snow crab fishery goes through cycles of low and high landings; the most recent period of high landings has been from 2012-2022 (Hébert et al. 2020; DFO 2023). The CFAs are further delineated into ten-minute grid cells (approximately 220-240km^2) each having their own identification code, hereafter called DFO grid cell ID. These DFO grid cells are used to define fishing closures that can be implemented throughout the fishing season. Time-area fishing closures can happen for two reasons: 1) when the proportion of soft-shell crabs is too high and 2) when NARW are detected in the area. Soft-shell crabs are vulnerable, have low meat content, and represent future recruitments, therefore it is not financially wise to harvest them (DFO 2023). Both these closures can cause displacement of effort for snow crab fishing (Hébert et al. 2020; Cole et al. 2021); however, one is to ensure a healthy snow crab stock and the other is to protect NARW.

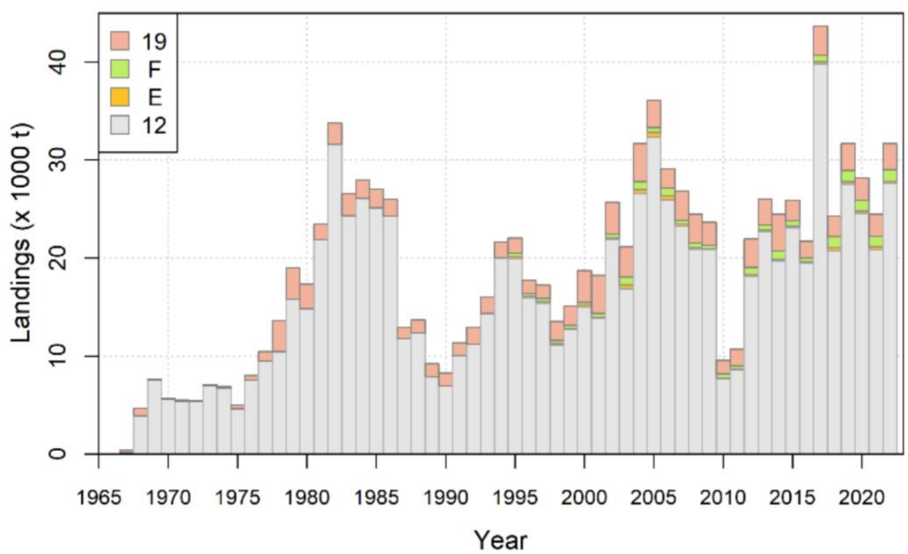

Figure 1.2: Snow Crab landings (tonnes) from 1967-2022 in the southern GoSL for Crab Fishing Areas 12 (grey), 12E (orange), 12F (green), and 19 (pink) (DFO 2023).

The snow crab fishery in the southern GoSL has a high overlap with NARW distribution in the GoSL, therefore it is the most impacted by the NARW fishery closures (Daoust et al. 2017; Bourque et al. 2020; Pettis et al., 2020). The method for harvesting snow crab in the southern GoSL is by using single pot traps which are connected to a buoyline, these are categorized as fixed-fishing gear. This vertical rope in the water column creates a threat of entanglement for whales. When a whale is entangled in one or multiple ropes, it could cause infections, starvation, and death (Van Der Hoop et al. 2016; Ramp et al. 2021). There are programs to disentangle whales; however, it is difficult to accomplish. Hence, the main solution to reduce the risk of entanglement is to prevent them from happening by implementing fishing closures or changing fishing methods (i.e., on-demand gear) when whales are detected. Risk of entanglement from the southern GoSL snow crab fishery has been studied for the NARW (Cole & Brillant *in prep*) and found that there has been an average risk reduction of 62% for entanglement from 2018-2021 due to these management measures.

1.3 Fisheries Management Measures and Fishery Closures

The mass mortality event in 2017 triggered emergency measures in July of that year to prevent further deaths from occurring including the closure of the snow crab fishery for the rest of the season (Davies & Brillant 2019). In 2018, the first precautionary measures to prevent entanglements were implemented, including different types of large-scale time-area fishery closures. These fisheries management measures have changed in almost every year from 2018 to 2022 (Appendix A). In 2018, the snow crab fishing season closed as of June 30th for CFAs 12, 12E, and 12F; and a static closure area, based on 90% of NARW sightings in 2017, was implemented and prevented any fishing from occurring in the area (DFO 2018). Also, dynamic (temporary) closure areas would close nine DFO grid cells for a minimum of 15 days when a NARW was sighted and could be extended for another 15 days if a NARW was sighted again in the closed area during an aerial survey; if not, two aerial surveys during this period with no detections resulted in the dynamic closure area being lifted at the end of the 15-day period (DFO 2018). In 2019, the fishing season remained the same, but the static closure was 63% smaller than the previous year and was determined on the 90% of the 2018 NARW sightings; additionally, a shallow water protocol was added to the dynamic closures (DFO 2019a). This shallow water protocol accounts for DFO grid cells in less than 10 fathoms and between 10 and 20 fathoms (DFO 2019a). The shallow water protocol means that DFO grid cells shallower than 20 fathoms would be subject to dynamic closures only if a NARW was detected in those depths

(DFO 2019a). In 2020, the fishing season remained the same, but ice breakers tried to free the ports to start the season earlier (DFO 2020b). The ice breaker operations are meant to allow fish harvesters to harvest their quota before NARW migrate northward towards the GoSL. The static closure ended, and a season-long protocol was implemented such that when a NARW was detected more than once in a 15-day period that area would remain closed to al fishing until mid-November (DFO 2020b). The dynamic (temporary) closure protocol along with the shallow water protocol impacted all non-tented fixed gear and expanded to cover all the GoSL, BoF, Roseway Basin, and Grand Manan Basin (DFO 2020b). Finally, acoustic detections of NARW could trigger closures (DFO 2020b). In 2021, the fishing season and ice breaker operation was the same as 2020; and similar season-long, shallow water, and temporary protocols to 2020, but to trigger season-long or extension of the temporary protocol depending on the area, a NARW must be detected between 9 and 15 days of an existing temporary closure (DFO 2021b). These measures have continued with no changes since 2021 (DFO 2022b). However, due to closures, CFAs 12E and 12F were completely closed in 2021, so in 2022 new access criteria was created so fish harvesters from those CFAs could harvest in CFA 12 if the same thing occurred (DFO 2022b).

Fishing closures due to NARW detections increase the amount of work for these fish harvesters. When a NARW was detected, they are given a minimum 48h notice from DFO to retrieve their gear from the area to be closed and find a new place to set their traps (Cole et al. 2021). This displacement of effort was studied by Cole et al. (2021) and showed that fishing efforts were displaced in areas that had previously low fishing effort. This can impact the revenue of snow crab fisher harvesters due to increase in effort to meet their quota and pose a risk to other whales.

1.4 Other Large Whales in the Gulf of St. Lawrence

While NARW have been the primary focus of recent threat mitigation measures, Atlantic Canada is frequented by 22 species of cetaceans, and many are endangered (Wimmer & Maclean 2021). Indeed, large baleen whales like blue, fin, and humpback whales frequent the GoSL for reasons such as feeding (Baird 2003; DFO 2016; DFO 2017). These whales are important to the ecosystem since they provide ecosystem services like nutrient cycling.

1.4.1 Blue Whale

The Northwest Atlantic population of blue whales (*Balaenoptera musculus*) has been listed as endangered under SARA since 2005 (DFO 2016). They are the largest whales and feed primarily on krill (DFO 2020). Many things are unknown about this whale population such as if they stay on the GoSL year-round and their exact numbers which is estimated to be at around 250 individuals (DFO 2016; Lesage et al. 2017). Like NARW, the potential biological removal for blue whales is below one individual (Van der Hoop et al. 2012). They face similar threats to NARW like entanglement in fishing gear and vessel strikes (DFO 2016). DFO's recovery goal for this blue whale population is to reach a population of at least 1000 mature individuals (DFO 2016). Their objectives to attain this goal is to do more research on the population and their critical habitats; reduce disturbances from vessel noise, vessel strikes, entanglements, toxic contaminants, and further research on these threats (DFO 2016).

1.4.2 Fin Whale

The Atlantic fin whale (*Balaenoptera physalus*) population has been listed as special concern under SARA since 2006 (DFO 2017). It is the fastest whale and second largest (DFO 2017). These whales spend their summer in the GoSL, BoF, Gulf of Maine, and off the coast of Newfoundland and Labrador, but it is not known where they spend the winter months (DFO 2017). Fin whales feed on both zooplankton and fishes (DFO 2017). Like blue whales, the population estimates vary, Lawson and Gosselin (2009) estimated a minimum of 1352 individuals in Atlantic Canada and Van der Hoop et al. (2012) estimated 3269 individuals in 2007. Another study highlighted the reduction in survivorship during the period of 1990-2010 (Ramp et al. 2014). DFO's objective for this fin whale population is to prevent further decline in the population due to anthropogenic threats such as vessel strikes, entanglements, and vessel noise (DFO 2017).

1.4.3 Humpback Whale

The Western North Atlantic humpback whale (*Megaptera novaeanglia*) population has been listed as not at risk under SARA since 2003; it was previously listed as special concern in 1985 (Baird 2003). Despite being listed as not at risk, humpback whales are the second most commonly reported entangled whale in Atlantic Canada (Wimmer & Maclean 2021). This humpback population is recognized as having three breeding stocks: Gulf of Maine, GoSL, and Newfoundland and Labrador (Baird 2003). These humpback whales use the GoSL during the summer as feeding grounds (Baird 2003). Their diet consists of capelin, copepods, and herring (Baird 2003). Their population was estimated to be approximately 11,570 in 1993 (Baird 2003). Moreover, Kershaw et al. (2020) demonstrated that due to variability in prey, which is linked to climate change, humpback whale reproductive success has declined recently because female whales do not have enough energy reserves to become pregnant or maintain a calf. Consequently, despite their not at risk status, these whales face many of the same threats as other species such as vessel strikes and entanglements (Baird 2003).

1.5 Management Problem

Entanglements in fixed-fishing gear can cause serious and sub-lethal injuries that can affect the population (Johnson et al. 2005; Van der Hoop et al. 2016). It can heavily impact reproductive females by reducing their energy budget which can delay reproduction by years (Van Der Hoop et al. 2016). Moreover, these impacts from entanglements risk are important due to an additional factor: cryptic mortalities, human caused mortalities without an observed carcass (Pace et al. 2021). Even without carcasses, there are still whale deaths occurring from entanglements in fixed-fishing gear. Therefore, it is necessary to conduct entanglement risk assessments for whales to understand the magnitude of threat from fixed-fishing gear.

Entanglement rates for blue and fin whales in the GoSL are vastly underestimated (Ramp et al. 2021). For example, fin whales had an initial entanglement rate estimated at 6.5% based on vessel-based photoidentification, but this number increased to between 44.1 and 54.7% with aerial photography (Ramp et al. 2021). Additionally, minke whales and humpback whales are the first and second most commonly entangled whales in Atlantic Canada respectively. Ramp et al. (2021) estimated an 85% entanglement rate for humpbacks whales. This demonstrates a pattern of underestimation of entanglement risk for large whales and need for more detailed studies.

Despite the large focus on NARW for management, species other than NARW represent 94% of baleen whale incidents reported throughout Atlantic Canada (Wimmer & Maclean 2021). These other large baleen whales use the GoSL and face similar risks of entanglement as NARW (Van der Hoop et al. 2012). Unlike NARW though, fin and humpback whales are not as heavily impacted by migration timing (i.e., when they migrate from their breeding to feeding habitat) (Pendleton et al. 2022). This difference in migration timing could be explained by the fact that fin and humpback whales are more generalists in comparison to NARW that heavily rely on copepods which are impacted by warming waters and seasonal changes (Pendleton et al. 2022). This study implicates that large migratory whales are impacted differently by climate change and that fin whale migration is not as heavily studied (Pendleton et al. 2022). Additionally, a study by Doniol-Valcroze et al. (2007) explains that these whales species feed in different areas in the GoSL, for example, blue whales correlate heavily with sea surface thermal fronts whereas NARW do not. For blue and fin whales, it is recognized by DFO that the GoSL is an important area for these whale populations (DFO 2016; DFO 2017) and that it is a feeding ground for humpback whales (Baird 2003).

Although these four species of whale use the GoSL to feed, due to their diets, they might not use the same areas within the GoSL. Hence, the displaced fishing effort caused by NARW fishery closures might move fishing into areas that were previously less fished (Cole et al. 2021), and into areas where other whales occur which could impact their risk of entanglement.

The goal of this research was to determine if the NARW fishery closures positively or negatively affect entanglement risk to other large whales in the southern GoSL. The NARW fishery closures are determined by the fisheries management measures which change almost every year. These management measures can have impacts on more than one species; therefore, it is important to not transfer this entanglement problem to other whales. There were limitations on sighting data for minke whales so this study will provide estimates of entanglement risk for blue, fin, and humpback whales.

The objectives of this study were to determine the threat of entanglement from the snow crab fishery in the southern GoSL; create an occurrence distribution for each species; and calculate the risk of entanglement for each species through a co-occurrence model. The risk from years with fisheries management measures were compared to years without these measures to observe an increase or decrease in risk of entanglement for these whales. The results of this study will inform us on the positive or negative effects of NARW fisheries management measures on entanglement risk of blue, fin, and humpback whales.

Chapter 2: Methodology

2.1 Snow Crab Fishing Gear Occurrence

Snow crab fishery data was obtained from 2015-2022 DFO logbooks of the southern GoSL for the months of April through August for all CFAs (i.e. 12, 12E, 12F, and 19). These anonymous logbooks were provided by the DFO Gulf region and were validated for fishing locations by the statistics divisions of the Gulf and Quebec regions. These logbooks included data such as CFA, province, fishing week, date landed, date caught, estimated catch per day, estimated catch per trip, amount landed, number of traps per day, number of traps per trip, per unit effort per day, per unit effort per trip, and depth. For the purpose of this study, only the date caught, number of traps set per day, and locations in the form of latitude and longitude coordinates were kept. This data was plotted into ArcGIS Pro (version 3.1.2) then the DFO grid cell ID and shallow water protocol were added to the snow crab gear dataset. Additionally, this data was formatted and cleaned by removing invalid entries and blanks in R (version 4.3.1).

This study aims to observe the effects of the precautionary management fisheries measures therefore, the fishery data from the years 2015 to 2017 were averaged to create a baseline of years without these measures, hereafter baseline year. Each trap is attached to one rope in the water called a buoyline which represents a threat of entanglement; therefore, the number of traps equals the amount of threat. The number of traps were summed by day, month, shallow water protocol (10, 20, or over), DFO grid cell ID, and CFA for the averaged baseline year, and each year with precautionary measures (2018 to 2022).

Finally, the cleaned daily number of traps by DFO grid cell ID was divided by the sum of traps for all years (i.e. baseline, 2018, 2019, 2020, 2021, and 2022) to calculate the probability of gear to occur in a DFO grid cell for each year. This relativization, where the sum of all traps equals to one, allows for each day, month, location, and year to be compared to each other. In all, this results in the daily probability of threat by DFO grid cell for each year. Finally, the probability of gear was summed by month for each year since the analyses were done on a monthly and yearly scale.

2.2 Whale Occurrence

2.2.1 Sightings Data

For the blue, fin, and humpback whales, five datasets of visual sightings were received from the Marine Mammal Observation Network (MMON), DFO Maritimes Whale Sightings Database (XMAR), North Atlantic Right Whale Consortium (NARWC), Parks Canada, and Mingan Island Cetacean Society (MICS). Each dataset was cleaned in R to remove invalid or missing entries for date, species identification, count, or location (Appendix B). Then these datasets were formatted to keep the date, species identification, count, location in latitude and longitude. Certain datasets included a species certainty category so only definite certainties were kept. Data was not corrected for surveillance effort.

The blue, fin, and humpback whale datasets were plotted into ArcGIS Pro and joined to an ocean layer to remove any incorrect coordinates. After, those datasets were joined to a study area (40° to 55° N x -72° to -48° W) that represents the extent of Canadian waters (Carr, 2020) (Figure 2.1). The point data from the whale sightings were associated to a DFO grid cell ID. Moreover, in ArcGIS Pro, a raster grid to delimitate land and water was created using an expanded version of the study area to be used for the whale occurrence model (Figure 2.2).

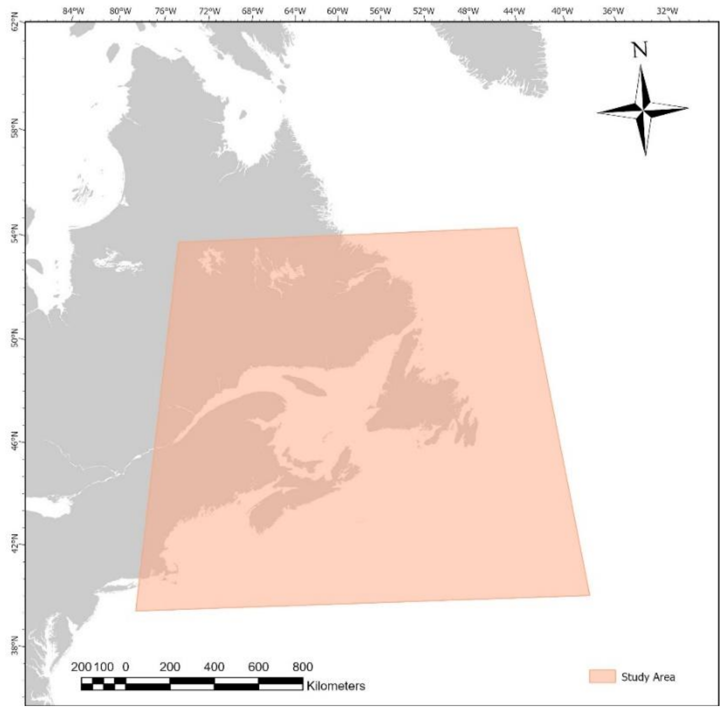

Figure 2.1: Map of study area (orange) used to represent Canadian waters (40° to 55° N x -72° to -48° W).

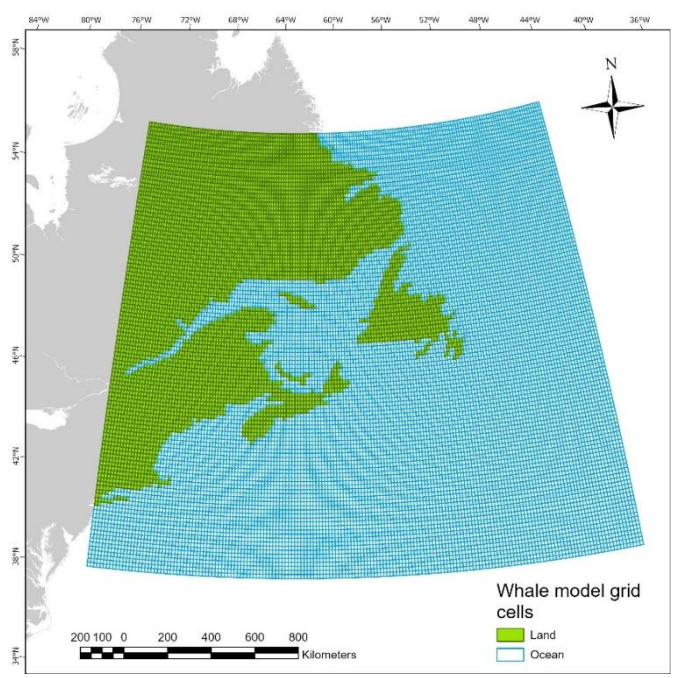

Figure 2.2: Map of grid cells used for the whale occurrence model where land is green cells and ocean is blue cells.

2.2.2 Whale Occurrence Model

The whale occurrence model used in this study calculates the probability of occurrence of a whale 24 and 48h before and after the whale was observed. This model expands point data to have a better estimate of occurrence for these whales. Based on a random walk model, Johnson et al. (2020) illustrates the location uncertainty of a traveling NARW 24h after a confirmed visual detection, which results in a radius of around 50km. From Baumgartner & Mate (2005), a NARW can swim a maximum distance of 80km in 24h; therefore, 50km divided by 80km results in 62.5% as a measure of the radius a whale is likely to be after a sighting given their max daily distance travelled. Hence, this whale occurrence model uses a location uncertainty index of 62.5% after 24h of a visual detection to determine this radius of occurrence for each species; the index remains the same after 48h. The swimming speeds of the whales is needed to calculate the maximum distances that they could travel in 24 and 48h. For this model, it is assumed that the whales are always traveling at a fix swimming speed.

The whale swimming speeds for blue, fin, and humpback whales were determined from peer-reviewed papers on studies of these three whale species (Appendix C). The determined maximum swim speed for blue whales was 5.4 km/h (Kshatriya & Blake 1988; Lesage et al. 2017); fin whales was 7.2 km/h (Bose & Lien 1989; Nortobartolo-di-Sciara et al. 2003; Goldbogen et al. 2007); and humpback whales was 4km/h (Noad & Cato 2007; Williams 2018; Horton et al. 2011). The maximum distances of travel in 24h period were calculated using these swim speeds. Then, the location uncertainty factor of 62.5% was applied to those distances and the results were rounded for simplicity. Therefore, the radius of occurrence for blue whales was estimated as for 80km every 24h period (i.e., 160km after 48h); for fin whales was 100km every 24h period (i.e., 200km after 48h); and humpback whales was 60km every 24h period (i.e., 120km after 48h).

The whale occurrence model uses the radius of occurrence, whale point data, and raster grid of land and water (Figure 2.2). It modifies the coordinates from the whale point data to the centroid of the DFO grid cell that it is located in. The model then calculates the distances to the centroid of all other grid cells in the study area, and only kepps the grid cells that fall within the

± 24h and ± 48h radius of occurrence, resulting in five days that have associated probabilities of occurrence for each whale point data. Day 0, the day of the visual detection, has a probability of occurrence of 1. For day ± 1 (± 24h) and day ± 2 (± 48h), the probability of occurrence is 1 divided by the number of cells within the respective radius of occurrence of those days. The model runs each year separately so whale point data that occurred January 1 or 2 or December 30 or 31 were removed from the datasets. Then, the datasets for all years were combined then averaged, before being relativized (i.e., daily grid cell sum divided by the sum of all grid cells) to create a relativized probability of occurrence for across all years. Daily relative occurrence was summed by month to provide the average monthly occurrence.

Finally, the whale occurrence data was joined in ArcGIS Pro to the DFO grid cell IDs and the shallow water protocol to match the snow crab fishery data.

2.3 Co-occurrence Model

The risk of entanglement is calculated using a co-occurrence model (Cole et al. in prep), which is the product of the probability of threat, which is buoylines from snow crab traps, and the probability of whale occurrence (equation 1). If these co-occur in time and space, it results in a risk of entanglement. Monthly estimates of threat occurrence and whale occurrence were used to estimate risk to allow for finer scale of analysis of the management measures. This risk was then relativized across years (i.e., baseline, 2018, 2019, 2020, 2021, and 2022) so they could be comparable.

$$Eq\ 1. risk\ of\ entanglement = threat\ from\ buoylines\ \times whale\ occurrence$$

The annual rate of change was calculated to determine if risk increased or decreased compared to the baseline year and to what magnitude.

Eq 2. $Rate\ of\ change_{Year\ X} = \frac{Risk\ of\ entanglement_{Year\ X} - Risk\ of\ entanglement_{Year\ baseline}}{Risk\ of\ entanglement_{Year\ baseline}} \times 100$

where Year X represents each respective year with fishery closures (i.e., 2018, 2019, 2020, 2021, or 2022).

2.4 Statistical Analysis

A nested analysis of variance (ANOVA) was applied to the relativized risk values to test differences between species, years, and months, where species and year were fixed factors and month was a random factor. A Student-Newman-Keuls (SNK) test was applied as a post-hoc test to determine the sources of significance from the ANOVA.

Chapter 3: Results

3.1 Threat from Snow Crab Fishery

Threat was calculated using the buoylines from the snow crab fishery in the southern GoSL from 2015-2022 where 2015-2017 were averaged for a baseline year (Table 3.1). This annual total indicates the total threat value in a given year as a sum of the monthly threat value, indicating the magnitude of threat across the study period. As threat was relativized, we are able to compare which years and months presented the highest threat. For example, the baseline average held the highest threat followed by 2019, 2020, 2018, 2022, then 2021. On a monthly basis, generally May has the highest threat (i.e., the most buoylines in the water) (Figure 3.1) and August is the lowest (Figure 3.2).

Table 3.1: Relativized threat from snow crab buoylines baseline to 2022 monthly and yearly breakdown

Threat	**April**	**May**	**June**	**July**	**August**	Yearly Total
Baseline	0.015	0.074	0.052	0.016	0.000275	0.233
2018	0.007	0.107	0.066	0.005	0.000009	0.158
2019	0.002	0.113	0.077	0.009	0.000250	0.212
2020	0.019	0.071	0.054	0.008	0.000088	0.164
2021	0.094	0.052	0.005	0.007	0.000349	0.115
2022	0.043	0.068	0.028	0.008	0.000672	0.119

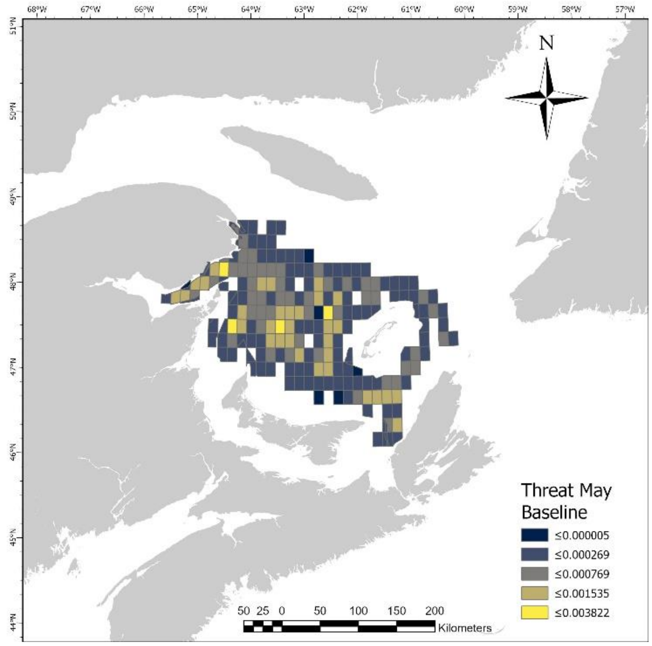

Figure 3.1: Baseline (2015-2017) probability of buoyline occurrence (i.e, threat) from the snow crab fishery in May. Dark colours (blue) indicate low probability and light colours (yellow) indicate higher probability of occurrence.

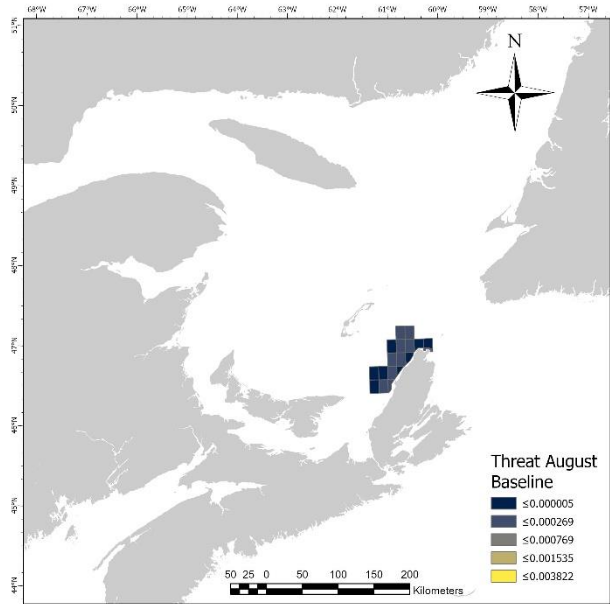

Figure 3.2: Baseline (2015-2017) probability of buoyline occurrence (i.e, threat) from the snow crab fishery in August. Dark colours (blue) indicate low probability and light colours (yellow) indicate higher probability of occurrence.

3.2 Whale Occurrence Distribution

3.2.1 Blue Whale Occurrence Distribution

The annual relative blue whale occurrence demonstrates blue whale presence in Atlantic Canada year-round. September is the month with the highest blue whale occurrence. The relativized blue whale occurrence during the snow crab fishing season shows a trend of increasing occurrence from April to August, where April has the lowest occurrence and August has the highest occurrence (Table 3.2). Additionally, Figure 3.3 to 3.7 illustrates this same trend and higher occurrences in the northern GoSL in July and August.

Table 3.2: Relativized blue whale occurrence by month. Bolded months represent blue whale occurrences during the southern Gulf of St. Lawrence snow crab fishing season.

Month	**Whale occurrence**
January	0.0070
February	0.0002
March	0.0067
April	**0.0130**
May	**0.0245**
June	**0.0591**
July	**0.1755**
August	**0.2921**
September	0.3083
October	0.0883
November	0.0182
December	0.0072

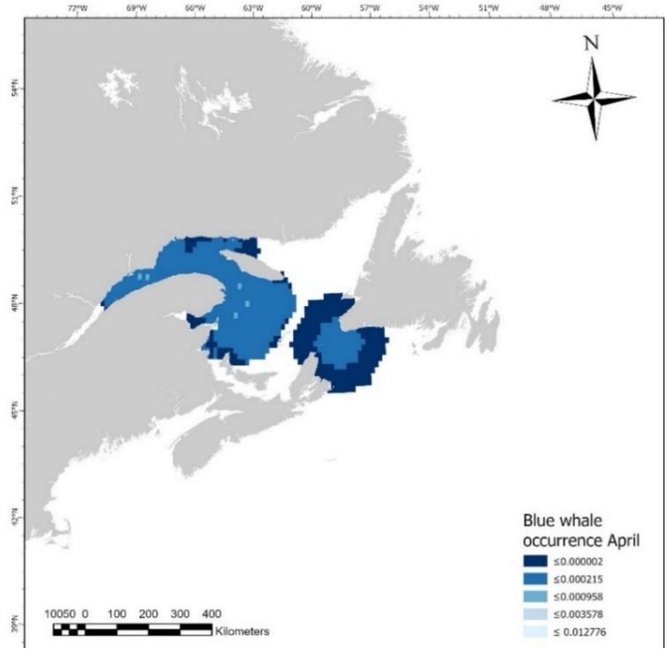

Figure 3.3: Probability of blue whale occurrence in April. Dark colours indicate lower likelihood of occurrence and light colours indicate higher likelihood of occurrence.

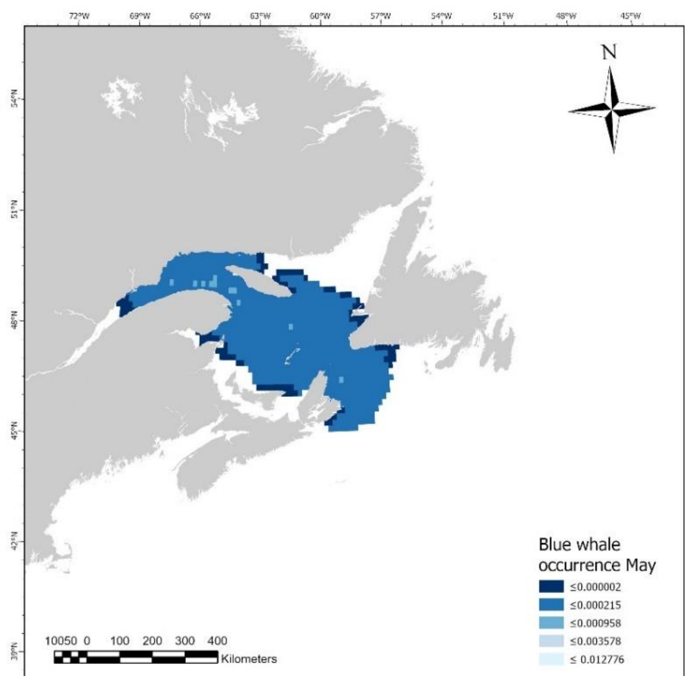

Figure 3.4: Probability of blue whale occurrence in May. Dark colours indicate lower likelihood of occurrence and light colours indicate higher likelihood of occurrence.

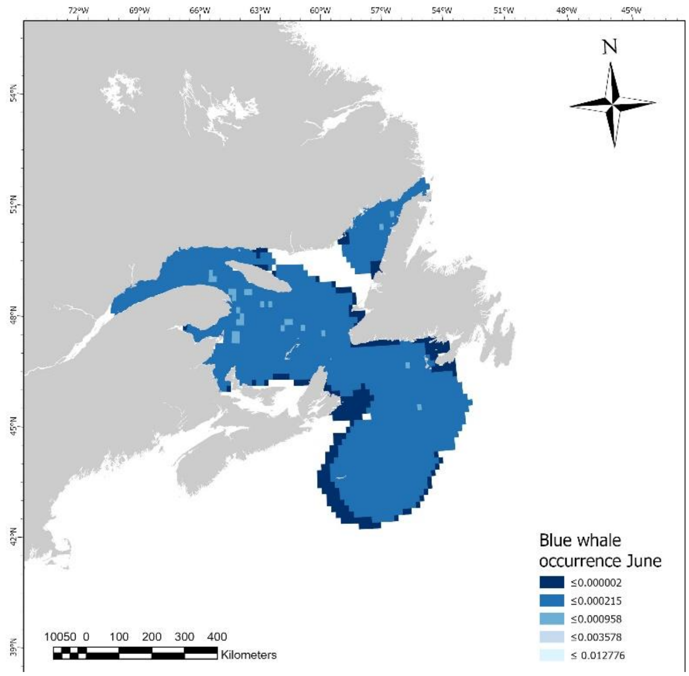

Figure 3.5: Probability of blue whale occurrence in June. Dark colours indicate lower likelihood of occurrence and light colours indicate higher likelihood of occurrence.

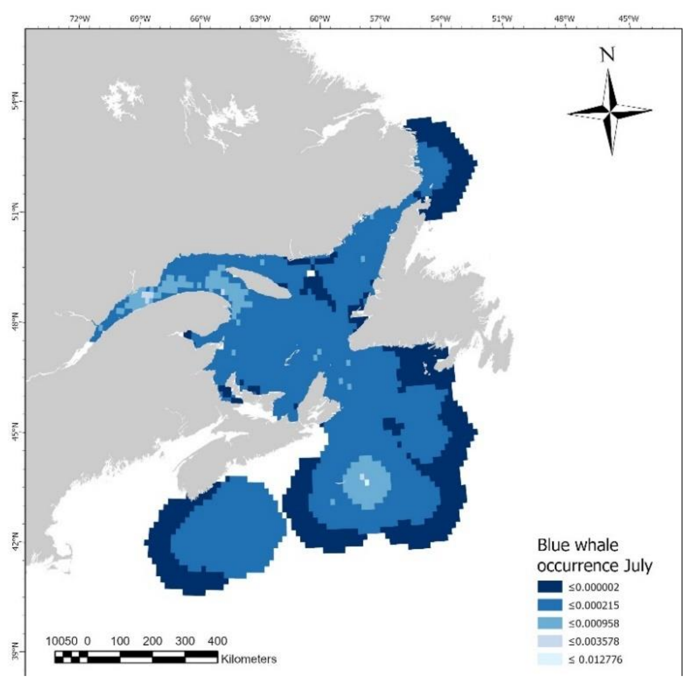

Figure 3.6: Probability of blue whale occurrence in July. Dark colours indicate lower likelihood of occurrence and light colours indicate higher likelihood of occurrence.

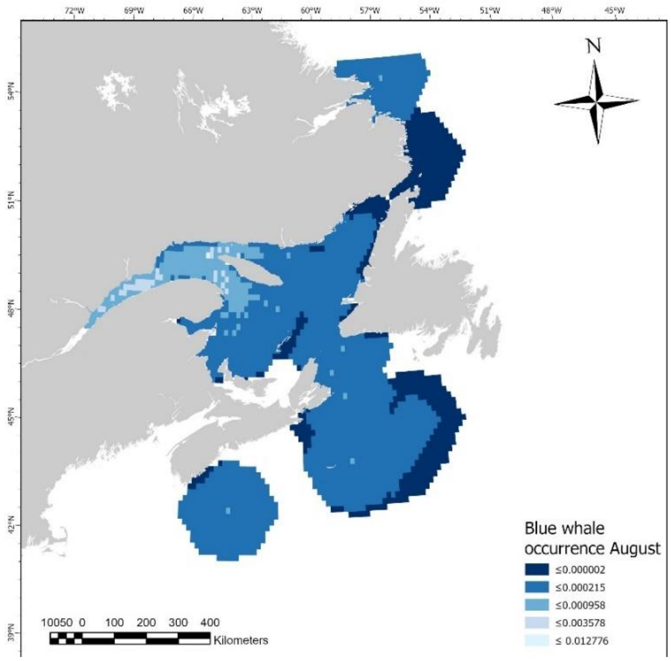

Figure 3.7: Probability of blue whale occurrence in August. Dark colours indicate lower likelihood of occurrence and light colours indicate higher likelihood of occurrence.

3.2.2 Fin Whale Occurrence Distribution

The annual relative fin whale occurrence shows year-round fin whale presence in Atlantic Canada and the highest occurrence is in July which is during the active GoSL snow crab fishing season. The relativized fin whale occurrence demonstrates a trend of increasing occurrence from April to August, where April has the lowest occurrence and August has the highest occurrence (Table 3.3) during the snow crab fishing season. Additionally, Figure 3.8 to 3.12 illustrates this same trend and higher occurrences in the northern GoSL in June, July, and August.

Table 3.3: Relativized fin whale occurrence by month. Bolded months represent fin whale occurrences during the southern Gulf of St. Lawrence snow crab fishing season.

Month	**Whale occurrence**
January	0.0004
February	0.0001
March	0.0008
April	**0.0041**
May	**0.0217**
June	**0.1026**
July	**0.3048**
August	**0.3823**
September	0.1245
October	0.0423
November	0.0131
December	0.0034

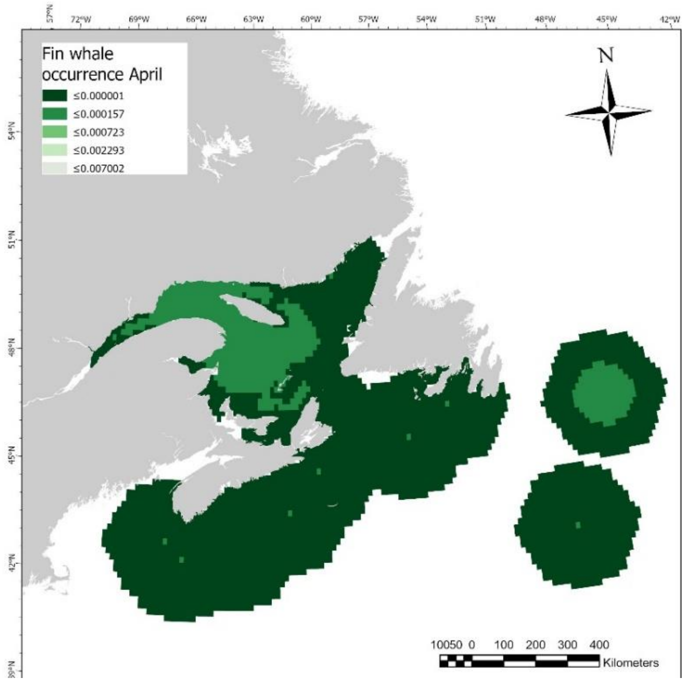

Figure 3.8: Probability of fin whale occurrence in April. Dark colours indicate lower likelihood of occurrence and light colours indicate higher likelihood of occurrence.

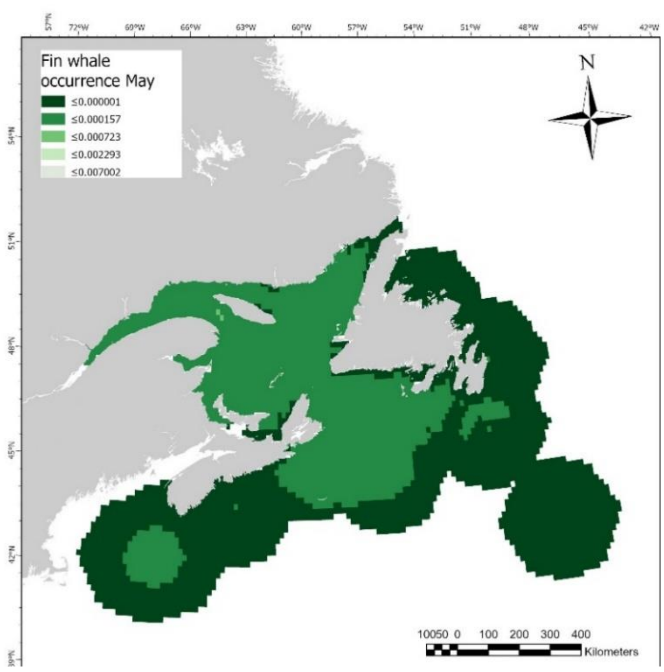

Figure 3.9: Probability of fin whale occurrence in May. Dark colours indicate lower likelihood of occurrence and light colours indicate higher likelihood of occurrence.

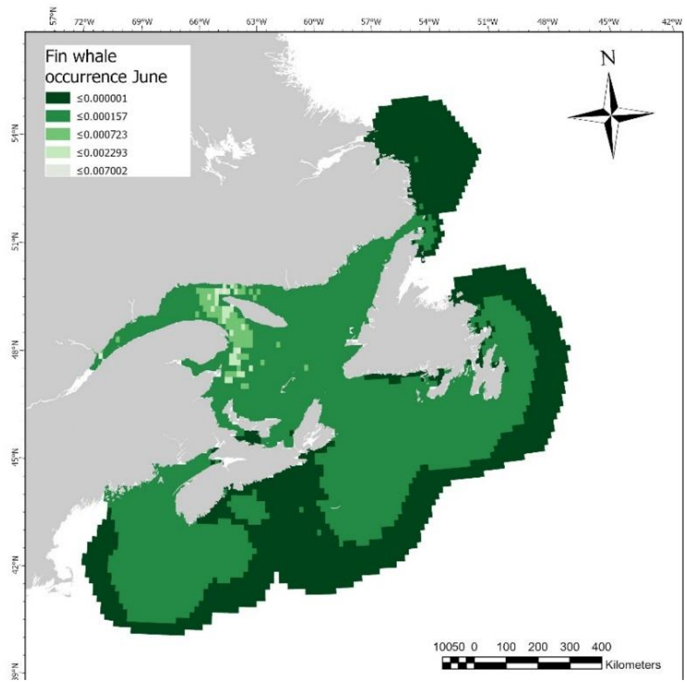

Figure 3.10: Probability of fin whale occurrence in June. Dark colours indicate lower likelihood of occurrence and light colours indicate higher likelihood of occurrence.

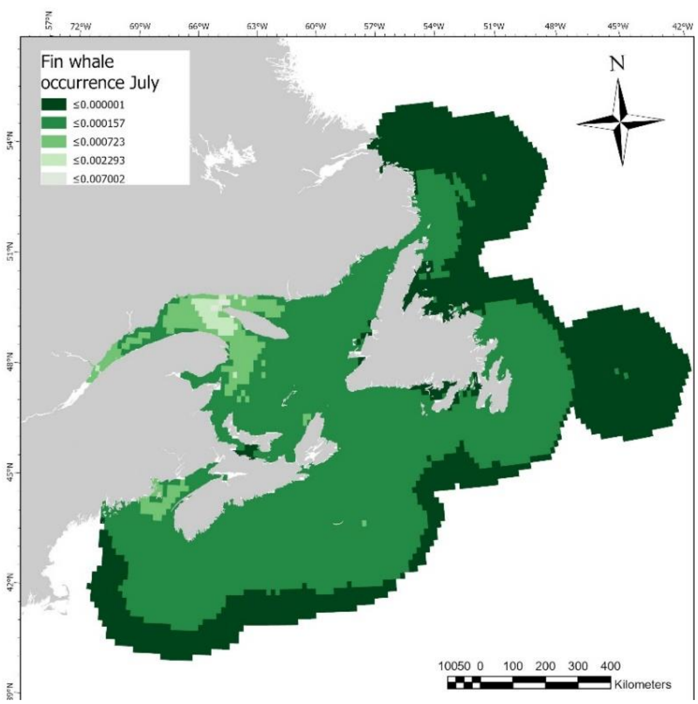

Figure 3.11: Probability of fin whale occurrence in July. Dark colours indicate lower likelihood of occurrence and light colours indicate higher likelihood of occurrence.

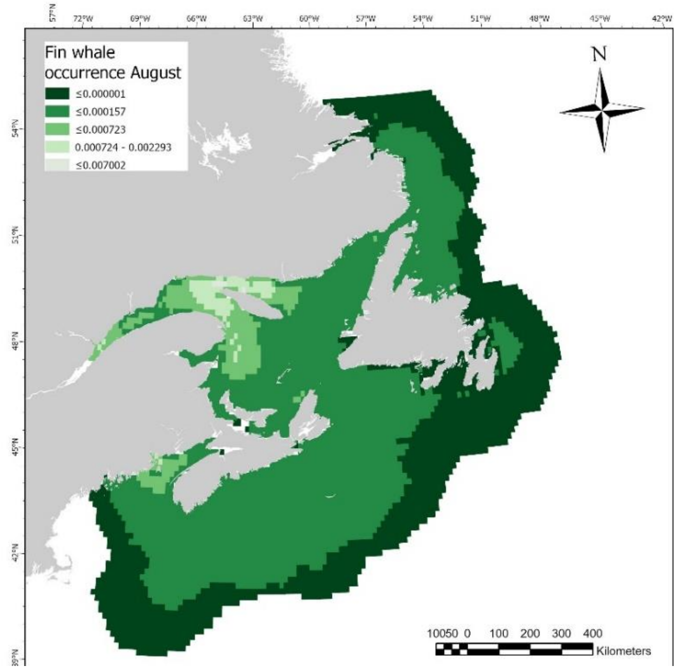

Figure 3.12: Probability of fin whale occurrence in August. Dark colours indicate lower likelihood of occurrence and light colours indicate higher likelihood of occurrence.

3.2.3 Humpback Whale Occurrence Distribution

The annual relative humpback whale occurrence shows year-round occurrence in Atlantic Canada and August is the month with the highest occurrence which is during the active GoSL snow crab fishing season. The relativized humpback whale occurrence during the snow crab fishing season demonstrates a trend of increasing occurrence from April to August, where April has the lowest occurrence and August has the highest occurrence (Table 3.4). Additionally, Figure 3.13 to 3.17 illustrates this same trend and higher occurrences in the northern GoSL and in the BoF in July and August.

Table 3.4: Relativized humpback whale occurrence by month. Bolded months represent humpback whale occurrences during the southern Gulf of St. Lawrence snow crab fishing season.

Month	**Whale occurrence**
January	0.0007
February	0.0001
March	0.0007
April	**0.0038**
May	**0.0454**
June	**0.1076**
July	**0.2400**
August	**0.3917**
September	0.1420
October	0.0467
November	0.0176
December	0.0036

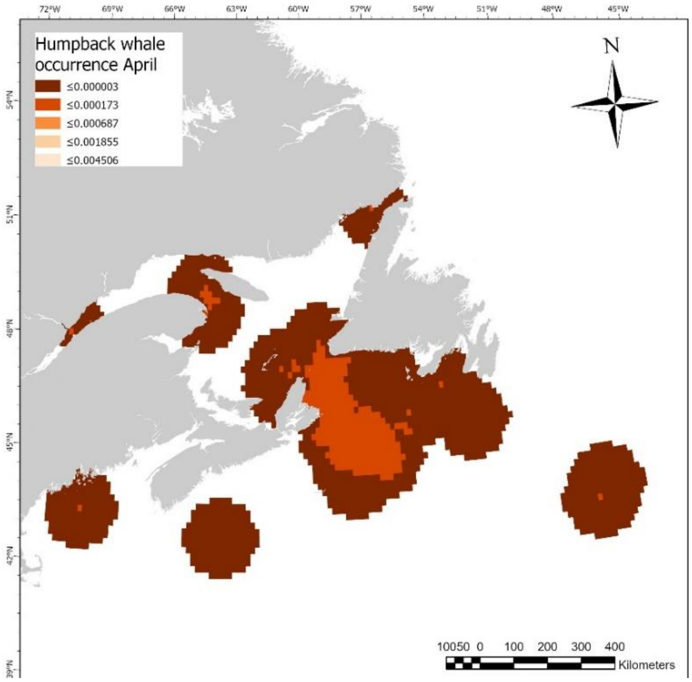

Figure 3.13: Probability of humpback whale occurrence in April. Dark colours indicate lower likelihood of occurrence and light colours indicate higher likelihood of occurrence.

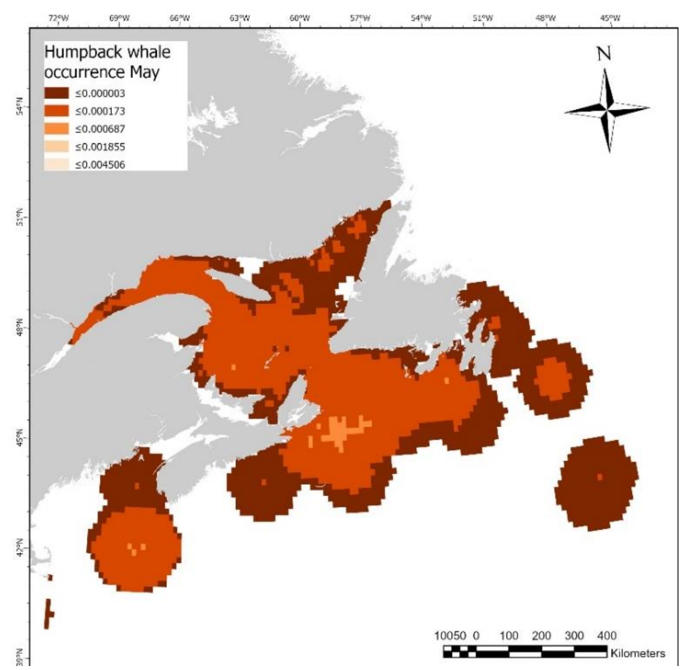

Figure 3.14: Probability of humpback whale occurrence in May. Dark colours indicate lower likelihood of occurrence and light colours indicate higher likelihood of occurrence.

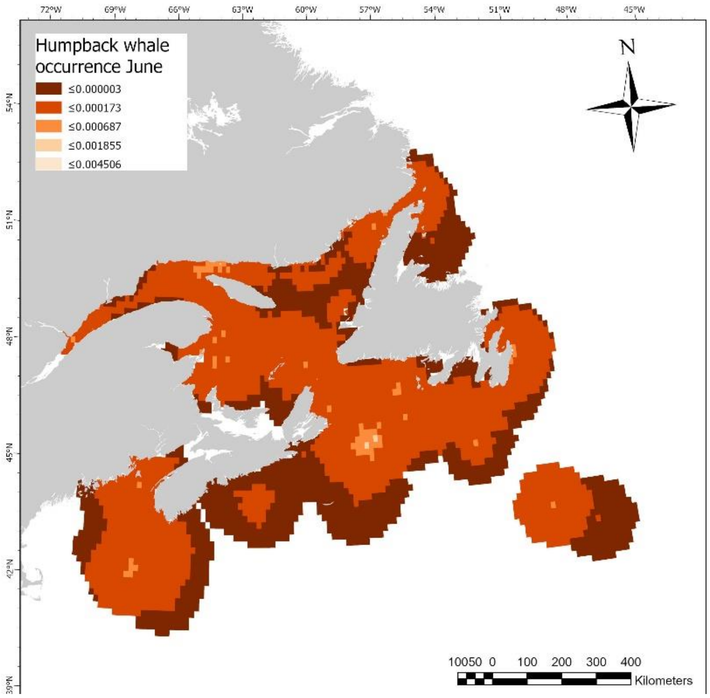

Figure 3.15: Probability of humpback whale occurrence in June. Dark colours indicate lower likelihood of occurrence and light colours indicate higher likelihood of occurrence.

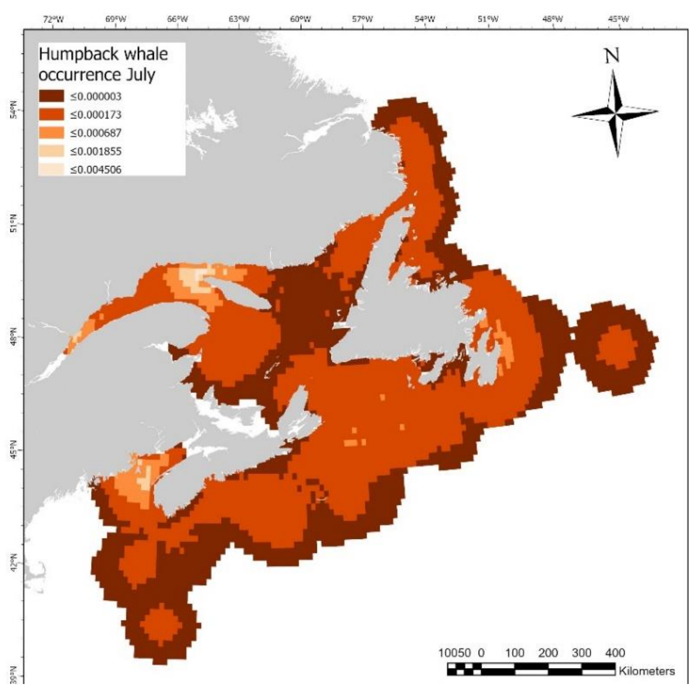

Figure 3.16: Probability of humpback whale occurrence in July. Dark colours indicate lower likelihood of occurrence and light colours indicate higher likelihood of occurrence.

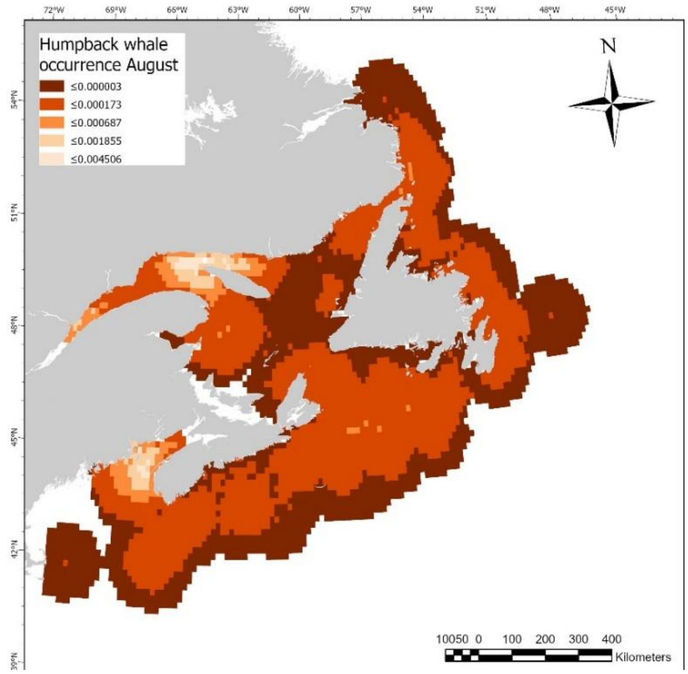

Figure 3.17: Probability of humpback whale occurrence in August. Dark colours indicate lower likelihood of occurrence and light colours indicate higher likelihood of occurrence.

3.3 Risk of Entanglement

3.3.1 Blue Whale Risk of Entanglement

The annual relativized risk for blue whales shows a general trend of decrease in risk throughout the years where the 2018 to 2022 values are all lower than the baseline (Figure 3.18). Nonetheless, the was an increase in risk from 2018 to 2019.

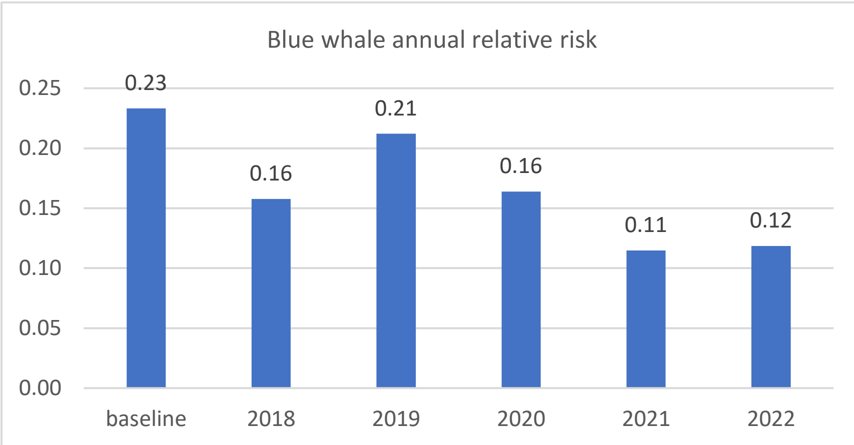

Figure 3.18: Annual relative entanglement risk for blue whale for baseline to 2022

Moreover, when looking at the monthly breakdown of the relativized risk, in general, August is the month with the least risk followed by April, July, May, then June (Table 3.5). Additionally, of note, April baseline has a lower risk value than April 2021 (Figure 3.19 and 3.20) and July baseline has a higher risk value than July for all years (Figure 3.21 and 3.22).

Table 3.5: Monthly and annual relative blue whale entanglement risk values for baseline to 2022.

	April	May	June	July	August	Yearly total
Baseline	0.0092	0.0391	0.1543	0.0306	0.00005	0.23
2018	0.0034	0.0626	0.0781	0.0135	0.000001	0.16
2019	0.0003	0.0561	0.1339	0.0218	0.00005	0.21
2020	0.0160	0.0287	0.0995	0.0195	0.00002	0.16
2021	0.0650	0.0275	0.0051	0.0172	0.00010	0.11
2022	0.0165	0.0337	0.0489	0.0191	0.00013	0.12

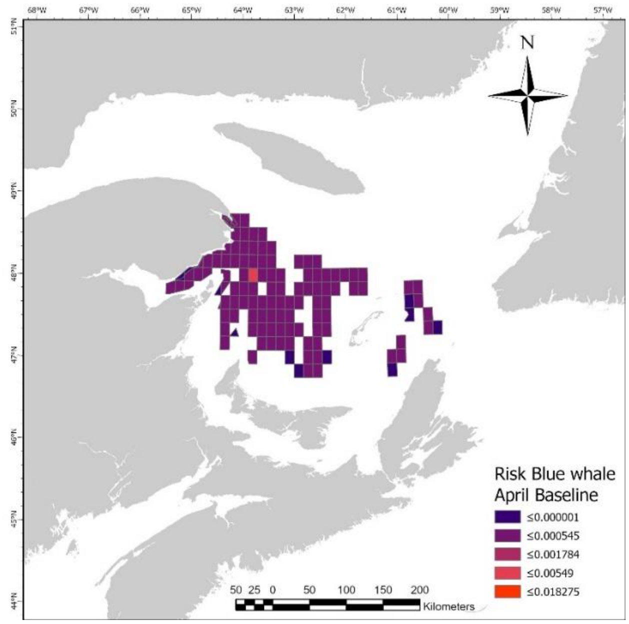

Figure 3.19: April baseline probability of entanglement (i.e., relative risk of entanglement) to blue whales before management measures were implemented. Cool colours (purple) represent lower probability of entanglement and warm (red) indicates higher probability of entanglement.

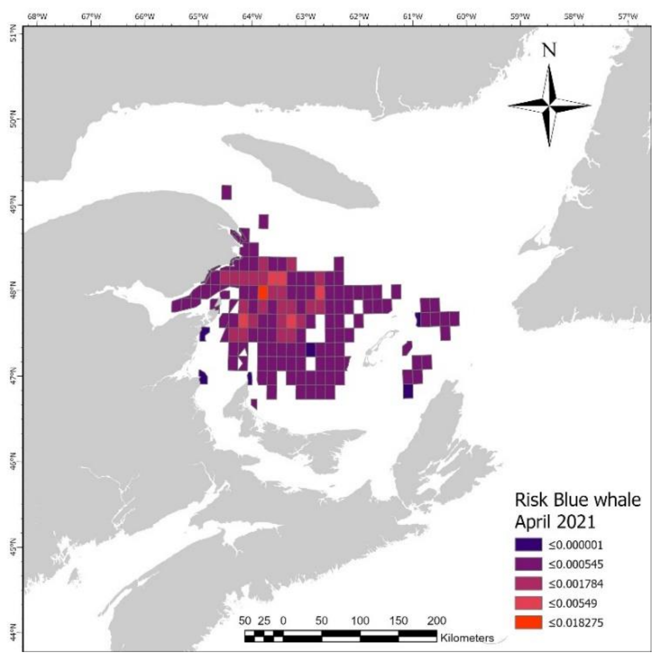

Figure 3.20: April 2021 probability of entanglement (i.e., relative risk of entanglement) to blue whales after management measures were implemented. Cool colours (purple) represent lower probability of entanglement and warm (red) indicates higher probability of entanglement.

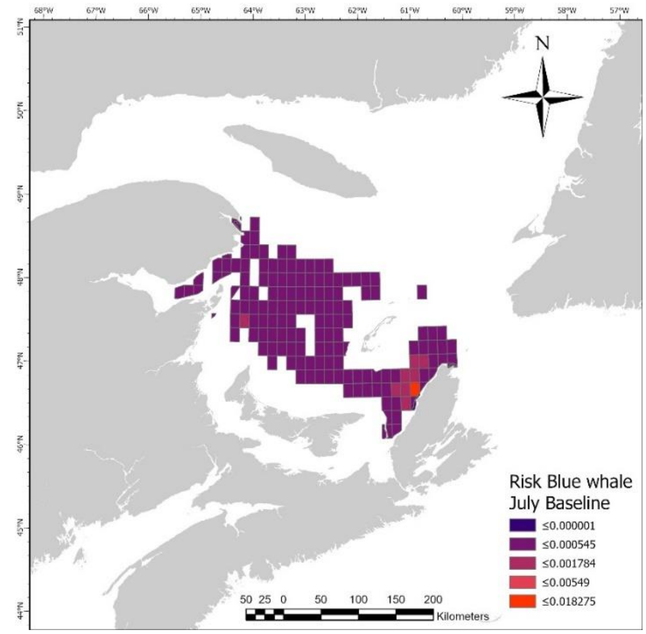

Figure 3.21: July baseline probability of entanglement (i.e., relative risk of entanglement) to blue whales before management measures were implemented. Cool colours (purple) represent lower probability of entanglement and warm (red) indicates higher probability of entanglement.

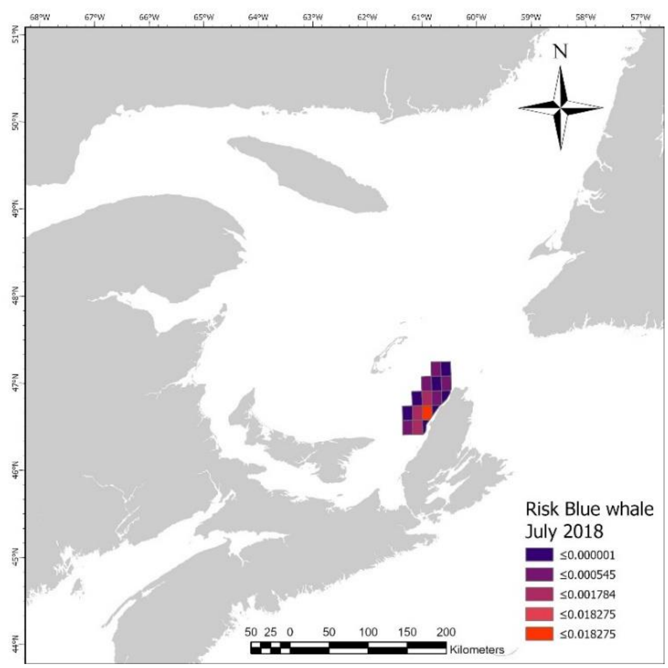

Figure 3.22: July 2018 probability of entanglement (i.e., relative risk of entanglement) to blue whales before management measures were implemented. Cool colours (purple) represent lower probability of entanglement and warm (red) indicates higher probability of entanglement.

3.3.2 Fin Whale Risk of Entanglement

The annual relativized risk for fin whales shows a general trend of decrease in risk throughout the years where 2018 to 2022 values are all lower than the baseline except for 2019 which was higher than the baseline (Figure 3.18).

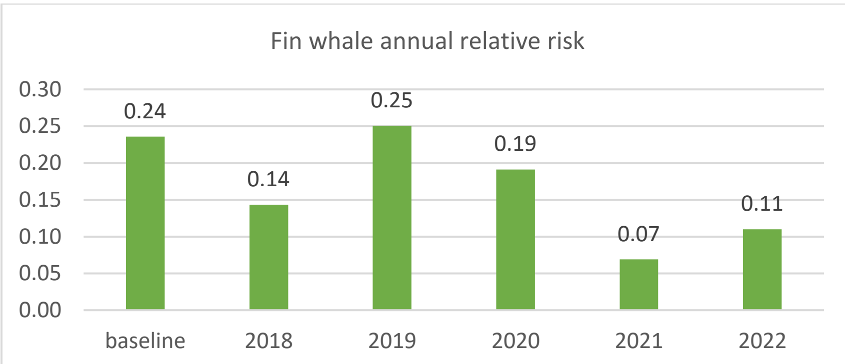

Figure 3.23: Annual relative entanglement risk for fin whale for baseline to 2022

In general, the monthly breakdown of the relativized risk shows that August is the month with the least risk followed by April, May, July then June (Table 3.6). As with blue whales, April baseline has a lower risk value than April 2021 (Figure 3.24 and 3.25) and July baseline has a higher risk value than July in all other years (Figure 3.26 and 3.27).

Table 3.6: Monthly and annual relative fin whale entanglement risk values for baseline to 2022.

	April	May	June	July	August	Yearly total
Baseline	0.0014	0.0376	0.1383	0.0571	0.0013	0.24
2018	0.0007	0.0370	0.0811	0.0245	0.00001	0.14
2019	0.00006	0.0580	0.1510	0.0407	0.0007	0.25
2020	0.0022	0.0423	0.1103	0.0362	0.0001	0.19
2021	0.0107	0.0207	0.0053	0.0317	0.0007	0.07
2022	0.0031	0.0262	0.0423	0.0359	0.0019	0.11

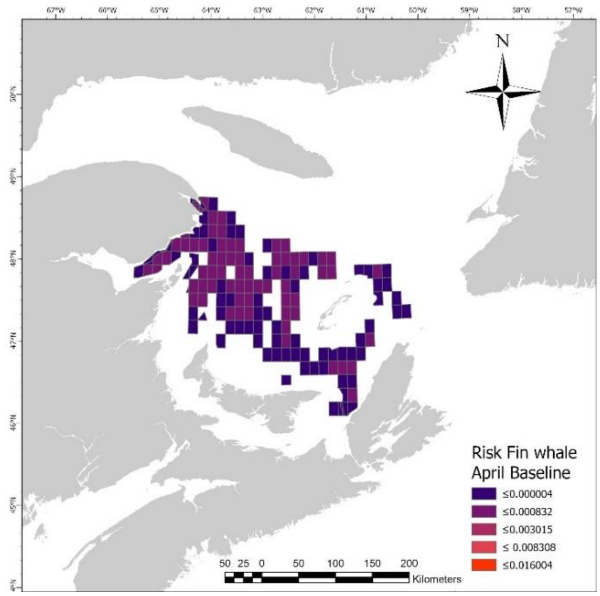

Figure 3.24: April baseline probability of entanglement (i.e., relative risk of entanglement) to fin whales before management measures were implemented. Cool colours (purple) represent lower probability of entanglement and warm (red) indicates higher probability of entanglement.

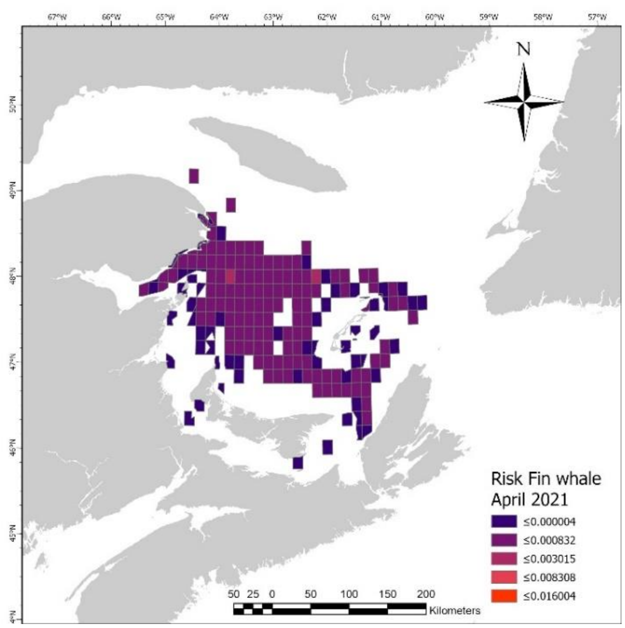

Figure 3.25: April 2021 probability of entanglement (i.e., relative risk of entanglement) to fin whales after management measures were implemented. Cool colours (purple) represent lower probability of entanglement and warm (red) indicates higher probability of entanglement.

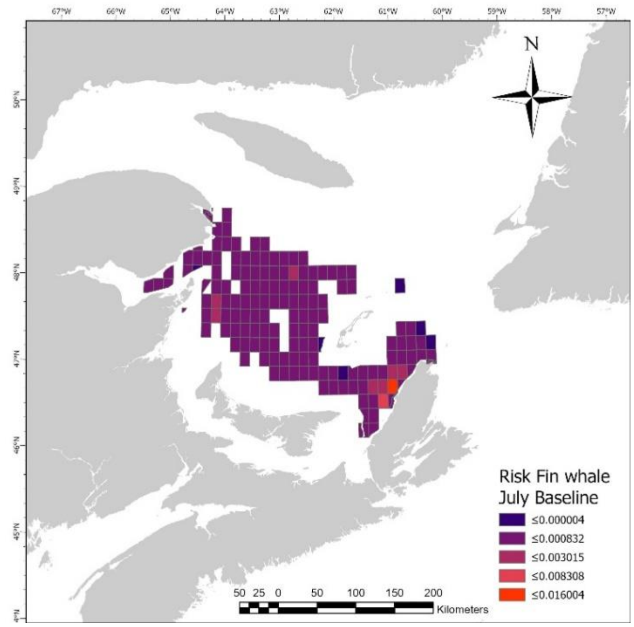

Figure 3.26: July baseline probability of entanglement (i.e., relative risk of entanglement) to fin whales before management measures were implemented. Cool colours (purple) represent lower probability of entanglement and warm (red) indicates higher probability of entanglement.

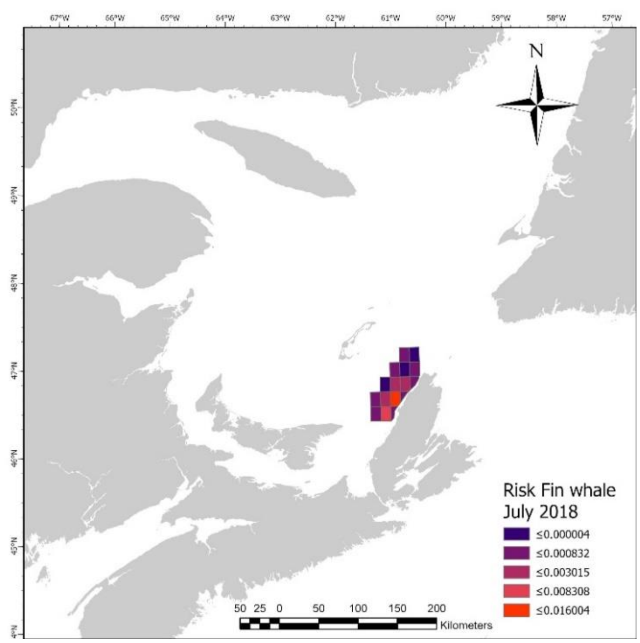

Figure 3.27: July 2018 probability of entanglement (i.e., risk of entanglement) to fin whales after management measures were implemented. Cool colours (purple) represent lower probability of entanglement and warm (red) indicates higher probability of entanglement.

3.3.3 Humpback Whale Risk of Entanglement

The annual relativized risk for humpback whales shows only a decrease in risk values for the years 2018, 2021 and 2022 in comparison to the baseline; the years 2019 and 2020 had higher risk values than the baseline (Figure 3.28).

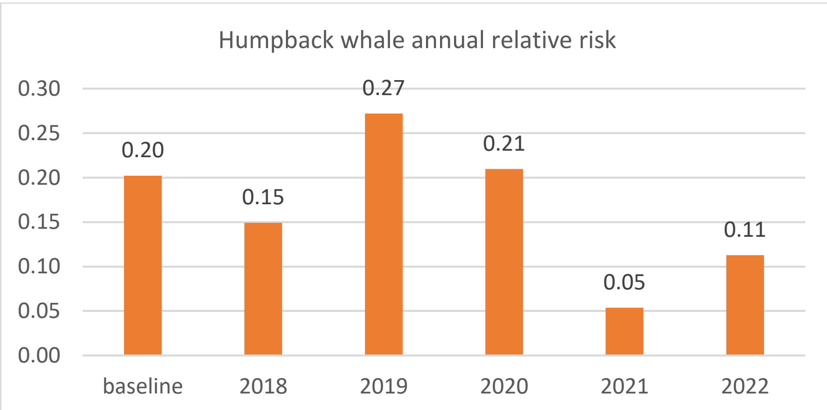

Figure 3.28: Annual relative entanglement risk for humpback whale for baseline to 2022

For humpback whales, the monthly breakdown of the relativized risk shows that August is the month with the least risk followed by April, July, May then June (Table 3.7). Similarly to blue and fin whales, April baseline has a lower risk value than April 2021 (Figure 3.29 and 3.30) and July baseline has a higher risk value than July in all other years (Figure 3.31 and 3.32).

Table 3.7: Monthly and annual relative humnpback whale entanglement risk values for baseline to 2022.

	April	May	June	July	August	Yearly total
Baseline	0.0004	0.0779	0.1156	0.0082	0.00023	0.20
2018	0.0002	0.0770	0.0692	0.0029	0.000004	0.15
2019	0.00006	0.1447	0.1214	0.0058	0.00021	0.27
2020	0.0003	0.1071	0.0972	0.0050	0.00005	0.21
2021	0.0021	0.0430	0.0041	0.0042	0.00023	0.05
2022	0.0010	0.0704	0.0361	0.0049	0.00052	0.11

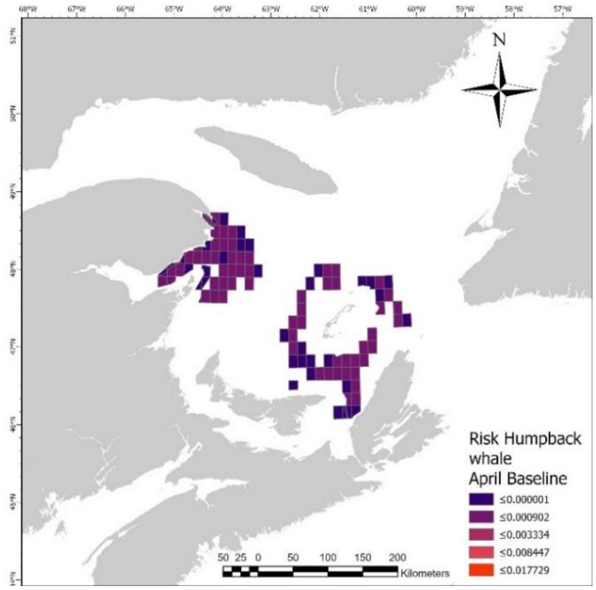

Figure 3.29: April baseline probability of entanglement (i.e., relative risk of entanglement) to humpback whales before management measures were implemented. Cool colours (purple) represent lower probability of entanglement and warm (red) indicates higher probability of entanglement.

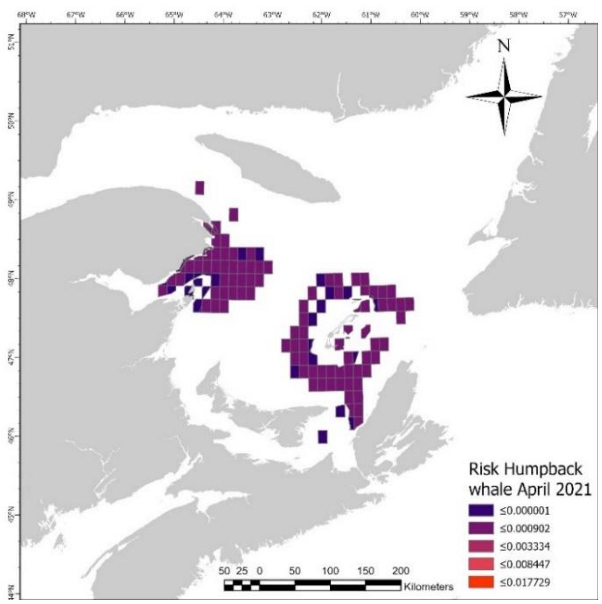

Figure 3.30: April 2021 probability of entanglement (i.e., relative risk of entanglement) to humpback whales after management measures were implemented. Cool colours (purple) represent lower probability of entanglement and warm (red) indicates higher probability of entanglement.

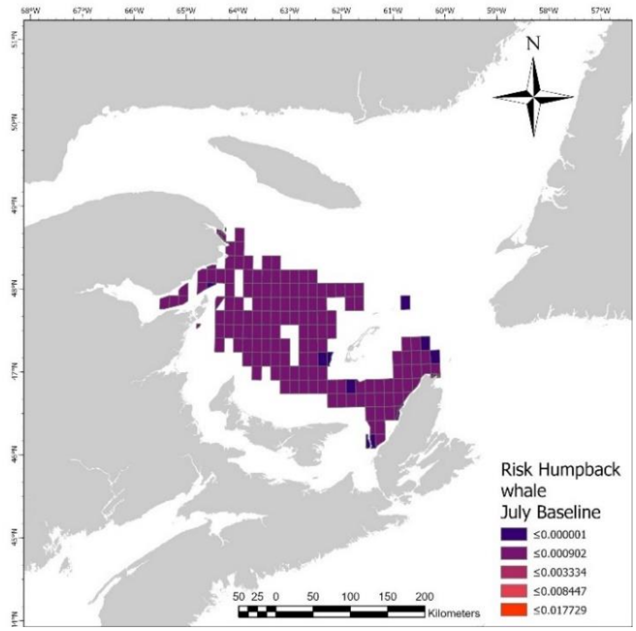

Figure 3.31: July baseline probability of entanglement (i.e., relative risk of entanglement) to humpback whales before management measures were implemented. Cool colours (purple) represent lower probability of entanglement and warm (red) indicates higher probability of entanglement.

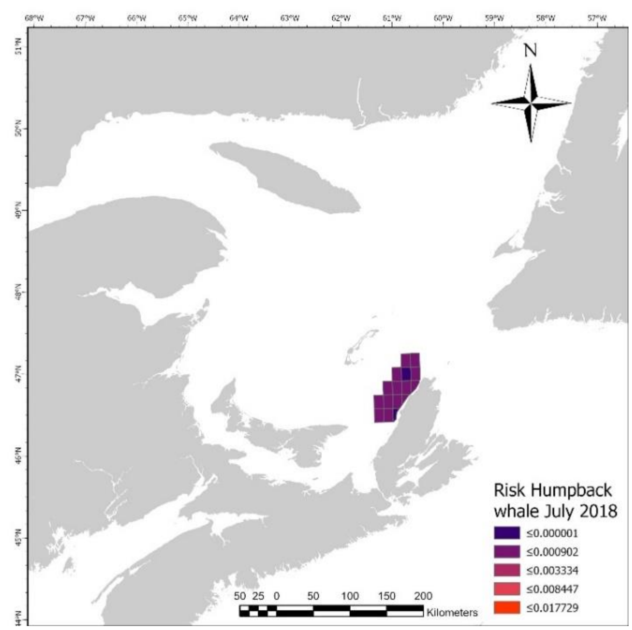

Figure 3.32: July 2018 probability of entanglement (i.e., relative risk of entanglement) to humpback whales after management measures were implemented. Cool colours (purple) represent lower probability of entanglement and warm (red) indicates higher probability of entanglement.

3.4 Change in Risk for Whale Entanglement

3.4.1 Annual Change in Risk for Blue, Fin, and Humpback Whales

Change in risk was calculated with a rate of change (equation 2) using relative risk for all three species. Blue whales had a relative risk reduction for all years; 2019 being the year with the least reduction (Figure 3.33). Fin whales showed a similar trend; however, 2019 has a slight increase in relative risk (Figure 3.33). Humpback whales had a relative risk reduction in 2018, 2021, and 2022, but a substantial relative risk increase in 2019 and a more negligible one in 2020 (Figure 3.33). This summarizes a general trend of relative risk reduction in 2018, 2021, and 2020 while 2019 and 2020 showed some variability in relative risk amongst the species.

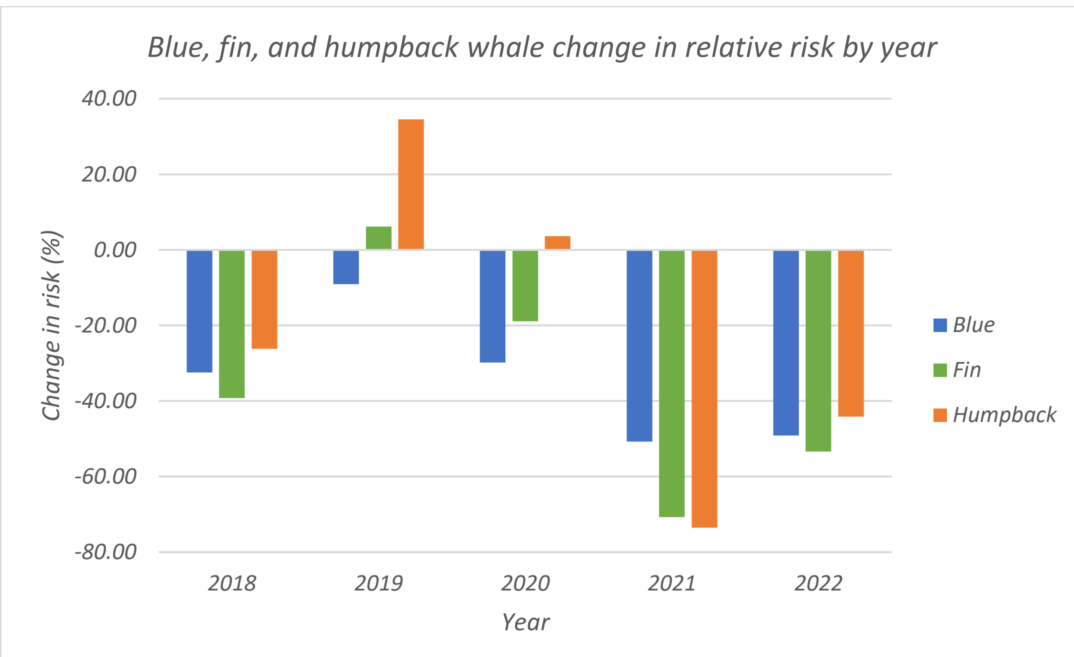

Figure 3.33: Rate of change in relative entanglement risk for blue (blue), fin (green), and humpback (orange) whales for 2018 to 2022 in comparison to the baseline (2015-2017).

3.4.2 Blue Whale Change in Risk

The monthly breakdown of rate of change of relativized entanglement risk for blue whales shows some variability throughout the years for each month. April has risk reduction for 2018 and 2019, but then has risk increase for the other years (Table 3.9). May only has risk reduction for 2020-2022 (Table 3.9). There seems to be a general reduction in risk throughout the years for the month of June and same for July (Table 3.9). On the contrary, August has variability with risk reduction in 2018 and 2020, but a slight risk increase in 2019 and larger increases in 2021 and 2022 (Table 3.9).

Table 3.8: Monthly rate of change of relative blue whale entanglement risk for 2018-2022. Negative values indicate the magnitude of entanglement risk reduction, whereas positive values indicate the magnitude of entanglement risk increase.

	April	May	June	July	August	Yearly total
2018	-62.36	60.30	-49.41	-55.97	-96.96	-32.40
2019	-97.24	43.69	-13.25	-28.79	11.05	-9.04
2020	75.27	-26.49	-35.55	-36.24	-55.62	-29.78
2021	610.87	-29.74	-96.72	-43.83	114.30	-50.76
2022	80.63	-13.36	-68.29	-37.42	179.31	-49.15

3.4.3 Fin Whale Change in Risk

Like blue whale monthly rate of change, there is variability throughout the years for each month of entanglement risk for fin whales. April has a risk reduction for 2018 and 2019, but then has risk increase for the other years (Table 3.10). May has risk reduction for 2018, 2021, and 2022 (Table 3.10). June has risk reduction for all years except for 2019 and large risk reductions for 2021 and 2022 (Table 3.10). July has risk reduction for all years (Table 3.10). Finally, August has large risk reductions for all years except a risk increase in 2022 (Table 3.10).

Table 3.9: Monthly rate of change of relative fin whale entanglement risk for 2018-2022. Negative values indicate the magnitude of entanglement risk reduction, whereas positive values indicate the magnitude of entanglement risk increase.

	April	May	June	July	August	Yearly total
2018	-49.33	-1.45	-41.38	-57.16	-99.18	-39.21
2019	-95.84	54.26	9.13	-28.73	-45.16	6.21
2020	54.12	12.48	-20.25	-36.57	-90.71	-18.92
2021	643.22	-45.04	-96.16	-44.45	-50.90	-70.70
2022	114.71	-30.19	-68.93	-37.20	42.03	-53.32

3.4.4 Humpback Whale Change in Risk

The monthly change of entanglement risk for humpbacks has more variability than that of blue and fin whales. April has risk reduction for 2018-2020, but then has large risk increases for 2021 and 2022 (Table 3.11). May has lower risk reduction values for 2018, 2021, and 2022 and risk increases for 2019 and 2020 (Table 3.11). June has risk reduction for all years expect 2019 and July has risk reduction for all years (Table 3.11). Lastly, August has risk reduction for all years except 2022 (Table 3.11).

Table 3.10: Monthly rate of change of relative humpback whale entanglement risk for 2018-2022. Negative values indicate the magnitude of entanglement risk reduction, whereas positive values indicate the magnitude of entanglement risk increase.

	April	May	June	July	August	Yearly total
2018	-37.59	-1.05	-40.15	-65.12	-98.13	-26.17
2019	-83.75	85.85	5.03	-29.30	-10.68	34.56
2020	-21.91	37.56	-15.91	-38.43	-78.94	3.68
2021	447.75	-44.82	-96.47	-48.68	-3.67	-73.51
2022	148.83	-9.62	-68.74	-39.66	123.93	-44.17

3.5 Statistical Analysis of Relative Risk

The results for the nested ANOVA of relative entanglement risk values determined that the relationship between year and month and between species, year, and month were significant (Table 3.11).

Table 3.11: Results from the ANOVA test comparing relative entanglement risk for blue, fin, and humpback whales across months and years.

	Degrees of freedom	Sum of squares	Mean square	F value	Pr ()
Species	2	0.0000000	0.00000	0.0000	1.0000
Year	5	0.0003980	0.000079605	0.4809	0.7870
Species:Year	10	0.0000373	0.000003731	0.3046	0.9765
Year:Month	24	0.0039730	0.000165540	102.4584	< 2e-16
Species:Year:Month	48	0.0005879	0.000012248	7.5807	< 2e-16
Residual	2700	0.0043624	0.000001616	-	

The results of the Student-Newman-Keuls test showed no statistically significant differences among the years for blue whales. On the other hand, for fin and humpback whales, 2021 was significantly different from the baseline and 2021 and 2022 were significantly different from 2019. Additionally, 2021 was significantly different from 2020 for humpback whales.

Chapter 4: Discussion

4.1 Threat from Snow Crab Fishery

Due to its high overlap with NARW distribution in the GoSL, the southern GoSL snow crab fishery poses the most threat for NARW. 2019 was the year with the highest threat after the baseline year which coincided with the second mass mortality event of NARW (DFO 2020a). The landings for 2019 (31,707 tonnes) are similar to that of 2022 (31,661 tonnes) (DFO 2023); however, the threat for 2019 (0.212) is almost double that of 2022 (0.119) which could be linked to catch per unit effort. There is variation in the magnitude of threat across the years; however, 2022 and 2021 were the years with the least threat so recently there is a general trend of decreasing threat. Moreover, on a monthly basis, May has the highest threat and August has the lowest. The snow crab fishing season for CFA 12, 12E, and 12F normally starts at the end of April. This could be explained by the fact that May and June would have higher threat since there is an increase in fishing during those months until the quota is harvested. Finally, only CFA 19 fishes in August and has a much smaller quota than the other CFAs since it is a smaller area and has less license holders, hence there is less threat. Overall, it is important to understand the temporal and spatial distribution of threat in order to locate potential high risk areas.

4.2 Whale Occurrence Distribution

Even though DFO is uncertain about the occurrences of these whales during the winter (DFO 2016; DFO 2017) blue, fin, and humpback whales have an annual presence, from January to December, in Atlantic Canada. Nonetheless, the majority of their occurrences coincided with the snow crab fishery season from April to August; 56.42% of the blue whale occurrence coincided with these months, while fin whale occurrence was 81.55%, and humpback whale occurrence was 78.85%. These whale occurrences followed a similar trend of distribution where their occurrence density increased as the months progressed from April to August. Additionally, there is a pattern of high density of all three whale species around Gaspésie and Anticosti Island. It could not be determined if this is related to higher data collection effort in that region compared to the southern GoSL or higher density of whale occurrences. We received five datasets to create a whale occurrence distribution; three of these datasets are from Quebec locations (MONN, Parks Canada, and MICS) so the collection of the data would most likely come from the north of the GoSL. This might have biased the data since the threat from the snow crab fishery gear is located in the southern GoSL. Doniol-Valcroze et al. (2007) determined that blue, fin, and humpback whales use different areas to feed than NARW in the GoSL. Therefore, since NARW distribution coincides highly with the snow crab fishery (Daoust et al. 2017; Bourque et al. 2020; Pettis et al., 2020), there a possibility that blue, fin, and humpback whales do not coincide as much with this fishery due to their differing distributions. Moreover, acoustic data was not incorporated in this model. Data from the DFO systematic surveys including the southern GoSL, has been received since the completion of the analysis and will be incorporated into future research on this topic. This additional data would provide a different whale occurrence distribution for these whales since they cover all of the GoSL. Nonetheless, it is important to mention that while more data is better, evaluation of management measures and decision-making does not always need more data which is the basis of the precautionary approach (DFO 2009b).

4.3 Risk of Entanglement

For blue whales, the annual risk decreases from 2018 to 2022 except for a large increase in 2019 and a minimal increase in 2022. For fin whales, it follows a similar trend; however, the increase in 2019 is higher than the baseline. For humpback whales, both 2019 and 2020 were above the risk of the baseline year. In all, for all three whales, there is a similar trend of overall risk decrease after the baseline year, but an increase in risk in 2019. This anomaly in 2019 is reflected in the results of the threat distribution as well. The management measures changed a lot from 2018 to 2019 to 2020 which could explain these trends. The static closure area which encompassed the majority of the NARW occurrences in the GoSL was 63% smaller in 2019 than in 2018 (DFO 2019a). Additionally, fisheries management measures changed in 2020 from static and dynamic closures to season-long and temporary closures (DFO 2020b). Thus, these annual management measures might have heavily impacted the amount of risk for these other whales.

However, when we look at the monthly trends, we gain further insight into how specific NARW fisheries management had positive and negative impacts on blue, fin, and humpback whales that may have influenced this annual trend. One of the management measures to reduce risk of entanglement for NARW is to start the snow crab fishing season as early as possible in April (i.e., when the ice melts) before the NARW migrate northwards from the United States. To further help start the season earlier, ice breaker operations have been implemented since 2020 to help get fish harvesters fishing sooner. An unintended consequence of this NARW management measures is that the risk of entanglement was shown to be higher in April 2021 in comparison to April baseline. April 2021 started during the first week of the month whereas April baseline started at the end of the month. This could be due to the fact that blue, fin, and humpback whales have different migration timing than NARW (Pendleton et al. 2022) and that they remain in Atlantic Canada year-round as mentioned above. Also, this management measure poses safety hazards for fish harvesters to start early in April due to bad weather (M Landry, personal communication, October 25, 2023). In all, while an earlier start date may be valuable for reducing risk in the later part of the fishing season, an early start date in April may actually increase risk to blue, fin, and humpback whales during these early months as well as to fish harvesters.

On the other hand, another management measure was to finish the season on June 30th for CFA 12, 12E, and 12F which has been in place since the precautionary measures were implemented in 2018. This resulted in less risk for July in all years from 2018 to 2022 in comparison to the July baseline for all whales. Therefore, this NARW management measure can be considered positive as it also affords protection to blue, fin, and humpback whales, especially during the months where their occurrence is starting to increase in the GoSL.

The nested ANOVA and SNK tests were significant for certain years and species. For blue whales, the annual relative risk was not significant for any years, therefore indicating that despite a negative trend (i.e., risk reduction) across the years, the risk level has remained consistent from year to year. For fin and humpback whales, 2021, which had lower risk, was the only year that was significantly different from the baseline year. This indicates that there was significant risk reduction in this year for these species, and that the management measures were effective in this year. However, for fin and humpback whales, 2021 and 2022 were also significantly different from 2019. This is interesting as 2019 and 2022 showed no significant differences to the risk level in the other years, indicating that years without significance contribute similar levels of risk, as with blue whales (despite the general negative trend). Therefore, this difference must come from the increase in risk in 2019 versus the larger risk reduction values in the other years. There were significant changes to the management measures in 2021 and 2022 in comparison to 2019, including the use of static and dynamic management versus season-long and temporary closures and the incorporation of acoustic detections in 2021 and 2022. While 2019 had a small static area, the dynamic areas were smaller and relied on consistent detection of whales during the closure period. Whereas 2021 and 2022 could have season-long closures, potentially creating much larger extended gear-free area (similar to the static area) than what was used in 2019. Another measure was the criteria for when a NARW sighting would trigger a 15-day extension. In 2019, a second sighting during the 15-day period would trigger a 15-day extension (DFO 2019a), whereas in 2021 and 2022, a NARW sighting during day 9 and 15 would trigger a season-long closure (DFO 2021b; DFO 2022b). This different measure might explain why 2021 and 2022 were significantly different than 2019 in terms of risk.

4.4 Change in Risk

For all three whale species, the overall annual trend for the change in risk of entanglement is negative meaning there is risk reduction. For blue whales, the range in annual change in risk was -50.76 to -9.04%, for fin whales, it was -70.70 to 6.21%, and for humpback whales, it was -73.51 to 34.56%. These large ranges in change in risk throughout the years shows the importance of understanding the impacts of management measures. As mentioned above, 2019 was the second mass mortality event for NARW and this is also reflected in the risk data for these whale species. It is the year with the least risk reduction for blue whales and risk increase for fin and humpback whales. Additionally, some trends of risk increase and decrease were found when looking at the change in risk on monthly basis. For all three species, there was a substantial increase in risk when the harvesting season started earlier in April (i.e. when comparing baseline to 2021). Also, July consistently had risk reduction for blue, fin, and humpback whales.

4.5 Management Implications

DFO works with principles, approaches, and management plans to ensure sustainable fisheries. DFO acknowledges that ecosystem-based fisheries management is crucial for sustainable fisheries (DFO 2009a). This research study embodies the ecosystem approach by assessing the impacts of fisheries management on non-target species (DFO 2009a). Ecosystem-based fisheries management is a subset of integrated oceans management, which implies better decision-making from fisheries managers by considering all ocean activities (DFO 2009a). There is a specific plan for the GoSL: the Gulf of St. Lawrence integrated management plan (DFO 2019d). This plan highlights that fin and humpback whales are candidate ecologically significant species meaning that with further research, they could be considered species that play an important role in biodiversity within the GoSL (DFO 2019d). Moreover, one of the themes of this management plan is a risk-based management approach which helps to identify management priorities (DFO 2019d). The precautionary approach states that scientific uncertainty is not a reason to avoid actions that could harm serious resources (DFO 2009b). Also, depending on the health of the stock, socio-economic and biological factors could change; for example, biological factors will be prioritized if a stock is deemed in critical health (DFO 2009b). In sum, these approaches and principles confirm the importance of this study and future research on the impacts of fisheries management measures on non-target species.

In addition, SARA states that the government must provide for the recovery of endangered species, like blue whales, to prevent extinction and manage species of special concern, like fin whales, to prevent them from becoming threatened or endangered (ECCC 2008). Both these whale species are threatened by entanglements in fixed-fishing gear so measures to mitigate these threats must be taken (DFO 2016; DFO 2017). Hence, this study shows the benefits of NARW fishery closures by reducing the overall risk of entanglement of blue and fin whales. Although, humpback whales are listed as not at risk under SARA (Baird 2003), it is also important to protect them and prevent their uplisting to special concern.

Chapter 5: Conclusion

The purpose of this research was to assess the effects of NARW fishery management measures on the risk of entanglement of other whales in the GoSL. The results demonstrated that overall, there is a trend of risk reduction for entanglements to blue, fin, and humpback whales throughout the years (2018-2022) with NARW fishery closures with some variability in the significance of that decrease. Further, specific management measures can have positive or negative impacts on the risk of entanglement to these other whales.

This research has potential to expand to future research projects. This study can be done for other species such as minke whales, the whale with the highest entanglement rate in Atlantic Canada (Wimmer & Maclean 2021) and sei whales, endangered under SARA (DFO 2019). These baleen whales also occur in the GoSL and are at risk of entanglement in fixed-fishing gear. Another improvement to this study would be to include behavioural data to the whale occurrence model. This study assumed that whales were always traveling at the same speed; however, whales frequent the GoSL to feed and socialize as well. These behaviours would entail different swimming speeds therefore different occurrence distributions. The addition of acoustic data would also be an improvement to the whale occurrence model by providing more detection data. Finally, these whale occurrence distributions could be used to analyze the risk of other threats like vessel strikes.

This research shows the necessity for conducting risk assessments of management measures for non-target species. Indeed, other species should be taken into consideration in terms of temporal and spatial aspects when implementing management measures. A lot of research is focused on NARW due to their dire state, but other species are at risk or facing similar threats must be studied as well. It is important to keep in mind that management measures can control when and where fisheries can take place; we cannot control where the whales go. Therefore, the focus of this research is to understand how efficient we are at mitigating threats like entanglements in fishing gear. NARW are close to extinction thus the need to immediately reduce deaths from anthropogenic activities; however, blue, fin, and humpback whales also need protection from these threats. We should be taking proactive measures to prevent these other whales from nearing extinction like NARW.

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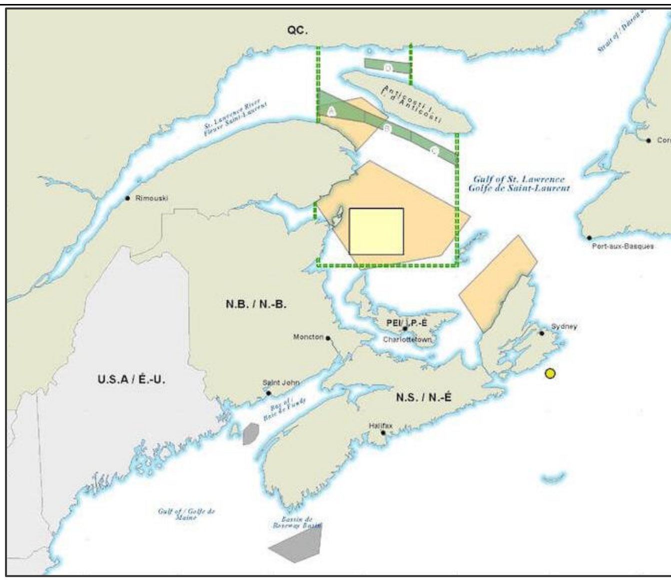
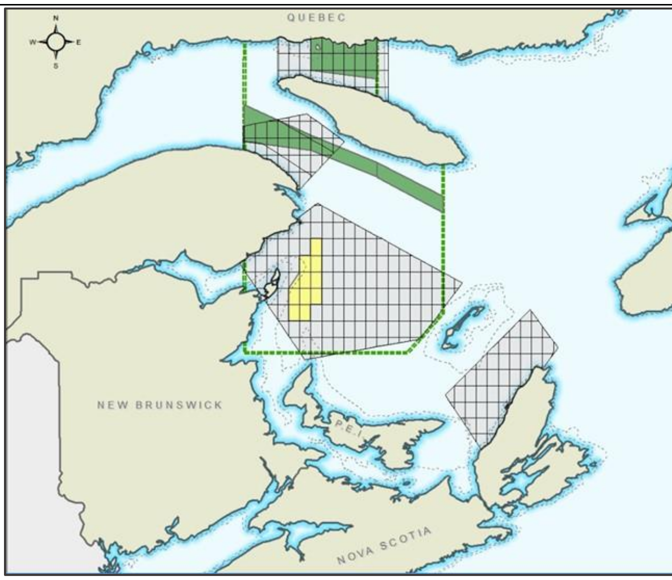
<u>APPENDICES</u>

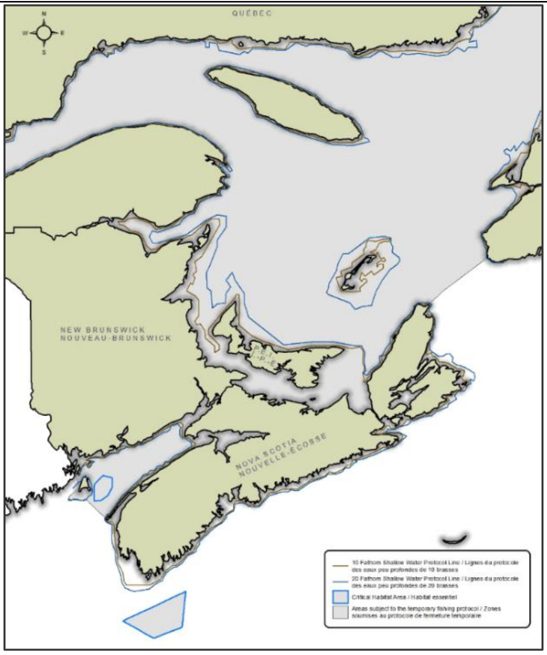
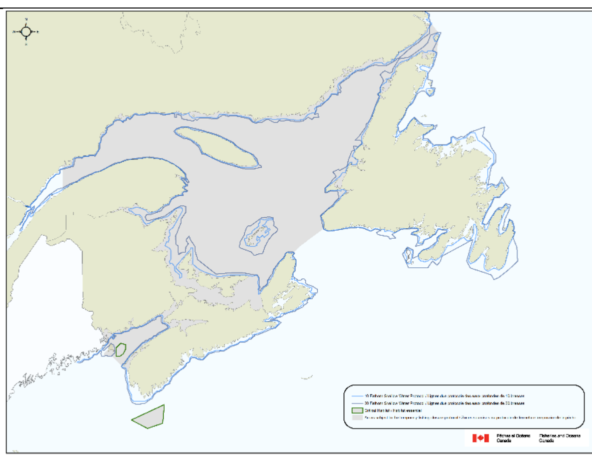
Appendix A – DFO NARW fisheries management measures from 2018-2022

Table A1: DFO fisheries management measures from 2018 to 2022 to protect NARW which includes maps, fishing season, static or season-long closure, and dynamic or temporary closures.

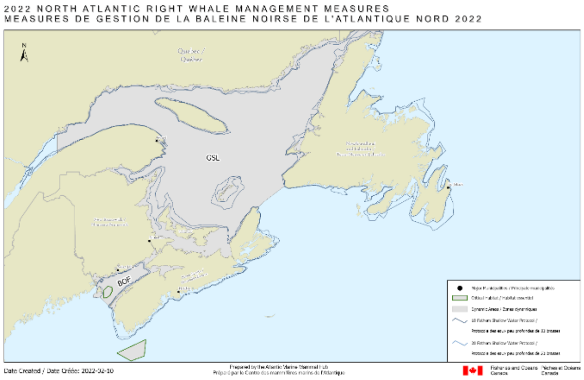
Year	**Map**	**Management measures**	
2018		Fishing Season	The fishery will close on June 30, 2018 at 24:00hrs. All gear must be removed from the water by the end of the day on June 30, 2018.
		Static closure	Also referred to as the static closure, this area will be in effect starting April 28, 2018 or sooner if whales are sighted (Figure 1). No fishing is permitted within this area. The size and shape of the closure was determined based on encompassing 90% of the sighted whales from 2017.
		Dynamic closure	a. This protocol allows DFO to close specific areas to fishing activities when the presence of a right whale is observed. It will use the existing soft-shell grid cells to close relevant areas. b. When at least one right whale is observed inside a dynamic management area (Figure 1), a total of nine grid cells will be closed to provide a buffer area around the sighting location to account for whale movement. c. Closures will be in force for a minimum period of 15 days and will be extended by another 15 days from the last right whale sighting. If right whales are not seen during at least two aerial surveillance flights during the 15-day period, the dynamic closure for the relevant sections will be lifted at the end of the period. Closures will be regulated through variation orders and

			fishers will be provided a notice of a minimum of 48 hours to retrieve gear prior to the closure.
2019		Fishing season	There is no change to the end date of the fishing season.
		Static closure	a. The size and shape of the static closure will be adjusted to encompass the area where 90% of the right whale sightings occurred in May and June 2018. b. The 2019 closure is approximately 63% smaller than the 2018 static closure and will have a more elongated shape (Figure 2). c. The grids removed from the 2018 static closure will now be part of the dynamic management area and subject to temporary closures. d. There are no changes related to the start date of the closure. It will close on April 28, 2019 or before if a right whale is observed in the Gulf of St. Lawrence before this date. Once closed, it will remain closed for all non-tended fixed gear fisheries until further notice.
		Dynamic closure	a. The shape of the dynamic management areas will mostly remain the same. The smaller static closure will result in a large area subject to dynamic management in the sGSL. An additional dynamic area has been identified North of Anticosti Island in Jacques Cartier Strait (Figure 2). b. If one or more right whales are observed in a dynamic management area, DFO will close grids based on the soft-shell crab grid system. c. A maximum of nine grids, the with central grid where the right whale is sighted, and up to 8 adjacent grids to account for a buffer will be closed.

			d. There will be lines to reflect as close as possible the 20 fa and 10 fa depths. This year, fisheries conducted in depths less than 20 fa (shallow water) will be subject to dynamic management protocols only if a right whale is observed in these waters. i. There are two shallow water protocol regions – between 10-20fa and from shore to 10fa e. Closures will be in force for a minimum period of 15 days, counted from the date of the right whale sighting and will be extended by 15 days from the last right whale sightings. If right whales are not seen during at least two aerial surveillance flights during the 15-day period, the relevant sections will be lifted at the end of the period. f. Fishers will be given a minimum of 48 hours' notice to remove gear g. Observations outside the dynamic and static areas will be considered on a case-by-case basis, with special attention for observations of 3 or more whales or a mother-calf pair.
2020		Fishing closure	There is no change to the end date of the fishing season, however ice breaker operations are to be attempted to free ports from ice to allow fishers to begin the season earlier
		Static closure	a. There will no longer be a static closure – instead, a new season-long closure protocol will be in place as soon as snow crab fisheries open in 2020. These closures will be applied to areas where whales are detected to be aggregating. b. If whales are detected in the same area more than once during a 15-day period, a

			designated area will be closed until November 15, 2020.
		Dynamic closure	a. The areas subject to dynamic (and thus, seasonal) closures include anywhere in the Gulf of St. Lawrence, the Bay of Fundy and critical habitats in Roseway Basin and Grand Manan Basin (Figure 3). b. These closures are in effect for all non-tended fixed gear fisheries. c. If one or more whale is detected in these areas, the designated area will be closed for 15 days and could extend beyond 15 days if whales remain in the area. d. Outside these defined areas, closures will be considered on a case-by-case basis with special consideration for sightings of 3 or more whales or a mother-calf pair. e. The same shallow water protocols apply as 2019. f. Acoustic recording devices can now be used to trigger closures.
2021		Fishing closure	There is no change to the end date of the fishing season, however ice breaker operations are to be attempted to free ports from ice to allow fishers to begin the season earlier.
		Season-long and temporary closures	a. The same dynamic (temporary) and season-long protocol that was introduced in 2020 is being maintained in 2021 (Figure 4). i. The GSL, Bay of Fundy, and Roseway Basin are all subject to the dynamic protocol, in which if a single right whale is visually or acoustically detected a defined area around the position of the detection (approximately 2000 km2) will be closed to non-tended fixed gear fisheries for 15 days.

			b. New for 2021, in order to trigger a season-long closure or extension of a dynamic/temporary closure, a whale will need to be detected again in a closed area during days 9-15 of the closure. i. In the BOF and RB, if a whale is detected again during the second half of the closure, the area will be closed for another 15 days ii. In the GSL, if a whale is detected again during the second half of the closure a season-long closure will be implemented; the area will remain closed until November 15, 2021. iii. If a whale is not detected again the area will reopen to fishing after day 15. iv. Two flights with no right whale detections will continue to be required before an area can re-open to fishing. If flights are unable to go out during days 9-15, the area will remain closed until two flights can indicate whether whales are likely no longer in the area v. Outside the dynamic zones, closures will be considered on a case-by-case basic, with special consideration for sightings of 3 or more whales or a mother-calf pair. c. The shallow water protocol introduced in 2019 continues to be in effect, in which the area from shore to the 10fa line and between the 10fa and 20fa lines will be subject to a temporary closure only if a whale is sighted within these depths.
2022		Fishing closure	There is no change to the end date of the fishing season, however ice breaker operations are to be attempted to free ports from ice to allow fishers to begin the season earlier.

		Season-long and temporary closures	a. The same dynamic (temporary) and season-long protocol that was introduced in 2021 is being maintained in 2022 (Figure 5). i. The GSL, Bay of Fundy, and Roseway Basin are all subject to the dynamic protocol, in which if a single right whale is visually or acoustically detected a defined area around the position of the detection (approximately 2000 km2) will be closed to non-tended fixed gear fisheries for 15 days. b. To trigger a season-long closure or extension of a dynamic/temporary closure, a whale will need to be detected again in a closed area during days 9-15 of the closure. i. In the BOF and RWB, if a whale is detected again during the second half of the closure, the area will be closed for another 15 days ii. In the GSL, if a whale is detected again during the second half of the closure a season-long closure will be implemented; the area will remain closed until November 15, 2022. iii. If a whale is not detected again the area will reopen to fishing after day 15. iv. Two flights with no right whale detections will continue to be required before an area can re-open to fishing. If flights are unable to go out during days 9-15, the area will remain closed until two flights can indicate whether whales are likely no longer in the area v. Outside the dynamic zones, closures will be considered on a case-by-case basis, with

			special consideration for sightings of 3 or more whales or a mother-calf pair. c. The shallow water protocol introduced in 2019 continues to be in effect, in which the area from shore to the 10fa line and between the 10fa and 20fa lines will be subject to a temporary closure only if a whale is sighted within these depths. d. In 2021, CFAs 12E and 12F were closed entirely due to right whale closures, as such for 2022 DFO has implemented a precautionary order that will allow fishers from these CFAs access to CFA 12 if they continue to be impacted by the closures in such a way the prohibits their ability to fish within their own CFA. Access criteria and announcements will be communicated via Notice to Harvesters.

Appendix B – Cleaning of whale sightings data

Table B1: Cleaning the five datasets for whale sightings in Atlantic Canada from 2015 to 2022.

	ROMM	**XMAR**	**NARWC**	**MICS**	**Parks Canada**	
Raw	10837	7772	1552	6587	2344	
Removed species	2583	5605	1533	6587	1233	
Removed uncertain	2380	4719	-	-	-	
Removed NA count	2380	4690	1553	6582	1233	
Removed NA lat	2378	4690	1533	6106	1233	
Removed NA long	2378	4690	1533	6106	1233	
Removed lat = 0	-	-	-	5718	-	**Total**
Total	**2378**	**4690**	**1533**	**5718**	**1233**	**15552**
Blue whale	313	234	53	218	45	**863**
Fin whale	1067	1499	910	3206	570	**7252**
Humpback whale	998	2957	570	2294	618	**7437**

Table B2: Further cleaning of whale sighting data in R and ArcGIS.

	Blue whale	**Fin whale**	**Humpback whale**
Cleaned in R	863	7252	7437
Clipped to ocean	849	7174	7357
Clipped to study area	838	7147	7341
Total	**838**	**7147**	**7341**
Removed Intersect	0	0	0
Removed Dec30-31/Jan1-2	-	2	4
Removed incorrect locations	1	3	1
Total	**837**	**7142**	**7336**

Appendix C – Literature scan of blue, fin, and humpback whale swim speeds.

Table C1: Results from literature scan on the traveling swim speeds of blue, fin, and humpback whales.

Whale species	Swim speed (km/h)	Description	Source
Humpback Whale	4 2.6	Sprint Routine	Williams 2018
	2.34 3.8-4 2	Singing Non-Singing Mom and calf	Noad & Cato 2007
	3.87 3.9 4.9	Migration to Maine/Canada Mom and calf No calf	Kennedy et al. 2014
	2	Singing in NE Atlantic	Stanistret et al. 2013
	5.4	Diving	Tomoko et al. 2018
	4	Migration, calculated from Table 1	Horton et al. 2011
	8.28 6.48-10.8	Max lunge (Table 1) Range lunge (modeled)	Goldbogen et al. 2012
	6.37	Swim speed (median, Table 1)	Gough et al. 2019
	2.65	Mean day/night	Calambokidis et al. 2019
Fin Whale	36 9	Sprint Routine	Williams 2018
	36 3.6-14.4	Max speed Foraging	Segre et al. 2016
	36 46.8 9 7.2-36 21.6-28.8	Max speed Theoretical max Sustained speed Swimming range Optimal speed	Bose & Lien 1989
	7.2	Speed before lunging (Defines speed for lunge as over 7.2km/h)	Goldbogen et al. 2007

	1.8-7.2 4 5.7 2.5-2.8 7.7 2-6 4 10.8 7.56-14.76 8.17 3.85	Average traveling long distance Average when calling Transiting (from Table 3) Searching Migratory Average speed from sources Average used for mapping (used 100km as distance swam in a day) Max lunge (Table 1) Range lunge (modeled) Swim speed (median, Table 1) Mean day/night	Nortobartolo-di-Sciara et al. 2003 Soule & Wilcock 2013 Silva et al. 2013 Edwards et al. 2015 Goldbogen et al. 2012 Gough et al. 2019 Calambokidis et al. 2019
Blue Whale	3.6-10.8 5.4 1.5-2 4.2-6.5 32.4 7.2 3.7 2.6 5.6 Below 3.6 7.6 3.0	Speed range Optimal speed Breeding ground Azores Traveling Sprint Routine Traveling Breeding grounds Traveling Before lunge (Figure 3) Gough et al. 2019 Swim speed (median, Table 1) Mean day/night	Kshatriya & Blake 1988 Silva et al. 2013 Williams 2018 Bailey et al. 2009 Lesage et al. 2017 Goldbogen & Madsen 2021 Gough et al. 2019 Calambokidis et al. 2019

Appendix D - Monthly change in risk of blue, fin, and humpback whales

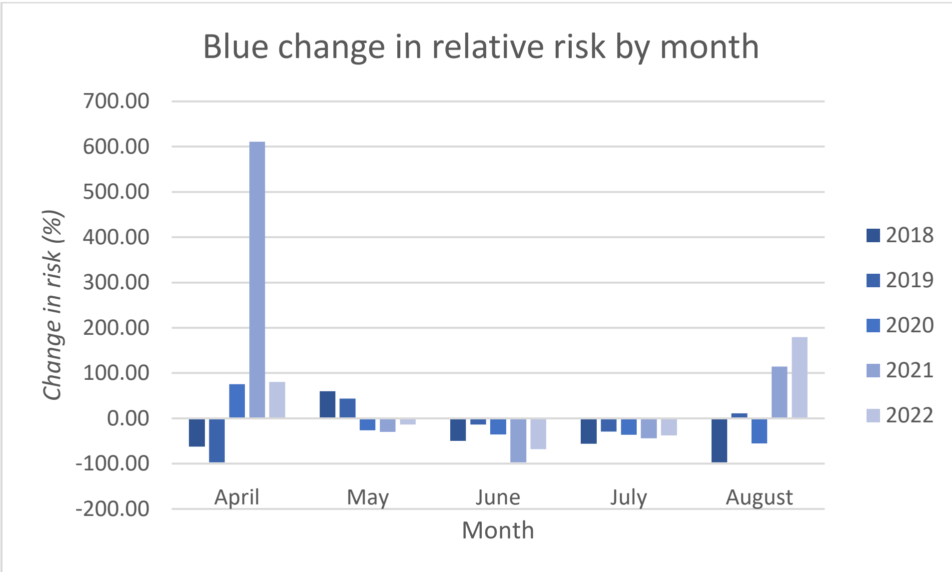


Figure D1: Monthly rate of change of blue whale relativized entanglement risk 2018-2022

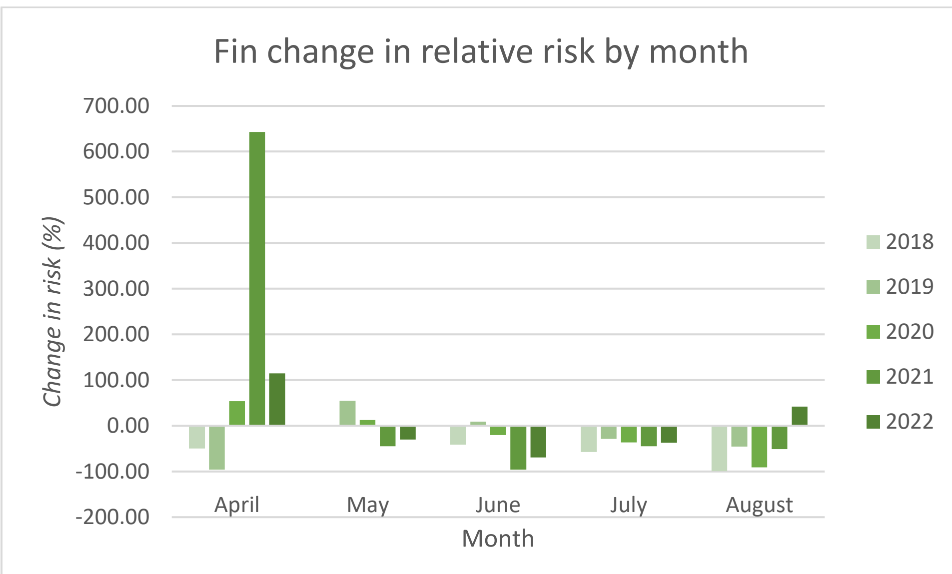


Figure D2: Monthly rate of change of fin whale relativized entanglement risk 2018-2022

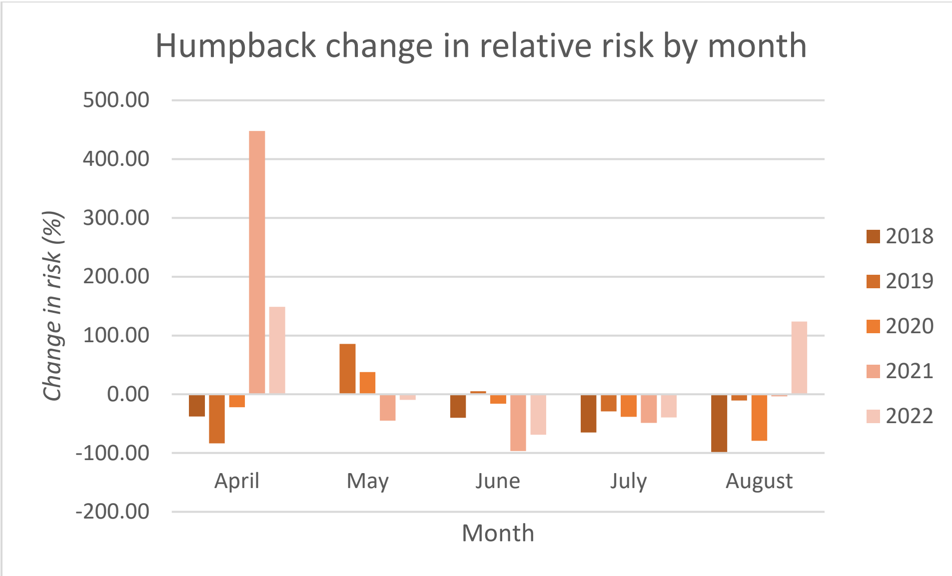


Figure D3: Monthly rate of change of humpback whale relativized entanglement risk 2018-2022