ASSESSING CHANGING BALEEN WHALE DISTRIBUTIONS AND INCIDENTS RELATIVE TO VESSEL ACTIVITY

By

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This thesis is dedicated to my family. Without them, this thesis would not exist. Thank you for putting up with me for the last two years, but most of all, for your unwavering support, love, generosity, and encouragement.

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Abstract

Baleen whales in the Northwest Atlantic Ocean (NWA) are increasingly affected by human pressures related to vessel activity, fisheries entanglement, and climate change. Vessel strikes and entanglement in fishing gear, in particular, often result in distress, injury, or death for these animals. These negative interactions or 'incidents' are consistently reported to marine animal response organizations throughout Atlantic Canada but have not yet been analyzed for scientific publication. Using all available incident reports, together with opportunistic sightings data, vessel activity data, and habitat suitability projections from species distribution models, I analysed areas where baleen whales are vulnerable to vessel-related incidents both now and in the near future. Current incident reduction strategies were also reviewed, and their present and likely future success was assessed based on my findings. Results suggest that cross-species areas of high current and future habitat suitability are strongly dependent on sea surface salinity and temperature and primarily exist in the Bay of Fundy, Scotian Shelf, Laurentian Channel, Flemish Cap, and Gulf of St. Lawrence. Areas where all species of baleen whales are vulnerable to incidents occur close to densely populated areas, around major shipping channels and fishing areas. Baleen whales may also be more vulnerable than expected to incidents involving small vessels. While some of these high-risk areas have mitigation efforts in place, they likely require new measures to ensure the safety of all species of baleen whale present there now and in the future.

List of Abbreviations

AIS – Automatic Identification System

AUC - Area Under the Curve

COSEWIC – Committee on the Status of Endangered Wildlife in Canada

CESM – Community Earth System Model

CMIP – Coupled Model Intercomparison Project

CWF - Canadian Wildlife Federation

DFO – Fisheries and Oceans Canada

ECSAS – Environment Canada Seabirds at Sea

ESM - Earth System Model

GEBCO – General Bathymetric Chart of the Oceans

GFW – Global Fishing Watch

GLM - Generalized Linear Model

HSV - Habitat Suitability Value

MARS – Marine Animal Response Society

MDA - Mean Decrease Accuracy

NA - North Atlantic

NARWC - North Atlantic Right Whale Consortium

NOAA – National Oceanic and Atmospheric Administration

NPP - Net Primary Production

NWA – North West Atlantic Ocean

RF - Random Forest

ROC - Relative Operating Characteristic

ROMM – Réseau D'observation de Mammifères Marins

RQPDLMM – Réseau Québécois D’urgences Pour Les Mammifères Marins

SARA – Species at Risk Act

SDM – Species Distribution Model

SSS - Sea Surface Salinity

SST - Sea Surface Temperature

TC – Transport Canada

WRS – Whale Release and Strandings

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Chapter 1 – Introduction

In the Northwest Atlantic Ocean (NWA), there are six extant species of large baleen whales: the sei (*Balaenoptera borealis*), North Atlantic (NA) right (*Eubalena glacialis*), blue (*Balaenoptera musculus*), fin (*Balaenoptera physalus*), minke (*Balaenoptera acutorostrata*), and humpback (*Megaptera novaeangliae*). These species have declined in global abundance due primarily to excessive whaling over the past few centuries (Baker & Clapham 2004, Magera et al. 2013). With increased conservation efforts over the past several decades, such as the 1986 International Whaling Commission moratorium on whaling, the incorporation of baleen whale protection into national policies, and regional fishery closures along with vessel slow-down and distance-keeping measures, some of these species' populations are now recovering from overhunting (Magera et al. 2013). For example, the southern Atlantic populations of blue (Calderan et al. 2020), fin (Viquerat and Herr 2017), humpback (Zerbini et al. 2010), and Southern right whales (Crespo et al. 2019) have begun to show evidence, through increased sightings, of recovery. Exact estimates of the magnitude of this recovery are still being determined, but population estimates currently range between 2-13% of pre-whaling values (Tulloch et al. 2016). Unfortunately, in the NWA evidence of this recovery has been difficult to detect for most species due to a lack of accurate historical and current stock assessments; however, in the early 2000s, NWA humpback whales did show signs of recovery until a more recent decline inflicted by various human pressures (NOAA 2021). This recent decline has also been found to be present in fin and NA right populations (COSEWIC 2019, COSEWIC 2013).

Although whaling is no longer a major threat to NWA baleen whales, other human pressures such as increased motorized vessel activity and entanglement in fishing gear are now threatening the survival and/or recovery of some baleen whale species, especially the NA right whale population which has declined below 400 individuals, with less than 100 breeding females (NOAA 2021, Record et al. 2019, Sharp et al. 2019). In this study, I focus on all six extant species in this region, assessing their current distributions and overlap with vessel activity.

1.1 – Study Species

All of the NWA baleen whale species share similar classically ‘K-selected’ life history characteristics such as late age of sexual maturity (5-15 years), long gestation periods (10-12 months for a single calf), and very long calving intervals (2-6 years) (Bannister 2009). Although these long developmental periods differ slightly for each species, they help to explain why population recovery occurs on decadal to centennial time scales (Magera et al. 2013, Bannister 2009). Further differences exist in these species in terms of their size, speed, diet, distribution, and other ecological characteristics.

The blue whale (*Balaenoptera musculus*) (Figure 1a) is the world's largest animal, growing up to 34 m long and weighing up to 150 mt (COSEWIC 2002). It is globally distributed, but several subspecies and multiple feeding subgroups exist in individual regions of the world’s oceans (COSEWIC 2002). The Atlantic blue whale population present in the NWA, are considered a genetically distinct feeding subgroup from other

Atlantic populations (Jossey et al. 2021) and has a relatively small number of individuals (Table 1). NWA blue whales have a diet that mainly consists of zooplankton, especially krill (euphausiids) (Sears and Perrin 2009), and mainly forage in areas with high concentrations of prey (typically located near frequent upwelling), resulting in prey-dependent habitat use (Moors-Murphy et al. 2019).

The fin whale (*Balaenoptera physalus*) (Figure 1b) is the second largest whale species, growing up to 26 m long and weighing up to 77 mt. Like the blue whale, they have a cosmopolitan distribution, but have a distinct north Atlantic population with a relatively larger number of individuals compared to other NWA baleen whales (Table 1). They are commonly seen in groups (COSEWIC 2019a), spending most of their time feeding on small schooling fish in coastal and shelf waters (coastal being < 12 nm from the coastline, and shelf being beyond that to the edge of the Scotian Shelf (Figure 3)), and travelling in far offshore, open waters (COSEWIC 2019a).

The humpback whale (*Megaptera novaeangliae*) (Figure 1c), another globally distributed species, also has a distinct Western North Atlantic population (Table 1). It is probably one of the most well-known whales in the NWA due to its conspicuous surface activity (COSEWIC 2003). Humpback whales can grow up to 18 m long and weigh up to 36 mt, and have large tails that have unique white markings on their underside which can be used to identify individuals (COSEWIC 2003). These whales have a diet of small crustaceans and fish, and sometimes exhibit a distinct feeding behaviour known as bubble net feeding, one of the various activities that makes them obvious to observers (COSEWIC 2003). Humpback whales have most commonly been sighted in coastal and shelf, productive waters (COSEWIC 2003).

The common minke whale (*Balaenoptera acutorostrata*) (Figure 1d) is the smallest species of baleen whale. They can grow up to 11 m long and weigh up to 9 mt (COSEWIC 2006). Their North Atlantic subspecies population is the most numerous of all baleen whale species (Table 1) (COSEWIC 2006). Minke whales have a diverse diet consisting of small crustaceans, schooling fish, and various kinds of plankton (COSEWIC 2006). Similar to fin whales, minkes have been found in coastal and shelf waters, but also spend much time in the open waters offshore (COSEWIC 2006).

The NA right whale (*Eubalaena glacialis*) (Figure 1e) is a rare species endemic to the NWA. They can grow up to 16 m long and weigh up to 63 mt (COSEWIC 2013). Over the past century, the life expectancy of these whales has almost halved due to human interactions (vessel strikes, entanglements, etc.), and has resulted in a population with very few individuals left (Table 1) (COSEWIC 2013). Like blue whales, these animals have a specialized diet and highly prey-dependent distribution, being sighted in areas where their main food source, the copepod genus *Calanus*, is most prevalent (Sorochan et al. 2023). In recent years, a northward shift in *Calanus* distribution (likely due to warming waters as a result of climate change) has been identified, and as a result NA right whales have also changed their distribution to follow suit (Pendleton et al. 2012, Record et al. 2019). The occurrence of NA right whales into more northern waters may be threatening the survival of the species, due to elevated mortality risk from vessel strikes and entanglements (Record et al. 2019).

Finally, sei whales (*Balaenoptera borealis*) (Figure 1f) are another large and globally extant species of baleen whale found in the NWA, with a distinct Atlantic population. Sei whales are the third largest cetacean species and can grow up to 18 m long and weigh up to 45 mt. These whales are known to be fast-swimming, off-shore, and solitary (COSEWIC 2019b). Their main food sources are plankton, small fish, and cephalopods - a food source they frequently dive for (COSEWIC 2019b). The Atlantic sei whale population is intermediate in comparison to the other five above (Table 1).

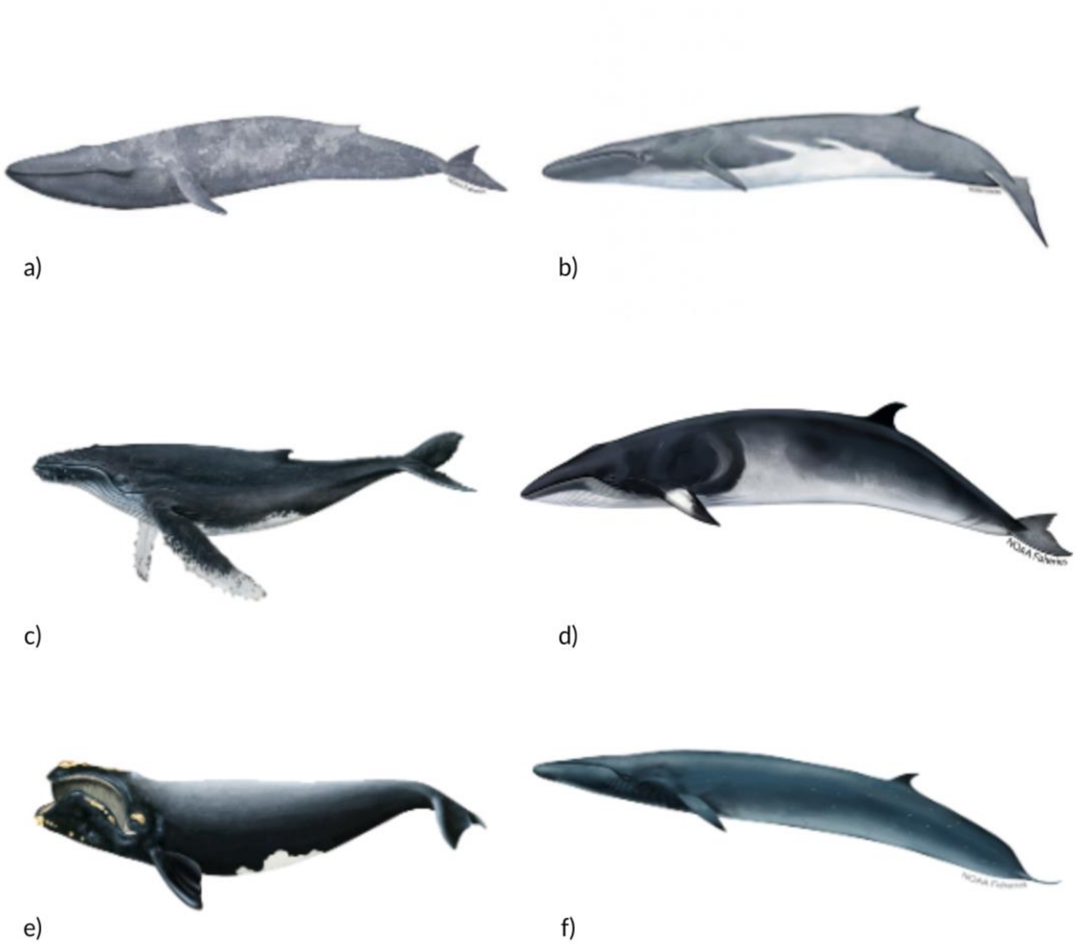

Figure 1. Study Species. Large baleen whale species of the North West Atlantic (NWA) a) blue whale (*Balaenoptera musculus*) (NOAA 2023a , b) fin whale (*Balaenoptera physalus*) (NOAA 2022a, c) humpback whale (*Megaptera novaeanglia*) (NOAA 2023b, d) minke whale (*Balaenoptera acutorostrata*) (NOAA 2022b), e) NA right whale (*Eubalaena glacialis*) (NOAA 2023c), f) sei whale (*Balaenoptera borealis*) (NOAA 2023d).

The six baleen whale populations of the NWA have similar seasonal distributions. During the summer months they migrate north to colder nutrient rich waters to meet their caloric needs in various feeding grounds along the eastern coast of North America (Davis et al. 2020). Once feeding comes to an end due to the caloric needs for breeding being met (COSEWIC 2019), these species migrate south to warmer tropical waters where their mating and breeding grounds are located (Davis et al. 2020). These breeding grounds have been found all over the southern north Atlantic, including the Caribbean, off the eastern coast of Mexico, and as far south as the equator (Davis et al. 2020). For example, the north Atlantic population of humpback whales is known to migrate from NWA feeding grounds down to the West Indies and Cape Verde to calve and mate, with more calving and mating areas likely to be discovered (COSEWIC 2003). Some whales' breeding grounds are located closer to their feeding grounds, off the coast of the southern United States (Davis et al. 2020), like the NA right whale. These seasonal distributions are well known for species such as the humpback and NA right whales, but the migratory pathways and seasonal distributions for the populations of blue, fin, minke, and sei whales are less well known (COSEWIC 2002, 2003, 2006, 2013, 2019a,b, Davis et al. 2020).

1.2 – Anthropogenic Threats to Baleen Whales

Collisions with vessels can be dangerous to all whales, causing sharp or blunt trauma from impact and sometimes leading to death (Figure 2a) (Magera et al. 2013). Until recently it was thought that only large vessels could inflict injuries or death, but it has since become clear that motorized vessels of any size, moving at any speed, can cause severe damage (Kelley et al. 2020). Data suggest that between 1970 and 2006, 53% of NA right whale fatalities resulted from vessel strikes (Sharp et al. 2019, Campbell-Malone et al. 2008). Between 1985 and 1992, 30% of carefully examined humpback whale carcasses had sustained injuries from collisions with ships (Wiley et al. 1994). Globally, fin whales have become the baleen whale species most frequently observed to be injured by vessel strikes (Van Waerebeek & Leaper 2008, Wimmer et al. 2021).

In addition to the dangers of vessel strikes, all cetaceans are at risk of becoming entangled in both active and lost fishing gear (Figure 2b) (Vanderlaan et al. 2011). Entanglement is not always lethal, as they can sometimes free themselves, but baleen whales have been known to carry gear for long periods of time, often leading to injury and/or exhaustion and, as a result, death (Figure 2b) (Clapham et al. 1999). Entanglements have been well studied for NWA populations of NA right and humpback whales, with 16% encountering at least one entanglement in fishing gear per year, with a significant increase in the frequency of observed entanglements over the last 30 years (Knowlton et al. 2012, Robbins and Matilla 2012). For NA right whales, 83% of individuals show scarring from fishing gear entanglements (Knowlton et al. 2012). Entanglement occurrence rates and severity for baleen whales other than these two species are poorly known (Knowlton et al. 2015).

Figure 2. Vessel Strikes and Entanglements. Photographs of deceased NA right whales after a vessel strike; “Right Whale Punctuation” (2019) (a) and a fishing gear entanglement; “Right whale Starboard” (2017) (b). Both photos taken in the Gulf of St. Lawrence. Image credits: (a) NEFSC taken under SARA Permit DFO-MAR-2016-02 (Amendment 1) and NMFS Permit 17355. (b) Marine Animal Response Society, collected under federal SARA permit issued to MARS.

1.3 – Vessel Activity in the NWA

The NWA is responsible for the majority (73%) of Canada’s fishing activity (Government of Canada 2006), and also includes two of Canada’s busiest international ports (Government of Canada 2019). In addition to these two sources of vessel activity within the NWA, there are numerous naval, recreational, research, and other industry vessels present in these waters (GFW 2022). As a result, resident baleen whales in this region are at considerable risk. Some notable areas of dense vessel activity include the St. Lawrence Seaway (Great Lakes Commission 2023), a shipping and transport route connecting the Atlantic Ocean to the Great Lakes; coastal and shelf areas near Halifax, Nova Scotia, and St. John’s, Newfoundland, both home to busy ports for the import and export of goods as well as significant fishing and naval activity; and areas such as Yarmouth and Digby (NS) and further north along the Scotian Shelf that support recreational boating, whale watching organizations, ferry routes and, most prevalently, the majority of Canadian fishing fleets (DFO 2021a, DFO 2021b, Pelot and Wootton 2004, Konrad 2020, Quebec Maritime).

1.4 – Baleen Whale Incidents

When a baleen whale is seen entangled, injured, unwell, or dead, often because of vessel strikes or entanglement, it is commonly reported to marine animal response organizations. These events are collectively known as “incidents”. In Atlantic Canada, the Marine Animal Response Society (MARS) responds to reports for the Maritime provinces (Nova Scotia, PEI, and New Brunswick), Whale Release and Strandings (WRS) covers Newfoundland and Labrador, and the Réseau Québécois D’urgences Pour Les Mammifères Marins (RQDPLMM) operates off the coast of Quebec and within the Gulf of St. Lawrence (Wimmer et al. 2021). The incident reports that they compile contain valuable information about where vessel strikes and entanglements occur in the NWA. Between 2004 and 2019, 46% of studied fatal incidents (61) were due to entanglement, 15% (21) were due to vessel strikes, 3% (4) were due to trauma, and 3%

(4) were due to entrapment. The rest can be attributed to illness, were inconclusive, or due to multiple causes. Of the recorded entanglements, over half (53%) (32) were minke whales, 10% (6) were NA right whales, 14% (9) were humpback whales, and 5% (3) were fin whales. Of the vessel strikes, 48% (10) were NA right whales, 29% (6) were minke whales, and 14% (3) were fin whales (Wimmer et al. 2021). Evidence of ship strikes and entanglement has been found for all six baleen whale species in the NWA (Laist et al. 2001, Van Der Hoop et al. 2013). Our knowledge on these processes is very fragmentary as many incidents go unreported, particularly for whales that sink after their death, namely the Balaenopterids (blue, minke, fin and sei whales) (Moore 2014). Moreover, the physical evidence on surviving whales is not always visible, so the available data represent a subsample of unknown proportions (Kelley et al. 2020). Furthermore, where an incident is reported is unlikely to be where the incident actually took place. This is due to the fact that most incidents are reported after an incident has taken place, and the affected whale(s) (i.e. injured or exhausted animals or carcasses) drift to shore (Wimmer et al. 2021).

1.5 – Baleen Whale Management

Vessel strikes and entanglements, combined with the legacy of low population density after whaling, has led to the listing of half of NWA baleen whales under the Species at Risk Act (SARA), the legal instrument to designate and protect threatened wildlife in Canada (Table 1). The responsibility for monitoring populations lies with the Fisheries and Oceans Canada (DFO), which helps inform the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), a Canadian science body that analyzes species' conservation status to help inform government decision-making (Government of Canada 2021). Under SARA, the NA right and NWA blue whale populations have been assessed as Endangered, and the NWA fin whale population has been listed as Special Concern (Government of Canada 2021). In addition, under COSEWIC, the NWA sei whale has been listed as Endangered (Government of Canada 2021). Vessel strikes and entanglements and their impact on NWA baleen whales are monitored and managed jointly by DFO and Transport Canada (TC). To reduce the risk of incidents to all baleen whales, DFO has implemented distance-keeping measures (Fisheries Act 1985) and ghost gear retrieval initiatives (DFO 2022a). Due to the current population status of the NA right whale, more extensive measures have been put in place to reduce incidents for this species (Koubrak et al. 2020), such as targeted time-area fisheries closures and both mandatory and voluntary slow-down measures within seasonal management areas (TC 2021) that are based on visual and acoustic detections of this species (DFO 2022a). Vessels longer than 20m are expected to slow-down to a maximum speed of 10 knots in a slow-down zone (TC 2021). Additionally, fishers affected by these closures are displaced to other areas to resume fishing, increasing vessel and fishing activity elsewhere, with unknown consequences for other species (Kelley et al. 2020). Although some of these regulations have been in place since 2018, they only address one SARA or COSEWIC-listed whale species, while three others co-exist within NWA waters (Table 1, Government of Canada 2021). The effectiveness of this range of management strategies for whales other than NA right whales has not yet been analyzed, though has been found to be effective for the NA right whale given that mortality has decreased significantly since implementation (Koubrak et al. 2020, 2022).

Table 1. COSEWIC and SARA Statuses and Population Estimates of NWA Large Baleen Whales. Population estimates, Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and Species at Risk Act (SARA) statuses, and year of designation of large baleen whale populations in the Northwest Atlantic (NWA) (COSEWIC 2002, 2003, 2006, 2013, 2019a,b).

Whale Species	Population Estimate	COSEWIC Status	Year COSEWIC Assessed	SARA Status	Year SARA Listed
NA right whale	<400	Endangered	2013	Endangered	2005
Blue whale Atlantic Population	<250	Endangered	2012	Endangered	2005
Sei whale Atlantic Population	<1000	Endangered	2019	Not Listed	N/A
Fin whale Atlantic Population	~1,500	Special Concern	2019	Special Concern	2006
Common Minke whale North Atlantic Subspecies	~15,000	Not at Risk	2006	Not Listed	N/A
Humpback whale Western North Atlantic Population	~11,000	Not at Risk	2003	Not Listed	N/A

1.6 – Thesis Objectives

The goal of this thesis is to broaden existing knowledge of harmful interactions between baleen whales and human vessel activity in the NWA, to identify potential incident hotspots, and to examine how interactions might change with shifting species distributions into the future. To understand these interactions, I combine a detailed examination of NWA vessel activity with baleen whale presence observations, with the aim of helping to strengthen our understanding of where these harmful interactions may be occurring. Finally, I examine how these harmful human and baleen whale interactions may change over the next century in the context of climate change, using a well-established climate scenario. Based on my results, I provide recommendations to help guide DFO and TC's incident mitigation strategies to help protect more baleen whale species in a changing ocean landscape.

In addition to this Introductory Chapter, the subsequent Chapter 2 presents a thorough characterization of the three databases used in this thesis. Additionally, it explores relationships between vessel activity, baleen whale presence, and baleen whale incidents in the NWA through the use of regression models and overlap indices. Building on this, Chapter 3 outlines the development of a species distribution model to project baleen whale distribution presently and under future climate conditions. Chapter 3 then explores the relationships between vessel activity, baleen whale habitat suitability, and baleen whale incidents. Finally, Chapter 4 summarizes the main findings, discusses potential management implications, and outlines future directions for the research.

Chapter 2 – Determining Associations Between Baleen Whale Presence, Vessel Activity, and Baleen Whale Incidents in the Northwest Atlantic

2.1 – Introduction

It is evident that human pressures such as vessel and fishing activity pose a threat to the survival of declining NWA baleen whale populations (Wimmer et al. 2021). It is important to analyze vessel activity, whale presence, and incident report data, as they contain valuable insight into how, why, and where incidents may be occurring.

In recent years, researchers have begun to more readily use vessel and fishing activity data to help inform spatially targeted efforts to reduce risks to threatened baleen whale populations. These data have been used to inform management measures in areas with a high density of vessel activity, such as the Gulf of St. Lawrence, where slow-down areas and fishery closures were created to protect NA right whales (Fisheries Act 1985, TC 2021). Scientists have also begun to use these data to determine areas where vessel strikes may be likely, along with the lethality of vessel strikes based on vessel speeds (Kelley et al. 2020, Nichol et al. 2017, Vanderlaan et al. 2008). However, such analyses have yet to be conducted for the five remaining NWA baleen whale species, which is the focus on this thesis. To achieve this goal, my research is using available data to improve our knowledge of all baleen whales' distributions relative to human vessel activity.

Over the last few decades, there have been an increase in efforts to study and map baleen whale habitat use and distribution using acoustic telemetry, ship and aerial surveys (Ceballos et al. 2022). There has also been an increase in data collection by other stakeholders such as whale watching organizations, the Canadian army, and citizen scientists (Team Whale 2022). Such data can provide information on where whales reside and where potential important habitat is located (i.e., areas where whales are likely to congregate). However, this type of data is often biased by sampling effort. Whales can only be detected in places where there is some level of observation effort, and hence areas without such effort are unknown in terms of their suitability for these species. Additionally, areas that are under sampled, such as many offshore areas, are also likely to underestimate the likelihood of whale presence.

Incident data for baleen whales are not frequently used in scientific analyses due to the limitations in data compilation, availability and accessibility, and potential issues with spatially varying incident report collection effort. Furthermore, incidents are often reported after the event itself has taken place, when the affected whales wash up near shore and become visible (Wimmer et al. 2021). Nevertheless, these reports contain important information on what kinds of incidents take place in the NWA and may be indicative of the general areas where baleen whale incidents are likely to occur. Not only are incident reports useful in terms of incident prevention, but they can also provide information on species occurrence, composition, and habitat use (Maldini et al. 2015).

In combination, the data on vessel activity and baleen whale presence, together with the information provided by the incident reports, can help provide a baseline to explore where baleen whales may be at highest risk of being involved in incidents such as vessel strikes or entanglement in the NWA.

2.1.2 – Chapter 2 Objectives

The main objective of this chapter is to determine if there is a relationship between vessel activity, baleen whale presence, and baleen whale incidents. I hypothesize that all species of NWA baleen whales are at similar incident risk because their regional distribution strongly overlaps with vessel activity. I explore this relationship in two ways; first, by using a generalized linear model to determine if vessel activity and baleen whale presence can predict baleen whale incidents in the NWA, and second, by using multiple overlap indices to determine if vessel activity, baleen whale presence, and incidents share a significant amount of space in the NWA. These analyses were conducted for all baleen whales aggregated together and each species individually, both integrated over time and seasonally. Finally, based on my results, some preliminary management recommendations are provided.

2.2 – Methods

2.2.1 – Study Area

The study region is the Canadian Northwest Atlantic Ocean (NWA), and in particular five areas along Canada's east coast; the Laurentian Channel, Bay of Fundy, Scotian Shelf, Gulf of St Lawrence, and coastal, shelf, and offshore Newfoundland (Figure 3).

Figure 3. Study Area. Map of the study area: the Northwest Atlantic Ocean consisting of areas off the coasts of and beyond Quebec, New Brunswick, PEI, Nova Scotia, and Newfoundland and Labrador. Map from Google Maps.

2.2.2 – Opportunistic Sightings Data

Opportunistic sightings (or presences) of baleen whales in the NWA from 1963-2022 were compiled from DFO (Team Whale 2022), the North Atlantic Right Whale Consortium (NARWC) (NARWC 2022), Environment Canada Seabirds at Sea (ECSAS) (Canadian Wildlife Service 2021), the Whitehead Lab (Team Whale 2022), and the Réseau D'observation de Mammifères Marins (ROMM) (ROMM 2015, ROMM 2017). Opportunistic sightings refer to any recorded sighting of a baleen whale and are reported by different types of observers, such as at-sea fishery observers, military and naval observers, aerial survey observations, and whale watching tour operators. These data were compiled into a whale observation database and manually checked for duplicate observations (identical date, location, and species). Any duplicates and observations that appeared to be incorrectly reported (sightings not in the study area or missing location information) were removed, leaving a total of 81,892 observations, however it is possible some duplicates remained. The database was organized by species (including an unidentified whale category for baleen whales where the species was not reported), reporting organization, observation location, and observation date. The number of whale observations per 1° grid cell was then calculated across all years and seasons, for all baleen whales combined and for individual species.

2.2.3 – Vessel Activity Data

Data on vessel activity in the NWA was obtained from Global Fishing Watch (GFW), an international non-profit organization that tracks vessels worldwide and provides extensive archives of fishing and other vessel activity from 2012-2023 (GFW 2022, Kroodsma et al. 2018). Vessel locations and associated dates and times were acquired via Automatic Identification System (AIS) transponders, a vessel tracking system used to prevent collisions (GFW 2022). The AIS transponder located on each vessel broadcasts its identity, position, length (m), and speed, among other information, to nearby vessels, land stations and satellites (GFW 2022). GFW provided a compilation of these AIS vessel detections for the region of interest for all vessels that were either required to use (vessels 20 m or more in length) (TC 2020) or voluntarily used AIS transponders from 2017-2021. Each data point provides information on how many hours of vessel activity occurred in a 1° by 1° grid cell for each month of each year. The average number of hours of vessel activity per 1° grid cell was calculated for the whole time period (Jan 2017 to Dec 2021) and seasonally (months 1-3 characterized as winter, months 4-6 characterized as spring, months 7-9 characterized as summer, and months 10-12 characterized as fall) using vector geometry methods in QGIS (QGIS 2022). Additionally, the average number of hours of vessel activity per grid cell was calculated for both small (smaller than 24.4 meters) and large (larger than 24.4 meters, as designated by DFO) vessels (TC 2020). All subsequent data processing and averaging was carried out in QGIS using the same methods.

In order to test for differences in small and large vessel activity distributions, the hours of vessel activity per 1° grid cell for both kinds of vessel activity were normalized, compared, and then subtracted from another to determine grid cells where there was a large discrepancy between the type of vessel activity that occurred there.

2.2.4 – Incident Report Data

For the purposes of this study, an incident refers to reported distress, injury, or death of any baleen whale in the NWA. Data on all reported baleen whale incidents from 2004-2019 were collected via marine animal incident hotlines and compiled into a database by the NWA marine animal response organizations MARS, WRS, and RQDPLMM (MARS 2021), for a total of 1,359 incident reports. When an incident is called into these respective hotlines, the on-call team works to collect as much information about the incident as possible. This includes collecting latitude and longitude coordinates, photos and videos, and details on animal behaviour and condition to help determine the incident type, species affected, cause of death, or any other relevant incident conclusions. If resources are available, these teams may even perform necropsies and/or sampling to help further determine the incident type or cause of death and input this information into the incident database. It is important to note that where the incident is reported is unlikely match the precise location where the incident took place. This is because most incident reports are called into respective hotlines after an incident has taken place, and the affected whales (i.e. injured or exhausted animals or carcasses) become stuck or washed up near-shore (Wimmer et al. 2021), although a subset of incidents, however, were observed and reported at sea. For this reason, compilation of incidents onto a 1° grid was chosen, to aggregate over a larger (~100km) area, and help account for differences between incident and reporting locations.

Incident reports were classified into three categories based on animal state: alive, dead, or unknown if the status could not be determined (Wimmer et al. 2021). Incidents were additionally classified into 10 type categories: entanglement, free-swimming entanglement, entrapment, natural entrapment, beached carcass, floating carcass, injured/sick, stranding, vagrant, and unknown (Wimmer et al. 2021). For the purposes of this study, entanglement refers to a whale that is carrying gear, and entrapment refers to a whale that is reported within a human-made structure or impeded by a natural barrier that it cannot escape on its own (Wimmer et al. 2021). The number of incident reports per 1° grid cell was calculated across years and seasons, for all baleen whales combined and for individual species.

2.2.5 – Modelling Approach

To determine if vessel activity and baleen whale presence were significant predictors of incident risk, a generalized linear model (GLM) was built in R Version 4.2.1 (R Core Team 2022). Before constructing the model, data exploration techniques recommended by Zuur et al. (2010) were undertaken to ensure all model assumptions were met. All whale observation and vessel density values from outside the study area were removed.

Vessel density (V) was calculated as the average number of vessel hours per 1° grid cell. This was done separately for total (V_t), small (V_s), and large (V_l) vessels. Baleen whale presence (NW, number of baleen whale observations per 1° grid cell), and season (spring, summer, winter, and fall) were the predictor variables in the model, with baleen whale incidents (NI, number of baleen whale incidents per 1° grid cell) as the response variable. Season was included in only the overall baleen whale model due to its potential biological significance for representing the seasonal presence of migratory baleen whales in the study area. It was not included in the individual species models as there was insufficient data for some seasons for some species. The vessel density covariates were logarithmically transformed to standardize the variance (Zuur et al. 2010). The response variable was assumed to be negative-binomially distributed (NB), as it consisted of over-dispersed, zero-inflated count data. The ‘pscl’ package (Zeileis et al. 2008) was used to fit the model. To check for spatial autocorrelation, correlograms of model residuals were plotted and, as a result, a binary weighted autocovariate term (SA) was incorporated into the model. The model's residuals with the autocovariate term added were again plotted to ensure that the spatial autocorrelation had been accounted for. The final model was therefore specified as:

$$NI \sim NB\ (\mu, \theta)$$

$$\log(\mu) = \beta_0 + \mathrm{V}_{(\mathrm{t\ or\ s\ or\ l})} + \mathrm{NW} + \mathrm{Season} + \mathrm{SA} \qquad (1)$$

Where μ is the mean, θ is the dispersion parameter, and β_0 is the intercept. Separate analyses were conducted for each of the six baleen whale species, once for the unidentified baleen whales, and once for all baleen whale species combined.

2.2.6 – Overlap Indexes and Correlations

To further investigate the robustness of observed relationships and relative incident risk, the spatial overlap between vessel density (total, and small and large vessels) and baleen whale sightings in the NWA was quantified by calculating Schoener's D (D) and Warren's I (I) similarity statistics, commonly used in spatial statistics (Schoener 1968, Warren et al. 2008). These two indexes quantify the extent of spatial overlap between two variables over an environmental gradient (Schoener 1968, Warren et al. 2008), and output a range of values from 0-1, indicating no overlap to perfect overlap respectively (Bendriñana-Romano et al. 2021). The Warren's Index incorporates a metric called Hellinger's distance in its calculation, but there is little difference in the qualitative results of both indexes (Schoener 1968, Warren et al. 2008). These metrics were calculated across the study area, along with the Spearman's correlation (Cor) between the two variables at the 1° grid resolution. Overlap and correlation were also conducted for vessel density (total, and small and large vessels) and baleen whale incidents, and baleen whale presences and baleen whale incidents to further explore any potential relationships between where incidents were observed and the presence of these two explanatory variables. Each of these three metrics, along with their significance at the 0.05 level, between the five predictor variables were calculated. I used a randomized reshuffling approach by generating 1,000 permutations of the vessel activity data in R (i.e., resampling the data without replacement and redistributed over the study area), calculating the overlap index for each of these permutations, and constructing the distribution of these permutation overlaps. Statistical significance was then calculated by comparing the observed overlap to the permuted distribution, with the observed overlap being considered statistically significant if it fell outside the 95% range of the generated distribution. These calculations were conducted again for all six baleen whale species individually, the unidentified whales, and all baleen whales combined.

Finally, to test the sensitivity of these indices, the GLM was run with just the number of incidents per 1° grid cell as a function of the number of whale observations per 1° grid cell, to see if the results generated by the simplified GLM matched the overlap indices for the same predictor variables together.

2.3 – Results

2.3.1 – Vessel Activity Data

Across the study region, between 2017 and 2021, there were a total of 82,141,732 hours of vessel activity logged from vessels equipped with AIS technology. Of these, 9,565,993 hours (12%) were logged by small vessels and 27,293,476 hours (33%) belonged to large vessels. Based on the small proportion of data for which vessel size was known, there was significantly more large vessel activity than small vessel activity ($P>0.001$). The remaining hours belonged to vessels of unknown lengths (55%). The average number of hours of vessel activity per year was 16,428,346, with a standard deviation of 2,077,974. Most vessel activity occurred in the summer, with significantly ($P<0.001$) less activity occurring in the spring, fall, and especially winter (Table 2). At the 1° resolution, the average number of hours of vessel activity per grid cell between 2017-2021 was 3,501 ± 528 (GFW 2022). Areas where vessel density was highest were concentrated around the Gulf of St. Lawrence shipping channel, along the Scotian Shelf and in the Bay of Fundy within popular fishing areas, off the northern coast of Cape Breton Island, within heavily used routes between Prince Edward Island, the Magdalen Islands and Nova Scotia, off the north-east shore of Anticosti Island, and off the south-east coast of Newfoundland (Figure 4a,b). Little vessel activity occurred north of Labrador (Figure 4a,b). Most small vessel activity occurred in coastal and shelf areas, whereas large vessel activity occurred throughout the entire study area (Figure A2a,b). The areas where there were the biggest discrepancies between small and large vessel activity distribution were located in the Gulf of St. Lawrence, parts of the Laurentian Channel, parts of the Scotian Shelf, offshore, and Newfoundland waters (Figure A2c).

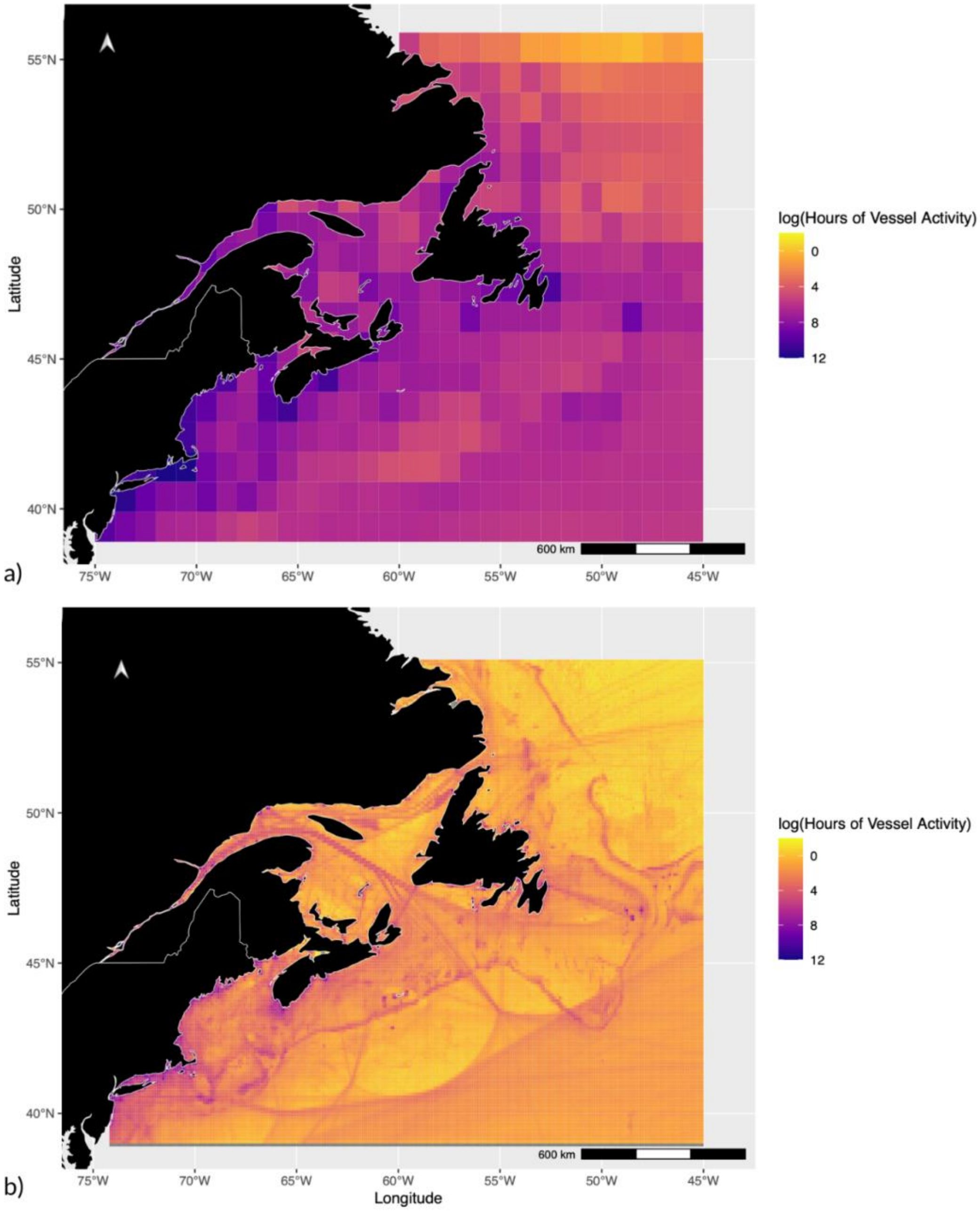

Figure 4. **NWA Vessel Activity**. Mean hours of vessel activity per 1° grid cell (a) and per 0.1° grid cell (b) between 2017 and 2021 within the study area, on a logarithmic scale. Data derived from AIS technology collected and provided by Global Fishing Watch (GFW 2022).

Table 2. Vessel Activity Per Season. Hours of vessel activity per season in the NWA between 2017 and 2021 at the 1° grid cell resolution. Data derived from AIS technology collected and provided by Global Fishing Watch (GFW 2022).

Season	**Vessel Activity (Hours)**
Summer	31,287,974
Spring	20,203,033
Fall	18,015,663
Winter	12,635,063
Total	**82,141,732**

2.3.2 – Opportunistic Sightings Data

Between 1963 and 2022, there were 81,892 opportunistic sightings of baleen whales, with an average of 1,917 ± 1,341 observations per year. Most whale observations occurred in the summer (~84%, 68,748 observations), with substantially fewer observations occurring in the spring (~9%), fall (~7%), and winter (~0.3%) (7,124, 5,740, and 269 observations, respectively) (Table 3). The majority of whale observations took place on board a ship, with a much smaller amount having been observed aerially and even fewer from shore. NA right whales were the species with the most opportunistic sightings (~36%, 29,904 sightings), followed by humpback whales (~26%), fin whales (~16%), and minke whales (~15%) (21,190, 13,458, and 12,380 sightings, respectively) (Table 3). Blue whale and sei whale sightings were relatively rare, as they only had 848 (~1%) and 1,320 (~2%) recorded sightings, respectively (Table 3). Additionally, there were 2,792 sightings where the species could not be determined, labelled unidentified whales (Table 3). At the 1° resolution, the mean number of whale observations per grid cell was 210 ± 2,531. Areas where whale sightings were highest included the Bay of Fundy, the entirety of the Scotian Shelf, the Gulf of St. Lawrence, and the north-east coast of Newfoundland (Figure 5). Few whale observations occurred far offshore or in any areas north of the north-east coast of Newfoundland (Figure 5).

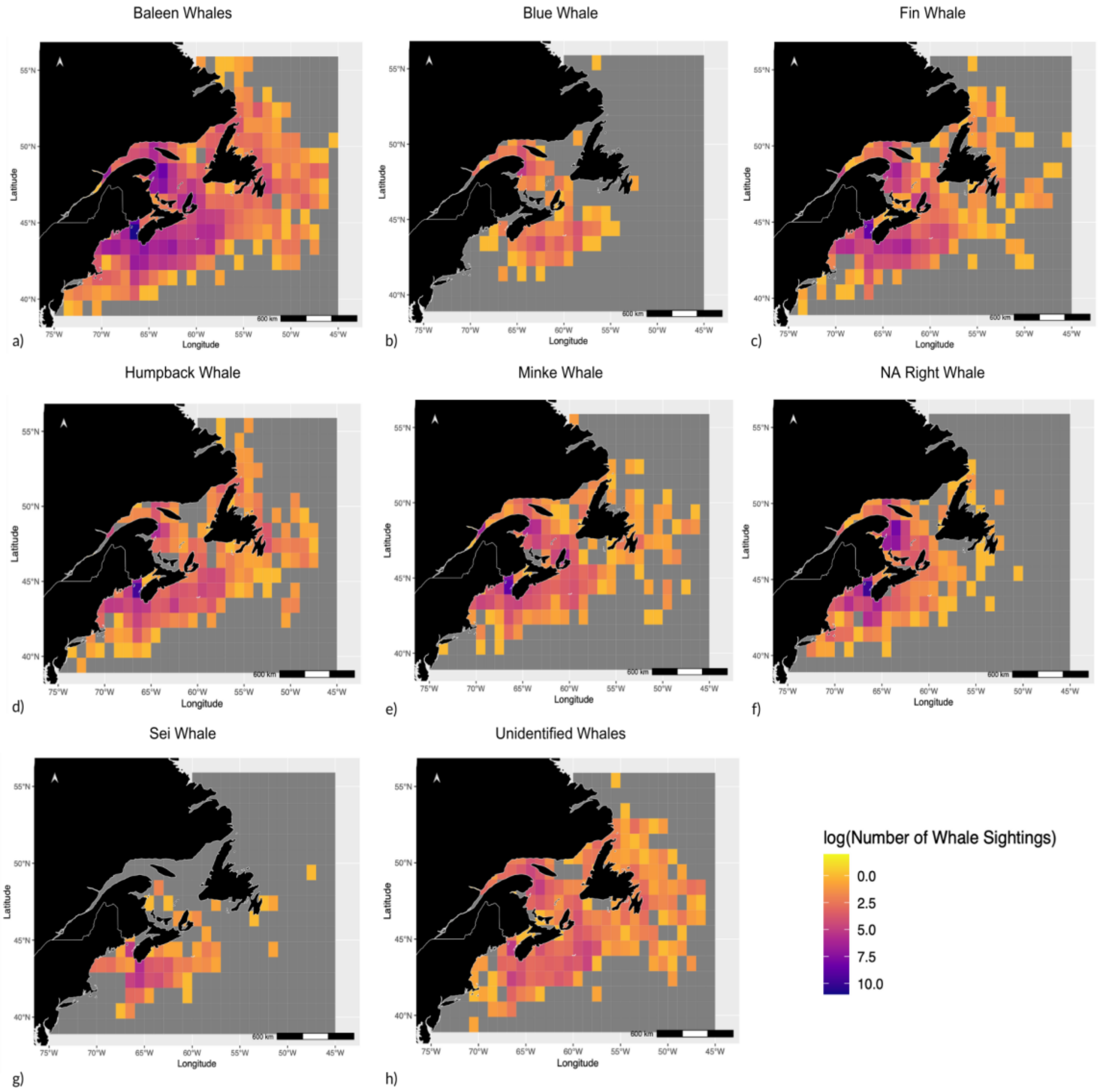

Figure 5. Baleen Whale Sightings. The total number of baleen whale (a), blue whale (b), fin whale (c), humpback whale (d), minke whale (e), NA right whale (f), sei whale (g), and unidentified whale (h) sightings per 1° grid cell between 1963 and 2022 within the study area, on the logarithmic scale. Data collected and provided by DFO (Team Whale 2021), the North Atlantic Right Whale Consortium (NARWC) (NARWC 2021), Environment Canada Seabirds at Sea (ECSAS) (Canadian Wildlife Service 2021), the Whitehead Lab (Team Whale 2021), and the Réseau D'observation de Mammifères Marins (ROMM) (ROMM 2015, ROMM 2017). Grey grid cells represent areas without data.

Table 3. Baleen Whale Sightings Per Season. Number of baleen whale opportunistic sightings per species and per season in the NWA between 1963 and 2022. Data collected and provided by DFO (Team Whale 2021), the North Atlantic Right Whale Consortium (NARWC) (NARWC 2021), Environment Canada Seabirds at Sea (ECSAS) (Canadian Wildlife Service 2021), the Whitehead Lab (Team Whale 2021), and the Réseau D'observation de Mammifères Marins (ROMM) (ROMM 2015, ROMM 2017).

Species	Summer	Fall	Winter	Spring	Total
NA right whale	26,687	1,469	79	1,666	29,904
Humpback whale	18,337	1,231	45	1,577	21,190
Fin whale	10,568	1,565	84	1,238	13,458
Minke whale	10,050	606	15	1,704	12,380
Sei whale	813	254	4	249	1,320
Blue whale	656	105	4	83	848
Unidentified whales	1,637	510	38	607	2,792
Total	68,748	5,740	269	7,124	**81,892**

2.3.3 – Incident Report Data

Between 2004 and 2019 a total of 1,359 baleen whale incidents were reported. The average number of baleen whale incidents per year was 85 ± 25. Since 2004, there has been a significant increase in baleen whale incidents overall and each year consecutively ($P<0.01$) (Figure 6). It can also be seen that the number of incidents almost doubles in 2017, and remains high until 2019 (Figure 6). Most incidents were reported in the summer (~55%, 746 incident reports) and spring (~28%, 378 incident reports), with significantly (P<0.001) fewer incidents reported in the fall (~13%, 176 incident reports) and winter (~4%, 59 incident reports) (Table 4). Of these incident reports 22% (305) were located offshore, whereas 88% (1,054) were coastal and shelf. 34% (457) of incidents involved humpback whales, 29% (391) involved minke whales, 7% (102) involved fin whales, 5% (68) involved NA right whales, 2% (27) involved blue whales, and 1% (14) involved sei whales (Table 4). The remaining 22% (300) of incidents involved whales where the species could not be identified (Wimmer et al. 2021) (Table 4). 59% (796) of incidents involved dead baleen whales, 41% (557) of incidents involved live animals, and in <1% (6) of the incident reports, the state of the animal was unknown (Wimmer et al. 2021). Each incident was also classified into one of 10 incident types: 30% (411) entanglements, 30% (401) beached carcasses, 28% (385) floating carcasses, 4% (51) injured or sick, 2% (33) strandings, 2% (30) free swimming entanglements, 2% (23) entrapments, 1% (15) natural entrapments, >1% (1) vagrant, and >1% unknown (Wimmer et al. 2021). At the 1° resolution, the average number of incident reports per grid cell was 3 ± 9. The majority of incidents were reported on and around the Magdalen Islands, off the coast of south-west Nova Scotia in the Bay of Fundy, in the Gulf of St. Lawrence (especially off the north-east coast of Quebec), and off the north-east coast of Newfoundland (Figure 7).

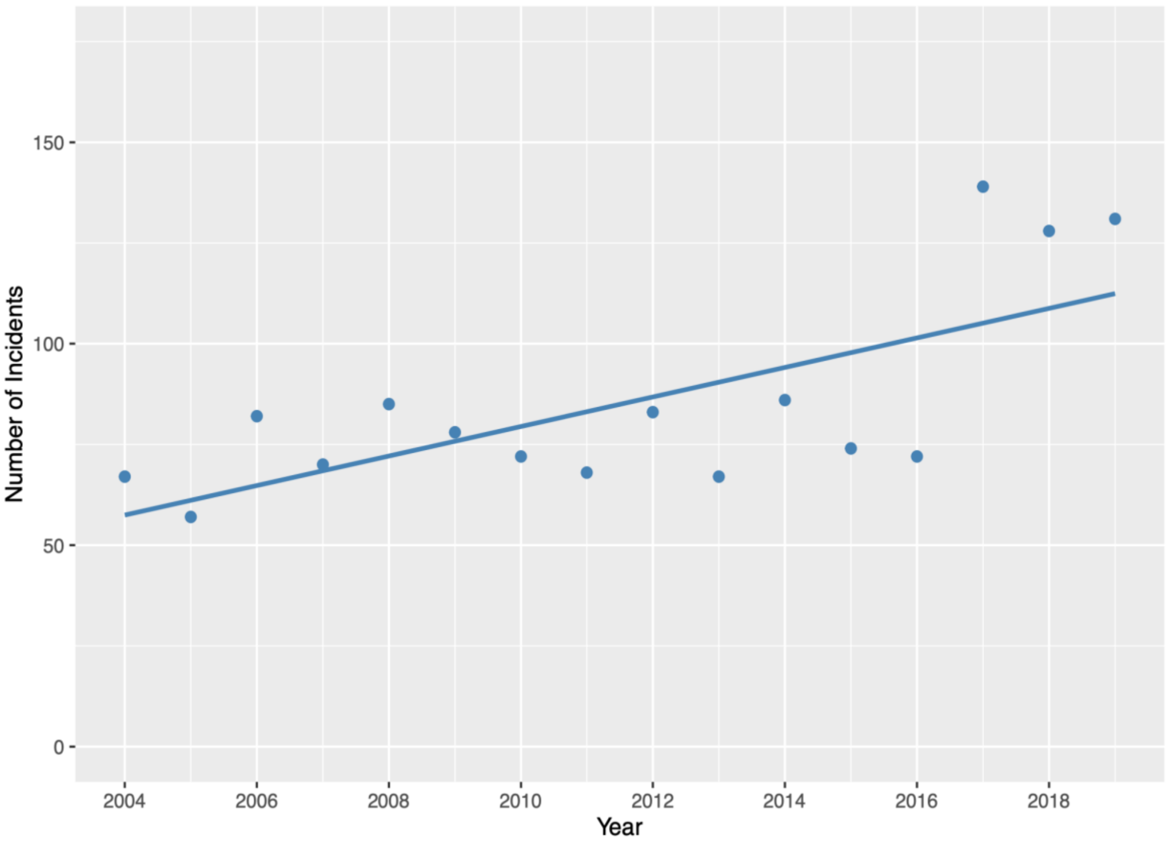

Figure 6. Baleen Whale Incident Reports Per Year. Data collected and provided by MARS, Whale Release and Strandings, and Réseau Québécois D'urgences Pour Les Mammifères Marins (MARS 2021). Regression line is included.

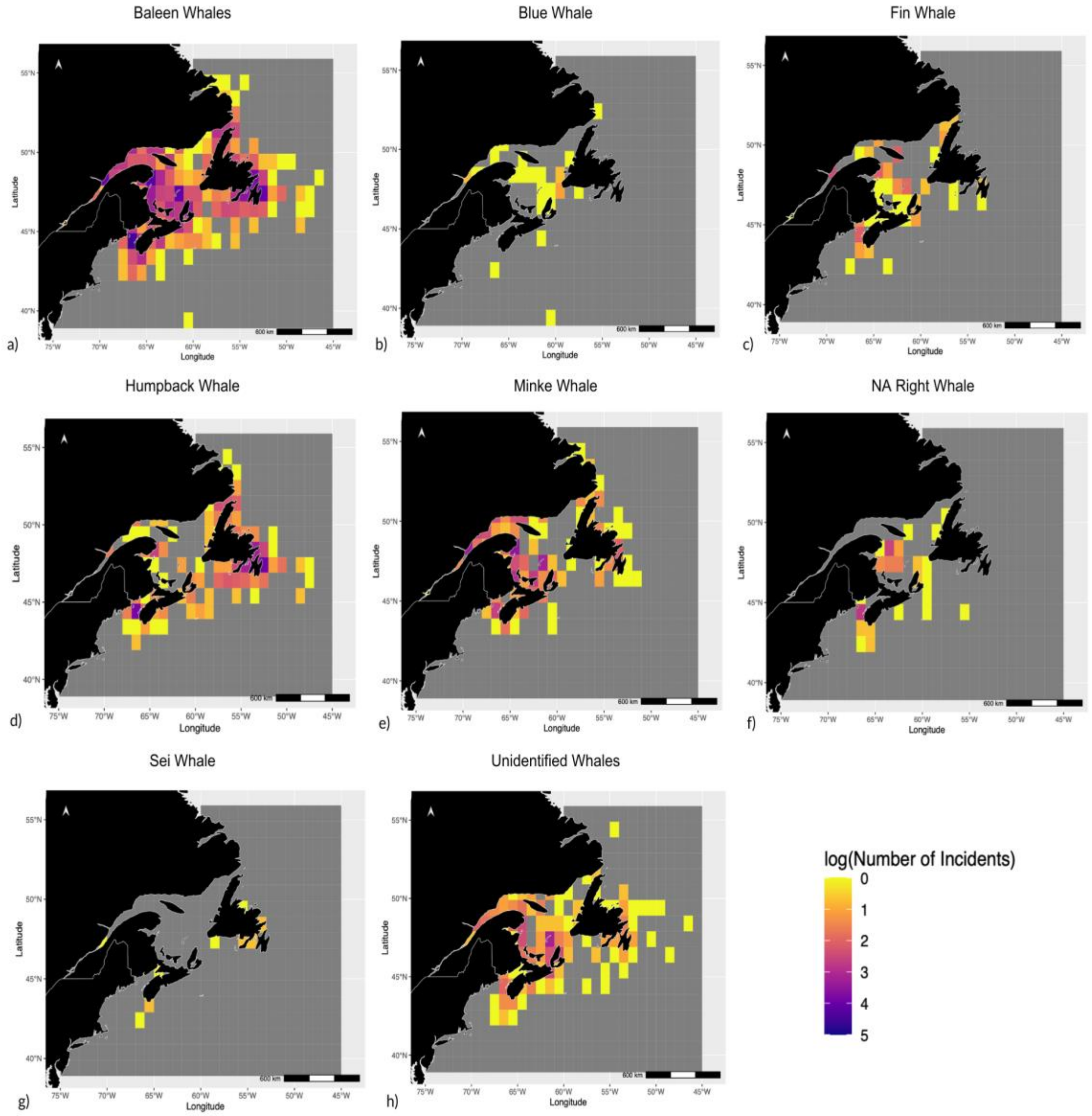

Figure 7. Baleen Whale Incidents. The total number of baleen whale (a), blue whale (b), fin whale (c), humpback whale (d), minke whale (e), NA right whale (f), sei whale (g), and unidentified whale (h) incidents per 1° grid cell between 2004 and 2019 within the study area, on the logarithmic scale. Data collected and provided by MARS, Whale Release and Strandings, and Réseau Québécois D'urgences Pour Les Mammifères Marins (MARS 2021). Grey grid cells represent areas without data.

Table 4. Baleen Whale Incidents Per Season. Number of baleen whale incident reports per species and season in the NWA between 2004 and 2019. Data collected and provided by MARS, Whale Release and Strandings, and Réseau Québécois D'urgences Pour Les Mammifères Marins (MARS 2021).

Species	**Summer**	**Fall**	**Winter**	**Spring**	**Number of Incidents**
NA right whale	46	2	1	19	68
Humpback whale	269	51	18	119	457
Fin whale	54	13	6	29	102
Minke whale	204	57	9	121	391
Sei whale	8	2	0	3	14
Blue whale	9	3	7	8	27
Unidentified whales	156	46	18	79	300
Total	746	176	59	378	**1,359**

2.3.4 – Model Results

2.3.4.1 – All Baleen Whales

The average number of hours of total and large vessel activity per 1° grid cell were significant positive predictors of the number of incidents per 1° grid cell for all baleen whales in the generalized linear model (Table 5, Table A1); higher total and large vessel activity were positively correlated with more incidents (or incident report effort).

The number of observed whales per 1° grid cell and the amount of small vessel activity per 1° grid cell had no significant relationship to the number of recorded incidents per 1° grid cell for all baleen whales (Table 5).

2.3.4.2 – Species-Level Analyses

For sei, minke, fin, and unidentified whales, total vessel activity was a significant predictor of number of incidents, whereas the number of observed whales had no significant relationship to the number of incidents in the generalized linear model (Table 5). For sei and minke whales, both small and large vessel activity were found to have a significant relationship with the number of incidents; however, for fin whales, only total vessel activity was found significant (Table 5, Table A1). For the unidentified whales, only large vessel activity was found to be significant (Table 5, Table A1). Both small and large vessel activity were found to be significant predictors for blue whale incidents (Table 5, Table A1). For NA right whales, vessel activity was not a significant predictor of the number of incidents (Table 5, Table A1). However, the number of NA right whale observations had a positive relationship to the number of NA right whale incidents (Table 5, Table A1). For humpbacks, vessel activity (total) and the number of observed humpback whales were significant positive predictors of the number of humpback whale incidents (Table 5, Table A1). In summary, for 4 of 6 species, total vessel activity was found to be a significant predictor of the number of incidents (or incident report effort); for 4 of 6 species, large vessel activity was found to be significant; for 3 of 6 species, small vessel activity was found to be significant; and for 2 of 6 species, the number of observations was found to be significant.

Table 5. Predicting Baleen Whale Incidents. Estimated regression parameters, standard errors, and P-values for the zero-inflated negative binomial generalized linear model used in this analysis to predict baleen whale incidents from the number of whales sighted per cell (1963-2022), and the number of vessel hours logged per cell (2017-2021). Values are reported for the overall baleen whale analysis, and each individual species model.

Species	Covariate	Estimate	Standard Error	P-Value
All baleen whales	*log(Vessel Hours)*	*0.376*	*0.040*	*<0.001*
	Number of Whales	<0.001	<0.001	0.434
	Spring	*0.709*	*0.134*	*<0.001*
	Fall	*-1.364*	*0.154*	*<0.001*
	Winter	*-2.371*	*0.200*	*<0.001*
NA right whale	log(Vessel Hours)	-0.018	0.178	0.920
	Number of Whales	*<0.001*	*<0.001*	*0.002*
Humpback whale	*log(Vessel Hours)*	*0.397*	*0.097*	*<0.001*
	Number of Whales	*<0.001*	*<0.001*	*0.019*
Fin whale	*log(Vessel Hours)*	*0.265*	*0.133*	*0.047*
	Number of Whales	*<0.001*	*<0.001*	*0.057*
Minke whale	*log(Vessel Hours)*	*0.041*	*0.089*	*<0.001*
	Number of Whales	<0.001	<0.001	0.119
Sei whale	*log(Vessel Hours)*	*1.176*	*0.392*	*0.003*
	Number of Whales	-0.006	0.0040	0.123
Blue whale	log(Vessel Hours)	-0.010	0.189	0.957
	Number of Whales	0.009	0.007	0.226
Unidentified whales	*log(Vessel Hours)*	*0.458*	*0.068*	*<0.001*
	Number of Whales	<0.001	0.0023	0.790

2.3.5 – Overlap Indices and Correlations

2.3.5.1 – All Baleen Whales

Over the study period, and all seasons combined, vessel activity (total, and both small and large vessels) showed significant overlap with baleen whale presences (or sightings effort) and the two variables were positively and significantly correlated (Table 6, Table A2). Vessel activity (total, and both small and large vessels) also showed significant overlap with incident reports (or incident report effort) and was also positively and significantly correlated (Table 7, Table A3). These results are consistent with the GLM analysis (Table 5, Table A1). Lastly, whale observations and incident reports (or sightings and incident report effort) showed the strongest and most significant overlap and were also positively and significantly correlated (Table 8). These results are not consistent with the GLM analysis, which showed an insignificant relationship (Table 5). However, a positive relationship was identified in both the model and overlap indices (Table 5).

2.3.5.2 – Species-Level Analyses

Vessel activity (total) showed non-significant overlap with blue and sei whale presences, and a small but significant overlap with fin, humpback, minke, NA right, sei, and unidentified whale presences (or sightings effort for these species) (Table 6). Small vessels only showed significant overlap with blue, fin, humpback, sei, and unidentified whales, whereas large vessels only showed significant overlap with humpback, minke, and sei whales (Table A2). Overall, vessel activity (total, small, and large vessels) and baleen whale presences (or sightings effort) were positively and significantly correlated, with minke, humpback, NA right, fin, and unidentified whales having the strongest correlations (Table 6, Table A2). Sei and blue whales followed with much weaker positive correlations (Table 6, Table A2).

Table 6. Overlap Between Vessel Activity and Whale Observations. Schoener's D, Warren's Index, and Spearman's Correlation for an overlap analysis between vessel activity and baleen whale presence are reported**.** An asterisk indicates the reported value was significant at the 0.05 level (the value was outside of the 95% confidence interval bound generated from the simulations - see Methods). Values are reported for the overall baleen whale analysis, and for each individual species analysis.

Species	Schoener's D	Warren's Index	Spearman's Correlation
All baleen whales	0.15*	0.34*	0.57*
NA right whale	0.08*	0.24*	0.50*
Humpback whale	0.12*	0.29*	0.52*
Fin whale	0.15*	0.35*	0.47*
Minke whale	0.14*	0.35*	0.54*
Sei whale	0.10	0.29*	0.29*
Blue whale	0.09	0.25	0.28*
Unidentified whales	0.21*	0.43*	0.45*

Fin, humpback, minke, and unidentified whale incidents (or incident report effort) showed a significant overlap between total vessel activity and incident presence (Table 7). Blue, NA right, and sei whales showed no significant overlap between total vessel activity and incident presence (Table 7). These results were consistent with the GLM analysis for all species except the Sei whale (Table 5). Small vessels only demonstrated significant overlap with NA right whale incidents, whereas large vessels only showed significant overlap with the minke and unidentified whale incidents (or incident report effort) (Table A3). These results were not consistent with the GLM analysis which found small and large vessel activity to be significant predictors of blue and sei whale incidents, small vessel activity a non-significant predictor of NA right whale incidents and both small and large vessel activity a significant predictor of minke whale incidents (Table A1, Table A3). However, the results were consistent with the GLM analysis for fin and humpback whales as both the GLM and overlap indices concluded a non-significant relationship between small and large vessel activity and fin and humpback incidents, respectively (Table A1, Table A3). All seven species groups showed a significant and positive correlation between vessel activity (total, small and large vessels) and baleen whale incidents (or incident report effort) with unidentified whales having the strongest correlation (Table 7). These results are consistent with the GLM analysis, with the exception of blue whales demonstrating a significant negative relationship to total and small vessel activity, NA right whales demonstrating a significant negative relationship to total and large vessel activity, and humpbacks demonstrating a significant negative relationship to small vessel activity (Table A1).

Table 7. Overlap Between Vessel Activity and Incidents. Schoener's D, Warren's Index, and Spearman's Correlation for vessel activity and incident reports. Asterisk indicates the reported value was significant at the 0.05 level (the value was outside of the 95% confidence interval bound generated from the simulations - see Methods). Values are reported for the overall baleen whale analysis and for each individual species analysis.

Species	Schoener's D	Warren's Index	Spearman's Correlation
All baleen whales	0.24*	0.47*	0.44*
NA right whale	0.09	0.21*	0.24*
Humpback whale	0.18*	0.39*	0.39*
Fin whale	0.13*	0.30*	0.26*
Minke whale	0.19*	0.38*	0.35*
Sei whale	0.05	0.19*	0.13*
Blue whale	0.05	0.19	0.21*
Unidentified whales	0.22*	0.42*	0.41*

Baleen whale presences and incident reports (or sightings and incident report effort) showed a significant overlap for all seven species groups (Table 8). These results are only consistent with the GLM analysis for the humpback and NA right whales, as for the rest of the species baleen whale presence was not a significant predictor of baleen whale incidents (Table 5). The largest overlap was for NA right whales followed by unidentified, fin, minke, humpback, sei, and blue whales (Table 8). All species populations except sei whales showed a weak, but significant positive correlation, with the strongest results for humpback whales, followed by minke, NA right, unidentified, blue, fin (Table 8). Sei whales showed a non-significant positive correlation (Table 8). These results are consistent with the GLM analysis (Table 5).

Table 8. Overlap Between Baleen Whale Presence and Incidents. Schoener's D, Warren's Index, and Spearman's Correlation for baleen whale presence and incident reports. Asterisk indicates the reported value was significant at the 0.05 level (the value was outside of the 95% confidence interval bound generated from the simulations - see Methods). Values are reported for the overall baleen whale analysis and for each individual species analysis.

Species	Schoener's D	Warren's Index	Spearman's Correlation
All baleen whales	0.26*	0.58*	0.61*
NA right Whale	0.48*	0.78*	0.45*
Humpback Whale	0.21*	0.51*	0.54*
Fin Whale	0.26*	0.51*	0.30*
Minke Whale	0.23*	0.50*	0.46*
Sei Whale	0.21*	0.26*	0.04*
Blue Whale	0.17*	0.35*	0.32*
Unidentified Whales	0.37*	0.57*	0.51*

2.4 – Discussion

In this chapter I explored potential relationships between vessel activity, baleen whale presence and baleen whale incidents in the NWA. I found that all species of baleen whale may experience similar risk of being involved in an incident given the significant relationships found between at least one type of vessel activity and baleen whale presence. Evaluating and understanding these relationships may provide insights for baleen whale conservation and management, especially given the current threat status of multiple populations in the NWA.

2.4.1 – Vessel Activity

Vessel activity in the NWA was highest in the summer months. This is unsurprising as most recreational, whale-watching, and fishing vessels are present on the water during this time and are less prevalent for the remainder of the year (GFW 2021; Ryan Stanley *pers. comm.).* Each area with high vessel activity had multiple fisheries, was a popular maritime shipping or transport route, and, especially in summer, was an area where whale-watching and recreational boating takes place (Figure 4a,b). For example, the Gulf of St. Lawrence, especially near the Seaway shipping channel, is an area with a high year-round concentration of activity (Great Lakes Commission) (Figure 4a,b). This channel is an important shipping and transport route, as it connects the Atlantic Ocean to the Great Lakes, and large ports in Canada and the USA. In combination with intensive fishing and numerous whale watching activities, this results in one of the most activity-dense areas in the study region (DFO 2021a, Quebec Maritime) (Figure 4a,b). Another similar location was the Scotian Shelf. This area contains groundfish and shellfish fisheries, whale watching ventures, and, in the most activity-dense parts, includes busy shipping and transport routes, especially in the Halifax, Shelburne, and Yarmouth areas (Figure 4a,b). Both these regions were also where most of the small and large vessel activity overlapped (Figure A2). There were other regions with a slightly lower vessel density, without major Canadian or international shipping routes, but with smaller maritime shipping, transport and fishing (groundfish and shellfish) activity (Pelot and Wootton 2004, Konrad 2020, DFO 2021b). These areas included the northern coast of Cape Breton Island, between Prince Edward Island, the Magdalen Islands and Nova Scotia, off the north-east shore of Anticosti Island, and off the south-east coast of Newfoundland (Figure 4a,b). Very little vessel activity took place north of Labrador (Figure 4a,b). This is expected as this area does not contain any major shipping or transport routes, fisheries, or recreational activities, and is impacted by sea ice for much of the year (Pelot and Wootton 2004, DFO 2021b).

Most large vessel activity overlapped with the primarily coastal and shelf small vessel activity, but not all small vessel activity overlapped with large vessel activity, given the both coastal and shelf and offshore distribution of large vessel activity (Figure A2). This is unsurprising as a lot of vessel activity that occurs near the shore involves small vessels such as ferries, coastal and shelf fishing, whale watching, and recreational vessels, among others. Conversely, large vessels can be used for both offshore and coastal and shelf activities such as fishing, coastal and shelf transport, transatlantic shipping, and military endeavors (DFO 2021b). The much larger footprint of large vessel activity may explain why the majority of whales had large vessel activity as a significant predictor of incidents as well as a significant overlap in their presences. It is important to note that not all small vessels are required to have AIS detection, only vessels greater than 20 m or longer are required to have it in Canada (with some exceptions depending on the contents of the vessels) (TC 2021), which may have resulted in a larger proportion of small vessel activity being missing from the dataset used. Additionally, most vessel activity was missing corresponding vessel size data, increasing the uncertainty in the relationships between small and large vessel activity with baleen whale sightings and incidents. This missing size data can likely better inform us of the roles of small and large vessel activity play in baleen whale incidents.

2.4.2 – Baleen Whale Presence and Habitat Use

Like vessel activity, the majority of baleen whale observations (or baleen whale sightings effort) occurred in the summer, with fewer sightings taking place in the spring, fall, and winter (Table 3). This seasonal difference in observations is expected as most baleen whales are usually only present in the study area within the summer months due to feeding in the NWA at this time (Davis et al. 2020). During the rest of the year (spring, fall, and winter), some whales are travelling either to or from, or residing in, their mating grounds south of the NWA. This could explain much fewer observations in the spring and fall and the near-zero observations in winter. This being said, recent studies have also shown presence of baleen whales in NWA year-round (Davis et al. 2020). Whale presence was spatially and temporally similar to that found in acoustic telemetry studies (Davis et al. 2020, Delarue et al. 2022). However, the sightings data suggested a stronger presence in coastal and shelf regions the Gulf of St. Lawrence than in the literature, which may be due to the lack of acoustic receivers in that region (Davis et al. 2020). In addition to migration patterns, due to bad weather and lower visibility, sightings effort is lower in the spring, fall, and winter, leading to fewer sighting records of these species than in the summer, which likely further biases seasonal differences (Gomez and Moors-Murphy 2014). This lack of sightings effort in the colder seasons is reinforced by the seasonal trend in vessel activity (Table 2), as most of the observed sightings in this analysis were made from ships. It is therefore difficult to disentangle to what extent the seasonal patterns of presences are due to biological features (e.g. migration), seasonal variation in observation effort, or both.

NA right whales were the most commonly sighted species in the observation dataset. This is surprising as they are the most endangered, but due to dedicated species monitoring from directed aerial surveys, their coastal and shelf habitats, slow movement and conspicuous surface behaviours, they may more often be detected than other species (Johnson et al. 2020). NA right whale sightings were followed by humpbacks, then fins, minkes, blues and seis. Baleen whales were seen all throughout the study area, but sighting density was highest in the Bay of Fundy, the Scotian Shelf, the Gulf of St. Lawrence, and the north-east coast of Newfoundland (Figure 5). This sightings density is likely due to concentrated sightings effort in these areas, however, each of these areas is also known to be important habitat for baleen whales in the NWA due to food type and availability (Davis et al. 2020, Delarue et al. 2022, Moors-Murphy et al. 2019). For example, there was a high blue whale density in the lower Gulf of St. Lawrence Estuary, the north-east Gulf of St. Lawrence, offshore beyond the southern part of the Scotian Shelf, and off the southern coast of Newfoundland; all areas considered to be important blue whale habitat in the region likely because of high productivity and food availability (Figure 5b) (Lesage et al. 2017, Moors-Murphy et al. 2019). Blue whale presence in the Scotian Shelf and Newfoundland areas was also identified in acoustic telemetry studies, confirming their offshore presence (Davis et al. 2020, Delarue et al. 2022). Blue whale presence in the Gulf of St. Lawrence is also shown by frequent acoustic detections (Simard et al. 2016).

Humpbacks, fins, and minkes similarly had sightings distributed throughout the entire study area but with the densest concentrations in the same areas as the blue whale, including strong similarities between blue and fin whale presences offshore (Davis et al. 2020, Delarue et al. 2022). Critical habitat for these three species is less well known. However, satellite telemetry, acoustic (Davis et al. 2020, Delarue et al. 2022), and survey studies have confirmed seasonal humpback whale presence off the coasts of Nova Scotia and Newfoundland (Kennedy et al. 2013), within the Gully MPA (Kowarski et al. 2018) and within the Gulf of St. Lawrence (Doniol-Valcroze et al. 2007). There is even less information for fin whales. A study compiling what is known about fin whale distribution in the region indicates that historically they were present in the aforementioned areas (Edwards et al. 2015). Surveys have also confirmed minke whale presence in the Bay of Fundy (Johnston et al. 2005) and within the Gulf of St. Lawrence (Doniol-Valcroze et al. 2007). Minke whales have also been seen off the coasts of Nova Scotia and Newfoundland (Team Whale 2022), but their offshore distribution has not been well studied.

There was a high concentration of NA right whale observations within the Roseway and Grand Manan Basins (Bay of Fundy), both of which are known critical habitats for these animals (Figure 5f) (Vanderhoop et al. 2012, Davies and Brilliant 2019); however, this may be changing given evolving ocean conditions and increased sightings in the Gulf of St. Lawrence (Record et al. 2019). The recent change in distribution has also been shown in multiple acoustic telemetry studies and confirmed by prey abundance and presence studies (Davis et al. 2017, Record et al. 2019). Finally, in my data, sei whales had a limited presence in the Bay of Fundy and the southern part of the Scotian Shelf but were mostly seen offshore. This could be due to the fact that sei whales have been found to sometimes use offshore habitats (Davis et al. 2020), where there is less sighting effort. It is important to note that it is often difficult to distinguish them from other balaenopterids, which may also have affected the number of sightings (Wimmer et al. 2021). Although sei whale distributions are not well studied, the sei whale presence locations in this study are also confirmed by acoustic and satellite telemetry studies (Davis et al. 2020), indicating a strong year-round presence of sei whales off the coasts of Nova Scotia and Newfoundland (Prieto et al. 2014, Macklin 2022).

2.4.3 – Baleen Whale Incident Reports and Presence

Reported incidents may provide valuable information on the interactions between humans and baleen whales, in addition to distribution, health, and physiology. However, given the nature of how incidents are reported and a lack of resources for detailed follow-up studies, it is often difficult to collect all necessary information from each incident. Of particular relevance here is the uncertainty as to where and how an incident took place. Most reports are called into respective hotlines after an incident has taken place, and the affected whales (i.e., injured or exhausted animals or carcasses) have become stuck or washed up near shore after having drifted on ocean currents (Wimmer et al. 2021). Incidents have been called in anywhere from immediately to years after the incident likely occurred. It has not yet been determined how far these animals may drift before being reported; however, it is likely that if the animal is found in good condition, the incident did occur in the vicinity of where it was reported. Limiting my analysis to only those incidents where the whale was reported as being in good condition may have made for a more accurate representation of baleen whale incident distribution, yet would have reduced the sample size of incidents by 43% for all baleen whales, 30% for blue whales, 22% for fin whales, 74% for humpback whales, 29% for minke whales, 59% for NA right whales, 36% for sei whales, and 18% for unidentified whales. Incidents that are not reported immediately after a negative interaction mainly consist of dead and decomposed animals (Wimmer et al. 2021). These represent most reported incidents (Wimmer et al. 2021) and make it very difficult to extract information about the cause of death or identify signs of human interaction (Wimmer et al. 2021). For incidents that are immediately reported, it is often a lack of resources (money, equipment, personnel, etc.) that limits the information gained from the incident report (Wimmer et al. 2021). The incident reports used in this study were mainly collected in the summer months, likely due to a combination of baleen whale seasonality patterns and higher observation and collection efforts (beach use, people near shore, etc.) (Table 4).

An increase of baleen whale incidents was also identified in recent years, especially beginning in 2017 where there was an almost quadrupling in humpback, fin, and NA right whale incidents, and doubling in sei and unidentified whale incidents (Figure 6). This can partially be attributed to an increase in incident reporting efforts, including aerial surveys (Wimmer et al. 2021), but also reflects two mass mortality events that took place for NA right whales in 2017 and 2019 (Koubrak et al. 2020). These seasonal, temporal, and effort-related patterns were also identified in related studies characterizing Canadian maritime (Nemiroff et al. 2010) and Gulf of St. Lawrence (Truchon et al. 2013) stranding events.

Most incidents involved humpback whales, followed by minkes, fins, NA rights, blues, and seis (Table 4). The number of incidents recorded for each species is generally proportional to the estimated regional population size (Wimmer et al. 2021), meaning no species seems to be at disproportionate risk. Most incidents were reported near the Magdalen Islands, near south-west Nova Scotia, within the Bay of Fundy, in the Gulf of St. Lawrence near the north-east coast of Quebec, and near the north-east coast of Newfoundland (Figure 7). As previously mentioned, there is clear evidence of incidents for all baleen whale species in the NWA (Laist et al. 2001, Van Der Hoop et al. 2013). In the limited studies on this issue, it has been determined that within the Gulf of St. Lawrence, minke and NA right whale incidents are common (Truchon et al. 2013, Sharp et al. 2019).

In the present database, most incident reports were distributed along coastlines. This, again, is likely due to the drifting of affected animals to where they are more likely to be observed. Offshore incidents are likely underreported due to lack of offshore observation effort. The concentration of incident observations along the coast is consistent with several other studies (Truchon et al. 2013, Nemiroff et al. 2010). However, the aggregation of this data to the 1° grid, which integrates data from a larger area, should have helped to make the issue of a mismatch between incident occurrence and incident observation less prominent. The concentrations of incident reports may also be influenced by human population density, knowledge of a response organization’s existence in respective areas, the fact that some areas are popular whale-watching and fishing areas, and that many shoreline areas are not accessible and therefore are missing incident reports (Nemiroff 2010, Wimmer et al. 2021). These factors may bias results towards coastal and shelf areas where incidents are likely to be observed, and away from areas where there is little observational effort. Strategies to improve incident collection effort are discussed more in depth below (See Chapter 2 Limitations).

2.4.4 – Model Interpretation

Total and large vessel activity was a significant predictor of all baleen whale incidents at a 1° resolution, indicating a positive relationship between the number of incidents (or incident report effort) and vessel activity total and for large vessels (Table 5, Table A1). However, neither small vessel activity nor the number of whales observed was a significant predictor of the number of incidents (Table A1). The overall baleen whale model also detected a seasonal influence on the relative number of incidents (or incident report effort), as most baleen whale sightings and vessel hours took place in the summer months (for the reasons previously discussed), skewing the data.

For the individual species analyses, vessel activity (total, small, and large vessels) was not a significant predictor of the number of incidents (or incident report effort) for NA right whales (Table 5, Table A1). This is an interesting result as literature suggests that NA right whales are the third most likely species of baleen whale to be at risk of a collision with a vessel (Van Waerebeek & Leaper 2008), so one might expect vessel activity to be a significant predictor of NA right whale incidents. This may be due to the relatively small number of NA right whale incidents (Table 4), which may not have provided enough statistical power to detect a significant relationship with any type of vessel activity. Small and large vessel activity, but not total vessel activity, were found to be a significant predictor of blue whale incidents (Table 5, Table A1). Blue whales have been found in very few vessel-strike and entanglement reports, so it seems reasonable that total vessel activity would not be correlated with incidents (or incident report effort) (Van Waerebeek & Leaper 2008). In contrast, total vessel activity was a significant predictor of incidents involving the remaining species (sei, minke, fin, humpback, and unidentified) (Table 5). Additionally, both small and large vessel activity had a significant relationship with sei and minke whale incidents and large vessels were a significant predictor of incidents for fin whales (Table A1). These findings are consistent with existing literature that suggests fin and humpback whales are the species most frequently involved in vessel strikes (Van Waerebeek & Leaper 2008), and, for humpbacks, entanglement (Themelis et al. 2016).

It is difficult to disentangle these differences in the relationships with small and large vessel activity as both all whales and small and large vessel activity had mainly coastal and shelf distributions, which may explain some of the correlation seen in the analyses. As mentioned previously, perhaps due to the larger footprint of large vessel activity, it was deemed a significant predictor of incidents for more species. However, it is interesting to see that certain species may be at higher risk of vessel strike from different sized vessels. It would be interesting to investigate the types of vessels involved in the existing incident reports. It is also important to reiterate that there may be some correlation between the vessel activity and sightings (or sightings effort) given that most sightings were made aboard vessels, however, this correlation likely did not majorly affect the results, as single predictor models did not demonstrate any noteworthy changes in significance. In the majority of my GLM results, there appears to be an increase of incidents (or incident report effort) with an increase in vessel activity, whether it be total, small, or large. There were few cases where at least one type of vessel activity showed a negative relationship to baleen whale incidents (blue, NA right, and humpback whales); however, these coefficients were small and non-significant, indicating a limited explanatory power (Table 5, Table A1). The overwhelming positive relationship between vessel activity and incidents (or incident report effort) provides support to the idea that vessel-caused incidents are likely to occur for multiple baleen whale species in the NWA.

In contrast to vessel activity, the number of whales observed (or sightings effort) was not a significant predictor of the number of incidents for any species, with the exception of NA right whales and humpback whales (Table 5). For these two species, in areas where the number of whales observed (or sightings effort) was higher, the number of incidents was also generally higher. It is difficult to conclude why the differences in the individual species results exist, but it could be due to the fact that NA right and humpback whales were the most frequently sighted, leading to larger sample sizes that may better predict incidents for these species. Additionally, these species occur also closest to the shore (Figure 5d,f), allowing their distribution to be more fully sampled by human observers that also concentrate along the shore. In general, my study has found that the more whale sightings (or sightings effort) there are, the more incidents there are. Evidently, where there is a greater concentration of whales, there is more risk for vessels and entangling gear to come into contact with them.

2.4.5 – Interpretations of Overlap Analyses

Using multiple overlap indices, generally, vessel activity (total, and both small and large vessels) and baleen whale sightings (or sightings effort) overlapped and were positively and significantly correlated (Table 6, Table A2), meaning that areas with more baleen whale sightings (or effort) tended to also have more vessel activity. This makes sense as most sightings were made from vessels. Some vessels specifically target areas where we know baleen whales already exist, such as research cruises or whale-watching vessels (Gomez et al. 2020). In addition, ad-hoc observations from other vessels are likely to be more frequent where there is a higher vessel density. Thus, observation efforts interact with true whale densities to affect observation rates, likely leading to substantial biases and challenges with using observational data to determine the likelihood of whale presences. However, an overlapping relationship between vessel activity and baleen whale observations was also described by Vanderlaan et al. (2008) when researching where NA right whales and vessels may encounter one another on the Scotian Shelf. Additionally, in a study looking at the overlap between blue whale presences and fishing vessel activity in Patagonia, Chile, using the same indices, a strong overlap and positive correlation between whales and vessels were found (Bedriñana-Romano et al. 2021). Thus, these relationships appear to be present in multiple regions (Bedriñana-Romano et al. 2021).

A similar significant overlap and positive correlation was found between vessel activity (total, large, and small vessels) and incident reports (or incident report effort) (Table 7, Table A3). This result reinforces the GLM results which also suggest that most vessel activity is a significant predictor of all baleen whale incidents (or incident report effort) (Table 5, Table A1). This outcome, in conjunction with the existing literature, may confirm that there are areas in the NWA where vessel-derived baleen whale incidents are probable (Vanderlaan et al. 2008). There are also multiple studies that show overlapping and positively correlated relationships between vessels and baleen whale incidents outside of the NWA (Currie et al. 2017, Nichol et al. 2017). In particular, studies demonstrating the risk of vessel strikes to humpback whales off the south-east coast of the United States (Currie et al. 2017), fin and humpback whales off of Vancouver Island (Nichol et al. 2017), and blue whales off of California's coast (Fonnesbeck et al. 2008) all support the potential existence of these relationships in the NWA.

Whale observations and incident reports (or sightings and incident report effort) also had a similar significant overlap and showed a positive significant correlation (Table 8), meaning areas with more whale observations tended to have more incidents. This result is contrary to what the GLM suggests, as the number of whale observations was not a significant predictor of overall baleen whale incidents (Table 5). However, a positive relationship was identified in both the model and overlap indices. This might suggest that the overlap indices are more sensitive than the GLM. Alternatively, the differing results may be explained by the fact that there are other terms that are present in the GLM that account for other factors such as vessel activity and spatial autocorrelation. The sensitivity of both methods was tested by running the GLM with just whale observations as a function of incidents (Table A4). Only then do the observations become a significant predictor of incidents for all baleen whales, and therefore also align with the significant overlap. This may demonstrate that the GLM accounts for important nuances the overlap indices cannot.

For individual species analyses, all species except the blue and sei whales had significant overlap with vessel activity (total) (Table 6). Blue and sei whales have the fewest observations, a factor that may have influenced this lack of significant overlap. The remaining significant overlaps suggest and confirm the findings of Vanderlaan et al. (2008), that there are areas in the NWA where baleen whale incidents are likely. This relationship was significantly and positively correlated for all species, indicating that where there is more vessel activity, there are more individual species observations (Table 6). This again could either indicate that areas with high vessel traffic are likely to have more incidents, or that there is more observer effort in time-periods of reporting incidents in areas with high vessel traffic, which may be attributed to population density and therefore observers. Fin, humpback, minke, and unidentified whales showed a significant overlap between vessel activity (total) and incidents (Table 7). This result also helps support the literature that suggests fin and humpback whales are the most frequently recorded species being involved in vessel strikes and entanglements (Van Waerebeek & Leaper 2008, Themelis et al. 2016). However, blue, NA right, and sei whales showed no significant overlap between vessel activity (total) and incident presence (Table 7). These results reflect the GLM results that suggest if vessel activity is or is not a significant predictor for these species, respectively (Table 5). These results have likely been impacted by the fact that the three species with no significant overlap are also the species with the least reported incidents, providing less statistical power. Additionally, small vessels demonstrated significant overlap only with NA right whale incidents (contrary to the GLM), whereas large vessels showed significant overlap with only minke (consistent with the GLM) and unidentified whale incidents (contrary to the GLM) (Table A3). The

NA right whale sightings can be mostly seen coastally and along the shelf (Figure 5f) which also aligns with the small vessel activity distribution (Figure 4), which could explain their significant overlap. Minke and unidentified whales were distributed both coastally, along the shelf and somewhat offshore (Figure 5e,h), similarly to the large vessel activity (Figure A2b), which also may be the reason for their significant overlap. All species-level analyses of vessel activity (total, small, and large vessels) and incident reports showed a positive and significant correlation, indicating that where there is more vessel activity there are likely to be more incidents (or incident report effort) (Table A2, Table A3), once again lending more support to the existence of high vessel strike and entanglement risk in the NWA.

The largest and most significant overlap for all individual species was between species presences and species incident reports (or sightings and incident report effort) (Table 8). However, only for the humpback and NA right whales, did the significance of the overlap between these two variables reflect the GLM results that showed whale presence as a significant predictor of incidents (Table 5, Table 8). For all species (except the sei whale), the relationship between whale and incident presences was positively correlated, showing that where there are more individual species observations (or effort), there are likely to be more individual species incidents (or incident report effort) (Table 8). These results suggest that we need to pay special attention to areas where there are large concentrations of baleen whales, especially humpback and NA right whales, as incidents are most likely to occur there. This has already been done for NA right whales, as previously discussed, but not for any other whale species.

Overall, these results and relationships demonstrate that in general, incidents between vessels and whales are likely, as vessel activity (total, small, or large), baleen whale presences, and incidents (and sightings and incident effort) all overlap spatially in the NWA. My findings resemble another study where blue whale presence and fishing vessel activity in Patagonia, Chile, had a strong overlap and positive correlation, as well as other studies suggesting frequent harmful interactions between vessel activity and baleen whales (Currie et al. 2017, Nichol et al. 2017, Fonnesbeck et al. 2008).

2.4.6 – Chapter 2 Limitations

This study is necessarily limited in its interpretation due to the potential sampling bias associated with the baleen whale opportunistic sightings and the lack of available effort data to correct for this. Thus, I consider the relationship between incidents and vessel densities to be more robust than that between sightings and incidents. Something that would help with this challenge would be the provision of 'effort data': information associated with how each sighting was collected (i.e. survey tracks for any observations collected by surveys, boating routes and schedules for whale watch vessels, navy ships, and recreational vessels associated with the observations collected by those methods), as well as, ideally, effort data in cells where zero whale observations were recorded. This information would allow us to standardize the observations to account for any sampling bias (Gomez et al. 2020). The specific effects of this sampling bias have been explored throughout this discussion, but in general it likely overrepresents areas with high sighting effort. Additionally, there is likely a lack of sighting effort in areas (particularly further offshore) where suitable whale habitat may occur (Gomez et al. 2020). It is also important to mention that given most sightings were made aboard vessels, the vessel activity and whale sightings may be correlated. However, as previously stated, when the GLMs were run with each predictor individually, the results generally did not change, supporting the robustness of the original GLM.

There is also the potential for behaviourally-driven differences in the whale sightings and/or incident reports. Although NWA baleen whale non-acoustic behaviour is not well studied, it is known that multiple baleen whale species can demonstrate differing behaviours or strategies such as diving, breaching, spyhopping, bubble net feeding, and more (Wiley et al. 2011). These behaviours could potentially lead to an increased or decreased chance of being sighted or being involved in an incident. Additionally, human behaviours or choices, such as sighting ability or boat speed may affect the rate of sightings as well. The influence these behaviours may have is beyond the scope of this thesis, due to the lack of data and uncertainty regarding baleen whale and human behaviour, yet may be worth integrating into such analyses as further information becomes available.

In the absence of effort data and given the biases in the observation data, an alternative approach to understand how the likelihood of a whale presence relates to vessel density and incident probability may be warranted, particularly given the importance of this topic for management and conservation. One approach would be to use species distribution models (SDMs) to relate environmental covariates to habitat suitability for individual species and hence to construct a species niche, which would enable the construction of a map of relative habitat suitability, even in areas where there is limited or no sampling (Gomez et al. 2020).

Finally, as previously stated, there may have been much vessel activity data missing from the NWA, especially from small vessels, which includes many fishing vessels, as not all are required to use AIS. Additionally, there may be many ships that do not abide by the laws that require vessels to use the tracking technology. Even within the vessel data that has been acquired from AIS, the majority of entries are missing vessel size information, leaving a lot of room for uncertainty within the results derived from the vessel size analyses. Had the 55% of data that did not have a designated vessel size, contained this metadata, the relationships between small and large vessel activity and baleen whale sightings and incidents may be different. This missing data and uncertainty provides reasoning to increase proper AIS use and enforcement, in order to obtain and use better data on vessel activity and size.

2.4.7 – Conclusions

This chapter has shown that several large baleen whales in the NWA share a similar risk of being involved in an incident as demonstrated by the relationships between baleen whale sightings, vessel activity, and baleen whale incidents in the NWA. This being said, it is important to keep in mind that due to the nature of the data used in this chapter, it is difficult to disentangle observer and incident report effort from actual baleen whale presence and incident occurrence. From this chapter, I conclude that it is important that all whales are considered in future management and conservation measures, significantly expanding the scale of protective efforts beyond critically endangered NA right whales Effective management is essential to enable these whales to recover from previous depletion, and it begins with making the most of the available data, even in the face of its limitations.

Chapter 3 – Determining Current and Future Baleen Whale Habitat Suitability and Incident Hotspots in a Changing Northwest Atlantic

3.1 – Introduction

As the previous chapter, and independent research have shown (Laist et al. 2001), all six species of baleen whale found in the NWA are at risk of being struck by a ship or entangled in fishing gear, both of which are thought to be major sources of mortality (Laist et al. 2001, Van Der Hoop et al. 2013). Studying the factors that predict these incidents across regions and species is a relatively recent focus in baleen whale science (Winkler et al. 2020). To robustly ascertain causes, risks, where they are most likely to occur, and mitigation approaches, requires comprehensive information on the range, distribution, and habitat use of NWA baleen whales.

3.1.1 – Common Baleen Whale Study Limitations

Most knowledge of baleen whale distributions derives from research surveys, acoustic telemetry, and citizen observations (Ceballos et al. 2022). This knowledge also varies among species (Davis et al. 2020). For example, much is known about humpback and NA right whale distribution and habitat use; however, little is known about blue, fin, minke, and sei whales in this regard (Davis et al. 2020). This is likely due to the fact that humpbacks and NA right whales have a strong coastal and shelf presence, where there is a lot of research effort, whereas the remaining species are likely to use offshore areas where there is little research effort, as indicated by recent acoustic studies (Davis et al.

2020). Data from research surveys and citizen observations were used in the second chapter of this thesis to develop a baseline of baleen whale occurrence and vulnerability to incidents. However, a bias in sampling effort may have biased the assessment of baleen whale distributions towards well-observed areas. We can only confirm a whale species within observed regions; we cannot infer presence in other regions where there is no sampling effort, and we cannot confirm absence (Gomez et al. 2020). Additionally, observation effort can also be biased due to factors like accessibility, seasonal differences, weather, and resource availability (such as funding, research vessel access, personnel availability, etc.) (Gomez et al. 2020). One way to reduce the impacts of observational effort bias in species presence data is by using a species distribution model to generate habitat suitability maps that include areas which are under- or unsampled.

3.1.2 – Species Distribution Models

Species distribution models (SDMs) use environmental data to predict species distributions across space and time (Guisan et al. 2017, Elith et al. 2006). SDMs can integrate data sources such as research surveys and citizen observations to identify species' presence (and sometimes absence) locations and then relate these to environmental variables at these locations to help construct the environmental niche for each species. They can then extrapolate this niche to regions with environmental data but without species observations or with reduced sampling effort to project locations where suitable habitat exists, reducing (not eliminating) the impact of sampling or effort bias when assessing the distribution of these species (under specific assumptions; Guisan et al. 2017).

Two common types of SDMs are presence-only or presence-absence models, where the first kind only includes locations where the species was recorded as present (as used in this thesis), and the second also models locations where the species was both present and absent (Guisan et al. 2017). To account for the missing absence data in presence-only models, pseudo-absences are typically used, which are usually randomly generated background locations (Guisan et al. 2017). With SDMs, there is also the capability to project distributions or habitat suitability into the future under climate change using environmental projections generated by Earth System Models (ESMs) that simulate current and future oceanography and biogeochemistry (Tittensor et al. 2010). Using model projections of future environmental conditions, it becomes possible to model how species distributions or habitat suitability may alter with climate change.

SDMs are increasingly used in the study of NWA cetacean distributions (Pendleton et al. 2012, Roberts et al. 2016, Moors-Murphy et al. 2019, Gomez et al. 2020). For example, studies by Moors-Murphy et al. (2019) and Gomez et al. (2016) determined areas of high blue whale habitat suitability off the Scotian Shelf and within the Laurentian Channel using a Maximum Entropy (MaxEnt) SDM. Following this, habitat suitability layers for fin, humpback, minke, and sei whales were calculated by Gomez et al. 2020 using a MaxEnt SDM, finding the highest overall suitability across species within the Bay of Fundy, off the Scotian Shelf, within the Laurentian Channel, and off the north-east coasts of Newfoundland and Labrador. These pioneering studies had a similar domain as the present work but excluded the Gulf of St. Lawrence in their analyses, and did not consider incident data. In modelling efforts focused on baleen whale distribution in the USA, baleen whale density has also been predicted to be high in the Bay of Fundy and off the Scotian Shelf (Roberts et al. 2016). There are also multiple efforts underway, by organizations such as DFO and the Canadian Wildlife Federation (CWF) to more accurately model baleen whale distribution. To build on such research, this thesis uses an ensemble SDM approach to project baleen whale habitat suitability in the region of interest for all species of baleen whale. One further advantage of using this approach is that changes in species distribution can be inferred from projected changes in environmental parameters.

3.1.3 – Baleen Whales and Climate Change

The distributions of some baleen whale species are beginning to be impacted by climate change (Becker et. al 2018). In part, this can be due to increasing sea surface temperatures driving changes in prey availability (Pendleton et al. 2012, Record et al. 2019). For example, *Calanus finmarchicus*, a copepod vital to the diet of a NA right whale, has declined in the Gulf of Maine and the Bay of Fundy (areas previously determined as critical NA right whale habitat), likely due to warming sea surface temperatures. As a result, NA right whales have shifted their distribution more north to the Gulf of St. Lawrence, where there may be more prey availability (Meyer-Gutbrod and Greene 2017, Record et al. 2019). This change in distribution impacts their conservation as there may be new or different threats to the species in this region, such as different risks of stranding, vessel strikes, or entanglement. A similar scenario seems to be unfolding for blue whales, where Pacific populations have been affected by melting sea ice altering marine algae availability in foraging areas (Convention on Migratory Species 2020). Algae are a crucial food source for krill, which is one of the main food sources for blue whales (Convention on Migratory Species 2020). It is not unreasonable to assume a similar interaction chain may be affecting blue whales in the NWA. These changes in prey availability are not only affecting baleen whale habitat use but are also likely to affect their breeding success, impacting growth and reproduction (Kershaw et al. 2021), putting further strain on these whales' populations.

The above examples indicate why it is important to understand how baleen whale distributions are and will be impacted due to climate change. Such information will enable scientists and policymakers to make informed decisions on how to better protect all baleen whale species from the various human pressures threatening them in combination with climate change. For example, this understanding could allow us to anticipate future regions of conflict between baleen whales and human use, resulting in preventative, long-term, and more thoughtful and dynamic baleen whale management.

Unfortunately, little research in this specific area exists yet, especially for the NWA. Global projections for baleen whale distribution and habitat suitability are available through the Aquamaps program (Aquamaps 2019). However, due to the global scale of the model, along with the fact that valuable regional datasets have not informed the model (only publicly available sparse data), the outputs do not reflect the known NWA baleen whale distributions and therefore make the projections less reliable. At the same time, these projections identify an offshore distribution for all baleen whales that shifts poleward under climate change conditions (Aquamaps 2019), which agrees with most literature suggesting a similar range shift (Meyer-Gutbrod et al. 2018). Changes in global marine mammal richness due to climate change have also been projected, identifying a loss in marine mammal diversity in the southern parts of the NWA, and a gain in the northernmost parts (Kaschner et al. 2011), also signifying a projected poleward shift in marine mammal distributions as climate change prevails.

To help address the knowledge gaps on baleen whale habitat suitability, this thesis develops current and future habitat suitability projections informed by more regional (Atlantic and NWA) data for each species of baleen whale in the NWA and at a finer resolution than previous global models.

3.1.4 – Chapter 3 Objectives

The first objective of this chapter is to project baleen whale habitat suitability in the NWA using a range of plausible species distribution models informed by biologically relevant environmental variables. The second objective is to address some of the challenges posed by the biased nature of the sightings data in Chapter 2 by using the modelled habitat suitability to investigate the potential relationships with vessel activity and, as a result, where baleen whales are most vulnerable to incidents in the NWA (incident hotspots). The third objective is to determine if projected incident hotspots will change over time as a result of changing species habitat suitability due to climate change. I tested the hypothesis that where there is high baleen whale habitat suitability and vessel density, there is high relative incident risk both currently and under climate change conditions. All three objectives were carried out for all six baleen whale species in the NWA.

3.2 – Methods

3.2.1 – Data Processing

3.2.1.1 – Biological Data Processing

Opportunistic sightings of baleen whales in the North Atlantic Ocean (ranging from Panama and Mauritania up to Greenland and Iceland) from 1904-2022 were compiled from DFO (Team Whale 2021), the North Atlantic NA Right Whale Consortium (NARWC) (NARWC 2021), Environment Canada Seabirds at Sea (ECSAS) (Canadian Wildlife Service 2021), the Whitehead Lab (Team Whale 2021), the Réseau D'observation de Mammifères Marins (ROMM) (ROMM 2015, ROMM 2017), and the Ocean Biodiversity Information System (OBIS) iD (OBIS 2023). The number of whale observations per 10km by 10km grid cell in the North Atlantic Ocean was then calculated and summed across all years for each species in QGIS. These were then turned into presence values by assigning a value of one to every grid cell that had one or more whale observations.

3.2.1.2 – Environmental Data

Environmental data used in this SDM (Table 9) were derived from the Community Earth System Model (CESM) which is part of the Coupled Model Intercomparison Project Phase 6 (CMIP6) project (Eyring et al. 2016). Past to present-day environmental data (averaged across 1985-2015), along with near-future (2035-2045) and mid-future (2045-2055) projections forced by the 2xCO_2 climate scenario, a scenario where CO_2 emissions are expected to double to 560ppm (akin to the Representative

Concentration Pathway 8.5, known as the high-emissions scenario, where little climate mitigation is implemented) were extracted on a 10km resolution grid (Danabasoglu et al. 2020). This scenario was chosen as it was the only high-resolution climate scenario available to me within the timeframe of this thesis. Bathymetric data were downloaded at the same 10km resolution from the General Bathymetric Chart of the Oceans (GEBCO) (GEBCO 2023). Environmental data were cropped to the same North Atlantic Ocean 10km grid as the biological data using the “sf” package in R (Pebesma et al. 2018). Correlations between environmental variables were calculated, and those with a correlation of > 0.7 were removed, as recommended by Zuur et al. (2010). In addition, any environmental variables not biologically relevant to baleen whale habitat suitability were also removed (Gomez at al. 2016). The remaining environmental variables in the SDM were mean sea surface temperature (SST), mean sea surface salinity (SSS), mean net primary production (NPP), mean bathymetry or ocean depth (Bathy), slope presence (Slope), and shelf presence (Shelf) (Table 9). SST and SSS both determine the density of water masses and therefore impact nutrient availability and hence maximum prey densities. They also determine environmental conditions relative to the physiological tolerances of whales and their prey (Snell et al. 2023, Buchan et al. 2022) (Table 9). NPP, the amount of net primary production in an ecosystem (Ashton et al. 2012), is important to baleen whale habitat suitability given productivity is closely linked to the availability of their prey through food chain interactions (i.e. the more productivity there is, the more prey availability there is as their prey eat primary producers) (Record et al. 2019) (Table 9). Bathymetric features such as mean ocean depth, and the presence of a slope (a steep drop off of seafloor) or shelf (the edge of a continent that is under the ocean) have been found to have an influence on factors such as nutrient cycling (Porter et al. 2018) which can have direct impacts on baleen whale prey availability (again through food chain interactions, as primary producers need nutrients) and therefore habitat suitability (Record et al. 2019) (Table 9). The same environmental variables were used for all six species. This is because although these whales might use different habitats, from what we currently know about these species prey availability is a key driver of their habitat use, which is directly linked to the chosen variables (Gomez et al. 2020) (Table 9).

Table 9. Environmental variables used in the SDM. Justifications for environmental variable choice are included.

Environmental Variable	Justification
Sea Surface Temperature (SST)	Important for nutrient mixing, prey availability of baleen whales, in addition to physiological tolerance and energetics.
Sea Surface Salinity (SSS)	Important for nutrient mixing, prey availability of baleen whales, in addition to physiological tolerance.
Net Primary Productivity (NPP)	Important for prey availability.
Bathymetry	Important for nutrient mixing, productivity, and therefore prey availability. Additionally important for habitat availability.
Slope	Important for nutrient mixing, productivity, and therefore prey availability.
Shelf	Important for nutrient mixing, productivity, and therefore prey availability.

3.2.2 – Species Distribution Models

A multi-model ensemble species distribution modelling approach was used to generate species distribution models in the Biomod2 package (Thullier et al., 2016) in R.

Three statistical models were used to create the ensemble for each species: a generalized linear model (GLM), a Random Forest (RF) model (using 1000 trees), and a Maximum Entropy (MaxEnt) model. These models were chosen due to the zero-inflated and presence-only nature of the sightings data and the use of multiple environmental predictors (Guisan et al. 2017). These three models have been shown to perform well for presence-only data, with emphasis on RF and MaxEnt models (Valavi et al. 2022). Additionally, GLMs are useful for data that has a lot of zero observations (and is therefore zero-inflated), as in this study (Thullier et al. 2016). RF models use decision trees informed by random subsets of presence and pseudo-absence data to project habitat suitability, whereas MaxEnt models project habitat suitability using the most probable presence estimates given the environmental variables, while avoiding extra assumptions and biases (Thullier et al. 2016). All three model types are able to integrate many environmental predictors, can estimate species distributions based solely on the environmental conditions at the occurrence locations and incorporate pseudo-absences, and can provide information on the environmental variables that provide the most importance to the models (Thullier et al. 2016). Other models such as General Additive Models, and Artificial Neural Networks were excluded to limit computing requirements but will likely be incorporated in future studies.

Individual species presence data and associated environmental data for the entire North Atlantic Ocean were extracted to appropriately determine the niche of each species. The model was created on the larger North Atlantic Ocean extent to (a) more properly characterize the environmental niche (by including data points which span a wider range of environmental conditions), which will (b) help avoid SDM clamping in future projections of the region of interest (Stohlgren et al. 2011). Clamping occurs when environmental data values are beyond the ranges used to create the model (Stohlgren et al. 2011).

Given the lack of true absences, 10,000 randomly distributed pseudo-absences were generated by sampling background environmental data across the region of interest (Guisan et al. 2017). Each model was evaluated by using cross-validation, partitioning the presence data randomly and using 80% to train the model and 20% to test it (Guisan et al. 2017). This cross-validation was repeated five times, and Area Under the Curve (AUC) values, a measure of model performance derived from the area under the Receiver Operating Characteristic (ROC) curve, were calculated for each partition and then averaged, resulting in a mean AUC for each model (Guisan et al. 2017).

Once individual models were run, an ensemble was created by using a weighted-average across models, weighting each according to its mean AUC score. Models with an AUC value of < 0.7 were excluded (Guisan et al. 2017). Environmental variables of importance were calculated for all models using a Mean Decrease Accuracy (MDA) approach, where the models performance excluding one environmental variable at a time is assessed to determine the importance of the missing variable in the accuracy of the models projections (Guisan et al. 2017). The higher the average MDA score, the more important the variable. The individual and ensemble niche models were then restricted to the high-resolution 10 x 10 km regional NWA (not North Atlantic) grid for each species, using both past to present day and projected future environmental data.

Habitat suitability values (HSVs) from the model projections were then extracted for use in the remaining analyses. It is important to note that high habitat suitability does not necessarily imply baleen whale presence, and low habitat suitability does not mean baleen whale absence: they simply refer to the relative suitability of the habitat, and other factors (e.g. biological interactions) may act to constrain or shape the actual distribution of the species.

3.2.3 – Summary of Chapter 2 Study Area, Data Collection and Processing

Using the HSVs generated from the SDM, the average ensemble HSV per 1° by 1° grid cell was calculated for each species, for both time-periods, under the CESM climate scenario using vector geometry methods in QGIS (QGIS 2022). All remaining methods regarding the study area, data collection, and processing (that have not already been clarified in Chapter 3) remain the same as in Chapter 2 methods: please refer back for more details. However, for this chapter, the assumption was made that vessel activity would remain constant overtime.

3.2.4 – Generalized Linear Modelling Approach

The GLM used to explore the relationship between whale presences, vessel activity, and incidents remained the same as described in Chapter 2 methods, but instead of using baleen whale observations as a predictor of baleen whale incidents, the past to present day baleen whale HSVs for each grid cell were used. Spatial autocorrelation was checked for these new models and was non-significant, so an autocovariate term was not included. This analysis was repeated six times, once for each of the baleen whale species. The final model for each species was therefore specified as:

$$NI \sim NB\ (\mu, \theta)$$

$$\log(\mu) = \beta_0 + V_{(\text{t or s or l})} + HSV_i \tag{2}$$

Where μ is the mean, θ is the dispersion parameter, and β_0 is the intercept. Where NI_i is the number of incidents for species *i*, V_t is the total vessel activity, V_s is the small vessel activity, V_l is the large vessel activity, and $HS_{i,j}$ is the habitat suitability for species *i* for the past to present day.

3.2.5 – Relative Incident Risk Hotspots

Incident risk hotspots, areas where the relative risk of a whale and a vessel entering the same grid cell is high (can also be defined by areas of co-occurrence), were calculated for each of the six species following methods developed by Vanderlaan et al. (2008). In this thesis, it is assumed that HSV values can be used to indicate areas where whales are likely to spend time, as opposed to species per unit effort, as used in the Vanderlaan et al. (2008) study. First, the relative risk $W_{i,j,k}$ of a whale of species *i* in time period *j* occupying a grid cell *k* relative to the other *n-1* grid cells present in the study area was calculated as (Vanderlaan et al. 2008):

$$W_{i,j,k} = \frac{HSV_{i,j,k}}{\sum_{k=1}^{n} HSV_{i,j,k}} \tag{3}$$

Second, the relative risk $B_{s,j,k}$ of a vessel of size *s* in time period *j*, occupying a grid cell *k* relative to the other *n-1* grid cells present in the study area was calculated using a similar approach (Vanderlaan et al. 2008). This was calculated for all vessels at all three time-periods and for small and large vessels only under the past to present day:

$$B_{j,k,s} = \frac{V_{j,k,s}}{\sum_{k=1}^{n} V_{j,k,s}} \tag{4}$$

To calculate the relative risk for a whale ($W_{i,j,k}$) encountering a vessel ($B_{j,k,s}$), and therefore a potential incident ($E_{i,j,k,s}$) the previous equations were multiplied for each grid cell (Vanderlaan et al. 2008):

$$E_{i,j,k,s} = W_{i,j,k} \cdot B_{s,j,k} \tag{5}$$

To make results easier for interpretation and comparison, encounter or relative incident risk values were normalized to values ranging from 0-1.

3.2.6 – Overlap Indices and Correlations

The methods used to calculate overlap indices were the same as those described in Chapter 2 methods. However, instead of calculating the overlap between vessel density and baleen whale sightings, the overlaps between vessel density and baleen whale habitat suitability were calculated using the HSVs for all three projected time-periods.

Additionally, the overlap indices and correlations, along with their significance values, were also calculated between the past to present day incident hotspots, and the incident reports to determine if the past to present day incident hotspots reflect where actual incidents are reported and if they share much of the same space in the NWA.

Finally, a simple linear regression was run, where the number of reported incidents at the 1° resolution was modelled as a function of past to present day relative risk of an incident, to determine if the observed incidents were significantly related to relative incident risk. Only grid cells that contained one or more incidents were included in this analysis, as it is not possible to properly establish whether grid cells without incidents were true zeros (i.e. no incidents) or whether there was simply a lack of observation effort. This model was fitted for each individual species and all whales combined. The variance (R^2) was then calculated for each model.

3.3 – Results

3.3.1 – Species Distribution Model

A species distribution model was developed for each species of baleen whale in the NWA. For all species models, at each time-period, the single models had high accuracy (AUC > 0.97) with the RF model being the most accurate (AUC > 0.97) for all species and time-periods, followed by the GLM (AUC > 0.92), and then the MaxEnt model (AUC > 0.90). The proportionally weighted ensemble model outperformed all three of the single models with very high classification accuracy (AUC > 0.98) for all of the baleen whale species and each time-period. Therefore, this model was used going forward.

The single models identified slightly different variables of importance for each species but remained the same across all three time-periods using an MDA approach (Table C5). For all species (with the exception of the humpback whale GLM and MaxEnt models and the NA right whale MaxEnt model), SSS (Figure C1) was identified as the most important environmental variable. The exception species models had SST (Figure C8) as the most important environmental variable. The ensembles all identified SSS as the most important environmental variable, with the exception of the humpback whale, where SST was identified as the most important across all time-periods (Table 10, Table 11, Table C5). The second most important variable was mostly identified as SST, again with the exception of the humpback, where SSS was second, and the blue whale, where bathymetry was second (Table 10, Table 11, Table C5). The third most important variable was NPP for the fin and NA right whale, and bathymetry was third for the humpback, minke, and sei whale (Table 10, Table 11, Table C5). SST was the third most important for the blue whale (Table 10, Table 11, Table C5). The least important variables were consistently shelf and slope, respectively, across all species (Table 10, Table 11, Table C5).

Table 10. Environmental variable ranking. Environmental variables of importance ranked by mean decrease accuracy (MDA) from the ensemble species distribution models for each species of baleen whale. 1 = variable of most importance, 6 = variable of least importance.

Species	SST	SSS	NPP	Bathy	Shelf	Slope
Blue whale	3	1	4	2	5	6
Fin whale	2	1	3	4	5	6
Humpback whale	1	2	4	3	5	6
Minke whale	2	1	4	3	5	6
NA right whale	2	1	3	4	5	6
Sei whale	2	1	4	3	5	6

Table 11. Variable of Importance Rankings by Number of Species. The number of baleen whale species that identified environmental variables of importance for the top three variables of importance, using the MDA scores, from the ensemble species distribution models.

Variable of Importance #1	Number of Baleen Whale Species
SST	1
SSS	5
Variable of Importance #2	
SST	4
SSS	1
Bathy	1
Variable of Importance #3	
SST	1
NPP	2
Bathy	3

3.3.2 – Species Distribution Model Outputs

3.3.2.1 – Past to Present-Day

The Bay of Fundy, Scotian Shelf, Laurentian Channel, Gulf of St. Lawrence, the south-west coast of Newfoundland, and waters near the Flemish Cap were all projected to be areas of high habitat suitability across all baleen whale species (Figure 8a, 9a, 10a, 11a, 12a, 13a). There was especially high habitat suitability in the Gulf of St. Lawrence for blue and NA right whales (Figure 8a, Figure 12a). Blue and fin whales also showed high habitat suitability northwards along the Labrador coast (Figure 8a, 9a). Humpback, NA right, and sei whales showed especially high habitat suitability in the Bay of Fundy (Figure 10a, 12a, 13a). For all six species, the further away from the coast, the less suitable habitat became (Figure 8a, 9a, 10a, 11a, 12a, 13a), with offshore areas predicted to be less suitable across all species.

3.3.2.2 – Near-Future

Under the 2x CO_2 climate scenario, the habitat suitabilities remained similar for the near-future projection (2035-2045) (Figure 8c, 9c, 10c, 11c, 12c, 13c). However, for the blue and fin whale, the Gulf of St. Lawrence was projected to become more suitable, whereas for all other species, it becomes slightly less suitable (Figure 8b, 9b, 10b, 11b, 12b, 13b). The Laurentian Channel and Scotian Shelf was also projected to become more suitable for all species except the NA right, sei whale, and the blue whale within the Laurentian Channel (Figure 8b, 9b, 10b, 11b, 12b, 13b). For all species, offshore areas were projected to become more suitable, except the blue whale (Figure 8b, 9b, 10b, 11b, 12b, 13b).

3.3.2.3 – Mid-Future

For the mid-future (2045-2055) (Figure 8e, 9e, 10e, 11e, 12e, 13e), when compared to the near-future, the Scotian Shelf was projected to become more suitable for blue and sei whales, whereas for other species they are projected to be less suitable (Figure 8d, 9d, 10d, 11d, 12d, 13d). The Gulf of St. Lawrence was projected to be more suitable for all species except the blue and sei whale (Figure 8d, 9d, 10d, 11d, 12d, 13d). The south-west coast of Newfoundland was projected to increase in habitat suitability for humpback whales (Figure 8d, 9d, 10d, 11d, 12d, 13d). There was generally little change in habitat suitability offshore, with the exception of the sei whale, where suitability increases in areas off of Nova Scotia (Figure 8d, 9d, 10d, 11d, 12d, 13d).

When comparing the mid-future to the past to present day, the Gulf of St. Lawrence, Laurentian Channel, Scotian Shelf, and Newfoundland waters were projected to be more suitable for fin and humpback whales, whereas these areas were projected to become generally less suitable for the other species (Figure 8f, 9f, 10f, 11f, 12f, 13f). Offshore areas near the Flemish Cap were projected to get more suitable, whereas other areas east of the Scotian Shelf were projected to have varying degrees of habitat suitability gain and loss for all species (Figure 8f, 9f, 10f, 11f, 12f, 13f).

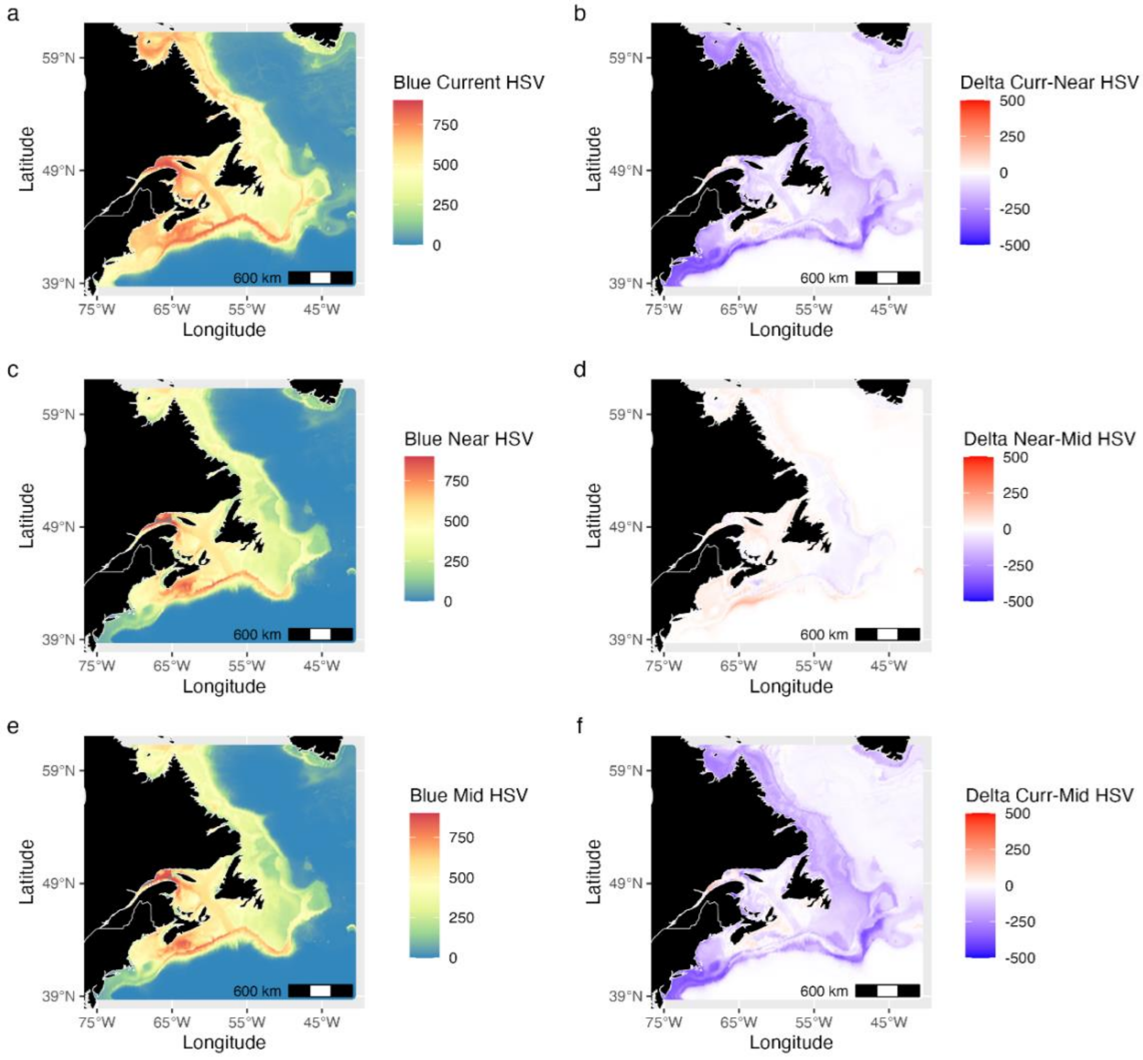

Figure 8. Habitat Suitability Estimates for Blue Whales in the NWA. Derived from an ensemble species distribution model. (a) Past to present-day (1985 – 2015). (b) Change in habitat suitability from the past to present day to near-future. (c) Near-future (2035-2045). (d) Change in habitat suitability from the near to mid-future. (e) Mid-future (2045-2055). (f) Change in habitat suitability from the past to present day to the mid-future. Future projections made under 2x CO_2 climate scenario. Red colours reflect high habitat suitability and blue colours reflect areas with lower habitat suitability.

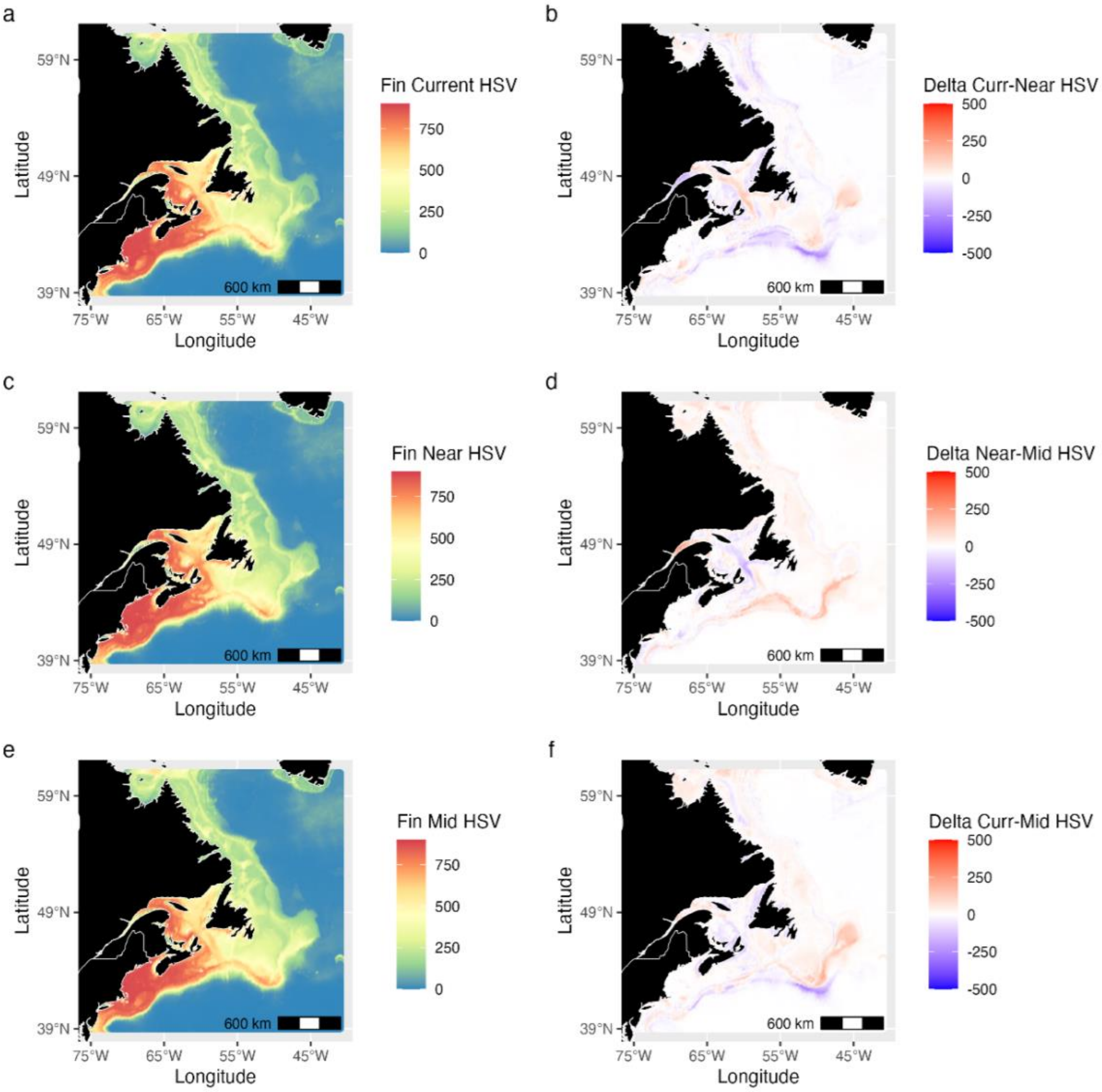

Figure 9. Habitat Suitability Estimates for Fin Whales in the NWA. Derived from an ensemble species distribution model. (a) Past to present-day (1985 – 2015). (b) Change in habitat suitability from the past to present day to near-future. (c) Near-future (2035-2045). (d) Change in habitat suitability from the near to mid-future. (e) Mid-future (2045-2055). (f) Change in habitat suitability from the past to present day to the mid-future. Future projections made under 2x CO_2 climate scenario. Red colours reflect high habitat suitability and blue colours reflect areas with lower habitat suitability.

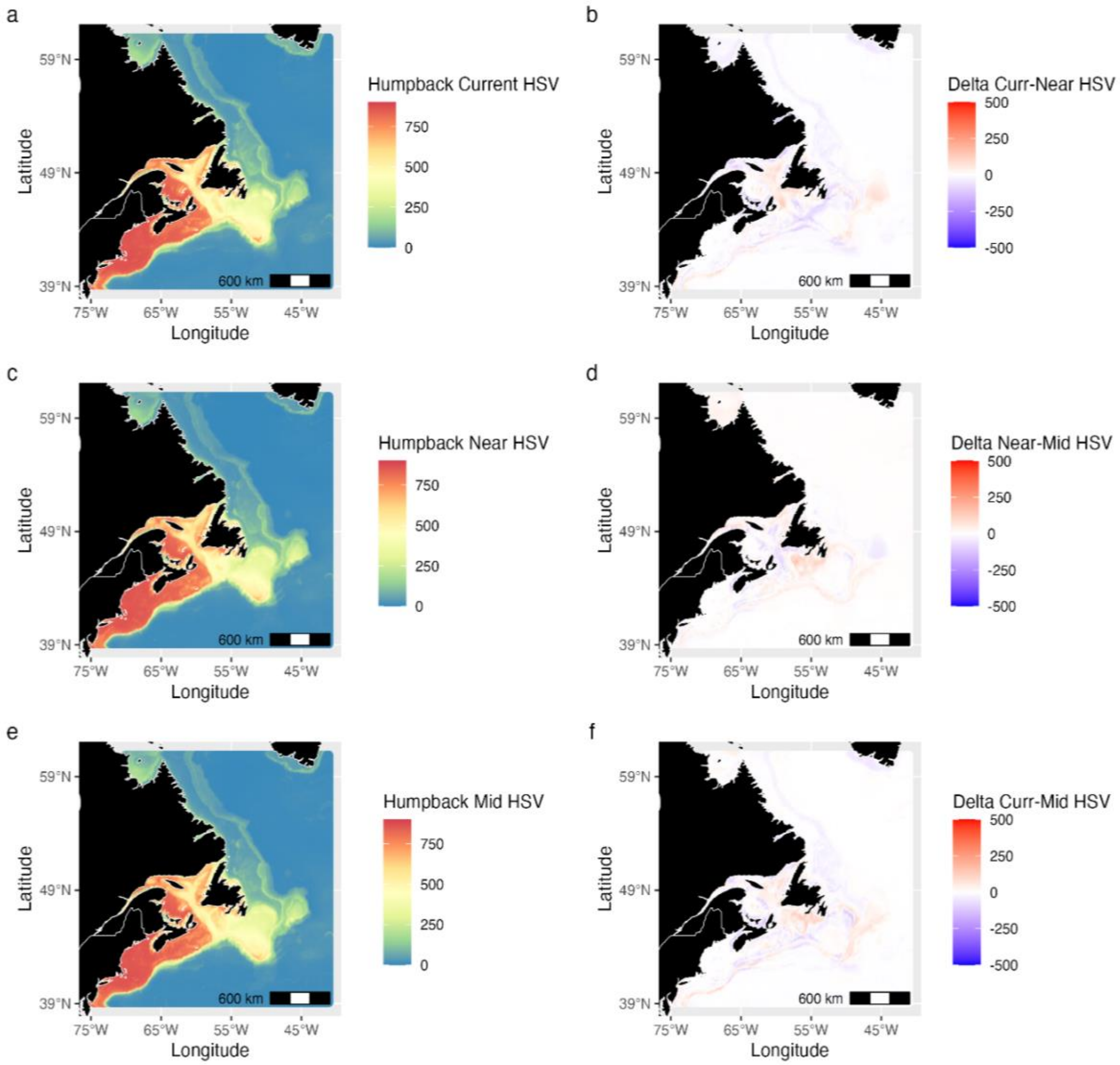

Figure 10. Habitat Suitability Estimates for Humpback Whales in the NWA. Derived from an ensemble species distribution model. (a) Past to present-day (1985 – 2015). (b) Change in habitat suitability from the past to present day to near-future. (c) Near-future (2035-2045). (d) Change in habitat suitability from the near to mid-future. (e) Mid-future (2045-2055). (f) Change in habitat suitability from the past to present day to the mid-future. Future projections made under 2x CO_2 climate scenario. Red colours reflect high habitat suitability and blue colours reflect areas with lower habitat suitability.

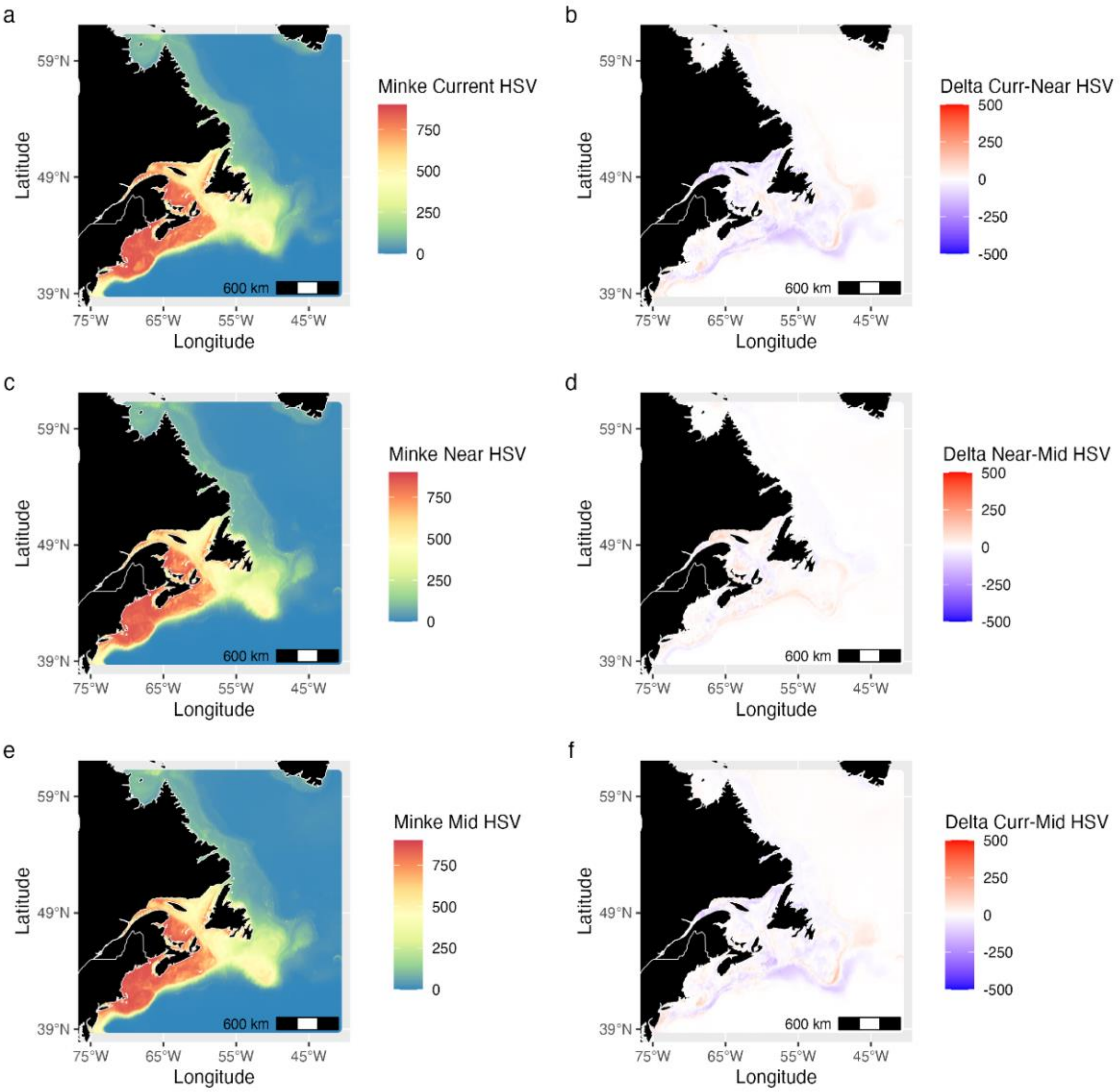

Figure 11. Habitat Suitability Estimates for Minke Whales in the NWA. Derived from an ensemble species distribution model. (a) Past to present-day (1985 – 2015). (b) Change in habitat suitability from the past to present day to near-future. (c) Near-future (2035-2045). (d) Change in habitat suitability from the near to mid-future. (e) Mid-future (2045-2055). (f) Change in habitat suitability from the past to present day to the mid-future. Future projections made under 2x CO_2 climate scenario. Red colours reflect high habitat suitability and blue colours reflect areas with lower habitat suitability.

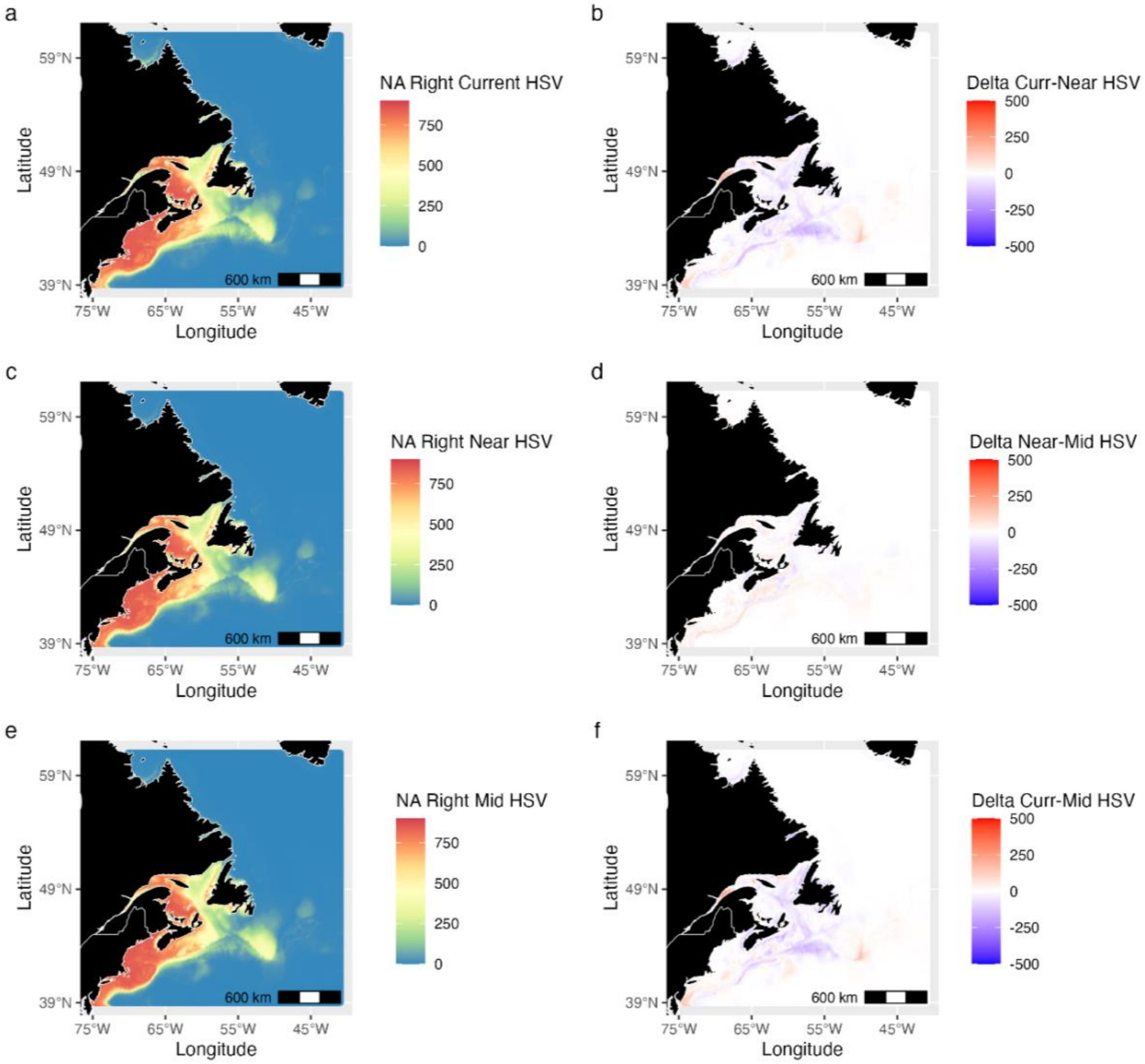

Figure 12. Habitat Suitability Estimates for NA Right Whales in the NWA. Derived from an ensemble species distribution model. (a) Past to present-day (1985 – 2015). (b) Change in habitat suitability from the past to present day to near-future. (c) Near-future (2035-2045). (d) Change in habitat suitability from the near to mid-future. (e) Mid-future (2045-2055). (f) Change in habitat suitability from the past to present day to the mid-future. Future projections made under 2x CO_2 climate scenario. Red colours reflect high habitat suitability and blue colours reflect areas with lower habitat suitability.

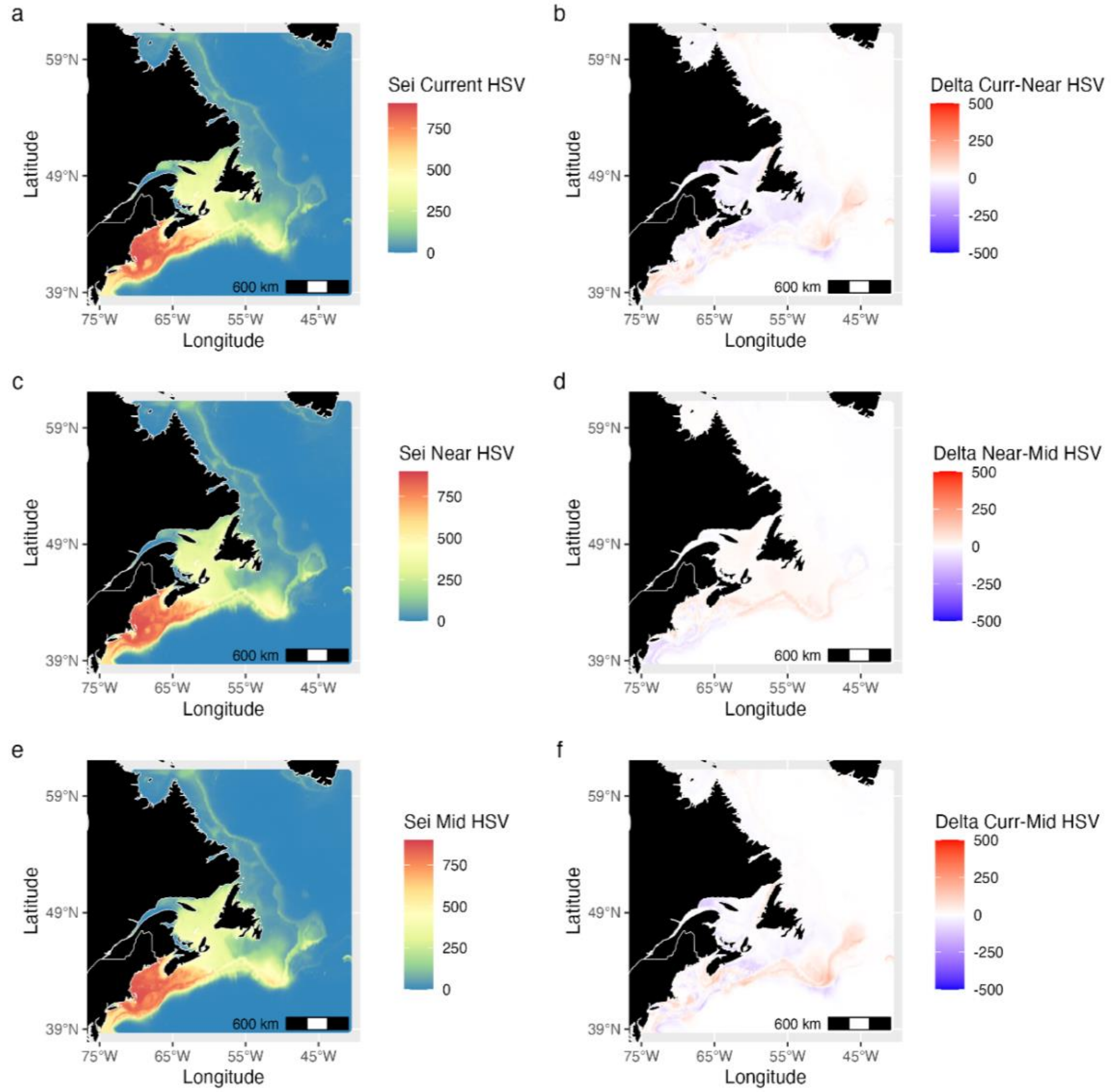

Figure 13. Habitat Suitability Estimates for Sei Whales in the NWA. Derived from an ensemble species distribution model. (a) Past to present-day (1985 – 2015). (b) Change in habitat suitability from the past to present day to near-future. (c) Near-future (2035-2045). (d) Change in habitat suitability from the near to mid-future. (e) Mid-future (2045-2055). (f) Change in habitat suitability from the past to present day to the mid-future. Future projections made under 2x CO_2 climate scenario. Red colours reflect high habitat suitability and blue colours reflect areas with lower habitat suitability.

3.3.3 – Generalized Linear Model Results

Using a negative-binomial generalized linear model, neither habitat suitability nor total vessel activity had a significant relationship to the number of incidents (or incident report effort) for blue or humpback whales (Table 12); however small vessel activity was found to be significant (Table C1). Only total and small vessel activity were found to be significant predictors of fin whale incidents (Table 12, Table C1). For minke and NA right whales, only habitat suitability was found to be a significant predictor of incidents (Table 12). Although total vessel activity was not significant for sei whales, both large and small vessel activity were significant predictors of incidents, along with habitat suitability (Table 12, Table C1). Therefore, total vessel activity was a significant predictor of incidents (or incident report effort) for 1 species, small vessel activity was significant for 4 species, large vessel activity was significant for 1 species, and habitat suitability was significant for 3 species (Table 12, Table C1).

Table 12. Predicting Baleen Whale Incidents Using Habitat Suitability. Estimated regression parameters, standard errors, and P-values for the zero-inflated negative-binomially distributed generalized linear model used to predict baleen whale incidents (see 3.2.3 Chapter 3 Methods). Values are reported for each individual species model.

Species	**Covariate**	**Estimate**	**Standard Error**	**P-Value**
Blue whale	log(Vessel Hours)	0.061	0.460	0.555
	Habitat Suitability	<0.001	0.003	0.893
Fin whale	*log(Vessel Hours)*	*0.808*	*0.362*	*0.027*
	Habitat Suitability	0.949	0.858	0.269
Humpback whale	log(Vessel Hours)	0.268	0.176	0.126
	Habitat Suitability	<0.001	<0.001	0.406
Minke whale	log(Vessel Hours)	0.174	0.172	0.313
	Habitat Suitability	*0.004*	*<0.001*	*<0.001*
NA right whale	log(Vessel Hours)	0.651	0.672	0.332
	Habitat Suitability	*0.009*	*0.001*	*<0.001*
Sei whale	log(Vessel Hours)	<0.001	0.757	0.062
	Habitat Suitability	*0.085*	*0.002*	*0.005*

3.3.4. – Relative Incident Risk Hotspots

3.3.4.1 – Past to Present-Day

Coastal and shelf areas throughout the entire study area, especially within the Bay of Fundy, Gulf of St. Lawrence, the Laurentian Channel, and waters off of St. John's, Newfoundland and Halifax and Yarmouth, Nova Scotia were areas where relative incident risk (or co-occurrence), calculated using methods from Vanderlaan et al. (2008) were projected to be the highest across all species (Figure 14a, 15a, 16a, 17a, 18a, 19a). There was also projected to be an area of high relative incident risk near the Flemish Cap, just east of St. John's, Newfoundland (Figure 14a, 15a, 16a, 17a, 18a, 19a). These areas of high relative risk also apply to the small vessels (Figure 14b, 15b, 16b, 17b, 18b, 19b); however, when looking at only the large vessels, there are fewer obvious areas of relative incident risk; i.e., the risk is more evenly distributed across the region (Figure 14c, 15c, 16c, 17c, 18c, 19c).

3.3.4.2 – Near-Future

Overall, areas where relative incident risk is projected to be high do not differ much from past to present day conditions under climate scenario 2x CO_2 at the near-future for all species. However, slight changes in relative incident risk in some areas are projected for each species (Figure 14a,d, 15a,d, 16a,d, 17a,d, 18a,d, 19a,d). For example, areas where blue whales are projected to be vulnerable to incidents near Yarmouth, Halifax, and St. John's show increases in relative risk over time (Figure 14a,d).

3.3.4.3 – Mid-Future

Changes from the past to present day to mid-future in relative incident risk (for all vessel types) are not very noticeable here (Figure 14d,e, 15d,e, 16d,e, 17d,e, 18d,e, 19d,e). Overall, it is still clear that the main places where relative incident risk is most notable are in Yarmouth, Halifax, St. John's, and Flemish Cap waters (Figure 14e, 15e, 16e, 17e, 18e, 19e). The number of areas where blue whales are vulnerable to incidents seem to increase with time; however, they remain relatively similar for other species (Figure 14d,e).

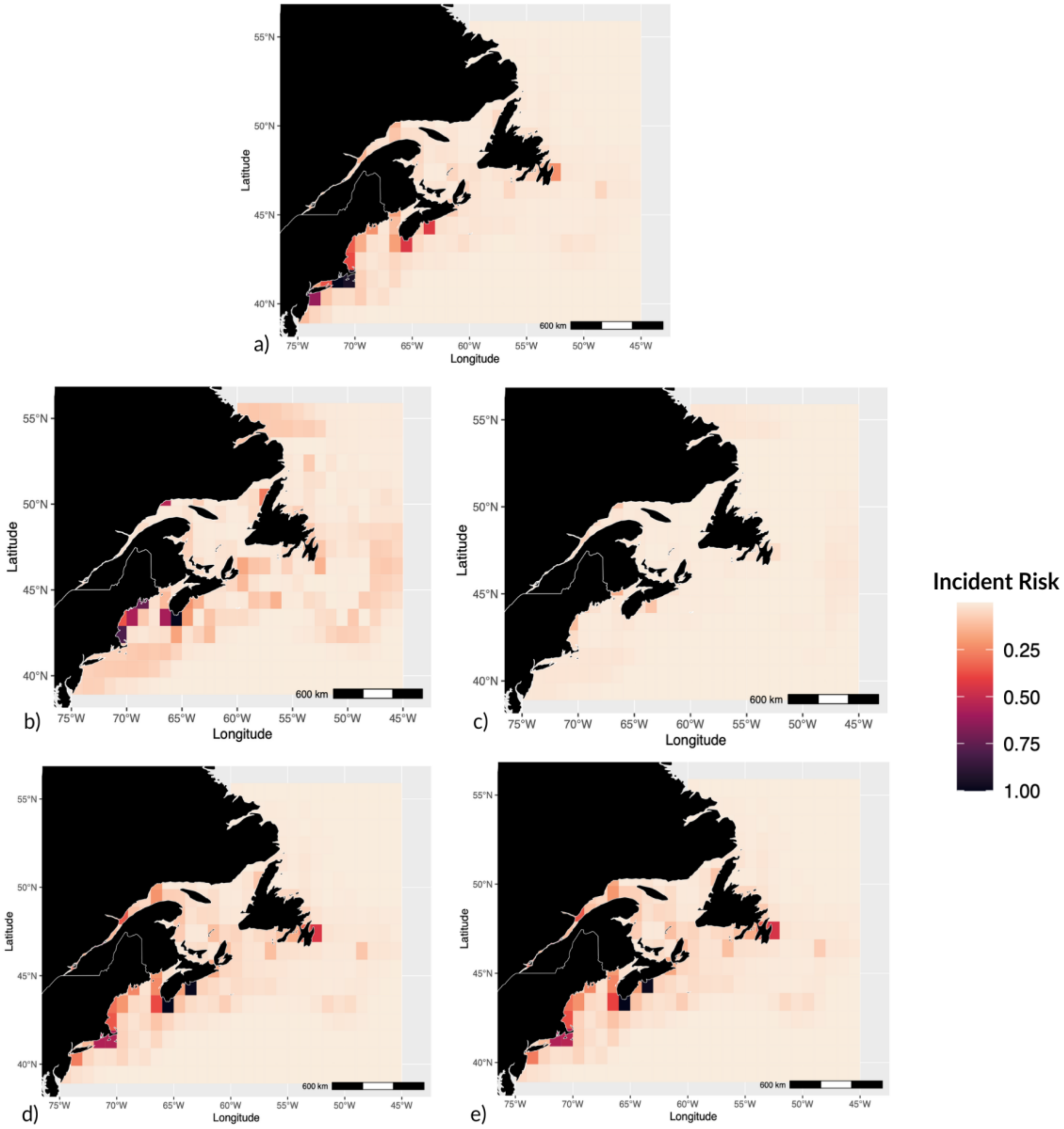

Figure 14. Relative Incident Risk for the Blue Whale. Relative incident risk for the past to present day (1985-2015) for all vessels (a), for small vessels (b), and large vessels (c). For the near-future (2035-2045) (d) and mid-future (2045-2055) (e) under climate scenario 2x CO_2. Dark values indicate where species are most vulnerable to incidents, light values indicate where species are less vulnerable to incidents.

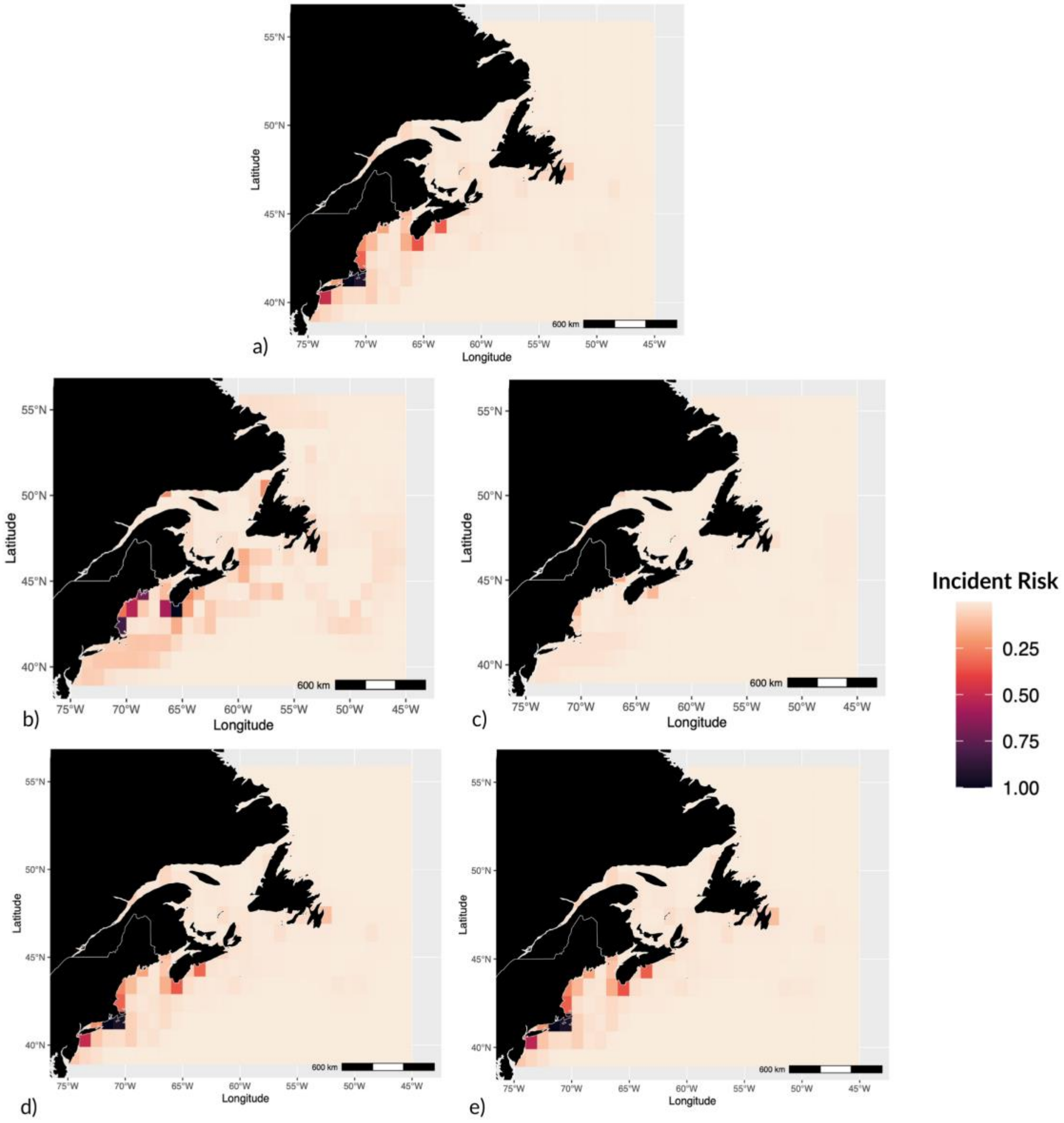

Figure 15. Relative Incident Risk for the Fin Whale. Relative incident risk for the past to present day (1985-2015) for all vessels (a), for small vessels (b), and large vessels (c). For the near-future (2035-2045) (d) and mid-future (2045-2055) (e) under climate scenario 2x CO_2. Dark values indicate where species are most vulnerable to incidents, light values indicate where species are less vulnerable to incidents.

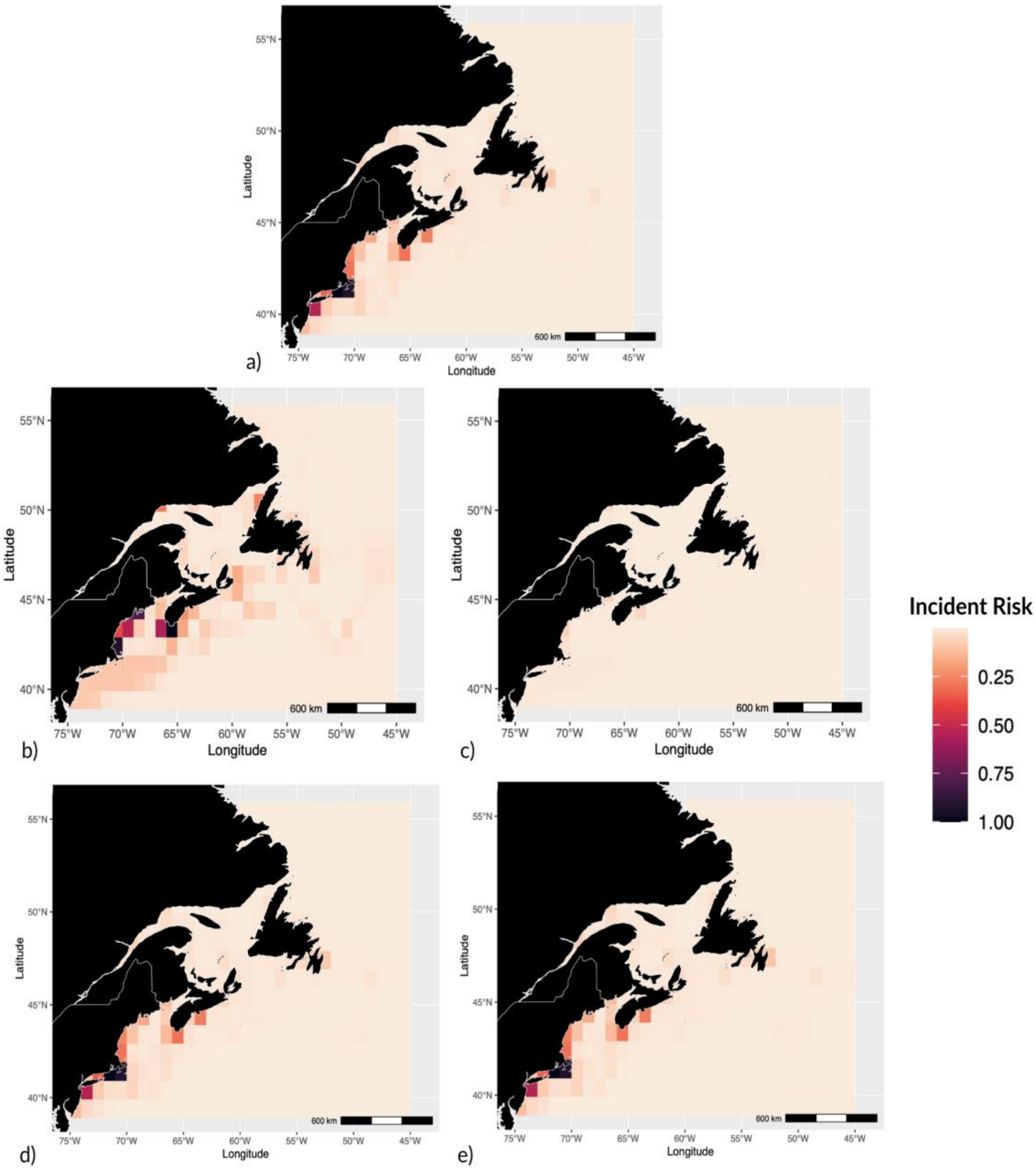

Figure 16. Relative Incident Risk for the Humpback Whale. Relative incident risk for the past to present day (1985-2015) for all vessels (a), for small vessels (b), and large vessels (c). For the near-future (2035-2045) (d) and mid-future (2045-2055) (e) under climate scenario 2x CO_2. Dark values indicate where species are most vulnerable to incidents, light values indicate where species are less vulnerable to incidents.

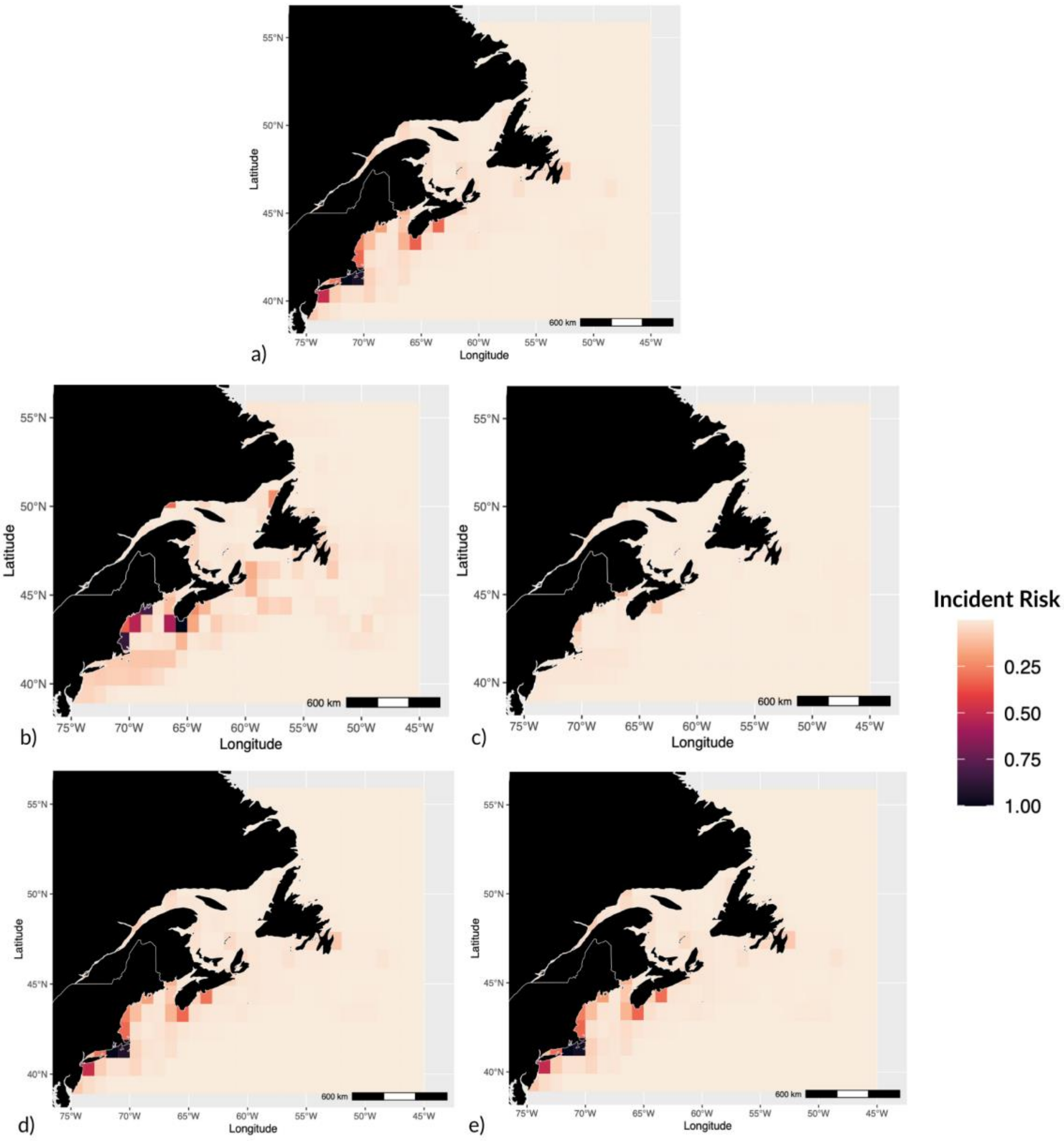

Figure 17. Relative Incident Risk for the Minke Whale. Relative incident risk for the past to present day (1985-2015) for all vessels (a), for small vessels (b), and large vessels (c). For the near-future (2035-2045) (d) and mid-future (2045-2055) (e) under climate scenario 2x CO_2. Dark values indicate where species are most vulnerable to incidents, light values indicate where species are less vulnerable to incidents.

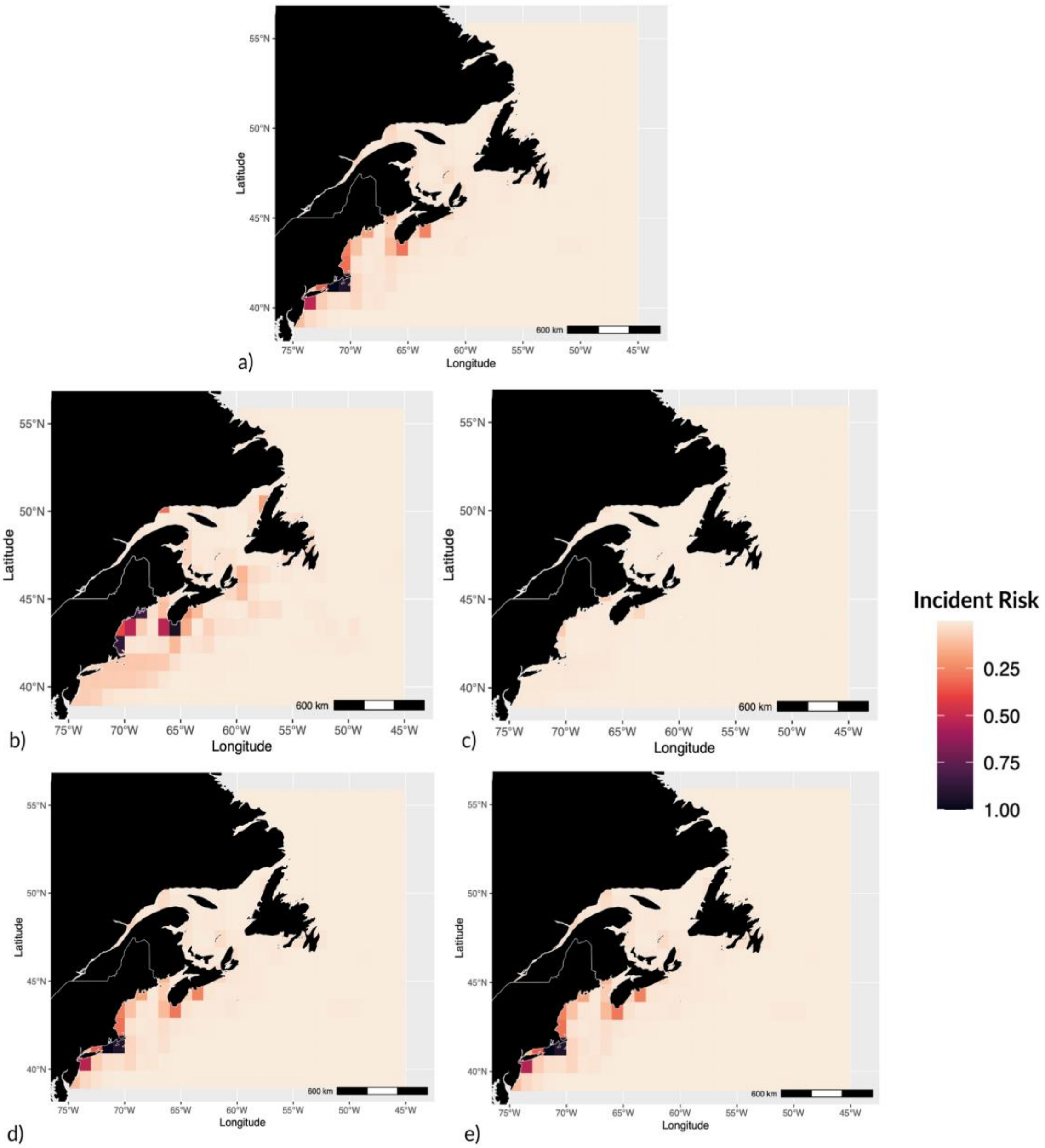

Figure 18. Relative Incident Risk for the NA Right Whale. Relative incident risk for the past to present day (1985-2015) for all vessels (a), for small vessels (b), and large vessels (c). For the near-future (2035-2045) (d) and mid-future (2045-2055) (e) under climate scenario 2x CO_2. Dark values indicate where species are most vulnerable to incidents, light values indicate where species are less vulnerable to incidents.

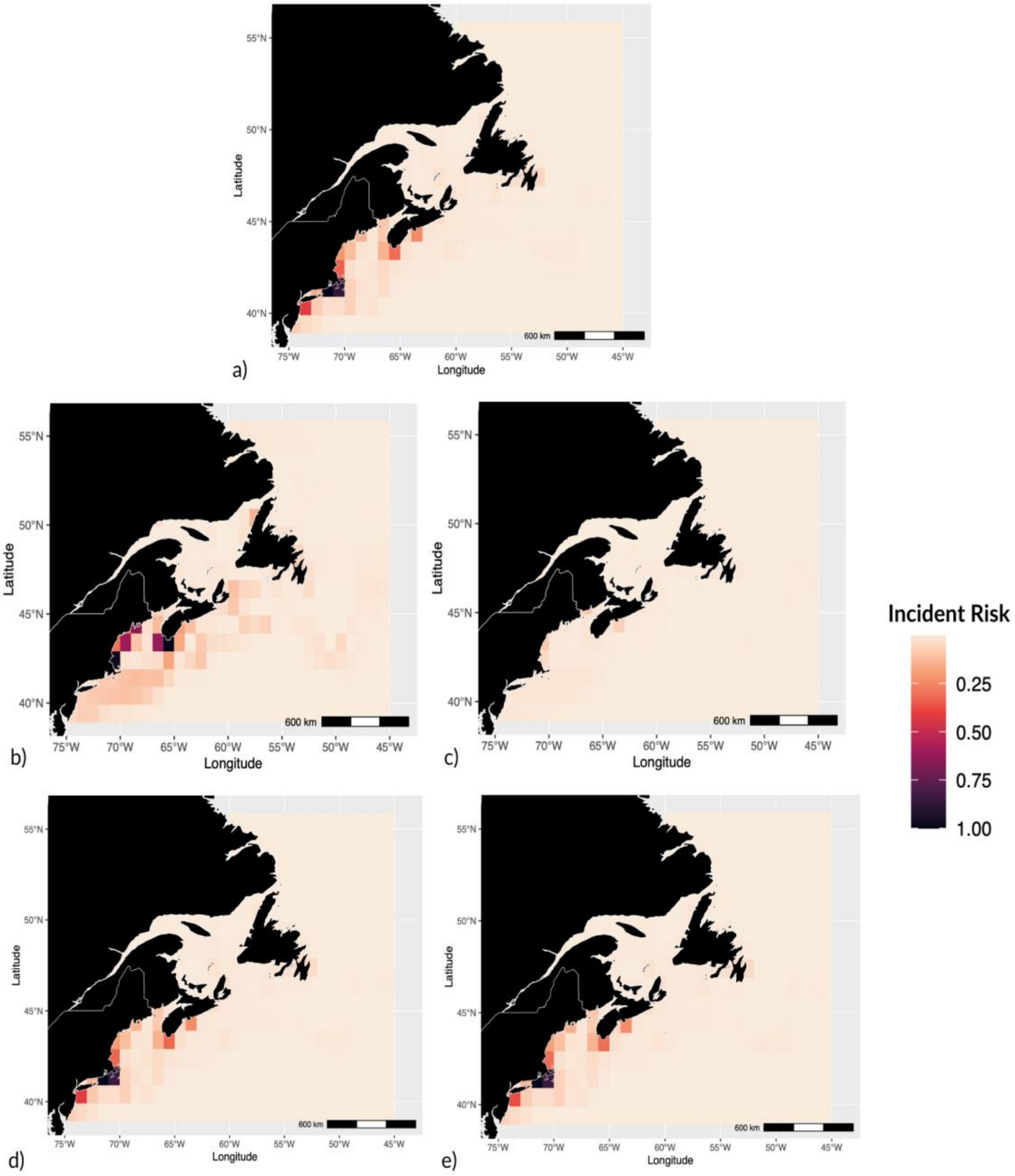

Figure 19. Relative Incident Risk for the Sei Whale. Relative incident risk for the past to present day (1985-2015) for all vessels (a), for small vessels (b), and large vessels (c). For the near-future (2035-2045) (d) and mid-future (2045-2055) (e) under climate scenario 2x CO_2. Dark values indicate where species are most vulnerable to incidents, light values indicate where species are less vulnerable to incidents.

3.3.5 – Overlap Indices and Correlations

3.3.5.1 – Past to Present-Day

Vessel activity (total, small, and large) and areas with high habitat suitability values displayed significant and strong overlap indices indicating they share much of the same space in the NWA for most species of baleen whale (Table 13, Table C2). However, blue and sei whales did not exhibit a significant overlap with large vessel activity (Table C2). These strong overlap values further support the existence of areas where whales are most vulnerable to incidents within the study area (Figure 14a, 15a, 16a, 17a, 18a, 19a). These indices were also found to be significantly and positively correlated for all species at this time-period (Figure C9a,b,c, C10a,b,c, C11a,b,c, C12a,b,c, C13a,b,c, C14a,b,c) (Table 13, Table C2).

Table 13. Overlap Between Vessel Activity and Past to Present-Day Baleen Whale Habitat Suitability. Schoener's D, Warren's Index, and Spearman's Correlation for total vessel activity and baleen whale habitat suitability for the past to present day. Asterisk indicates the reported value was significant at the 0.05 level (the value was outside of the 95% confidence interval bound generated from the simulations - see Methods). Values are reported for each individual species.

Species	Schoener's D	Warren's Index	Spearman's Correlation
Blue whale	0.31*	0.63*	0.45*
Fin whale	0.34*	0.67*	0.60*
Humpback whale	0.38*	0.71*	0.68*
Minke whale	0.37*	0.69*	0.59*
NA right whale	0.38*	0.71*	0.68*
Sei whale	0.35*	0.68*	0.57*

Overlap indexes were also calculated to determine the overlap between the past to present day relative incident risk and the actual incident reports (or incident report effort) (Table 14). Fin, humpback and minke relative incident risk and incident reports showed a strong and significant overlap (Figure 20b,c,d, Figure C15) (Table 14), whereas the other baleen whale species showed a smaller and non-significant overlap between the two variables (Figure 20a,e,f, Figure C15) (Table 14). All species showed a significant and positive Spearman's correlation with the incident reports, with humpback and minke whales showing the strongest correlation (Table 14).

Table 14. Overlap Between Past to Present-Day Relative Incident Risk and Incident Reports. Schoener's D, Warren's Index, and Spearman's Correlation for relative incident risk and baleen whale incident reports for the past to present day. Asterisk indicates the reported value was significant at the 0.05 level (the value was outside of the 95% confidence interval bound generated from the simulations - see Methods). Values are reported for each individual species.

Species	Schoener's D	Warren's Index	Spearman's Correlation
Blue whale	0.08	0.24*	0.23*
Fin whale	0.16*	0.34*	0.32*
Humpback whale	0.17*	0.38*	0.45*
Minke whale	0.21*	0.42*	0.46*
NA right whale	0.10	0.20*	0.29*
Sei whale	0.07	0.21*	0.17*

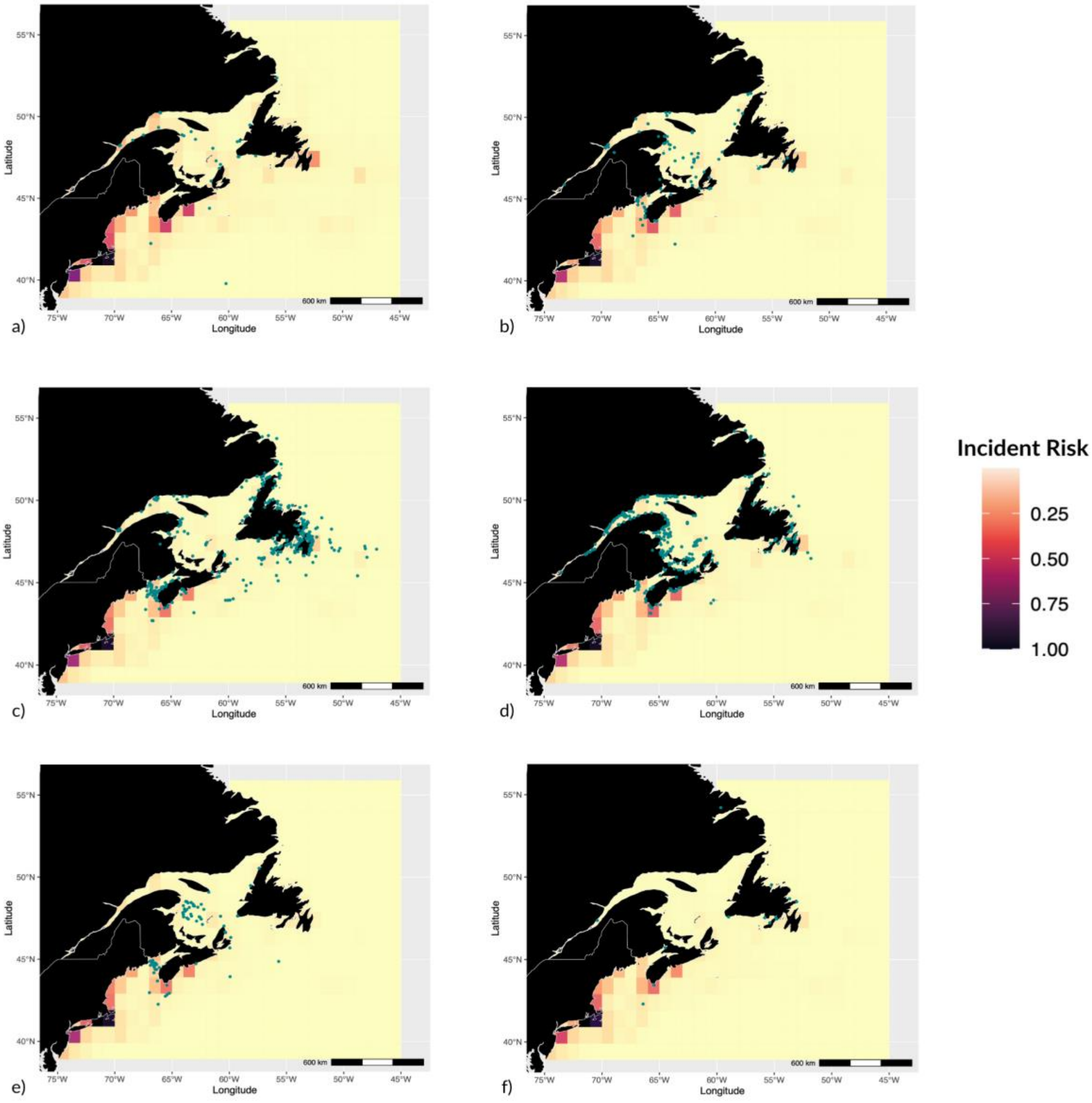

Figure 20. Relative Incident Risk and Incident Reports. Past to present-day relative incident risk for the blue (a), fin (b), humpback (c), minke (d), NA right (e), and sei (f) whale. Incidents from between 2004 and 2019 for each baleen whale have been overlaid using teal dots. Data collected and provided by MARS, Whale Release and Strandings, and Réseau Québécois D'urgences Pour Les Mammifères Marins (MARS 2021).

When the current relative risk of an incident was modelled as a function of the number of reported incidents (or incident report effort), relative incident risk was not a significant predictor of the number of incidents for any individual species (P>0.1) (Table C6). However, the average relative incident risk for all baleen whales combined was a very significant predictor of the number of baleen whale incidents (P<0.0005) (Table C6, Figure C15). All of the models outputs explained a low proportion of the variance, indicating limited explanatory power (Table C6).

3.3.5.2 – Near-Future

In the near-future under the 2x CO_2 climate scenario, the overlap between total, small, and large vessel activity and high baleen whale habitat suitability remains relatively high and significant (Table 13, Table 15). Once again, large vessel activity and blue and sei whale habitat suitability do not share a significant overlap (Table C3). These indexes remain positively and significantly correlated when examining the Spearman's correlation (Figure C9d,e,f, C10d,e,f, C11d,e,f, C12d,e,f, C13d,e,f, C14d,e,f) (Table 15).

Table 15. Overlap Between Vessel Activity and Near-Future Baleen Whale Habitat Suitability. Schoeners D, Warrens Index, and Spearman's Correlation for total vessel activity and baleen whale habitat suitability for the near-future. Asterisk indicates the reported value was significant at the 0.05 level (the value was outside of the 95% confidence interval bound generated from the simulations - see Methods). Values are reported for each individual species.

Species	Schoener's D	Warren's Index	Spearman's Correlation
Blue Whale	0.28*	0.57*	0.42*
Fin Whale	0.34*	0.67*	0.59*
Humpback Whale	0.38*	0.71*	0.41*
Minke Whale	0.38*	0.70*	0.60*
NA Right Whale	0.40*	0.72*	0.70*
Sei Whale	0.34*	0.67*	0.57*

3.3.5.3 – Mid-Future

In the mid-future, the overlap between vessel activity (total, small, and large) and habitat suitability remains relatively similar and significant (Table 16, Table C4). The non-significant overlap between blue and sei whale habitat suitability and large vessel activity is repeated here (Table C4). Like the former time-period (Table 15), the Spearman's Correlations remained significant and positively correlated for all species (Figure C9g,h,i, C10g,h,i, C11g,h,i, C12g,h,i, C13g,h,i, C14g,h,i) (Table 16).

Table 16. Overlap Between Vessel Activity and Mid-Future Baleen Whale Habitat Suitability. Schoeners D, Warrens Index, and Spearman's Correlation for total vessel activity and baleen whale habitat suitability for the mid-future. Asterisk indicates the reported value was significant at the 0.05 level (the value was outside of the 95% confidence interval bound generated from the simulations - see Methods). Values are reported for each individual species.

Species	Schoener's D	Warren's Index	Spearman's Correlation
Blue whale	0.28*	0.57*	0.42*
Fin whale	0.34*	0.67*	0.59*
Humpback whale	0.38*	0.71*	0.68*
Minke whale	0.38*	0.70*	0.60*
NA right whale	0.40*	0.72*	0.70*
Sei whale	0.34*	0.67*	0.57*

3.4 – Discussion

Using ensemble species distribution models, baleen whale habitat suitability was projected to be highest in the Bay of Fundy, off the Scotian Shelf, in the Gulf of St. Lawrence, and in waters near the Flemish Cap, both in the past to present day and for near and mid-future climate change projections. All species shared roughly similar habitat suitabilities. Using these habitat suitability outputs, I determined the areas in the NWA where all species are most vulnerable to incidents to be the Bay of Fundy, Gulf of St. Lawrence, the Laurentian Channel, near St. John's (NL), Halifax (NS), Yarmouth

(NS), and the Flemish Cap. These match well with observed incidents for all species of baleen whale together. Vessel activity for some combinations of size class (especially small) and baleen whale habitat suitability demonstrate significant overlap for all species. The results of this chapter can help to inform baleen whale incident management plans, to better protect all species of baleen whale.

3.4.1 – Species Distribution Models

3.4.1.1 – Model Use and Performance

All single and ensemble models developed in this thesis performed very well at classifying habitat, as indicated by AUC values above 0.9 (Guisan et al. 2017). The ensemble models outperformed the individual models; thus I considered ensemble models most appropriate to further explore incident risk.

3.4.1.2 – Variables of Importance

In the ensemble models, all species except humpback whales had SSS (Figure C1) as the most important environmental variable when projecting habitat suitability. Baleen whale habitat was most suitable in areas with lower salinity (Figures 8-13, Figure C1). This was an unsurprising result, as the Gulf of St. Lawrence was both a very frequented area with lower salinity. There is not much available research linking salinity to baleen whale habitat choice; however, there have been studies that suggest in coastal and shelf areas with less salinity, there is higher productivity (Russell et al. 2023, Da Silva et al.

2017), which could increase prey availability. A contrary conclusion was drawn in a few studies that suggest baleen whales prefer areas of higher salinity due to increased productivity (Gregr and Trites 2001, Buchan et al. 2022). These studies both involved Pacific populations of baleen whales and occurred in smaller regions, so it is possible that the oceanographic and biological mechanisms that occur in those places may be site-specific and do not apply to the NWA and its baleen whale species.

SST (Figure C8) was the second most important environmental variable for most species, which is unsurprising given the impacts of temperature on whale physiology as endotherms, but also its effects on nutrient and prey availability in the NWA. The models projected that areas with cooler water had higher suitability (Figures 8-13, Figure C8). Cooler waters in the NWA tend to be more nutrient-rich due to increased mixing, leading to elevated productivity and, therefore, prey availability (Wooster et al. 1976). The consequences of a change in temperature for prey availability have already been observed in the shifting distribution of NA right whale prey, *Calanus finmarchicus*, from the Bay of Fundy to the Gulf of St. Lawrence, as previously described (Record et al. 2019). Additionally, temperatures that are too high may cause metabolic stress to these animals, though the ecosystem impacts of such changes are only gradually becoming clear (Grady et al. 2019). Similarly, SST was found as the second most important environmental variable in MaxEnt models run by Gomez et al. (2020) for similar baleen whale species in the Scotian and Newfoundland Shelfs. SST was also identified as a very important environmental predictor of Southern right and humpback whale habitat suitability in South African waters, supporting the importance of temperature on prey driven baleen whale habitat choice (Purdon et al. 2020).

The third and fourth most important environmental variables were NPP and bathymetry, depending on species (Figure C9, Figure C10). Given productivity's close connection to baleen whale prey availability and its link to habitat choice through the other environmental variables (such as salinity and SST), one might expect it to be one of the most important variables, which made this ranking interesting. The models projected habitat suitability to be highest in areas where NPP was also the highest (Figures 8-13, Figure C9); however, there was not as much variability in NPP (Figure C9) as in the other environmental variables, which may have resulted in the models not detecting as dramatic of a relationship between NPP and whale presence, and therefore habitat suitability. A similar result was found by Gomez et al. (2020), when chlorophyl (used as a proxy for NPP) was found to be the third most important environmental variable in their baleen whale SDMs for the Scotian and Newfoundland Shelfs. In general, other studies have found that high primary productivity leads to better prey availability and, therefore, likely more suitable baleen whale habitat (Croll et al. 2005, Record et al. 2019).

Bathymetry (Figure C10), the mean depth of the ocean, and other geological features such as the slope and shelf, also have a close connection to productivity, as these features influence the way nutrients are mixed (Burnham et al. 2021). The models I used in this thesis did identify shallower areas along the Scotian shelf as having higher habitat suitability, especially for species that tend to use the open ocean such as blue and fin whales (Figures 8-13, Figure C10). This could be a result of increased mixing in these areas due to geological features (Burnham et al 2021) and therefore, increased productivity and prey availability. Burnham et al. (2021) similarly found that in areas near these geological features, productivity was increased, which then led fin whales to select those areas as habitat. Interestingly, Gomez et al. (2020) found ocean depth to be the most important environmental variable in their MaxEnt SDM, looking at baleen whale habitat suitability in the Soctian and Newfoundland Shelfs. In the South African study mentioned above, the same conclusion was drawn, as bathymetry was again found to be very important for habitat choice of Southern right and humpback whales (Purdon et al. 2020). Additionally, since the most dramatic bathymetric changes in the study area occurred offshore, where there are little to no whale observations, the model likely did not detect strong relationships between the features and whale presence, and therefore habitat suitability. Had there been more offshore observations informing the models used in this thesis, perhaps the bathymetric features may have been found to contribute more to baleen whale habitat suitability.

Although all the environmental variables used in these models may have served as good indicators of baleen whale prey availability, in addition to their individual contributions to whale habitat choice, the model may have been improved had actual data on prey availability been incorporated. Using an environmental variable such as zooplankton concentration (which includes most baleen whale prey species groups such as *Calanus sp.* and krill) as a predictor in this habitat suitability model would likely make for much more accurate projections given how dependent baleen whale distribution and habitat choice is on prey availability.

3.4.1.3 – Past to Present-Day Projected Suitability

High habitat suitability was projected in coastal and shelf areas for all species across all time-periods (Figures 8-13). This coastal and shelf habitat suitability was slightly more variable for blue and fin whales, which had more projected suitable habitat offshore near the Scotian Shelf and slope, and Flemish Cap, compared to other species (Figure 8a, 9a). This coastal and shelf feeding distribution is supported by the literature for all species, especially the blue, fin, humpback, and NA right whale (Davis et al. 2017, Davis et al. 2020, Doniol-Valcroze et al. 2017, Kowarski et al. 2018). This high coastal and shelf habitat suitability may be due to increased prey availability in these regions, especially the Bay of Fundy, Scotian Shelf, and Gulf of St. Lawrence - all areas where important baleen whale feeding grounds exist (Davis et al. 2017, Davis et al. 2020, Doniol-Valcroze et al. 2017, Kowarski et al. 2018, Moors-Murphy et al. 2019). For example, NA right whale habitat suitability was very high in the Gulf of St. Lawrence (Figure 12a), an area that has become an important feeding ground due to available prey in the region (Record et al. 2019). This same area, in addition to areas such as the Laurentian Channel, have also been observed to be an important feeding ground for blue whales (Moors-Murphy et al. 2019), or in other words, an area of high habitat suitability, which was also detected by the model (Figure 8a).

In addition, humpback, fin, and minke whales also showed very high habitat suitability in the Gulf of St. Lawrence, the Bay of Fundy, and off the Scotian shelf (Figure 9a, 10a, 11a). These three species are commonly sighted and acoustically detected in these regions of the NWA, again likely due to prey availability (Davis et al. 2020, Kowarski et al. 2018, Delarue et al. 2022).

Sei whale habitat suitability was highest in the Bay of Fundy and off the Scotian Shelf (Figure 13a). Sei whale presence in this area has been previously confirmed by acoustic research, and can therefore support that it may be a highly suitable region for this whale species (Davis et al. 2020).

In contrast to the other species, the blue, fin, minke, and humpback whale models projected suitable habitat north of Newfoundland, and northwards along the coast of Labrador (Figure 8a,9a,10a). This area has had fewer acoustic detections (Davis et al. 2020) and, according to the sightings data used in this thesis, is not well observed. Therefore, it may be an area of important but less well-known baleen whale habitat. It may be important to keep in mind when interpreting these results, that because most of the sightings that informed the SDMs were made by humans aboard vessels, there is potential the models projected habitat suitability for the vessel use patterns, of which observed the whales. Given the whales were still observed at the respective locations, it still renders the projections valid in terms of whale habitat suitability, however, it does not represent the entire extent of baleen whale habitat suitability in the NWA.

3.4.1.4 – Near and Mid-Future Projected Suitability

The models were also used to project baleen whale habitat suitability into the future across two time-periods, a near-future and a mid-future, using outputs from the CESM ESM forced by a 2x CO_2 scenario (Eyring et al. 2016). Under this climate scenario in the near-future, habitat suitability generally remains similar for all baleen whale species (Figure 8c,e, 9c,e, 10c,e, 11c,e, 12c,e, 13c,e). There are smaller regions of the NWA, such as the Gulf of St. Lawrence, that seem to show increased habitat suitability for blue and fin whales, with the Scotian Shelf having increased habitat suitability for blue, fin, humpback, and minke whales (Figure 8b,c, 9b,c, 10b,c, 11b,c).

These changes in habitat suitability are due to changes in temperature, salinity, and primary production that change the favourability of the habitat for these whales and their prey. The increase in habitat suitability in the Gulf of St. Lawrence and Scotian Shelf for these species corresponds with the decrease in salinity from the past to present day to the near-future in the same region (Figure C11). As previously mentioned, SSS was the most important environmental predictor for most whales, likely due to salinity's effect on productivity and/or the dramatic variability in salinity in relation to whale presence. As the literature suggests, lower salinity may lead to higher productivity, and therefore high prey availability, explaining baleen whale preference for lower salinity, and in this case, the Gulf of St. Lawrence (Figure C1), an area where whales were frequently observed. It is also interesting to note that offshore areas, near and beyond the Scotian Shelf, may become more suitable for all whale species (Figure 8b,c, 9b,c, 10b,c, 11b,c, 12b,c, 13b,c). This increase in offshore habitat suitability could be due to the corresponding changes in temperature, as offshore areas can be seen to be getting cooler, while coastal and shelf areas remain at a similar temperature (Figure C2). Again, SST was the second most (if not first most) important environmental predictor of baleen whale habitat suitability likely as a result of its effect on both whale physiology and thermal niche, and productivity and therefore prey availability. Cool waters make for higher productivity and prey availability, so baleen whale preference for cool water may explain the increase in offshore habitat suitability, given the cooler waters.

These changes in habitat suitability could indicate changes to these whales' distributions through similar mechanisms demonstrated by the increase in preference for the Gulf of St. Lawrence for NA right whales and blue whales, as a result of the increase in prey availability in that region due to increasing temperatures in previously used habitats.

At the mid-future, there are again mostly consistencies with the near-future, but areas such as the Scotian Shelf become slightly more suitable for blue and sei whales, and slightly less suitable for the others (Figure 8d,e, 9d,e, 10d,e, 11d,e, 12d,e, 13d,e). The Gulf of St. Lawrence is likely to become slightly more suitable for all whale species except both the blue and sei whale (Figure 8d,e, 9d,e, 10d,e, 11d,e, 12d,e, 13d,e). Perhaps the sole presence of these whales off the Scotian Shelf, along with the lack of sightings compared to the other species in the Gulf of St. Lawrence and therefore presences in the models, may be contributing to this result. Humpback whales show higher suitability close to the south-west coast of Newfoundland, while sei whales are likely to utilize more offshore areas (Figure 10d,e, 13d,e). These slight changes in habitat suitability are more difficult to interpret as there are no substantial projected changes in SSS, SST, or NPP from the near-future to the mid-future.

Identifying published research on projected baleen whale distribution or habitat suitability under a climate scenario was extremely difficult. When comparing the projected habitat suitabilities in this thesis to projected global baleen whale distributions under a different climate scenario from Aquamaps, both past to present day and future projected Aquamaps distributions are almost opposite to those projected in this model. This, again is likely a result of regional datasets not being used in the Aquamaps model as well as its large scale. These projections do however, identify an offshore distribution for all baleen whales that shifts polewards under climate change conditions (Aquamaps 2019), which agrees with most literature suggesting a similar range shift across multiple taxonomic groups (Kaschner et al. 2011, Meyer-Gutbrod et al. 2018, Cheung et al. 2009, Garcia Molinos et al. 2018, Morley et al. 2018). This poleward shift or offshore distributions are not captured by the models used in this thesis.

Overall, the model outputs and maps in this thesis suggest habitat suitability changes are occurring, which could be a result of changing prey distribution, and will continue to, due to warming waters and other oceanographic factors, especially for NA right, humpback, and blue whales (Pendleton et al. 2012, Record et al. 2019, Fleming et al. 2015, Hazen et al. 2013, Barlow et al. 2020).

3.4.2 – Generalized Linear Model Interpretations

Total or large vessel activity and habitat suitability were not significant predictors of incidents (or incident report effort) at the 1° resolution for blue and humpback whales (Table 12, Table C1). However, small vessel activity was found to be a significant predictor of blue, fin, humpback, and sei whale incidents, which may suggest that there is likely to be a relative increase in incidents (or incident report effort) with an increase in small vessel activity (Table C1). This result is interesting as blue, humpback, fin, and sei whales have been shown to use habitat (Figure 8, 9, 10, 13) where there is also a lot of small vessel presence (Figure A2a), as they both share a more coastal and shelf NWA distribution, especially in the summertime for reasons discussed in the previous chapter

(Davis et al. 2020) (Table C1). This may mean they are most vulnerable to incidents that involve small vessels (keeping the majority of missing vessel size data in mind). Since small vessels and baleen whale habitat suitability share a similar distribution, it is interesting that habitat suitability was not a significant predictor of incidents for these species.

Total vessel activity was found to be a significant predictor of fin whale incidents (or incident report effort) (Table 12), and large vessels were a significant predictor of sei whale incidents (Table C1), which may suggest a relative increase in more types of vessel activity may result in an increase in incidents for these species. This increase in incidents as a result of vessel activity supports the finding that fin and humpback whales are the species at most risk for vessel strikes (Van Waerebeek & Leaper 2008), and for humpbacks, entanglements (Themelis et al. 2016). It is difficult to disentangle why small vessels are not significant predictors of these species incidents given that they both have a strong coastal and shelf presence. Only habitat suitability was found to be a significant predictor of minke, NA right whale, and sei incidents (Table 12), which is interesting as, like the other species, they exist in areas with heavy vessel activity (Figure 11, Figure 12), so one would expect both vessel activity and habitat suitability to be significant predictors of incidents for these species. However, this result does suggest that an increase in habitat suitability for these species may result in a relative increase in incidents (or incident report effort). Minke whales were involved in the second most incidents (Table 4), so these two results suggest that areas of high minke whale habitat suitability should be monitored in order to protect them from incidents more effectively.

3.4.3 – Incident Risk Hotspots

The use of SDM-generated habitat suitability as a potential indicator for baleen whale distributions in baleen whale incident research is becoming more popular (Blondin et al. 2020). For example, when high temporal resolution whale habitat suitability distribution outputs from SDMs are combined with vessel data, estimates of ship strike risk are actually improved (Blondin et al. 2020).

Under past to present day ocean conditions, all whale species are projected to be most vulnerable to incidents within the Bay of Fundy, Gulf of St. Lawrence, the Laurentian Channel, near St. John's, Newfoundland, Halifax, Nova Scotia, Yarmouth, Nova Scotia, and the Flemish Cap (Figure 14a, 15a, 16a, 17a, 18a, 19a). These areas also tend to reflect where a majority of actual incidents are reported (Figure 20). These areas of relative incident risk correspond with areas of both highest population and fishing vessel density in the Canadian Maritimes (Canada Population 2022, DFO 2021), which provides further support for the idea that whales present in these areas are most vulnerable to incidents. The Bay of Fundy has previously been suggested as an area where vessel strikes are probable for NA right whales (Vanderlaan et al. 2008), supporting this study's results (Figure 18a) and can be reinforced by the fact that many of the NA right whale incidents were reported in the Bay of Fundy (Figure 20). Similar studies of baleen whale and vessel strike risk in other regions also found that risk was also highest near areas of high population and fishing activity density (Bendriñana-Romano et al. 2021, Nichol et al. 2017).

Presently, there are projected to be a lot more areas where whales are more vulnerable to incidents caused by small vessels than large vessels for all species, across the entire study area (Figure 14b, 15b, 16b, 17b, 18b, 19b). This finding, in conjunction with the findings of the generalized linear model (Table C1), which suggest an increase in incidents with an increase in small vessel activity for most baleen whale species, can indicate that special focus needs to be put on small vessel activity when it comes to baleen whale protection. However, it is still important to keep in mind that there is much missing vessel size data, which may change the relationship between vessel size and relative incident risk.

The locations of incident hotspots did not change much from past to present day ocean conditions to the near and mid-future conditions, due to the relatively small changes in habitat suitability. Unfortunately, areas where blue whales are found to be most vulnerable to incidents are projected to increase in relative risk in some areas of high fishing and population density over time (Figure 14a,d,e) which is especially concerning given the extreme vulnerability this species is already facing.

Overall, areas where whales are most vulnerable to incidents exist throughout the NWA and are similar for all species of baleen whale (Figures 14-19). This conclusion provides much impetus to put in place more robust incident mitigation strategies in these areas to protect all species of baleen whale.

3.4.4 – Overlap Indexes and Correlations

In all cases where the GLM predicted small vessel activity as a significant predictor of baleen whale incidents (or incident report effort) (Table C1), the overlap indices also determined both a significant overlap and a significant positive correlation

(Table C2), demonstrating where there is more small vessel activity, there is high habitat suitability. This finding helps provide evidence that small vessels contribute to the existence of incident hotspots, keeping in mind the missing vessel size data.

The incident risk hotspots do share much of the same space as the actual incident reports for only fin, humpback, and minke whales (Figure 20b,c,d). This is likely due to the fact that these are the three species with the highest number of incident reports (Table 4). However, it is important to keep in mind that the majority of incident reports exist in areas where population density is highest and coastline is most accessible, which likely caused some bias in where incident reports are located (Nemiroff et al. 2010).

Relative incident risk was a positive but non-significant predictor of individual species incident reports. However, it predicted incident reports for all baleen whales taken together (Table C6, Figure C15). This result was likely influenced by the larger sample size, and therefore stronger statistical power of the summed incidents; however this result also suggests that the calculated relative incident risk may be a reasonable indicator of where incidents are currently occurring in the NWA, and could therefore be further developed to be incorporated into baleen whale incident management. It is also important to keep in mind that only ~10% of the variance of the model residuals were explained by the full model, giving this result weak explanatory power. This analysis would be further improved if more data on individual species incidents was collected to increase sample sizes. It is difficult to interpret why the overlap indices detected a significant overlap for the individual species, where the GLM did not. This may indicate that one of the two analyses may not be accounting for an important factor, whether it be biological, physical, or statistical, that is influencing the degree to which relative incident risk and the number of incidents in the NWA are related to one another.

A more thorough breakdown and interpretation of these results can be found in Appendix B: Chapter 3 Overlap Indexes and Correlations.

3.4.5 – Chapter 3 Caveats and Future Directions

There are some limitations of this thesis, including the presence of a potential sampling bias in the opportunistic sightings data as well as the incident report data, as sampling effort data was not available. This will have resulted in missing baleen whale sightings and incidents outside of the sampled areas (Gomez et al. 2020). In order to mitigate the sampling bias in the opportunistic sightings, habitat suitability outputs from a high resolution (10km) regional species distribution models were used (Gomez et al. 2020).

However, due to the fact that this model was informed primarily by coastal and shelf opportunistic sightings, this may have led to underpredictions of habitat suitability for offshore, and in particular oceanic, areas. This impact is likely to have been exacerbated by including shelf and slope variables, and is likely to explain the low habitat suitability seen offshore, near the Scotian Shelf and slope, for all of the whale species (Figures 8-13). Therefore, it is recommended that interpretations of offshore habitat suitability be taken cautiously, and greater focus should be put on the coastal and shelf and shelf habitat suitability's. These models and their interpretations may also be more accurate if developed with only summer sightings data, as this is when most whales are observed most coastally and along the shelf (Davis et al. 2020), making the outputs most valuable for summer months. In order to improve this bias, there needs to be more sightings effort offshore. However, this is both difficult and expensive due to the amount of time, trained personnel, and equipment this may require. It may also be important to note that although whale sightings data were used to inform the model derived habitat suitability's, most of the sightings were made aboard vessels, by humans, so one may argue that the projected habitat suitability may not just represent baleen whale habitat suitability, but human vessel use suitability. This is something that should be kept in mind when using and interpreting the habitat suitabilities, especially within the relative incident risk hotspots. Nonetheless, the observational data sources used here are the only available data that can be used to study baleen whale distribution and incident risk for this region. This thesis demonstrates how this available data can be used, its limitations, and how it might be improved.

This model could also have been improved by the incorporation of baleen whale prey distribution as an environmental predictor of habitat suitability. Given how dependent baleen whale habitat use is on prey distribution and availability, a layer such as zooplankton concentration would likely improve the model outputs. Additionally, other data sources such as acoustic detections, historical whaling data, or restricted DFO survey data could be included to increase the knowledge of species presences, to inform the models.

Additionally, as indicated in the previous chapter, there may have been some discrepancy in where an incident took place versus where it was reported due to ocean currents drifting deceased, injured, or unwell animals (Nemiroff et al. 2010, Wimmer et al. 2021). In an attempt to account for this potential bias, a larger resolution grid was used to account for any shift in incident location.

I also made the assumption that habitat suitability can be utilised as a proxy for whale density when calculating relative incident risk. This may have caused relative incident risk to not be as robust, had effort correct whale density data been used, because as previously mentioned, habitat suitability does not necessarily reflect baleen whale distribution, but just areas that would be suitable for whales to exist in (or again human vessel use suitability).

Importantly, vessel activity was assumed to remain the same across all time-periods. Although potentially true for main shipping channels and transport routes in the NWA, it is possible that fishing activity may change its distribution over time as a result of changes in stock abundance and distribution. It would also be interesting to see if and how vessel activity could be modelled into the future in addition to baleen whale distributions, and determine how this may change incident risk. Additionally, the uncertainty regarding missing vessel size data continues to apply throughout this chapter, as if all the vessel activity data was size informed, perhaps the relationships between small and large vessel activity and baleen whale habitat suitability may be different. Again, this lack of vessel size metadata calls for proper AIS use enforcement by DFO and TC.

Finally, this chapter was carried out using environmental data from only one climate scenario, when numerous scenarios exist that could be explored in future work. Additionally, it was only projected into the future by a maximum of 33 years. Repeating these analyses using projected environmental data from multiple climate scenarios (that also project further into the future) and comparing them would make this chapter more robust in terms of climate change and its impact on baleen whale habitat suitability and incident risk.

3.4.6 – Conclusions

My research demonstrates that the baleen whales present in the NWA are projected to share similar areas of high habitat suitability, even under changing ocean conditions due to climate change. This shared habitat suitability in combination with NWA vessel activity indicates that areas such as coastal Halifax and Yarmouth, Nova Scotia, St. John's, Newfoundland and the Flemish Cap are regions where all species of baleen whale may be vulnerable to incidents even under climate change conditions. The findings in this chapter may be helpful for the development of baleen whale incident management plans, and can help provide information to enhance protection to more species of baleen whale now and into the future. This chapter also provides evidence of the need to continuously update existing baleen whale incident management plans to reflect changes in baleen whale habitat use due to climate change.

Chapter 4 – Conclusion

4.1 – Management Implications and Recommendations

This study suggests that all baleen whale species are at risk of being involved in harmful and potentially lethal incidents in the NWA and require some level of protection. A special emphasis should be put on species listed under SARA and COSEWIC given their low population numbers. This being said, one should not discount the immense ecological significance and contributions of the species with larger populations, such as humpback and minke whales, rendering their protection essential as well (Wimmer et al. 2021).

Areas where baleen whale incidents are likely are prevalent throughout densely populated areas of the NWA and may often involve smaller vessels. Additionally, areas where whales are most vulnerable to incidents are not projected to substantially change with climate change under the 2xCO2 climate scenario by 2055, despite shifting baleen whale habitat suitability. This could change, however, as prey distribution shift further, forcing whales into new areas (Record et al. 2019).

The current incident management strategies that exist in regions where areas of high relative incident risk occur for all baleen whales (Figures 14-19) include distance-keeping measures (Fisheries Act 1985) and gear-retrieval initiatives (DFO 2022a). For the NA right whale only, temporary mandatory and voluntary vessel slow-down measures (TC 2021) and targeted time-area fisheries closures exist (DFO 2022a) based on sightings of individuals during the fishing season. To reiterate, these management strategies only specifically address one species of baleen whale when three other species are also listed under SARA or COSEWIC as endangered or special concern (DFO 2022a). Moreover, this study and a review of available incident reports (Wimmer et al. 2021) suggest that all species of baleen whale are vulnerable to incidents at high-traffic locations. Humpbacks and fin whales, for example, are at highest risk of being involved in a vessel strike (Van Waerebeek & Leaper 2008, Nichol et al. 2017), but have no incident management strategies directed specifically to them in the region.

This study identifies areas of the NWA where mitigation efforts may be particularly important, including waters near Halifax and Yarmouth, Nova Scotia, St. John's, Newfoundland and the Flemish Cap. As both whale distribution and vessel activity may be changing into the future, effective whale protection measures need to adapt dynamically, match changes in human behaviour to changes in baleen whale behaviour. This is already being done for the NA right whale, but needs to be implemented for other vulnerable baleen whale species. It is understood that implementing similar management strategies for all whales would be a significant financial endeavour, and unrealistic from a stakeholder perspective, so it is my recommendation to find a way to use the NA right whale management strategies to protect more species of whale, bundling their protection. One low-cost, implementable regional, and dynamic management strategy to protect whales of all species could include speed restrictions or re-rerouting measures in the largely whale populated summer months for all vessels (including both small and large vessels), especially in areas where whale habitat is most suitable for all species, such as the Halifax (and the Scotian Shelf), Yarmouth (and the Bay of Fundy), Gulf of St. Lawrence (which is already in practice), St. John's, and the Flemish Cap. These regions could become seasonal management areas, which address both the NA right whale, and the remaining baleen whale species. Additionally, a reduction in the number of vessels that are allowed to be in those areas at once, may be helpful, however, a lot more difficult to implement (Gende et al. 2019). Ideally, (but again, unrealistically) when an observation of any large baleen whale of these species takes place, more specific and extensive regulations could be implemented, such as stricter speed restrictions, fishery closures, strict distance-keeping restrictions, and possibly further restrictions on vessel density (Gende et al. 2019). This being said, it is also important to keep in mind that the existing fishery closures that address NA right whale conservation, may actually benefit other whale species, however there is little existing research or data to show this yet. More research on the impacts of these measures on other species of baleen whale is necessary, especially in order to design management plans for the remaining species of whale.

In addition to these strategies, other measures such as the use of whale-safe fishing gear, increasing onboard whale observers, real-time AIS and radio whale observation signalling, and increased vessel strike, entanglement and whale ecology education in the NWA fishing and vessel communities may also help to prevent all whales from being involved in incidents (Van Der Hoop et al. 2013).

This study also suggests that small vessel activity may be important to consider in baleen whale incidents. This evidence is extremely important given the fact that all sizes of motorized vessel have the ability to injure, or be lethal to a whale, although it may be more commonly thought that only large vessels are able to cause harm (Kelley et al. 2020). This provides a strong impetus for improved regulation of smaller vessels in areas of high whale habitat suitability. As it currently stands, vessels only greater than 20 m must slow down in TC designated slow-down areas (TC 2021), areas that have high habitat suitability both in this thesis (Figures 8-13) and previous research (Gomez et al. 2016). This regulation excludes the majority of small vessels, and needs to be updated in order to effectively protect baleen whales.

In terms of incident reports, given how large baleen whales are, and depending on how accessible the incident is, a large response usually occurs, which includes a team of professionals, heavy machinery, safety equipment, necropsy materials, boats, and anything else that might be necessary (Wimmer et al. 2021). It is essential that organizations such as MARS have access to additional resources such as increased finances, personnel, and equipment to better enable these response organizations to study baleen whale incidents. This would ultimately help to better understand the negative interactions between humans and baleen whales, and therefore help implement more effective incident mitigation policies.

Finally, this research provides support to the idea that current mitigation efforts need to be designed with all species in mind in order to be more effective at protecting baleen whales (Koubrak et al. 2022).

4.2 – Final Thoughts

Knowledge on baleen whale distributions, habitat use and what drives it in the NWA, how it is changing over time, and how it interacts with human uses of the ocean needs to be greatly improved in order for us to protect them. This understanding begins with making the most of the available data, while acknowledging its limitations. In this thesis, I combined multiple sources of data and developed baleen whale habitat suitability projections to create a baseline for where incidents may occur for all baleen whales in the past to present day and under a changing climate. It is my hope that the findings of this study, along with their respective management implications, can help inform and improve baleen whale conservation moving forward for all species of baleen whale, and help fill existing knowledge gaps in this important area of study. Effective management of baleen whale and human interactions is essential not only for these whales' survival, but the well-being of our oceans.

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Appendix A – Chapter 2 Supplementary Figures and Tables

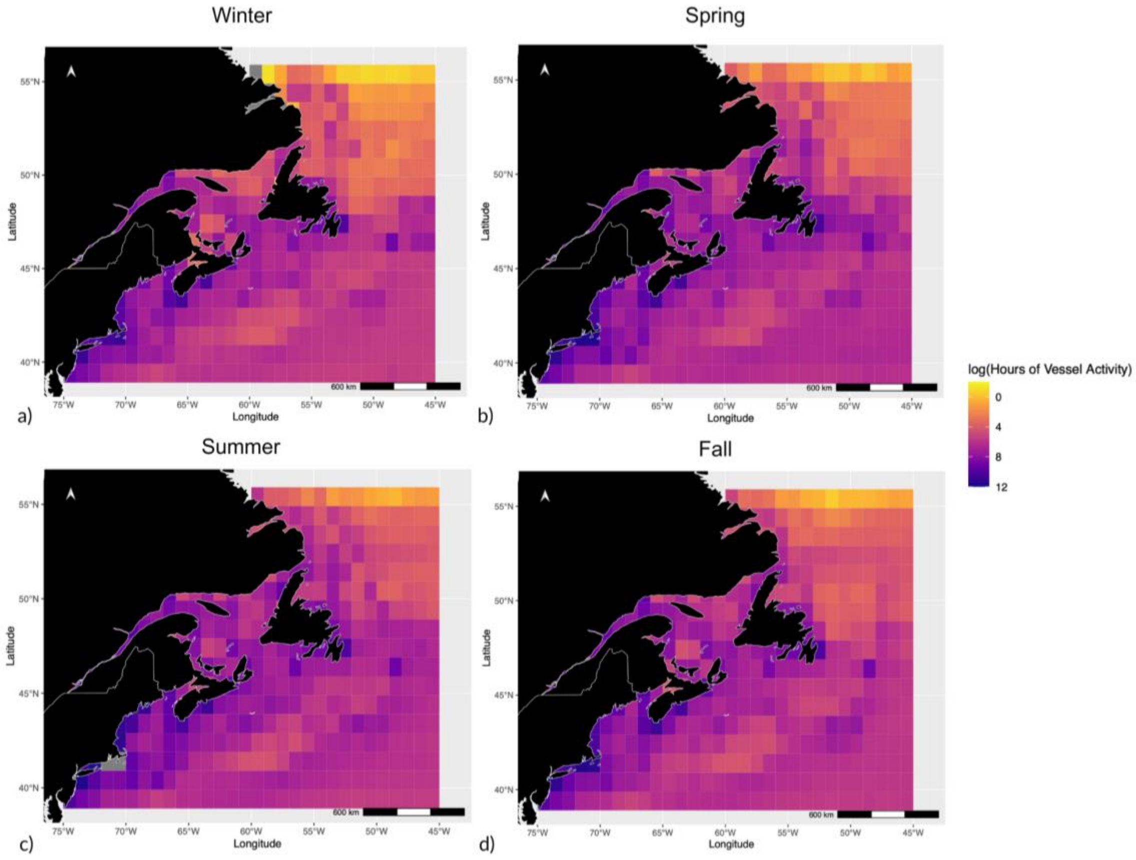

Figure A1. Average Vessel activity per Season. Average of vessel activity per 1° grid cell between 2017 and 2021 in winter (a), spring (b), summer (c), and fall (d) within the study area. Data derived from AIS technology collected and provided by Global Fishing Watch (GFW 2022).

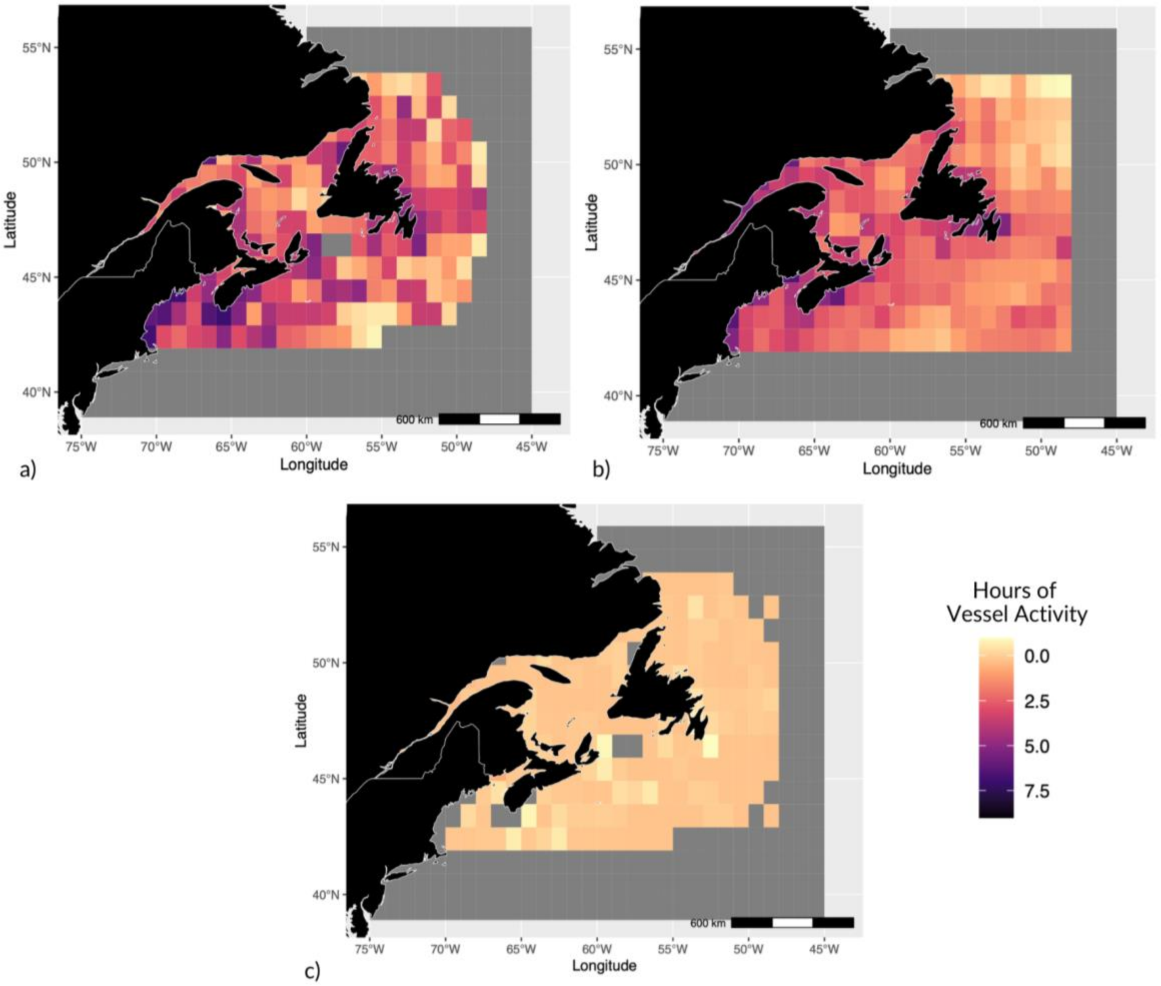

Figure A2. Average Vessel Activity per Size. Areas where small vessel (a) and large vessel (b) activity is most prominent as shown by the amount of hours of vessel activity per 1° grid cell. Areas where the biggest discrepancies in small and large vessel activity distribution is also shown (c). Data derived from AIS technology collected and provided by Global Fishing Watch (GFW 2022).

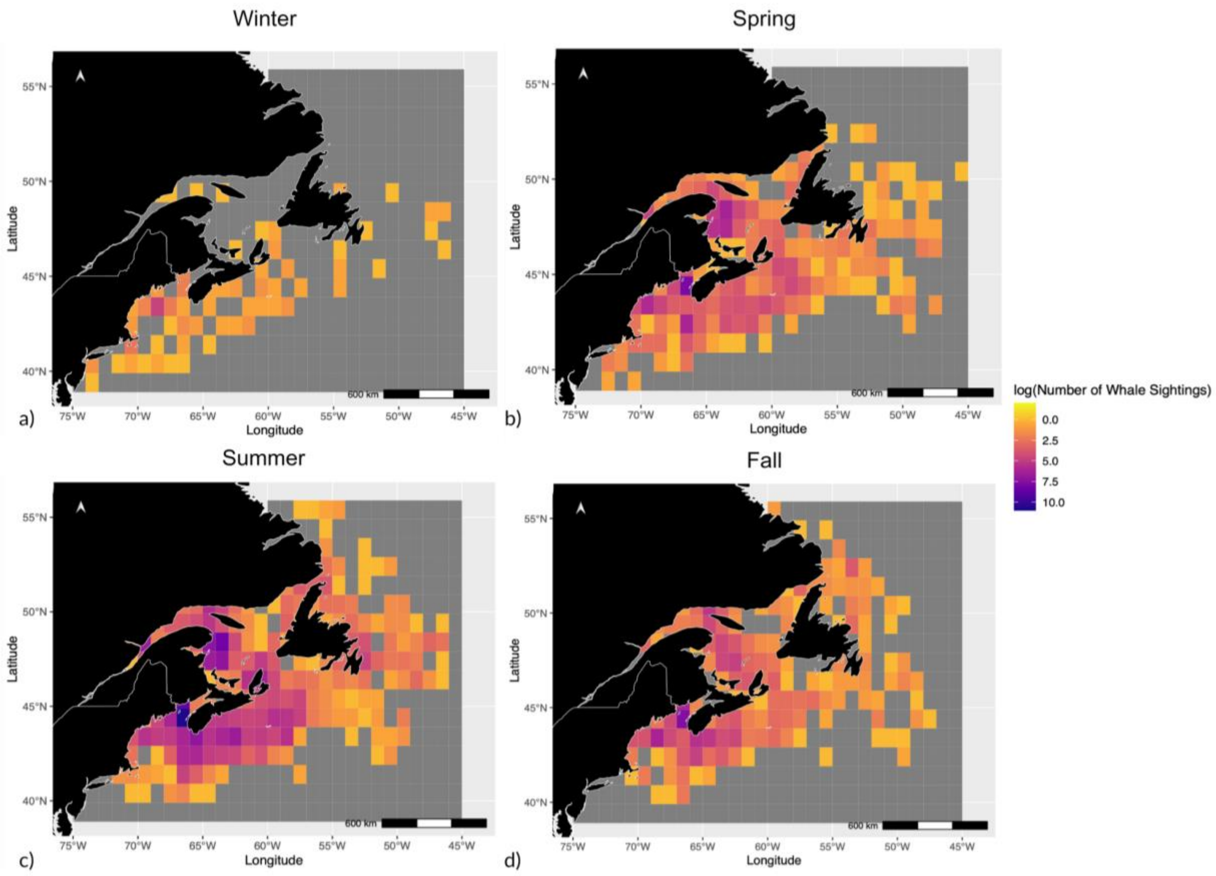

Figure A3. Baleen Whale Sightings per Season. The total number of baleen whale sightings per 1° grid cell in winter (a), spring (b), summer (c), and fall (d) between 1963 and 2021 within the study area, on the logarithmic scale. Data collected and provided by DFO (Team Whale 2021), the North Atlantic Right Whale Consortium (NARWC) (NARWC 2021), Environment Canada Seabirds at Sea (ECSAS) (Canadian Wildlife Service 2021), the Whitehead Lab (Team Whale 2021), and the Réseau D'observation de Mammifères Marins (ROMM) (ROMM 2015, ROMM 2017).

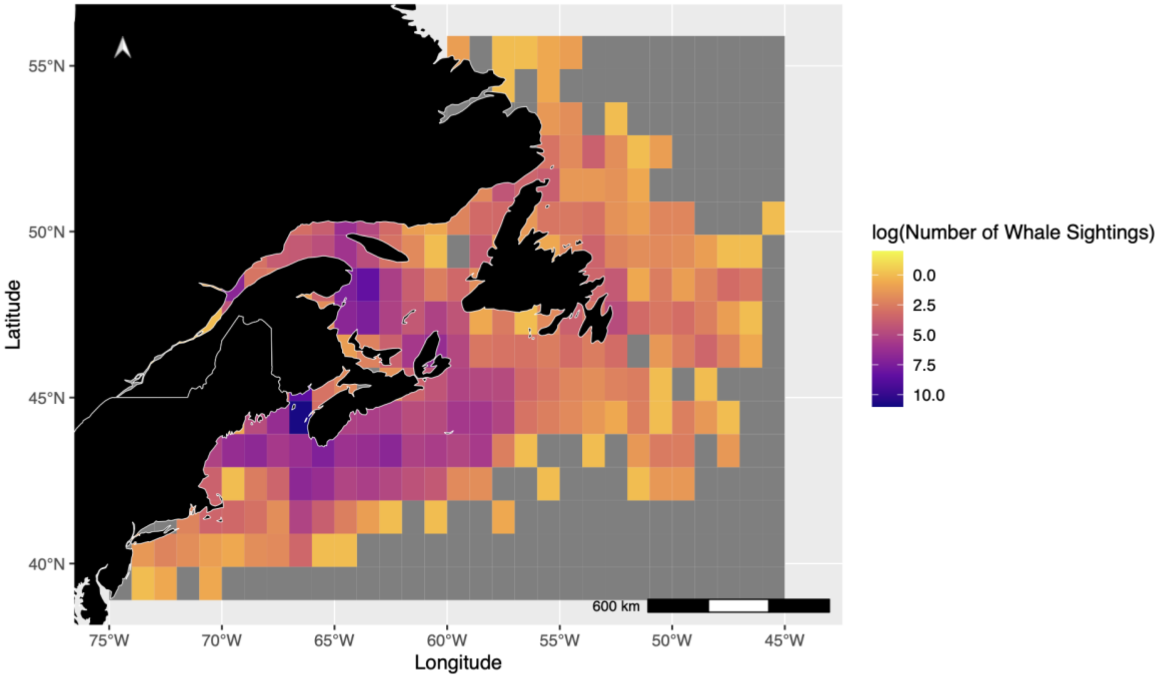

Figure A4. Baleen Whale Sightings. The total number of baleen whale sightings per 1° grid cell between 1963 and 2021 within the study area, on the logarithmic scale. Data collected and provided by DFO (Team Whale 2021), the North Atlantic Right Whale Consortium (NARWC) (NARWC 2021), Environment Canada Seabirds at Sea (ECSAS) (Canadian Wildlife Service 2021), the Whitehead Lab (Team Whale 2021), and the Réseau D'observation de Mammifères Marins (ROMM) (ROMM 2015, ROMM 2017).

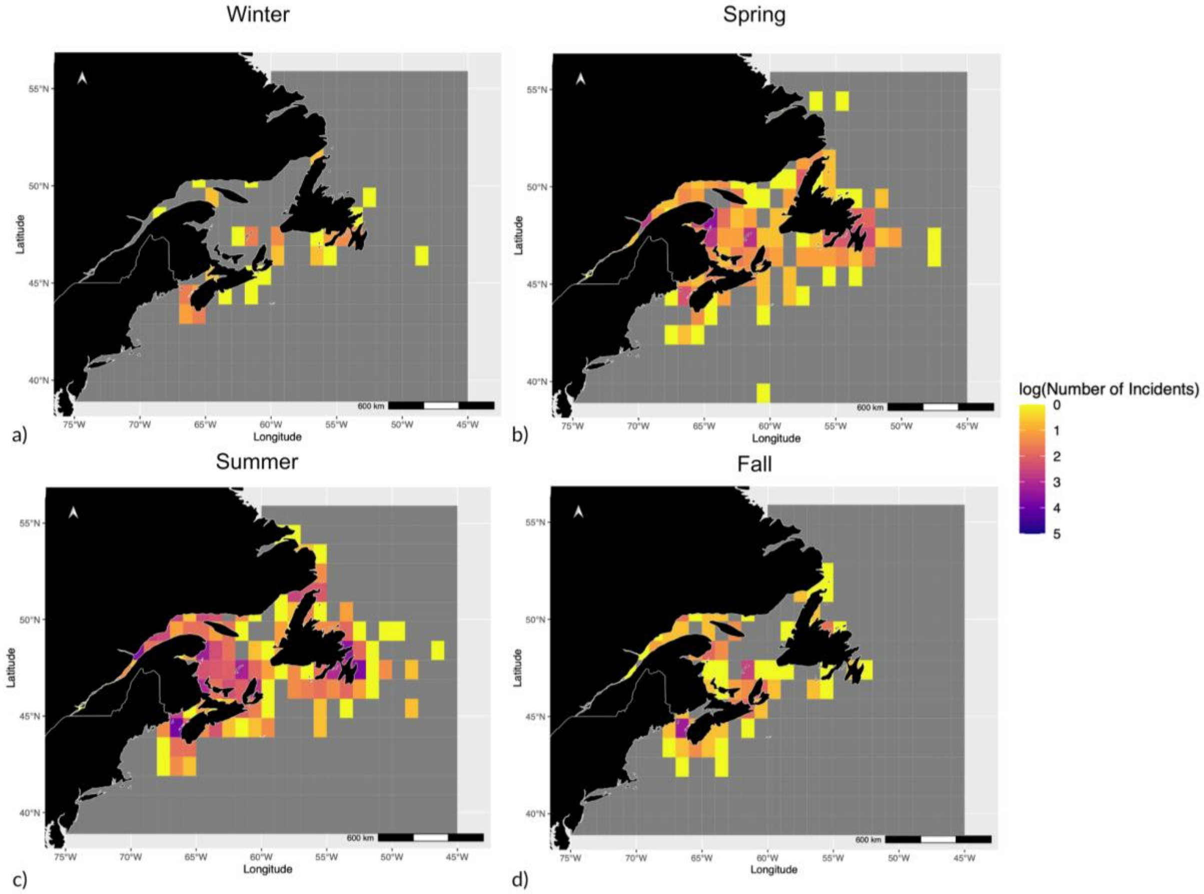

Figure A5. Baleen Whale Incidents per Season. The total number of baleen whale incidents per 1° grid cell in winter (a), spring (b), summer (c), and fall (d) between 2004 and 2019 within the study area, on the logarithmic scale. Data collected and provided by MARS, Whale Release and Strandings, and Réseau Québécois D'urgences Pour Les Mammifères Marins (MARS 2021).

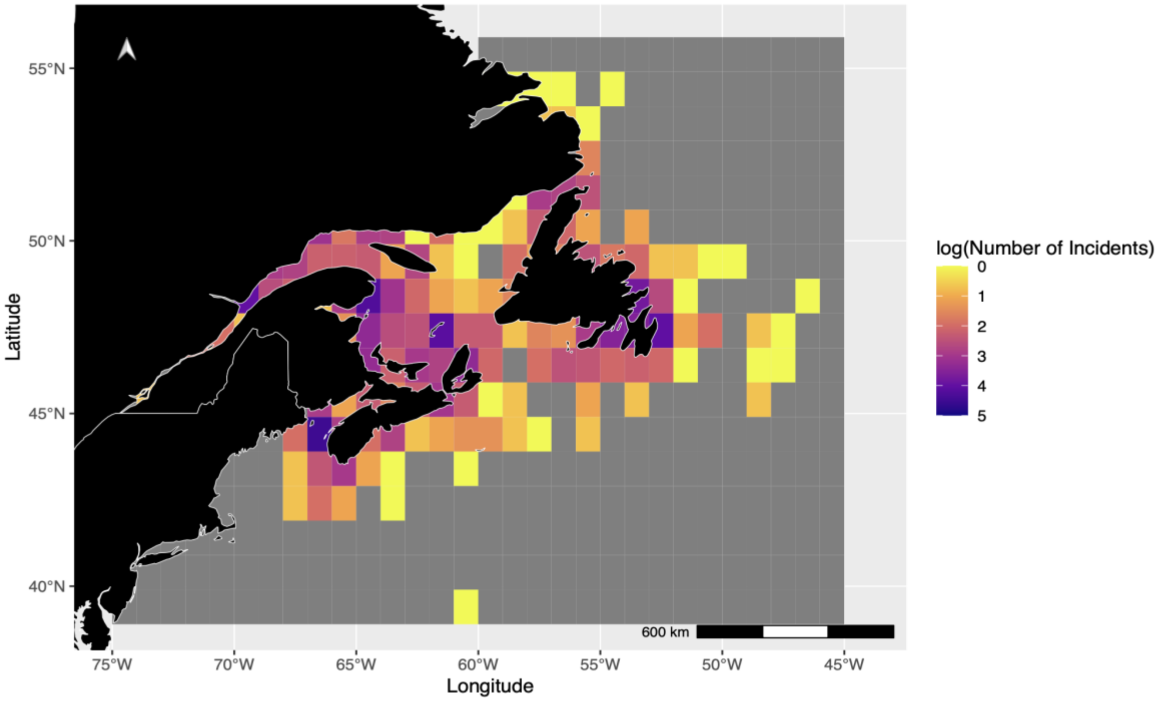

Figure A6. Baleen Whale Incidents. The total number of baleen whale incidents per 1° grid cell between 2004 and 2019 within the study area, on the logarithmic scale. Data collected and provided by MARS, Whale Release and Strandings, and Réseau Québécois D'urgences Pour Les Mammifères Marins (MARS 2021).

Table A1. Predicting Baleen Whale Incidents per Vessel Size. Estimated regression parameters, standard errors, and P-values for the zero-inflated negative binomial generalized linear model used in this analysis to predict baleen whale incidents from the number of whales sighted per cell (1963-2022), and the number of small and large vessel hours logged per cell (2017-2021). Values are reported for the overall baleen whale analysis, and each individual species model.

Species	Covariate	Estimate	Standard Error	P-Value
All baleen whales	*log(Small Vessel Hours)*	*0.121*	*0.007*	*0.065*
	log(Large Vessel Hours)	*0.380*	*0.007*	*<0.001*
NA right whale	log(Small Vessel Hours)	0.009	0.017	0.591
	log(Large Vessel Hours)	-2.032	1.447	0.160
Humpback whale	log(Small Vessel Hours)	-0.009	0.014	0.951
	log(Large Vessel Hours)	1.673	1.177	0.155
Fin whale	log(Small Vessel Hours)	0.157	0.207	0.449
	log(Large Vessel Hours)	1.179	1.301	0.365
Minke whale	*log(Small Vessel Hours)*	*0.201*	*0.101*	*0.048*
	log(Large Vessel Hours)	*0.396*	*0.101*	*<0.001*
Sei whale	*log(Small Vessel Hours)*	*0.906*	*0.408*	*0.026*
	log(Large Vessel Hours)	*1.061*	*0.467*	*0.023*
Blue whale	*log(Small Vessel Hours)*	*-1.324*	*0.505*	*0.009*
	log(Large Vessel Hours)	*9.054*	*2.182*	*<0.001*
Unidentified whales	log(Small Vessel Hours)	0.120	0.122	0.324
	log(Large Vessel Hours)	*1.587*	*0.593*	*0.007*

Table A2. Overlap Between Small and Large Vessel Activity and Baleen Whale Presence. Schoener's D (SD) , Warren's Index (WI) , and Spearman's Correlation (SC) for small and large vessel activity and baleen whale presence. Asterisk indicates the reported value was significant at the 0.05 level (the value was outside of the 95% confidence interval bound generated from the simulations - see Chapter 2 Methods). Values are reported for the overall baleen whale analysis, and each individual species analysis.

Species	Small SD	Large SD	Small WI	Large WI	Small SC	Large SC
All baleen whales	0.17*	0.12*	0.43*	0.28	0.48*	0.41*
NA right whale	0.10	0.06	0.30	0.18	0.36*	0.43*
Humpback whale	0.14*	0.10*	0.37	0.22	0.47*	0.32*
Fin whale	0.20*	0.12	0.46*	0.28	0.41*	0.26*
Minke whale	0.15	0.14*	0.41*	0.32	0.44*	0.13*
Sei whale	0.23*	0.05*	0.47*	0.17*	0.37*	0.15*
Blue whale	0.16*	0.07	0.35	0.20	0.20*	0.15*
Unidentified whales	0.30*	0.14*	0.57*	0.34*	0.34*	0.21*

Table A3. Overlap Between Small and Large Vessel Activity and Baleen Whale Incidents. Schoener's D (SD), Warren's Index (WI), and Spearman's Correlation (SC) for small and large vessel activity and baleen whale incidents. Asterisk indicates the reported value was significant at the 0.05 level (the value was outside of the 95% confidence interval bound generated from the simulations - see Methods). Values are reported for the overall baleen whale analysis, and each individual species analysis.

Species	Small SD	Large SD	Small WI	Large WI	Small SC	Large SC
All baleen whales	0.28*	0.22*	0.55*	0.44*	0.32*	0.58*
NA right whale	0.20*	0.04	0.31*	0.15	0.22*	0.17*
Humpback whale	0.24	0.16	0.50*	0.40	0.35*	0.45*
Fin whale	0.17	0.11	0.35	0.26	0.18*	0.14*
Minke whale	0.23	0.20*	0.45*	0.41*	0.29*	0.53*
Sei whale	0.11	0.03	0.25*	0.15	0.14*	0.21*
Blue whale	0.07	0.06	0.18	0.19	-0.01*	0.20*
Unidentified whales	0.25	0.21*	0.48	0.42	0.26*	0.55*

Table A4. Chapter 1 Generalized Linear Model Results for Overlap Indices Robustness Check. Estimated regression parameters, standard errors, and P-values for the zero-inflated negative binomial generalized linear model used in this analysis to test the relationship between baleen whale observations and baleen whale incidents (see Chapter 2 Methods). Values are reported for the overall baleen whale analysis, and each individual species model.

Species	P-Value
All baleen whales	<0.001
NA right whale	<0.001
Humpback whale	<0.001
Fin whale	0.005
Minke whale	0.009
Sei whale	0.353
Blue whale	0.600
Unidentified whales	0.244

Appendix B – Chapter 3 Overlap Indices and Correlations

Using the overlap indexes, a clear and significant overlap between total, small, and large vessel activity and areas of high habitat suitability was displayed for the past to present day, supporting the presence of incident risk hotspots in the NWA (Table 13, Table C2) (with the exception of Blue and Sei whales and large vessel activity). Additionally, all, small, and large vessel activity and baleen whale habitat suitability showed a significant and positive correlation for all species (Table 13, Table C2), suggesting in areas where there is more vessel activity, there is also higher habitat suitability. This was especially true for Humpback and NA Right whales (Table 13, Table C2). This result reflects the literature suggesting that NA Right whale habitat use strongly coincides with areas of dense vessel activity such as the Bay of Fundy and the Gulf of St. Lawrence (Vanderlaan et al. 2008). This positive correlation in conjunction with the fact that NA right whales, when put in the context of their population size, are at the highest risk of being hit by a vessel compared to any other baleen whale (Van der Hoop et al. 2013), provides support for the importance of effective incident management strategies for this species. The overlap between vessel activity and baleen whale habitat use has been observed before in similar populations of baleen whales (i.e. blue, NA right, and humpback) that also exist mainly near populated coast lines (Bendriñana-Romano et al. 2021, Vanderlaan et al 2008, Nichol et al. 2017).

These results may suggest that the overlap indices are a less robust method of determining relative incident risk as in the case of the blue, humpback, and minke whale, total vessel activity was not deemed a significant predictor of incidents (Table 12, Table C1), but total vessel activity and these species habitat suitabilities show significant overlap (Table 13, Table C2). Additionally, with the exception of the sei whale, large vessel activity was not a significant predictor of baleen whale incidents, but the overlap indicices again, show a significant overlap between large vessels and baleen whale habitat suitability (Table C1, Table C2). These differences may be a result of the fact that the incidents mostly occurred along coastlines (Figure 20), whereas the vessel activity and habitat suitability exist throughout the entire study area (Figure 1, Figures 8-13), allowing the indices to determine a stronger indication of relative incident risk than the GLM. However, the overlap indices did support the same conclusion as the GLM for the blue whales, displaying that large vessel activity and baleen whale habitat suitability do not have a significant overlap, and that large vessel activity is not a significant predictor of baleen whale incidents (Table C1, Table C2).

The overlap seen between vessel activity (total, small, and large) and habitat suitability was rather similar for the near and mid-future (Table 16, Table 17, Table C2, Table C3). However, due to small shifts in habitat suitability, differing degrees of overlap ensued over time (Table 15, Table 16, Table C2, Table C3). This justifies the importance of not only studying the impacts of climate change to baleen whales and their distribution, but incorporating climate change into management plans (Record et al. 2019), as they may become at different risk of harmful human interaction with changing ocean conditions (Reimer et al. 2016).

Appendix C – Chapter 3 Supplementary Figures and Tables

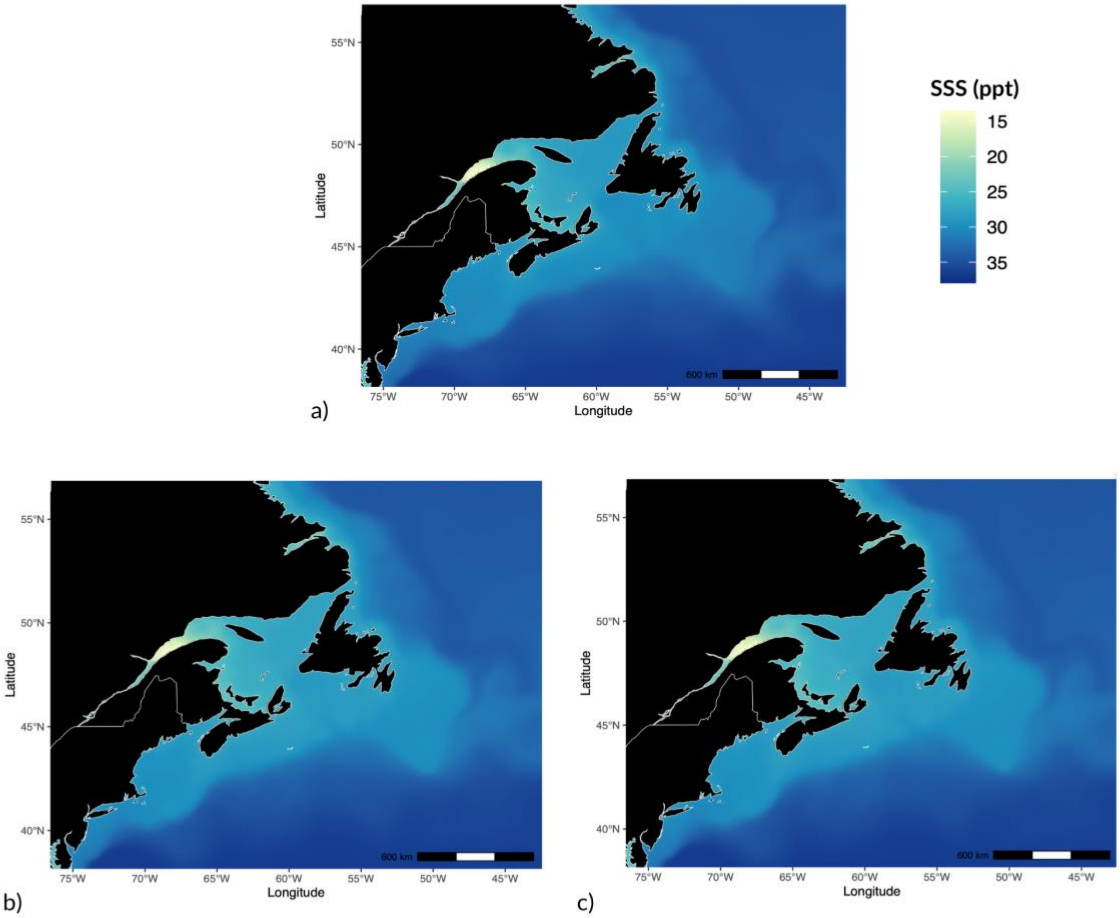

Figure C1. Average sea surface salinity (SSS) (ppt) per 10km grid cell in the NWA. Values are shown from the past to present day (1985-2015) (a), near-future (2035-2045) (b), and mid-future (2045-2055) (c). Future projections made under 2x CO_2 climate scenario. Data from the Community Earth System Model.

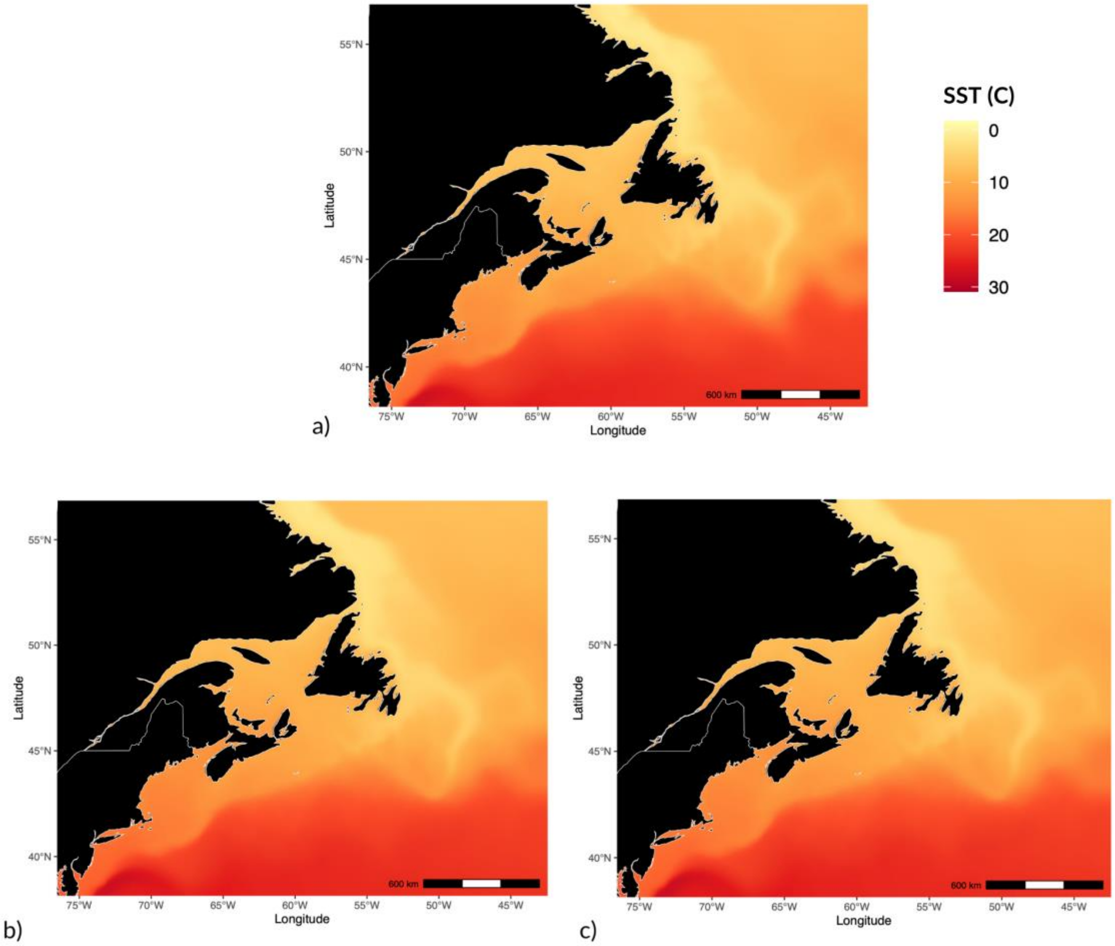

Figure C2. Average sea surface temperature (SST) (°C) per 10km grid cell in the NWA. Values are shown from the past to present day (1985-2015) (a), near-future (2035-2045) (b), and mid-future (2045-2055) (c). Future projections made under 2x CO_2 climate scenario. Data from the Community Earth System Model.

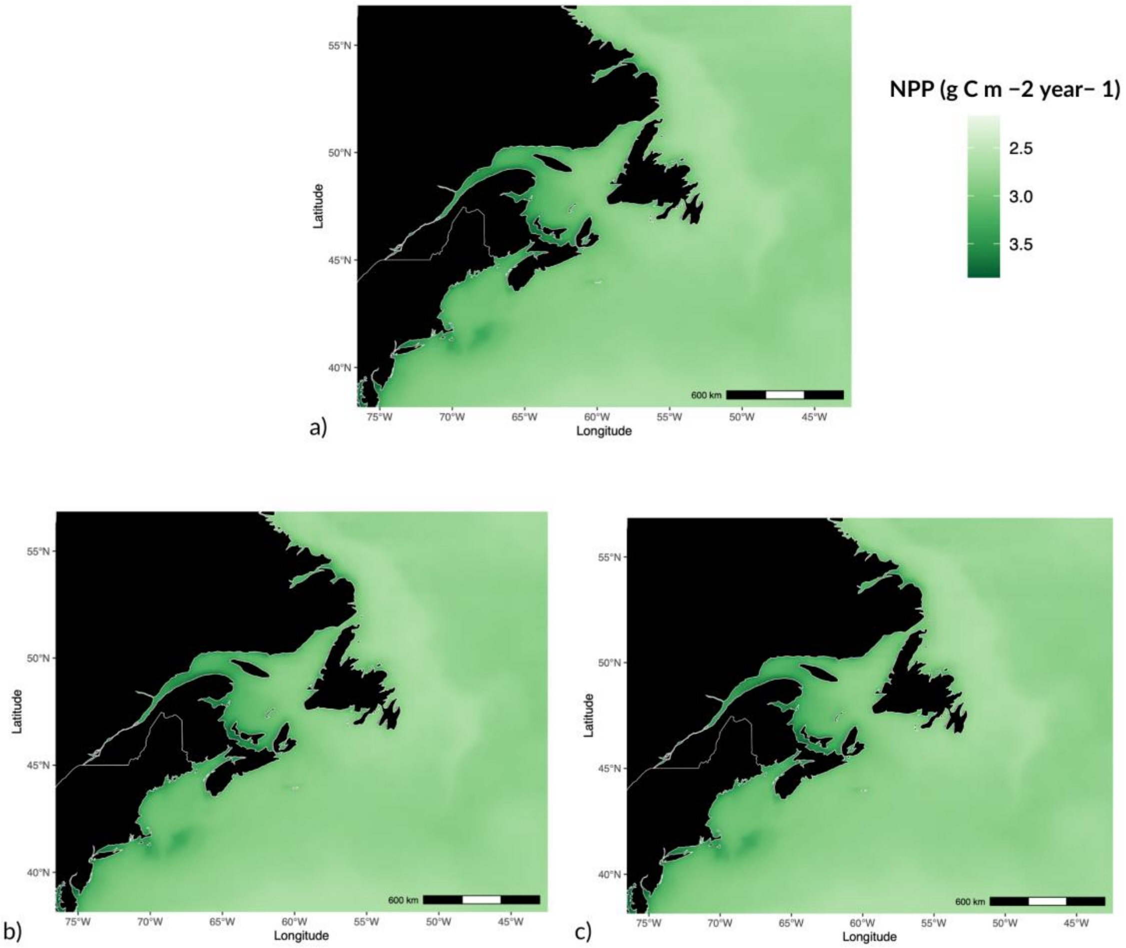

Figure C3. Average net primary productivity (NPP) (g C m $^{-2}$ year^{-1}) per 10km grid cell in the NWA. Values are shown from the past to present day (1985-2015) (a), near-future (2035-2045) (b), and mid-future (2045-2055) (c). Future projections made under 2x CO_2 climate scenario. Data from the Community Earth System Model.

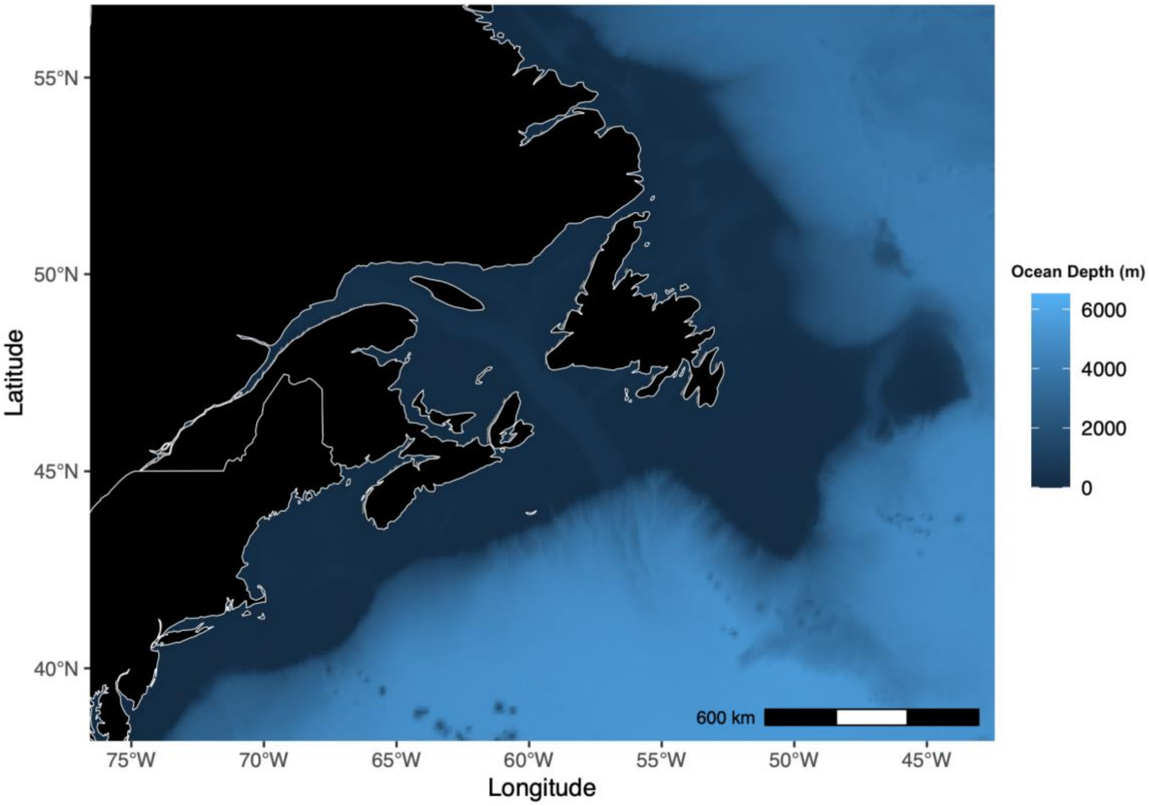

Figure C4. Average depth of the ocean, displayed for the NWA. Data from GEBCO.

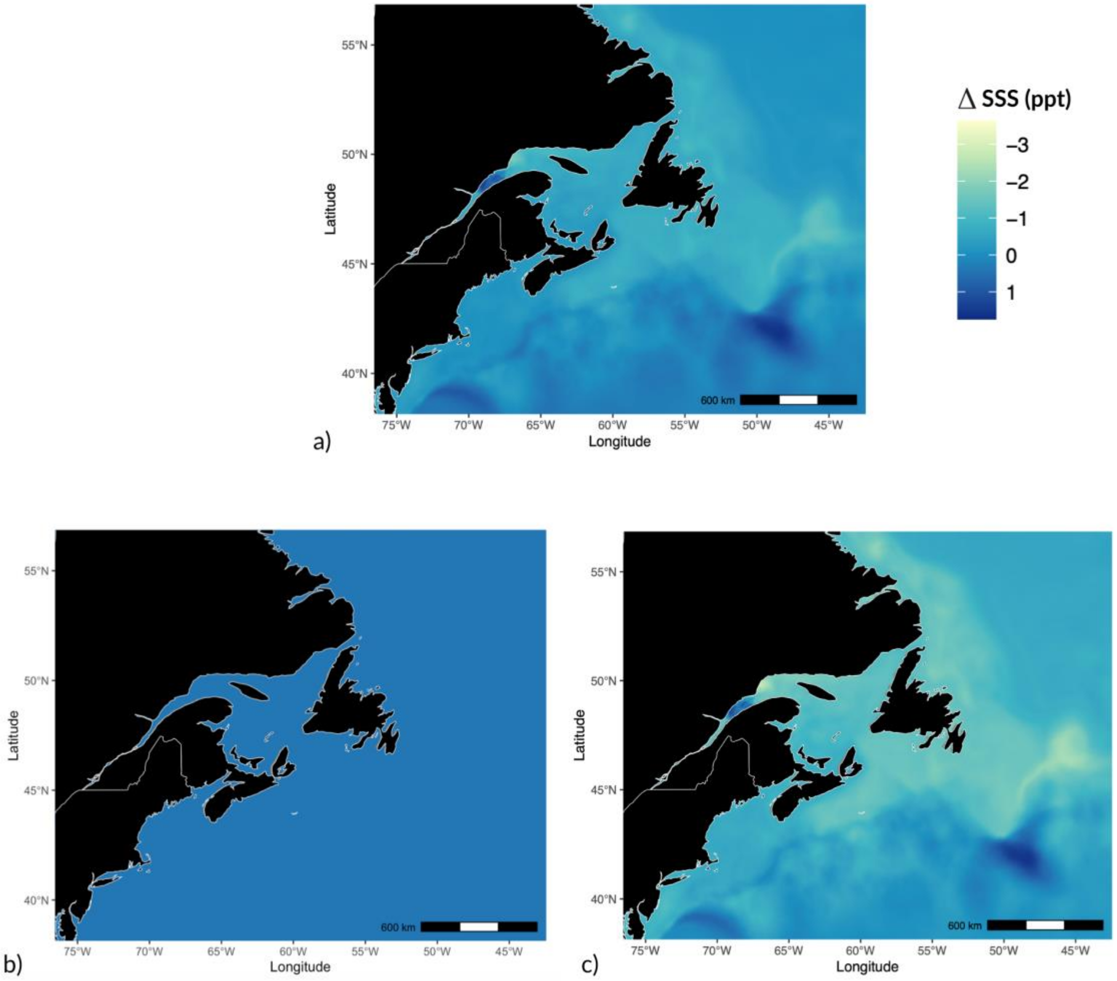

Figure C5. Change in SSS. Change in the average sea surface salinity (SSS) (ppt) per 10km grid cell in the NWA between the past to present day (1985-2015) and the near-future (2035-2045) (a), near-future and the mid-future (2045-2055) (b), and the past to present day and mid-future (c). Future projections made under 2x CO_2 climate scenario. Data from the Community Earth System Model.

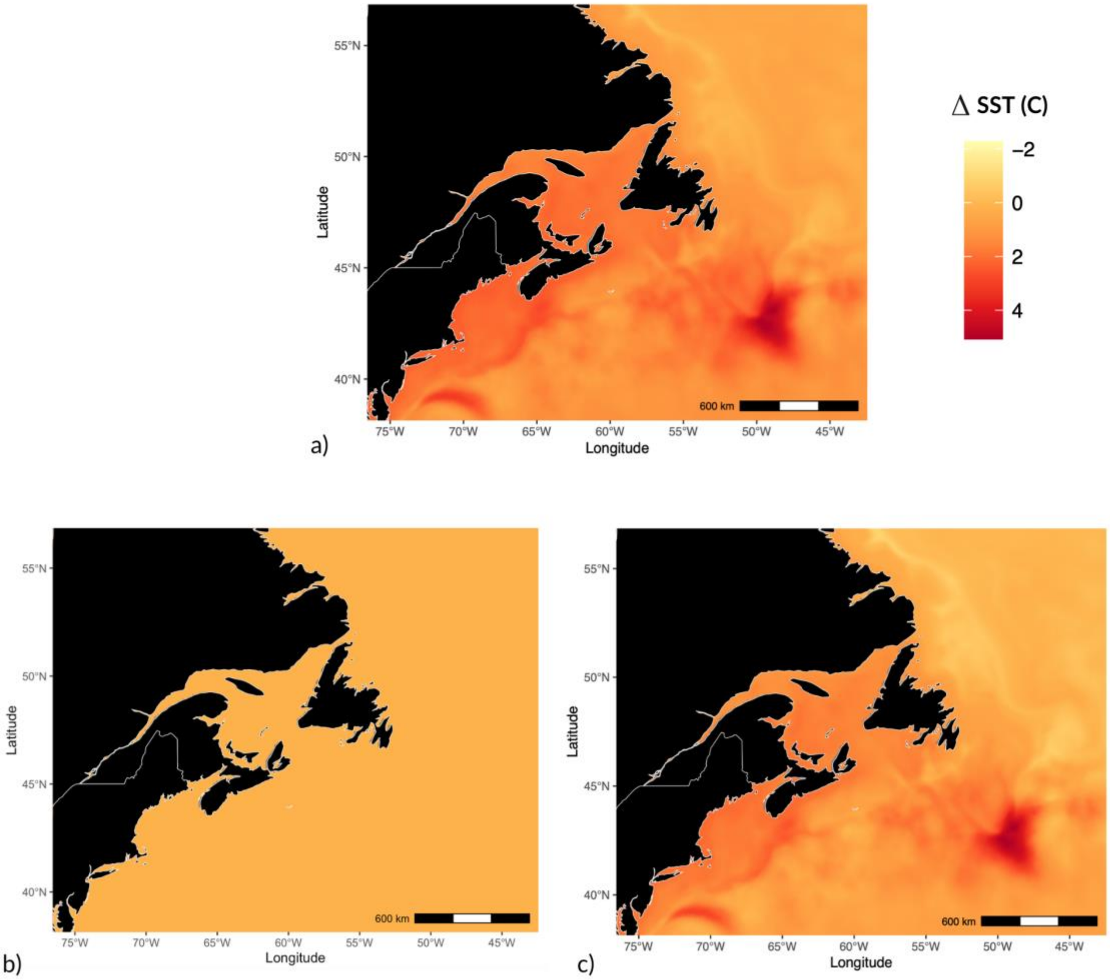

Figure C6. Change in SST. Change in the average sea surface temperature (SST) (°C) per 10km grid cell in the NWA between the past to present day (1985-2015) and the near-future (2035-2045) (a), near-future and the mid-future (2045-2055) (b), and the past to present day and mid-future (c). Future projections made under 2x CO_2 climate scenario. Data from the Community Earth System Model.

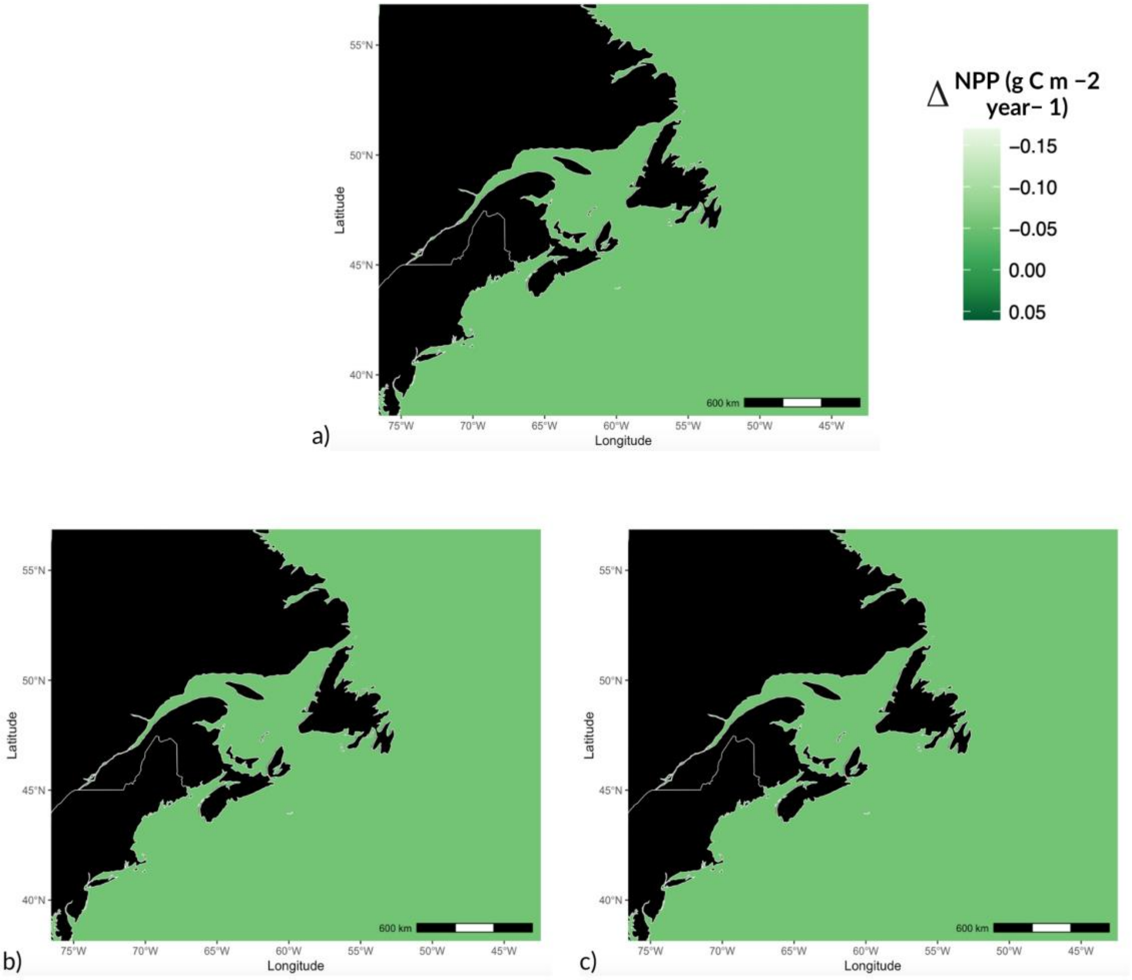

Figure C7. Change in NPP. Change in the average net primary productivity (NPP) (g C m $^{-2}$ year^{-1}) per 10km grid cell in the NWA between the past to present day (1985-2015) and the near-future (2035-2045) (a), near-future and the mid-future (2045-2055) (b), and the past to present day and mid-future (c). Future projections made under 2x CO_2 climate scenario. Data from the Community Earth System Model.

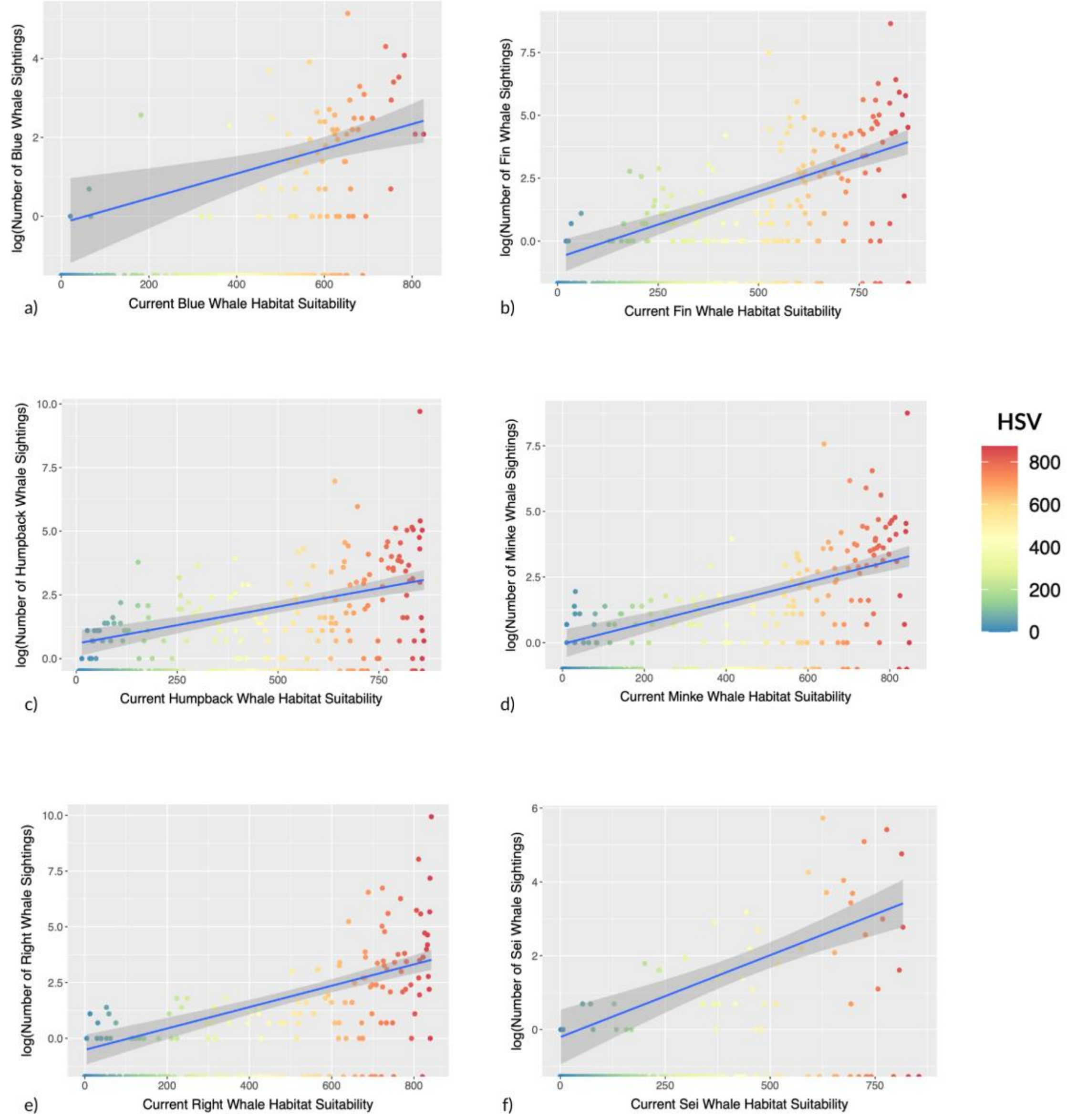

Figure C8. Habitat Suitability vs Opportunistic Sightings. Scatterplots displaying past to present day whale habitat suitability values for the blue (a), fin (b), humpback (c), minke (d), NA right (e), and sei (f) whale, versus the average number of opportunistic sightings per 1° grid cell. Warm coloured values reflect high habitat suitability, and cool coloured values reflect areas with lower habitat suitability. Opportunistic sightings have been log transformed to better display the relationships. A regression line with 95% confidence interval bounds is also included.

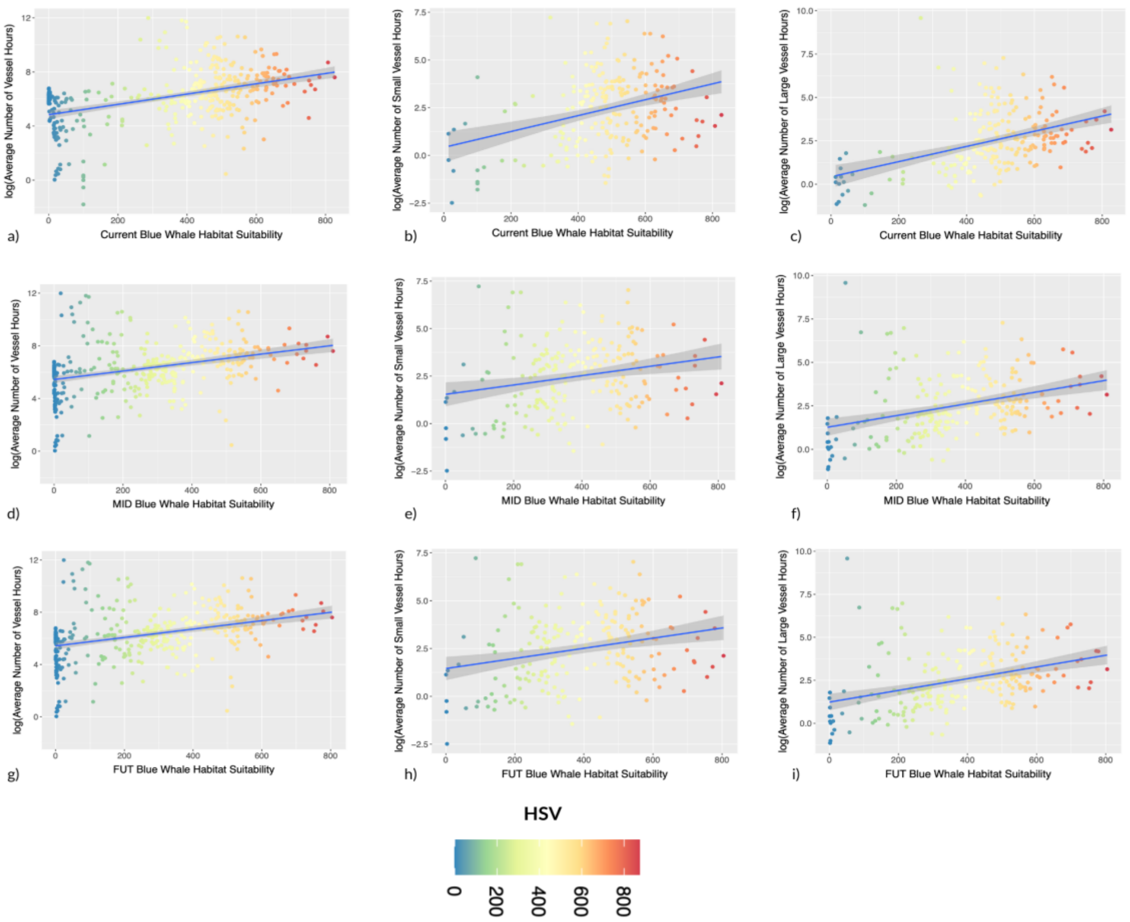

Figure C9. Blue Whale Habitat Suitability vs Average Vessel Hours. Scatterplots displaying blue whale habitat suitability index values from the SDM, versus the average number of vessel hours per 1° grid cell. Outputs for the past to present day (1985-2015) for all vessels (a), small vessels (b), and large vessels (c), for the near-future (2035-2045) for all vessels (d), small vessels (e), and large vessels (f), and the mid-future (2045-2055) for all vessels (g), small vessels (h), and large vessels (i) under climate scenario 2x CO_2. Warm coloured values reflect high habitat suitability, and cool coloured values reflect areas with lower habitat suitability. Vessel activity has been log transformed to better display the relationships. A regression line with 95% confidence interval bounds is also included.

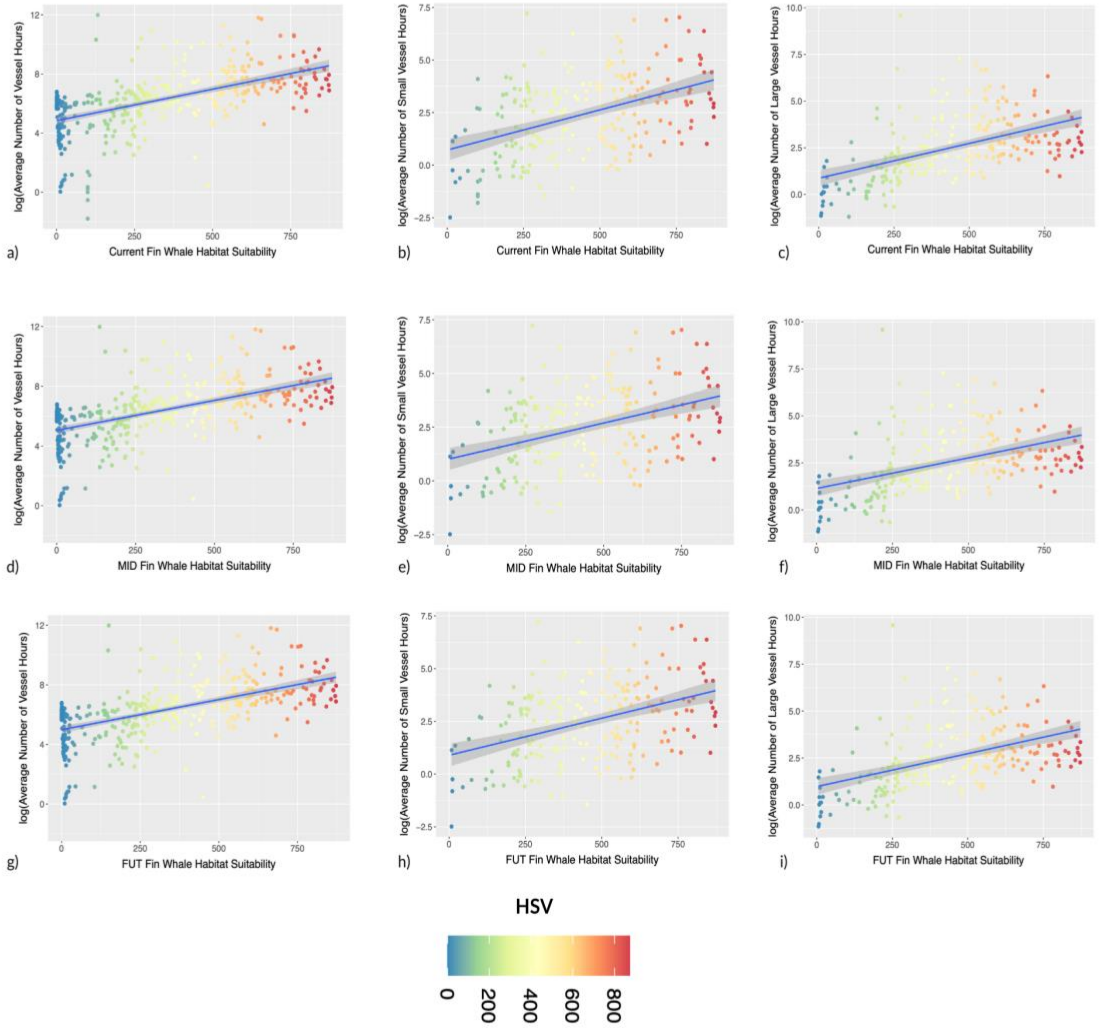

Figure C10. Fin Whale Habitat Suitability vs Average Vessel Hours. Scatterplots displaying fin whale habitat suitability index values from the SDM, versus the average number of vessel hours per 1° grid cell. Outputs for the past to present day (1985-2015) for all vessels (a), small vessels (b), and large vessels (c), for the near-future (2035-2045) for all vessels (d), small vessels (e), and large vessels (f), and the mid-future (2045-2055) for all vessels (g), small vessels (h), and large vessels (i) under climate scenario 2x CO_2. Warm coloured values reflect high habitat suitability, and cool coloured values reflect areas with lower habitat suitability. Vessel activity has been log transformed to better display the relationships. A regression line with 95% confidence interval bounds is also included.

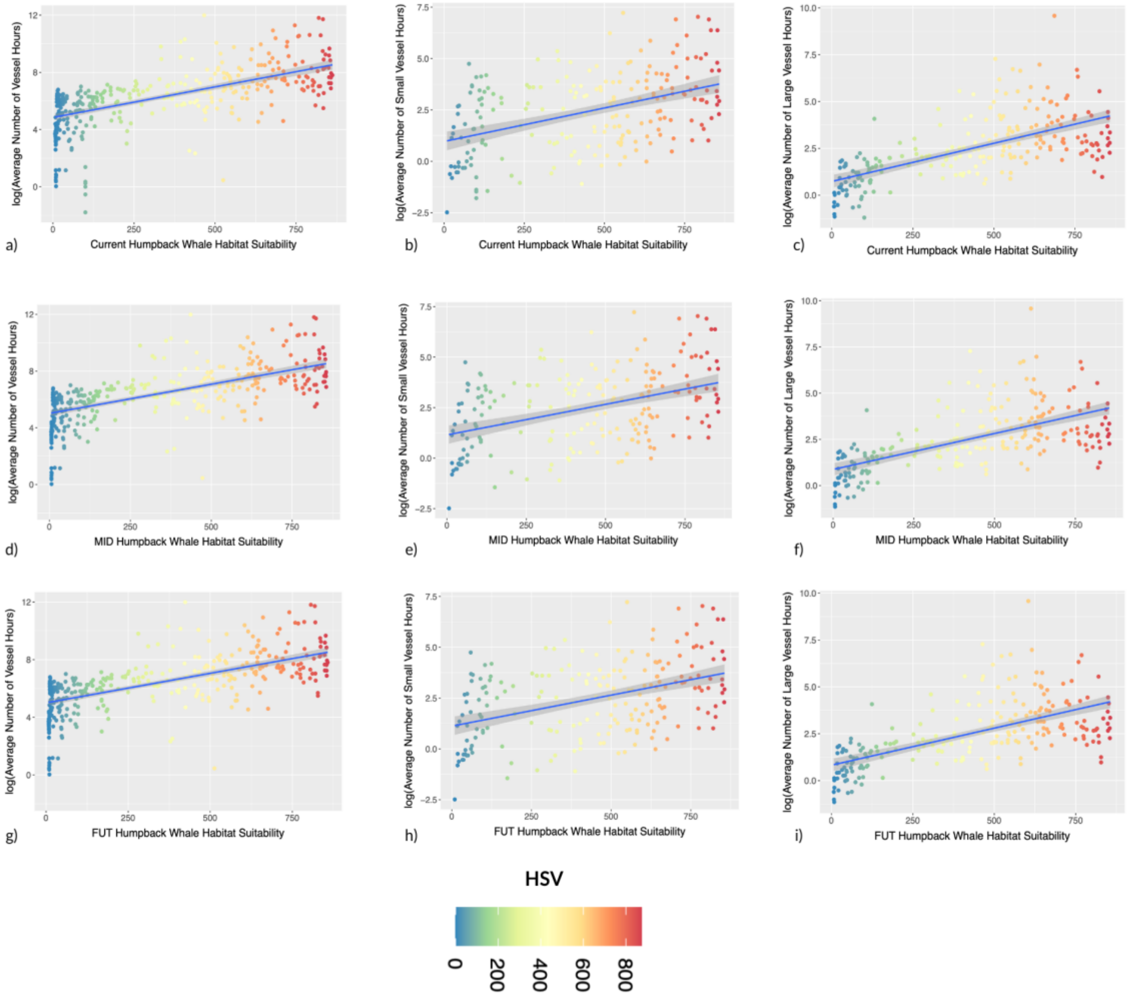

Figure C11. Humpback Whale Habitat Suitability vs Average Vessel Hours. Scatterplots displaying humpback whale habitat suitability index values from the SDM, versus the average number of vessel hours per 1° grid cell. Outputs for the past to present day (1985-2015) for all vessels (a), small vessels (b), and large vessels (c), for the near-future (2035-2045) for all vessels (d), small vessels (e), and large vessels (f), and the mid-future (2045-2055) for all vessels (g), small vessels (h), and large vessels (i) under climate scenario 2x CO_2. Warm coloured values reflect high habitat suitability, and cool coloured values reflect areas with lower habitat suitability. Vessel activity has been log transformed to better display the relationships. A regression line with 95% confidence interval bounds is also included.

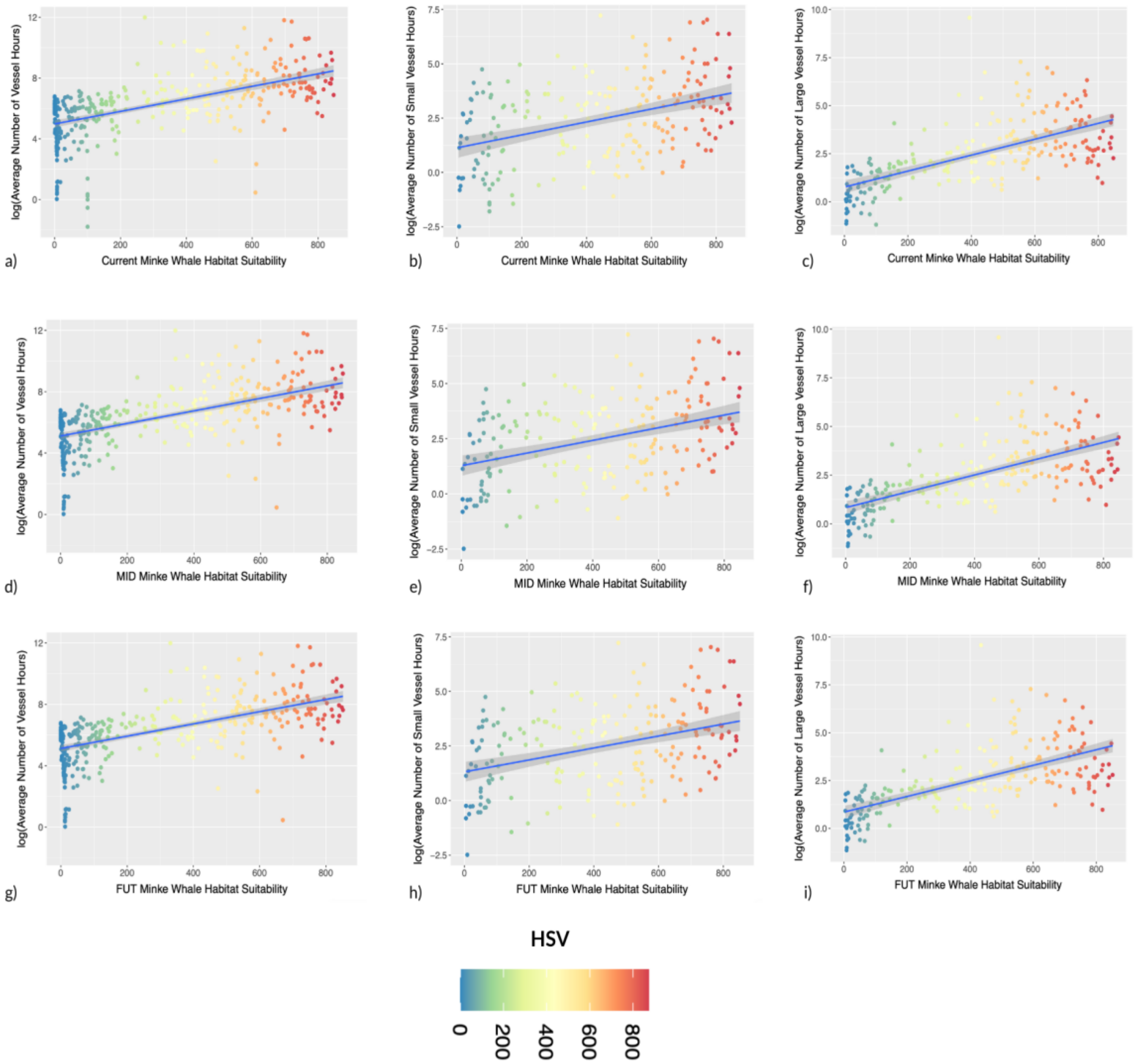

Figure C12. Minke Whale Habitat Suitability vs Average Vessel Hours. Scatterplots displaying minke whale habitat suitability index values from the SDM, versus the average number of vessel hours per 1° grid cell. Outputs for the past to present day (1985-2015) for all vessels (a), small vessels (b), and large vessels (c), for the near-future (2035-2045) for all vessels (d), small vessels (e), and large vessels (f), and the mid-future (2045-2055) for all vessels (g), small vessels (h), and large vessels (i) under climate scenario 2x CO_2. Warm coloured values reflect high habitat suitability, and cool coloured values reflect areas with lower habitat suitability. Vessel activity has been log transformed to better display the relationships. A regression line with 95% confidence interval bounds is also included.

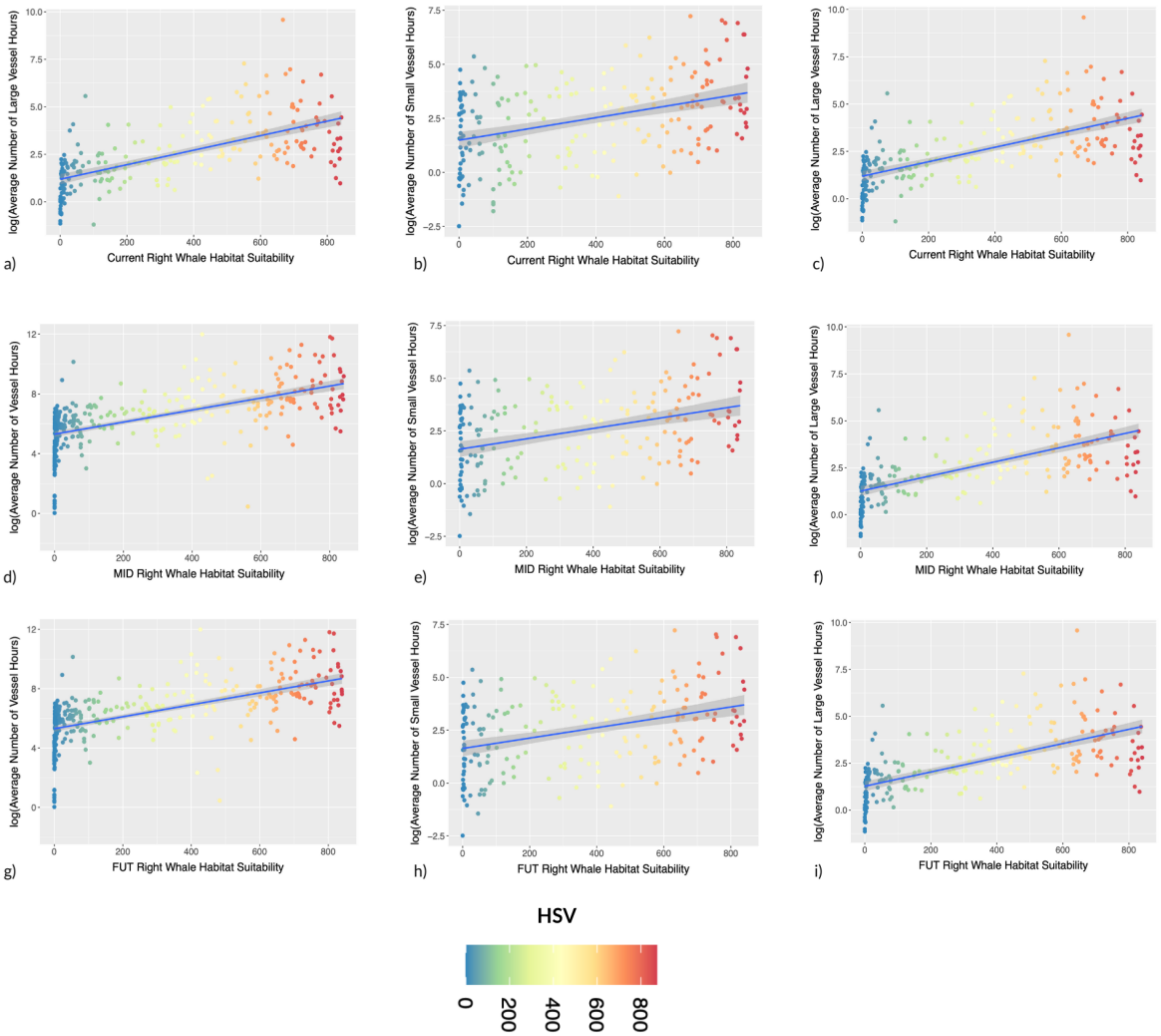

Figure C13. NA Right Whale Habitat Suitability vs Average Vessel Hours. Scatterplots displaying NA right whale habitat suitability index values from the SDM, versus the average number of vessel hours per 1° grid cell. Outputs for the Past to Present Day (1985-2015) for all vessels (a), small vessels (b), and large vessels (c), for the near-future (2035-2045) for all vessels (d), small vessels (e), and large vessels (f), and the mid-future (2045-2055) for all vessels (g), small vessels (h), and large vessels (i) under climate scenario 2x CO_2. Warm coloured values reflect high habitat suitability, and cool coloured values reflect areas with lower habitat suitability. Vessel activity has been log transformed to better display the relationships. A regression line with 95% confidence interval bounds is also included.

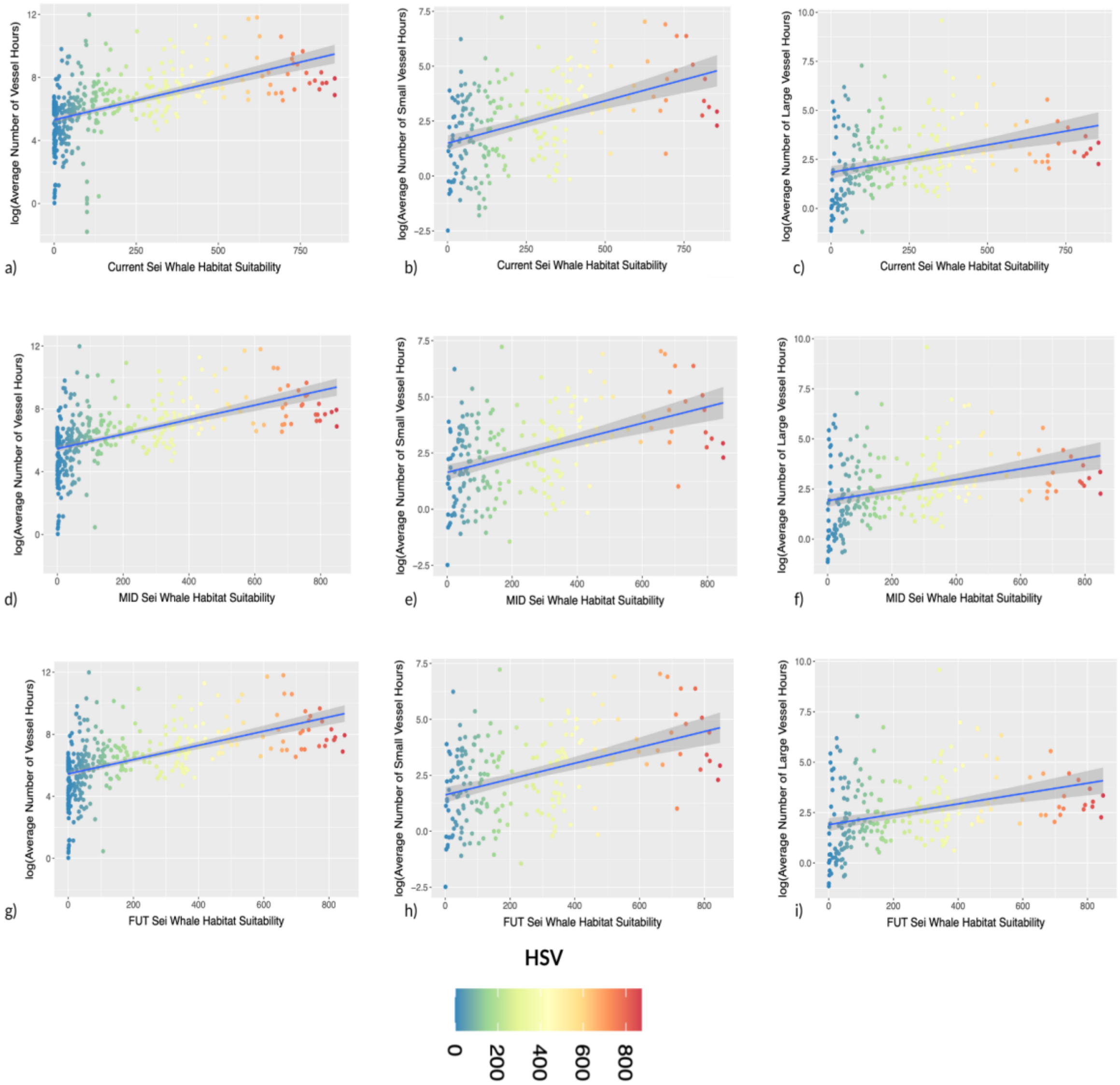

Figure C14. Sei Whale Habitat Suitability vs Average Vessel Hours. Scatterplots displaying sei whale habitat suitability index values from the SDM, versus the average number of vessel hours per 1° grid cell. Outputs for the past to present day (1985-2015) for all vessels (a), small vessels (b), and large vessels (c), for the near-future (2035-2045) for all vessels (d), small vessels (e), and large vessels (f), and the mid-future (2045-2055) for all vessels (g), small vessels (h), and large vessels (i) under climate scenario 2x CO_2. Warm coloured values reflect high habitat suitability, and cool coloured values reflect areas with lower habitat suitability. Vessel activity has been log transformed to better display the relationships. A regression line with 95% confidence interval bounds is also included.

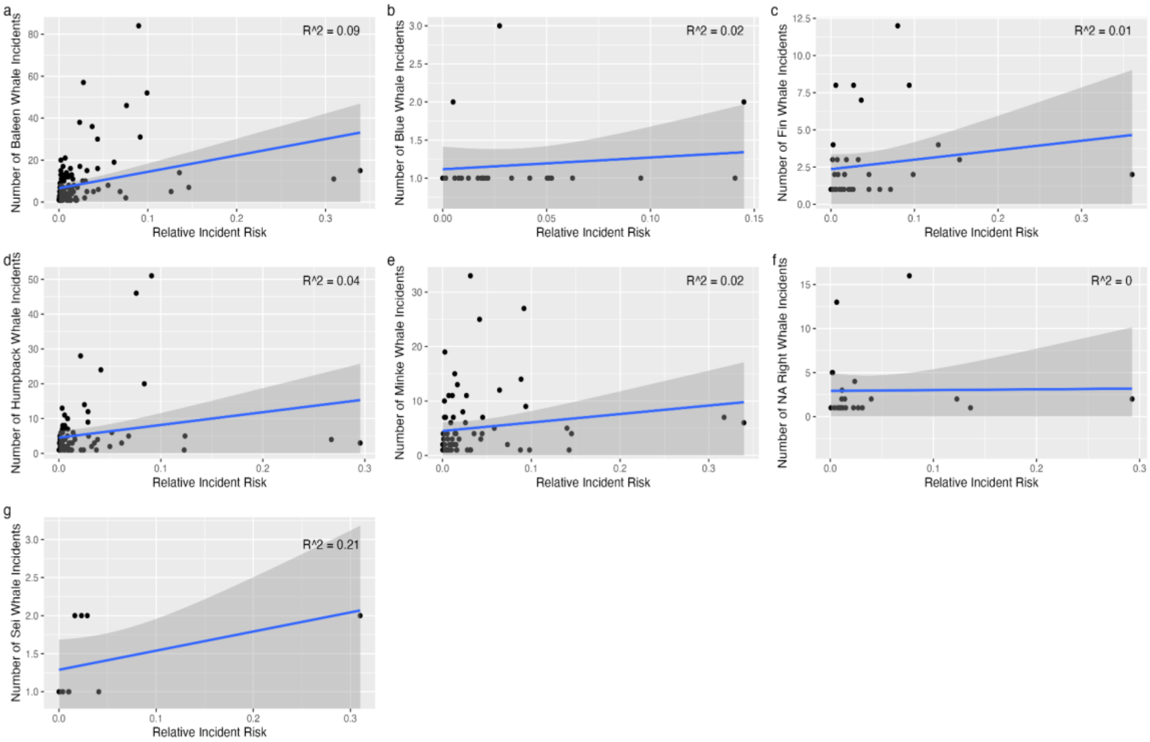

Figure C15. Relative Incident Risk vs Number of Baleen Whale Incidents. The relative risk of incidents plotted against the number of incidents per 1° grid cell for all baleen (a) blue (b), fin (c), humpback (d), minke (e), NA right (f), and sei (g) whales. A regression line, variances, and 95% confidence interval bounds are included.

Table C1. Predicting Baleen Whale Incidents per Vessel Size Using Habitat Suitability. Estimated regression parameters, standard errors, and P-values for the zero-inflated negative-binomially distributed generalized linear model used in this analysis to predict baleen whale incidents (see Chapter 3 Methods). Values are reported for each individual species model for the small and large vessel hour predictors.

Species	**Covariate**	**Estimate**	**Standard Error**	**P-Value**
Blue Whale	*log(Vessel Hours Small)*	*-0.672*	*0.225*	*0.003*
	log(Vessel Hours Large)	0.560	0.390	0.151
Fin Whale	*log(Vessel Hours Small)*	*-0.534*	*0.227*	*0.019*
	log(Vessel Hours Large)	-0.284	0.284	0.316
Humpback Whale	*log(Vessel Hours Small)*	*0.418*	*0.128*	*0.001*
	log(Vessel Hours Large)	0.010	0.179	0.955
Minke Whale	log(Vessel Hours Small)	-0.003	0.132	0.979
	log(Vessel Hours Large)	-0.013	0.157	0.932
NA Right Whale	log(Vessel Hours Small)	-0.223	0.247	0.366
	log(Vessel Hours Large)	-0.549	0.604	0.362
Sei Whale	*log(Vessel Hours Small)*	*0.930*	*0.423*	*0.027*
	log(Vessel Hours Large)	*2.376*	*0.749*	*0.002*

Table C2. Overlap Between Small and Large Vessel Activity and Past to Present Day Baleen Whale Habitat Suitability. Schoener's D (SD), Warren's Index (WI), and Spearman's Correlation (SC) for small and large vessel activity and baleen whale habitat suitability for the past to present day. Asterisk indicates the reported value was significant at the 0.05 level (the value was outside of the 95% confidence interval bound generated from the simulations - see Chapter 3 Methods). Values are reported for the overall baleen whale analysis, and each individual species analysis.

Species	Small SD	Large SD	Small WI	Large WI	Small SC	Large SC
Blue Whale	0.37*	0.23	0.62*	0.50*	0.27*	0.46*
Fin Whale	0.41*	0.25*	0.71*	0.52*	0.42*	0.59*
Humpback Whale	0.40*	0.27*	0.72*	0.56*	0.43*	0.69*
Minke Whale	0.39*	0.27*	0.70*	0.55*	0.38*	0.70*
NA Right Whale	0.39*	0.29*	0.70*	0.58*	0.35*	0.71*
Sei Whale	0.41*	0.22	0.72*	0.51*	0.42*	0.47*

Table C3. Overlap Between Small and Large Vessel Activity and Near-Future Baleen Whale Habitat Suitability. Schoener's D (SD), Warren's Index (WI), and Spearman's Correlation (SC) or small and large vessel activity and baleen whale habitat suitability for the near future. Asterisk indicates the reported value was significant at the 0.05 level (the value was outside of the 95% confidence interval bound generated from the simulations - see Chapter 3 Methods). Values are reported for the overall baleen whale analysis, and each individual species analysis.

Species	Small SD	Large SD	Small WI	Large WI	Small SC	Large SC
Blue Whale	0.37*	0.23	0.66	0.48	0.23*	0.43*
Fin Whale	0.41*	0.24*	0.71*	0.51*	0.39*	0.56*
Humpback Whale	0.41*	0.27*	0.72*	0.56*	0.41*	0.67*
Minke Whale	0.40*	0.27*	0.71*	0.56*	0.37*	0.71*
NA Right Whale	0.38*	0.29*	0.70*	0.58*	0.34*	0.72*
Sei Whale	0.41*	0.22	0.64*	0.50*	0.40*	0.43*

Table C4. Overlap Between Small and Large Vessel Activity and Mid-Future Baleen Whale Habitat Suitability. Schoener's D (SD), Warren's Index (WI), and Spearman's Correlation (SC) or small and large vessel activity and baleen whale habitat suitability for the mid-future. Asterisk indicates the reported value was significant at the 0.05 level (the value was outside of the 95% confidence interval bound generated from the simulations - see Chapter 3 Methods). Values are reported for the overall baleen whale analysis, and each individual species analysis.

Species	Small SD	Large SD	Small WI	Large WI	Small SC	Large SC
Blue Whale	0.37*	0.23	0.66	0.48	0.25*	0.46*
Fin Whale	0.41*	0.24*	0.71*	0.52*	0.39*	0.57*
Humpback Whale	0.40*	0.27*	0.72*	0.56*	0.41*	0.68*
Minke Whale	0.40*	0.27*	0.71*	0.56*	0.36*	0.70*
NA Right Whale	0.38*	0.29*	0.70*	0.58*	0.34*	0.72*
Sei Whale	0.41*	0.22	0.72*	0.50*	0.40*	0.42*

Table C5. Average Mean Decrease Accuracy (MDA) Scores for Environmental Variables of Importance. The average MDA scores for each environmental variable used in the ensemble SDMs for each species. The higher the score, the more important the variable.

	Variables of Importance					
Species	**SSS**	**SST**	**NPP**	**Bathy**	**Slope**	**Shelf**
Blue whale	0.776	0.292	0.142	0.397	0.036	0.085
Fin whale	0.895	0.351	0.118	0.086	0.007	0.110
Humpback whale	0.362	0.363	0.087	0.132	0.004	0.066
Minke whale	0.839	0.342	0.040	0.056	0.001	0.041
NA right whale	0.471	0.355	0.203	0.120	0.001	0.032
Sei whale	0.816	0.533	0.133	0.202	0.004	0.019

Table C6. Relative Incident Risk vs the Number of Incidents Generalized Linear Model Results. Estimated regression parameters, standard errors, P-values, and explained variances (R^2) for the generalized linear model used in this analysis to predict baleen whale incidents as a function of relative incident risk (see Chapter 3 Methods). Values are reported for each individual species model and all baleen whales together.

Species	**Estimate**	**Standard Error**	**P-Value**	**Variance Explained (R^2)**
All baleen whales	*78.14*	*21.78*	*<0.001*	*0.095*
Blue whale	1.544	2.627	0.563	0.016
Fin whale	1.055	0.678	0.121	0.006
Humpback whale	36.49	19.00	0.058	0.044
Minke whale	15.57	11.73	0.188	0.023
NA right whale	0.870	12.78	0.946	<0.001
Sei whale	2.513	1.721	0.182	0.210