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Habitats Important to Blue Whales (*Balaenoptera musculus*) in the Western North Atlantic

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Blue whales (*Balaenoptera musculus*) in the northwest Atlantic are considered endangered under the Species at Risk Act. Lack of data precluded the identification of critical habitat in the Recovery Strategy published in 2010, which instead included a schedule of studies that, when completed, would allow critical habitat to be identified. After five years of intensive studies, we provide here a review of the available information and current state of knowledge regarding habitats important for Northwest Atlantic blue whales. This information comes from: 1) whaling catch records, 2) photo-identification studies, 3) land, aerial and ship-board surveys, 4) passive acoustic monitoring, 5) satellite and radio telemetry, 6) ice entrapment reports, 7) opportunistic sighting reports, and 8) species distribution modelling.

Blue whales feed while in Canadian waters and their distribution is linked to aggregations of krill. Prey depth strongly interplays with prey density and biomasses in defining habitat quality and bioenergetics of foraging. Arctic krill (*Thysanoessa* spp.) and northern krill (*Meganyctiphanes norvegica*) are their two main prey, but the species consumed likely varies seasonally, spatially and among individuals. As a result, habitats important for blue whales were identified using information on blue whale distribution in combination with that of areas of krill aggregations (either observed or predicted). Using the bounding box approach, four areas were identified as important foraging/feeding and socializing areas for blue whales: the lower St. Lawrence Estuary and northwestern Gulf of St. Lawrence, the shelf waters south and southwest of Newfoundland, the Mecatina Trough area, including the head of the Esquiman Channel, and the continental shelf edge of Nova Scotia, Newfoundland and the Grand Banks. Two areas were identified as transit corridors: the Honguedo and Cabot Strait. Wintering areas of blue whales appear relatively diffuse, and include the Gulf of St. Lawrence, southwest Newfoundland, and Scotian Shelf, as well as the mid-Atlantic Bight off the U.S. coast, and warm and deep oceanic waters off this area. Whether breeding occurs in this latter region is unknown. Important features and attributes of important habitats to blue whales include sufficient quantity and quality of prey, free access to transit corridors, enough physical space to freely maneuver, water of sufficient quality to not result in loss of function, and an acoustic environment that does not interfere with communication, passive detection of prey or navigation, or impede use of important habitats by blue whales or their prey. Anthropogenic activities that are likely to result in the loss of functions of these important habitats include those that would result in reduced prey availability or accessibility, acoustic disturbance, environmental contamination, and physical disturbance. It is unclear whether the important habitats identified in this report are sufficient to insure the survival of the Northwest Atlantic blue whales and to meet population recovery goals outlined in the Recovery Strategy. There is a need to expand research efforts outside of the summer period, and to offshore waters and other areas where blue whale sightings are limited but where significant krill aggregations suggest they may be important to blue whales.

Habitats Importants pour les rorquals bleus (*Balaenoptera musculus*) dans l'ouest de l'Atlantique Nord

RÉSUMÉ

Les rorquals bleus (*Balaenoptera musculus*) de l'ouest de l'Atlantique Nord sont considérés en voie de disparition en vertu de la Loi sur les Espèces en Péril. Un manque d'information a empêché l'identification de leur habitat essentiel dans la stratégie de rétablissement publiée en 2010, qui proposait en contrepartie un calendrier d'études qui, une fois complété, permettrait son identification. Après cinq ans d'études intensives, nous présentons ici une revue de l'information disponible et de l'état des connaissances relativement aux habitats importants pour le rorqual bleu du nord-ouest Atlantique. Cette information provient de : 1) archives des prises de la chasse, 2) photo-identification, 3) relevés côtiers, aériens et par bateaux, 4) monitorage par acoustique passive, 5) télémétrie radio et satellite, 6) emprisonnement par les glaces, 7) observations anecdotiques, et 8) modélisation.

Les rorquals bleus se nourrissent dans les eaux canadiennes et leur distribution est liée aux agrégations de krill. La profondeur de leurs proies interagit fortement avec les biomasses et densités de proies pour définir la qualité d'un habitat et la bioénergétique de quête alimentaire. Le krill Arctique (*Thysanoessa* spp.) et le krill nordique (*Meganyctiphanes norvegica*) constituent leur deux principales proies, mais l'espèce consommée varie vraisemblablement spatialement, et entre les individus et les saisons. Il en découle que les habitats important pour les rorquals bleus ont été identifiés en combinant l'information sur la distribution des rorquals bleus avec celle concernant les aires d'agrégation de krill (observées ou prédites). En utilisant l'approche des boites englobantes, quatre aires ont été qualifiées d'importantes pour la quête alimentaire/l'alimentation et les interactions sociales des rorquals bleus: l'estuaire maritime du Saint-Laurent et le nord-ouest du golfe du Saint-Laurent, les eaux des plateaux au sud et au sud-ouest de Terre-Neuve, le secteur de la Fosse Mecatina, incluant la tête du chenal Esquiman, et la marge du plateau continental de la Nouvelle-Écosse, de Terre-Neuve, et des Grands Bancs. Deux aires ont été identifiées comme corridors de transit : le détroit de Honguedo et le détroit de Cabot. Les aires d'hivernage des rorquals bleus semblent relativement diffuses, et incluent le golfe du Saint-Laurent, le sud-ouest de Terre-Neuve et le plateau néo-écossais, ainsi que le mid-Atlantic Bight au large de la côte des États-Unis, et les eaux océaniques chaudes et profondes au large de cette région. On ne sait pas si les animaux se reproduisent dans cette dernière région. Les composantes et caractéristiques des habitats importants pour les rorquals bleus incluent des proies de qualité et en quantité suffisante, un accès libre aux corridors de transit, un espace physique suffisant pour manœuvrer librement, des eaux de qualité suffisantes pour ne pas résulter en une perte de fonction, et un environnement acoustique qui n'interfère pas avec la communication, la détection passive des proies ou la navigation, ou qui ne prévient pas l'utilisation des habitats importants pour les rorquals bleus ou leur proies. Les activités humaines qui sont susceptibles de résulter en une perte de fonction de ces importants habitats incluent celles qui résulteraient en une réduction d'accès aux proies ou de leur disponibilité, en des perturbations acoustiques, une contamination environnementale, ou à un dérangement physique. On ne peut dire si les habitats importants identifiés dans ce rapport sont suffisants pour assurer la survie et le rétablissement de la population de rorquals bleus de l'ouest de l'Atlantique Nord et pour rencontrer les objectifs de rétablissement décrits dans la stratégie de rétablissement. Il est nécessaire d'étendre les efforts de recherche hors de la période estivale et dans les eaux extracôtières et les autres régions où les observations de rorquals bleus sont limitées, mais où des agrégations significatives de krill suggèrent une certaine importance pour les rorquals bleus.

INTRODUCTION

The blue whale (*Balaenoptera musculus*) is the largest animal on Earth, and belongs to the family Balaenopteridae, which includes the rorquals. This species is ubiquitous, ranging in all the world's oceans (Yochem and Leatherwood 1985). Intensive whaling has considerably reduced blue whale populations, especially in the southern hemisphere. In the North Atlantic, at least 11,000 blue whales were taken between the late 1800s and 1960, including approximately 1,500 individuals in eastern Canadian waters (Jonsgård 1955; Sergeant 1966). Using the ratio of fin to blue whale catches as an index of blue whale stock size, Allen (1970) estimated that just over 1,100 blue whales probably constituted the entire historic western North Atlantic stock (Mitchell 1974). The number of blue whales currently remaining in the western North Atlantic is unknown, but it is estimated to be in the low hundreds (Sears and Calambokidis 2002). There is also no assessment of trends in abundance.

Whalers believed there were two blue whale populations in the North Atlantic (Ingebrigtsen 1929), but the International Whaling Commission has never adopted this view (Donovan 1991). There is currently no irrefutable evidence for concluding that blue whales in the western North Atlantic are distinct from those of the eastern North Atlantic. Stranding and sighting data indicate a distribution in the North Atlantic ranging from Iceland, Spitzbergen and Davis Strait, south to New England, the Caribbean, and west Africa (Senegal, Mauritanious, Canary Island and Cape Verde) (reviewed in Sears and Calambokidis 2002; Sears and Larsen 2002). However, the genetic structure and interconnections among these areas of potential aggregation are not well understood. Photo-identification data suggests a low degree of genetic exchange between western and eastern North Atlantic blue whales (Sears and Calambokidis 2002; Ramp and Sears 2013), with a single cross-Atlantic match between the Gulf of St. Lawrence (GSL) (1984 and 2015) and the Azores (2014) (Sears et al. 2015). Recent satellite telemetry data of a few blue whales tagged in the Azores and in the GSL have not indicated any movement across the North Atlantic (Silva et al. 2013; Lesage et al. 2016).

Photo-identification has confirmed that blue whales seen during the ice-free period in eastern Canada and eastern U.S. belong to the same population (Sears and Calambokidis 2002), and a match between eastern Canada and west Greenland (Sears and Larsen 2002) supports the view that the western North Atlantic stock extends to Davis Strait (Ingebrigtsen 1929; Jonsgård 1955). Currently, blue whales in the western North Atlantic (referred to as the "Atlantic population" by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and *Species at Risk Act* (SARA), are considered as a separate population under Canadian legislation, and have been listed as *Endangered* under the *SARA* since 2005.

The *SARA* requires preparation of a Recovery Strategy (see Beauchamp et al. 2009), and identification, to the extent possible, of habitats that are important for the survival and recovery of the population. The latter implies that a target for distribution and population size for what is considered a recovered population be defined. The target recovered population size for blue whales in the western North Atlantic was set at 1,000 mature individuals (Beauchamp et al. 2009), a number that corresponds to the COSEWIC criterion for down-listing the population from *Endangered* to *Not at risk*. However, no distribution target for recovery has been proposed.

The *SARA* also precludes any activity from destroying critical habitat ("the habitat that is necessary for the survival or recovery of a listed wildlife species and that is identified as the species' critical habitat in the recovery strategy or in an action plan for the species"; Canada Gazette 2003). The Government of Canada's draft *SARA* Policies - Overarching Policy Framework defines what may constitute habitat destruction: *"Destruction is determined on a case by case basis. Destruction would result if part of the critical habitat were degraded, either* *permanently or temporarily, such that it would not serve its function when needed by the species. Destruction may result from a single or multiple activities at one point in time or from the cumulative effects of one or more activities over time."* (Environment Canada 2009). It follows that there is a need to define critical habitat geographically, but also in terms of the area's functions, features, and attributes that could be compromised by human activities.

With this in mind, the objective of this paper is to review the best available information, including uncertainties and data gaps, to support the identification of habitats that were historically or that are currently important for the blue whale population in the western North Atlantic. This information will be used to predict, to the extent possible, the distribution and areas of aggregation of a fully-recovered population, and the amount of resources needed to achieve this goal. The following elements will be specifically addressed:

1) Habitat properties that blue whales need for completing life-cycle processes necessary for their survival and population recovery will be identified, including function(s), feature(s), and attribute(s) of the habitat, and a description of how the biological function(s) are supported by the specific habitat feature(s).
2) Information on the spatial extent of the areas within the distribution range of blue whales that are likely to have the habitat properties identified in 1) will be provided, and whether the identified habitat is sufficient to allow for the survival and recovery of the population will be determined. In the case of the negative, knowledge gaps preventing identification of blue whale critical habitat will be identified (e.g., data required, modeling approaches that should be used, research or activities that should be incorporated into the Schedule of Studies).
3) The activities most likely to destroy the habitat properties identified in 1) and 2) will be identified, and information on the extent and consequences of these activities will be provided. The threshold level at which destruction of habitat functions is likely to occur, and pathways of effects will be provided to the extent possible.

ANALYSIS AND DISCUSSION

ANNUAL CYCLE

The blue whale is a capital breeder, i.e., a species that supports the costs of reproduction and offspring provisioning from energy reserves acquired previously (Houston et al. 2007). This strategy allows for the theoretical separation in time and space of breeding and feeding areas, with seasonal movements between the two habitat types. In baleen whales, these movements are typically between high-latitude, productive feeding areas in summer, and less productive, low-latitude breeding areas in the winter (Kellogg 1929; Norris 1967). Until recently, this pattern was thought to be generally followed also by blue whales (Ingebrigtsen 1929; Jonsgård 1955; Sutcliffe et Brodie 1977; Gambell 1979). However, there is evidence that blue whales and other baleen whales associate with productive areas year-round (Mate et al. 1999; Branch et al. 2007; Simard et al. 2016; Moors-Murphy et al. 2017; GREMM, Tadoussac, QC, unpubl. data), and sporadically feed throughout the migration cycle (Bailey et al. 2009; Lesage et al. 2016), including at stop-over areas while migrating (Silva et al. 2013; Owen 2015). These observations suggest that the classical depiction of a north-south movement, and temporal and spatial segregation of breeding and feeding in baleen whales, including blue whales, might be too simplistic.

In the western North Atlantic, recent data provide evidence for blue whale movements that adhere to a north-south pattern (Clark 1995; Lesage et al. 2016). However, they also indicate that part of the blue whale population may reside in Canadian waters year-round (Moors-

Murphy et al. 2017; Simard et al. 2016). Data sources for documenting the annual cycle and seasonal movement patterns of blue whales include satellite telemetry, passive acoustic monitoring (PAM), line-transect aerial surveys, and anecdotal sighting reports.

The strongest evidences for a north-south movement comes from satellite telemetry data, which allowed tracking of the movements from two adult females tagged in the St. Lawrence Estuary (SLE) during late autumn, south to their wintering area in, and off, the mid-Atlantic Bight (Lesage et al. 2016; Figure 1). This technology, applied to 24 blue whales, also showed a uniform, southerly movement out of the GSL trough Cabot Strait in all seven whales tracked outside of the GSL. Acoustic tracking of a blue whale from Newfoundland-Labrador region south past Bermuda and into the West Indies using hydrophone arrays from the U.S. Navy's Integrated Undersea Surveillance System (IUSS) also supports the presence of blue whales at southern latitudes during winter (Clark 1995). Blue whale sightings, catch and attempted catch data extracted from the 18th and 19th century whaling logbooks, although scarce for the northwest Atlantic, also support the presence of blue whales at low latitudes during winter; data is however insufficient to document north-south movements (Reeves et al. 2004).

Evidence for blue whales remaining year-round in areas of what is thought to be their summer feeding ground come mainly from PAM and anecdotal sighting reports. These areas include the SLE and northwest and southern GSL, the Scotian Shelf, and the Grand Banks of Newfoundland (Clark 1995; Moors-Murphy et al. 2017; Simard et al. 2016; GREMM, Tadoussac, QC, unpubl. data). Winter detection of tonal calls (Moors-Murphy et al. 2017; Simard et al. 2016), which are thought to be produced by males as a breeding display while traveling (McDonald et al. 2001; Oleson et al. 2007), suggest that courtship might also take place in Canadian waters. Based on observations of winter courtship calls in other species such as fin and humpback whales, it has been hypothesized that perhaps some individuals begin singing on their migration route down south (Clapham and Mattila 1990; Clark and Gagnon 2004), or that these tonal calls are produced by younger males not migrating south, but staying to feed and practicing singing (e.g., Vu et al. 2012; Stanistreet et al. 2013).

DIET AND FORAGING BEHAVIOUR

Blue whales are stenophagic predators. They feed almost exclusively on euphausiids, although they may also occasionally consume copepods (Kawamura 1980). Data on blue whale diet in Canadian waters are limited. Stomach contents from the whaling period in the northern GSL and off Nova Scotia confirm blue whale's strong reliance on euphausiids, although no specific species were identified (Sergeant 1966). Anecdotal reports of surface feeding, and sampling of nearby waters confirm Arctic krill (*Thysanoessa raschii*) and northern krill (*Meganyctiphanes norvegica*) as prey of blue whales in the northern GSL (Sears et al. 1987; McQuinn et al. 2013a). Stable isotopes from 143 blue whales biopsy sampled in the SLE or northwestern GSL between 1995 and 2009 indicate a spring-summer diet dominated (average 70%) by Arctic krill, with northern krill and copepods (*Calanus* sp.) comprising on average 26% and 4% of the diet, respectively (Gavrilchuk et al. 2014). The relative importance of Arctic and northern krill varied among individuals within a given year, and changed over the study period with a progressive increase in consumption of northern krill over copepods after 2001 (Gavrilchuk et al. 2014).

It is not known if blue whales in regions other than the SLE and GSL, or at other times of year show similar preferences for Arctic krill. Oceanographic conditions are likely to vary among areas where blue whales forage, and may influence the relative abundance and availability of these two prey items which have known distinct temperature and depth preferenda (Mauchline 1980). The limited data available on krill distribution and correlated environmental variables suggest that Arctic krill is a more boreo-arctic species occupying shallower depths and colder waters, while northern krill is a boreo-temperate species that are found at deeper depths and warmer waters (Soulier 1965; Kulka et al. 1982; Simard et al. 1986; Zhukova 2009; Plourde et al. 2014; McQuinn et al. 2015). Stomach contents from 63 of 67 fin whales taken in Nova Scotia waters in the early 1900s were filled with northern krill (Brodie et al. 1978). This appears to reflect local availability rather than a specific preference by fin whales for this species. Although studies directly comparing biomasses of the two species on the Scotian Shelf have not been conducted, the specific focus on northern krill and not Arctic krill in studies examining potential krill exploitation, or relationships between fish populations and their “euphausiid” prey in this area suggests that northern krill is likely to be the most abundant species (Sameoto et al. 1993; Cochrane et al. 1991; 2000). Similarly, there is little information available on krill biomass in southern Newfoundland or the Grand Banks, but there are indications from the early 1960s that northern krill is less abundant in this area during summer than species of the genus *Thysanoessa*, including Arctic krill (Soulier 1965).

Blue whales, like other baleen whales, employ a particular strategy known as lunge feeding that allows individuals to engulf and filter large volumes of water and prey (Goldbogen et al. 2007). This behaviour involves a series of events that include acceleration of the body and lowering of the mandible which generates dynamic pressure that expands the buccal cavity. The volume of water engulfed exceeds 100% of body mass (Goldbogen et al. 2011), which reduces drastically the whale’s swim speed as its mouth opens. Mouth closure and contraction of the ventral pouch expels water through the baleen plates, resulting in the retention of prey. The biomechanics of this behaviour has been studied in great detail in blue whales and other large rorquals (e.g., Goldbogen et al. 2011; 2012a; Potvin et al. 2012), and has been exploited to identify individual lunges and study their foraging behaviour (e.g., Friedlaender et al. 2009; 2015; Owen 2015). One must note, however, that the technology used in the vast majority of studies relies partly on flow noise to identify lunges, and the increase in flow noise near the surface has limited power to detect surface feeding (Owen et al. 2016). This has led to the perception that blue whales don’t feed significantly at night when krill is close to the surface (e.g., Calambokidis et al. 2008; Goldbogen et al. 2011), which may not be accurate. Indeed, a study conducted on blue whales in the SLE using an alternative technology has allowed to identify individual lunges, regardless of where or when they occurred, i.e., at the surface or at depth, or during the day or night (Doniol-Valcroze et al. 2011). These data indicate that during the period from July to September, blue whales spend on average 69% of their time foraging, with the majority of their foraging effort occurring during nighttime (Doniol-Valcroze et al. 2011). Whether this rhythm prevails in the spring (March-June) is unknown. In the fall (September-November), area-restricted search patterns derived from satellite telemetry, a behaviour thought to be indicative of foraging, occurred on average during 60 to 75% of the time in blue whales from the SLE and GSL, suggesting that foraging remains a predominant activity at that time of the year (Lesage et al. 2016).

HABITAT REQUIREMENTS

Habitat requirements are poorly understood for blue whales, but likely vary according to age, sex, size, and reproductive status as a result of different energy requirements and survival strategies. Similarly to most marine mammals, the distribution of blue whales is likely dictated by key drivers such as food requirements and availability, sea ice, and to a lesser extent in the case of blue whales, predation risks.

Habitat requirements for the breeding period are based largely on movement data from other populations, and Southern Ocean whaling data. It is estimated that between 25 and 50% of blue whale females get pregnant each year, resulting in a calving interval of 2 to 4 years (see Sears et al. 2013 for a review). The timing of mating is unclear, but the 10 to 11 month gestation period suggests that mating occurs shortly following parturition, so sometime during winter. This also means that adult males and females are likely to converge in the same areas at some point during winter. Females nurse their calf for 6 to 7 months (Ottestad 1950; Yochem and Leatherwood 1985), which suggests they likely wean their calf in early- to mid-summer. Observations of female-calf pairs have been scarce in the SLE and GSL where most efforts were concentrated (Sears and Clambokidis 2002), and outside the GSL (Moors-Murphy and Lawson, pers. comm.). These observations suggest that females either 1) wean their calf before entering the SLE and GSL or before observation efforts begin, 2) use areas other than the SLE and GSL when accompanied by a calf, or 3) have abnormally low reproductive success. These various possibilities cannot be disentangled nor given preference at this time. Satellite tagging data from two females that reached wintering areas off the Mid-Atlantic Bight indicate that they spent considerable time in the Gulf Stream waters (Lesage et al. 2016). Movement towards subtropical, warmer waters at that time may contribute to reducing energy expenditures of the lean calves, and that of the fasting and nursing mothers, in addition to reducing the risk of ice entrapments in some parts of their wintering areas in Canadian waters. Satellite telemetry data one female tracked over its entire winter migration used canyons along the U.S. shelf break and underwater seamounts on her way to and from her wintering area, where area-restricted search, a behaviour that may be indicative of feeding, was documented (Lesage et al. 2016). This anecdotal report indicates periodic feeding at southern latitude, and in areas outside of Canadian waters.

As the largest predators on Earth, blue whales also have the highest absolute metabolic demands (Kshatriya and Blake 1988). Habitat requirements of blue whales during the feeding period are likely to be defined primarily by access to krill densities and biomasses high enough to fulfil those demands at the least cost. It is therefore not surprising to find blue whales associated with upwelling regions, bottom topography, and thermal fronts (Croll et al. 2005; Etnoyer et al. 2006; Doniol-Valcroze et al. 2007), which in turn are associated with krill aggregations (Simard et al. 1986; Simard and Lavoie 1999; Lavoie et al. 2000; Maps et al. 2015). However, blue whales are ultimately limited in their ability to exploit krill patches at depth by their breath-hold capacity, and the high energetic costs of their lunge-feeding foraging strategy (Croll et al. 2001; Potvin et al. 2012). It is therefore expected that krill depth and by consequence food accessibility also represents a significant parameter defining optimal foraging habitat (Doniol-Valcroze et al. 2011).

SEASONAL DISTRIBUTION AND DENSITIES

Information on blue whale seasonal distribution and areas of concentration, either current or historical, come from: 1) whaling catch records, 2) photo-identification studies, 3) land, aerial and ship-board surveys, 4) passive acoustic monitoring, 5) satellite and radio telemetry, 6) ice entrapment reports, 7) opportunistic sighting reports, and 8) species distribution modelling (Sergeant 1966; Sutcliffe and Brodie 1977; Pippard and Malcolm 1978; Sears and Williamson 1982; Sergeant 1982; Edds and Macfarlane 1987; Wenzel et al. 1988; Lavigueur et al. 1993; Clark 1995; Hooker et al. 1999; Lawson 2003; Stenson et al. 2003; Reeves et al. 2004; Ramp et al. 2006; Comtois et al. 2010; Doniol-Valcroze et al. 2012; Ramp and Sears 2013; Lesage et al. 2016; Moors-Murphy et al. 2017; Simard et al. 2016). Together, these studies indicate that blue whale distribution in the western North Atlantic changes seasonally. Individuals occur in waters ranging from Davis Strait south to the Gulf of Maine including Canadian waters during summer. They range from the SLE and GSL south to at least South Carolina and possibly further south during winter, although survey efforts north of the SLE and GSL and south of Canadian waters at that time of the year remains limited. Areas of blue whale concentrations are relatively well-documented in the SLE and northwestern GSL (nwGSL) during the summer and fall period owing to long-term survey efforts. However, this is not the case for most other regions or during other seasons where research efforts have been more limited or more recent.

Historical Distribution and Densities

The blue whale historical distribution is based largely on the IWC whaling records and Newfoundland Annual Fisheries Reports from the early 1900's to the early 1970's (Mitchel 1974; Mitchell and Reeves 1983; Sutcliffe and Brodie 1977; Dickinson and Sanger 2005; Abgrall 2009; Moors-Murphy et al. 2017). Substantial catches were made during this period in areas off Sept-Iles in the nwGSL (not shown on Figure 2), the Belle Isle Strait / Mecatina Trough in the northeastern GSL, around Newfoundland, in southern Labrador, and in Davis Strait. Blue whales were taken in limited numbers off Nova Scotia in the 1960s, but were observed regularly in this region from May to November, with most sightings between July and October (Sutcliffe and Brodie 1977) (Figure 2). Off northern Newfoundland and southern Labrador, including the Belle Isle Strait / Mecatina Trough, blue whales were mainly taken in June and July (Sergeant 1953; 1966; Jonsgård 1955). Around Newfoundland, most blue whales were taken off the south coast of the island, followed by the Belle Isle / northeastern GSL, with few taken to the east of Newfoundland, in coastal Labrador, and in northeast Newfoundland (Abgrall 2009). While the shore-based whaling station was in Sept-Iles on the north shore of the nwGSL, it is unclear where exactly blue whales were taken. However, the Mingan Island Cetacean Study (MICS) research group established their research station in the late 1970's just east of Sept-Iles on the basis of recurrent observations of blue whales in nearby waters (R. Sears, MICS, pers. comm.). Catch distribution were influenced by location of whaling stations; but assuming areas of higher catches also reflect those of blue whale concentrations, we conclude that the area off Sept-Iles in the nwGSL, along with southern Newfoundland and the Mecatina Trough region were particularly favourable habitat to blue whales. The Scotian Shelf would seem to be of lower importance for the species based on catches, but sighting reports during this period and more recent sighting and PAM data may change this perception (see below; Moors-Murphy et al. 2017).

The current use of these various areas by blue whales will be reviewed in the next section. However, there is evidence for a relatively contemporary change in blue whale distribution in the nwGSL where survey effort has been continuous over the past 37 years. Specifically, the area off Mingan and east of Sept-Iles where blue whales were taken in the early 1900s and where they were seen on a regular basis in the 1980s, has been essentially abandoned by blue whales since the early 1990s, although solitary animals are still occasionally reported in the area (Figure 3; Ramp and Sears 2013).

Similarly, there is also some evidence for a distribution shift on the Scotian Shelf. In the 1960's, many sightings were reported by whalers on the western Scotian Shelf, but more recent sightings are now rare despite there being some effort in those western SS areas.

Current Distribution and Densities

The vast majority of past survey efforts come from coastal waters of the SLE and nwGSL that are accessible using small craft, and mainly for the period from June to October. This region is thus where blue whale seasonal use is best understood. Blue whale sightings data are sporadically acquired in other regions of eastern Canadian and U.S. waters and are systematically forwarded to the MICS by all parties. Photo-identification data indicate that females are seen slightly more often than males in the SLE and GSL (Ramp et al. 2006), and that numbers using this region vary widely between years; over the period from 1980 to 2008, the number of blue whales visiting the SLE and GSL varied from a minimum of 22 to 109 different individuals depending on years (Ramp and Sears 2013). These data also indicate some degree of site fidelity with 67% of the individuals seen in more than one year (Ramp and Sears 2013).

The intensive and sustained survey efforts in coastal waters of the SLE and nwGSL over the past several decades (Ramp and Sears 2013), combined with more recent and regular systematic line-transect surveys (Kingsley and Reeves 1998; Lawson and Gosselin 2009; McQuinn et al. 2016), passive acoustic monitoring (Simard et al. 2016), satellite (Lesage et al. 2016) and radio telemetry (Doniol-Valcroze et al. 2012), and anecdotal reports (GREMM, Tadoussac, QC, unpubl. data) have allowed researchers to document seasonal blue whale density areas in this region throughout the year. In the SLE, blue whale call detections at moorings off Les Escoumins (five years: 2010-2015) and Betsiamites/Forestville (one year between July 2012 and 2013) indicate the presence of blue whales in this area mostly between July and January, with occasional detections in February-April (Figure 4; Simard et al. 2016). This is confirmed by anecdotal reports of blue whales during the period 1994-2012, and indicating a low in blue whale sightings in February in the SLE (GREMM, Tadoussac, QC, unpubl. data). In this region, reported numbers of blue whales from land-based and non-systematic boat-based surveys are generally higher in August and/or September compared to July (Edds and Macfarlane 1987; Sears and Ramp 2013). While satellite telemetry does not provide information on the relative number of individuals using the area seasonally, they indicate a continued use of the area during the fall (Lesage et al. 2016). The systematic vessel-based survey efforts by DFO, which covered the SLE weekly from April/May to October/November over the past six years is likely to provide the most consistent index for examining seasonal and multi–year trends and peak habitat use by blue whales, although these data are not available at this time (J.-F. Gosselin, unpubl. data).

Within the SLE, the northern slope of the Laurentian Channel, and shelf waters along the north shore of the sector located between Tadoussac and Portneuf are areas where blue whales are most likely to be found during summer, i.e., between July and mid-September, although they do occur and feed also over the deep waters of the Laurentian Channel (Figure 5; Doniol-Valcroze et al. 2012; Ramp and Sears 2013). Satellite telemetry indicates that blue whales continue to use these areas throughout the autumn (Lesage et al. 2016). Other sectors of the SLE where survey effort has been less intensive or regular, and are located further east, are also likely to be important to blue whales. These include the region off Betsiamites/Manicouagan where blue whale calls are detected year-round and where satellite tagging data indicate area-restricted search during the fall period (Simard et al. 2016; Lesage et al. 2016), and the sector off Les Méchins/Matane where survey effort has been more recent, non-systematic or sporadic (Ramp and Sears 2013; McQuinn et al. 2016). Additional and more systematic survey and PAM efforts are needed to document the seasonal use of these areas.

In the nwGSL, the sector of the Gaspé Peninsula located to the east of Rivière-au-Renard and extending south into the Shediak Valley to the east of Chandler, is also used recurrently by blue whales possibly during a large portion of the year (Figure 6). Sightings data from non-systematic but effort-corrected vessel-based surveys indicate concentrations of blue whales in this region from at least June/July to late summer, the period over which survey effort spans (Ramp and Sears 2013). These observations are corroborated by occasional systematic ship-based surveys conducted at the same period (McQuinn et al. 2016). Persistence of blue whales in the Gaspé area in the fall is verified by the successful tagging of blue whales in this area in September, and from local area-restricted search behaviour, indicative of foraging, in tagged individuals through October (Lesage et al. 2016). The detection of blue whale calls at a PAM station located at the entrance of Baie des Chaleurs and the Shediak Valley in late fall through February indicate that some blue whales persist in the northern part of the GSL through at least mid-winter (Simard et al. 2016). Regular anecdotal reports from various locations around the Gaspé Peninsula in January support these conclusions, although none have been reported in February during the 18 year period (1994-2012) of reporting (GREMM, Tadoussac, QC, unpubl. data).

Sectors where blue whales are most commonly observed around the Gaspé Peninsula include the slope areas off the northern Peninsula, the American Bank, the two basins located off the Gaspé Bay and to the north of the Ile Bonaventure (Figure 6; Ramp and Sears 2013; Lesage et al. 2016; McQuinn et al. 2016). Satellite telemetry data provide indications of the use of areas located further offshore that are less accessible with small crafts and thus that have gone undetected. These include the Shediak Valley, the slope waters of the Laurentian Channel, and the American and Orphan banks located off the tip of the Peninsula (Figure 6). The extent of use of these areas during the fall and at other times of the year needs to be investigated further.

Other areas of the nwGSL are also used seasonally by blue whales, but more survey effort is needed to qualify their relative importance to blue whales. These include the sectors east of Pointe-des-Monts (Pentecôte) and off Sept-Iles where several blue whales have been reported during a spring (Late April-May), summer and fall (early October) aerial survey in the early 1980’s (Sears and Williamson 1982), and where blue whales have been sporadically reported during summer and fall in more recent years (Ramp and Sears 2013; McQuinn et al. 2016; Lesage et al. 2016). Anecdotal reports in this sector confirm the presence of blue whales throughout the year (GREMM, Tadoussac, QC, unpubl. data). Other sectors include troughs located along the Laurentian Channel to the north and northwest of the Magdalen Islands, where three satellite tagged blue whales spent some time during the fall (Figure 6; Lesage et al. 2016).

The head of the Esquiman Channel and sector of the Strait of Belle Isle / Mecatina Trough was an area of intensive whaling in the early 1900’s (Figure 2; Sergeant 1966). These areas may still be used by blue whales, at least on a seasonal basis. Spring and summer aerial surveys conducted in the early 1980’s documented the presence of blue whales in this area, with larger numbers observed during summer (N = 7) compared to spring (N = 1) (Sears and Williamson 1982). Dedicated survey efforts in this region during the late 1980’s also provided regular observations of blue whales (Comtois et al. 2010). However, a PAM station located in the Strait and recording over a full year failed to detect blue whale calls (Simard et al. 2016). Anecdotal sightings from this region are relatively rare, with two reports in 18 years (GREMM, Tadoussac, QC, unpubl. data). More intensive and systematic survey effort is needed to qualify the current importance of this historically important habitat for blue whales.

Sporadic reports of ice-entrapment of blue whales in the southern Gulf and off the southwest coast of Newfoundland near St. Georges Bay from mid-February through April suggest that blue whales may use this sector and the Laurentian Channel at that time of year (Sergeant 1982; Stenson et al. 2003). A total of 26 ice entrapments involving at least 48 individuals have been reported since 1974, including an event in the Laurentian Channel in mid-March of 2014 that caused the death of at least 9 blue whales (Figure 7; Moors-Murphy et al. 2017). This latter observation indicates that relatively large number of blue whales may be found in this sector during springtime at least. PAM at a station located along the south slope of the Laurentian Channel across St. Georges Bay (referred to as ‘Old Harry’; Figure 4), and likely detecting calls around southwestern Newfoundland, provide evidence for a year-round occupancy of the area, with blue whale call detections spanning in all months (Figure 4; Simard et al. 2016). These observations, combined with satellite tagging data also indicate that Cabot Strait likely represents the main transit corridor for blue whales exiting and entering the GSL. All whales satellite-tracked outside the GSL exited via this route, whereas the one whale attempting re-entry of the GSL did so via Cabot Strait in early March (Lesage et al. 2016).

The current importance of Newfoundland and Labrador waters, including the Grand Banks, for blue whales is not fully understood. Over 20,000 nautical miles of survey effort off coastal and offshore waters of eastern Newfoundland and southern Labrador in the early 1980s failed to detect blue whales (Hay 1982; McLaren et al. 1982). While high noise levels may have masked some of the blue whale calls (H. Moors-Murphy, pers. comm.), PAM stations along the Labrador shelf and operating from late October to mid-March provided very few call detections, all in December and at the southern station (Moors-Murphy et al. 2017). Whaling data are of little use for documenting blue whale occurrence in this region, as whalers were limited by ice cover extent and did not typically venture in these waters (Sergeant 1966). More recent ship-board surveys and systematic aerial surveys conducted during the summer and fall provided only a handful of sightings in the Newfoundland/Labrador region, with only one blue whale observed off the northeast coast of Newfoundland (Moors-Murphy et al. 2017).

During these summer and fall surveys, the largest but yet limited number of blue whales seen in Newfoundland waters came from southwest and southern Newfoundland. Opportunistic sightings collected from various sources also support a greater use of southern Newfoundland waters by blue whales (Figure 8; Moors-Murphy et al. 2017). Their presence in southern Newfoundland during summer is reported near the French islands of St. Pierre et Miquelon (Desbrosse and Etcheberry 1987), while PAM data from a station located off the central Newfoundland south coast that was active between June and August also recorded blue whale calls in July and August (Moors-Murphy et al. 2017). The presence of blue whales in this region during the fall is supported by satellite tracking data from a few individuals that ventured into southern Newfoundland waters during the fall, including one whale that reached the Grand Banks in December (Figure 9; Lesage et al. 2016). PAM systems deployed in US waters detected blue whale calls throughout the winter, coming from the region of the Grand Banks (Clark 1995). Monitoring of individual tracks of blue whales using this technology also revealed the presence of several of these tracks in waters corresponding to the shelf edge in southern Newfoundland and the Grand Banks area, with several tracks located in much deeper waters (Figure 10; Clark 1995). Together, these data indicate less use of waters off eastern Newfoundland and Labrador, and a higher use of waters to the south of Newfoundland, both in near-shore and shelf edge areas, including the Grand Banks and possibly the deeper waters off the continental shelf (Moors-Murphy et al. 2017).

Information on blue whale current use of the Scotian Shelf is based largely on PAM, and a few multi-species vessel-based (Wimmer and Whitehead 2004), and aerial surveys (Lawson and Gosselin 2009). Vessel-based surveys were conducted mainly between June and September and targeted the shelf break, including some of the deep-water canyons thought to be important for bottlenose whales and sperm whales (i.e., primarily the Gully, Shortland and Haldimand canyons; Wimmer and Whitehead 2004; Whitehead 2013). The few aerial surveys conducted by DFO and the U.S. government covered the shelf and shelf break more systematically following line-transect sampling designs during July-August (see Moors-Murphy et al. 2017; Lawson and Gosselin 2009). Sightings from the whaling period came mainly from the Shelf itself and specifically its western half rather than the shelf break (Figure 2; Moors-Murphy et al. 2017). In contrast, sightings primarily occurred near the shelf break in more recent systematic summer surveys (Moors-Murphy et al. 2017), an observation supported by anecdotal sightings reports at all times of year (Figure 8; Moors-Murphy et al. 2017). Blue whale use of deep-water canyons and adjacent areas of the eastern Scotian Shelf is confirmed by regular sightings during vessel-based summer surveys (Whitehead 2013; Moors-Murphy et al. 2017), and by blue whale call detections throughout the year, but predominantly during summer and winter, on PAM stations located in and near these canyons (Moors-Murphy et al. 2017). Sightings in the spring and fall are scarce; satellite telemetry indicates blue whale movements through this area at these two periods, but whether they spend a significant amount of time in these areas remains unknown (Figure 1; Lesage et al. 2016).

Blue whales are rare in the shelf waters of the eastern U.S. where survey effort is continuous and systematic (see Reeve et al. 1998 for a review). They have occasionally been seen off

Cape Cod in summer and fall (Wenzel et al. 1988), and in the Gulf of Maine, with 17 sightings reported over a period of 28 years (Ramp and Sears 2013). The six individuals with an exact position available and reported by Ramp and Sears (2013) indicated the use of the Jeffrey's Ledge and Stellwagen Bank area, with one sighting coming from the Bay of Fundy.

There are very little data to determine the contemporary use and relative importance of the Davis Strait and areas off West Greenland to blue whales. Only four sightings of blue whales were reported to the MICS over the past 37 years from these areas (Ramp and Sears 2013).

Connectivity Among Areas and Transit Corridors

The satellite tagging data indicate a strong connectivity among the various areas of concentration of blue whales in Canadian waters (Figure 9; Lesage et al. 2016). Specifically, they indicate movements of blue whales between the SLE and several areas of concentration in the nwGSL, southern Newfoundland, the Grand Banks, the Scotian Shelf, and U.S. and international waters. These data also indicate that Cabot Strait represents the main corridor for movements in and out of the GSL, whereas the Honguedo Strait represents the obliged transit area to access the nwGSL and SLE. The absence of blue whale calls on the PAM station located in Belle-Isle Strait during the full year of recording suggests that this region may not be used as entry/exit route (Simard et al. 2016).

FORAGING HABITAT SELECTION AND SUITABILITY

Foraging energetics and whale-krill associations

Blue whale foraging behaviour and energetics have been studied in great details in the Pacific and in the SLE and GSL (e.g., Croll et al. 2001; Calambokidis et al. 2008; Goldbogen et al. 2011; 2012a; 2012b; 2013; 2015; Doniol-Valcroze et al. 2011; 2012; Potvin et al. 2012; McQuinn et al. 2013a; Friedlaender et al. 2015; Hazen et al. 2015). In the SLE, blue whales conform to optimality rules when foraging (Doniol-Valcroze et al. 2011). Optimal foraging theory predicts that blue whales should increase the time spent in a food patch as its depth increases (Mori 1998), up to their physiological limit (Goldbogen et al. 2011), and that for equal-quality prey aggregations, blue whales should preferentially exploit patches located closer to the surface. Blue whales in the SLE increased foraging time and the number of lunges (foraging attempts) per dive as diving depth increased, and showed higher feeding rates at shallow depths, confirming the benefit of foraging close to the surface when possible. Blue whales also rarely fed at depths deeper than 100 m during the day in this area (Doniol-Valcroze et al. 2011; 2012), even though they are capable of feeding at depths approaching 300 m (e.g., Calambokidis et al. 2008). The majority of their feeding activity was also at night, when krill was near the surface and feeding rate (number of mouthful per hour) was the highest (Doniol-Valcroze et al. 2011).

Acoustic mapping of krill densities by species in combination with marine mammal observation data (MMO) during regional-scale surveys in the nwGSL have advanced our understanding of the medium- and fine-scale associations between blue whales and their prey (McQuinn et al. 2016). McQuinn et al (2015; 2016) have summarized the information on krill densities in the SLE and GSL for missions conducted between May and September of 2000-2014. They have determined that significant krill aggregations were located northeast of Anticosti Island, in the western Anticosti Gyre, in the Pentecôte area at the mouth of the SLE, in the Laurentian Channel and along the north and south shores of the SLE, in the Gaspé Current and off Gaspé (Figure 11). Some of these are slope regions that have been previously flagged for their high krill biomasses (e.g., Berkes 1976; Simard et al. 1986; Simard and Lavoie 1999; Lavoie et al. 2000). Slope areas were also identified as important blue whale foraging areas in a study coupling topographical features to observations of foraging individuals (Figure 5a; Doniol-Valcroze et al. 2012). The failure to identify offshore waters as a suitable habitat for blue whale foraging in the latter study may result from not including krill data as predictors for habitat suitability. In recent years, addition of MMOs and acoustic distinction between krill species (McQuinn et al. 2013b) has allowed examination of species-specific associations. Overall, blue whale densities were the greatest in slope areas where Arctic krill was the dominant species (McQuinn et al. 2016), and in areas where krill aggregations were located closer to the surface (Figure 12; McQuinn et al. 2013a; 2016). Specifically, no blue whales in the SLE and GSL were observed when the mean biomass·stratum^{-1} of Arctic krill in the top 100 m was low (average 2,000 tonnes·stratum^{-1}) even though krill biomass below 100 m was high (average 80,000 tonnes stratum-1. In contrast, blue whales were present in strata with much smaller mean biomass of Arctic krill (approx. 25,000 tonnes·stratum^{-1}) when biomass of krill located at depths above 100 m was high (average 10,000 tonnes·stratum^{-1}) (McQuinn et al. 2013a). Additional data collection and analysis further indicated that blue whales were specifically associated with shallow water krill swarms (0-80 m) more than all other krill configurations in daytime (McQuinn et al. 2016). While this association may pertain to any krill species at these shallow depths, the dataset indicated a statistical association only for *T. raschii*.

The benefits for a blue whale feeding on a given prey concentration is determined by the combination of local density, lipid or energetic content, both of which may vary seasonally according to body condition and reproductive status as well as by prey species. These benefits need to be put into the perspective of the costs associated with prey capture, such as the energy expenditure to reach depths where each of the prey is located. The two main prey of blue whales, Arctic krill and northern krill, differ drastically in size and energy content, with northern krill being larger than Arctic krill (both *T. inermis* and *T. raschii*), but the latter being a more energetically dense prey (J. Cabrol, UQAR, Rimouski, unpubl. data). They also differ in their vertical distribution, with northern krill generally occupying deeper, warmer waters than Arctic krill (e.g., Plourde et al. 2014; McQuinn et al. 2015). In the SLE and GSL at least, Arctic krill is also generally more densely aggregated than northern krill (McQuinn et al. 2015). This makes a mouthful of Arctic krill more rewarding than a mouthful of northern krill at equal energy density (kJ g^{-1}). In other regions such as the Scotian Shelf or the Gulf of Maine where northern krill appears to be a lot more abundant than Arctic krill (Kulka et al. 1982; Corey 1983), blue whales may have no other choice but to feed at greater depths on northern krill to reap benefits.

In the SLE and GSL, the study coupling hydroacoustic surveys with blue whale observations indicated that blue whales are more strongly associated with prey patches consisting of Arctic krill than of northern krill (see above; McQuinn et al. 2013a; 2016). This does not mean that blue whales do not exploit northern krill in this or other areas. Diet data indicate that this species is part of the blue whale diet during spring and summer (Gavrilchuk et al. 2014), and blue whales are physiologically capable of reaching depths where northern krill are located (e.g., Calambokidis et al. 2008). Whether northern krill are consumed at depth or when they occur closer to the surface is unclear. It is possible that blue whales consume northern krill more frequently at night when they move nearer to the surface, or when they form dense surface swarms during daytime (Kulka et al. 1982). There are several anecdotal reports of blue whales surface-feeding on this species in the SLE and GSL suggesting that reports of daytime surface feeding on northern krill are plausible (e.g., Sears et al. 1987; Lesage, DFO, Mont-Joli, pers. obs.; McQuinn, pers. obs.). Northern krill also appear to have increased in abundance in the SLE and GSL over the past four years (McQuinn et al. 2016), a phenomenon that is mirrored in the diet of blue whales (Gavrilchuk et al. 2014). Both species should therefore be considered as important prey for blue whales.

Coupling of surface observations of blue whales with density estimations of krill obtained via hydroacoustic surveys indicates that blue whales exploit aggregations of krill; however they are not associated with the densest part of the aggregations (measured at 63 g m^{-2}) (McQuinn et al. 2016). In this study, blue whales tended to occur more often on the periphery (within 3 km) of, as opposed to directly over, the densest aggregations within patches. This observation suggests that their behaviour may not be driven solely by total biomass or integrated density of krill aggregations; above a certain density (at least 31 g m^2) (McQuinn et al. 2013a), other aspects of the patch, such as their depth location and relative accessibility, may become more important (McQuinn et al. 2016).

Overall, these results confirm that prey depth strongly interplays with prey density and biomasses in defining habitat quality and bioenergetics of foraging. Recent studies add complexity to the definition of a profitable foraging habitat and to energetic efficiency models. One study indicates that blue whales perform more acrobatic and energetically costly manoeuvres when foraging on low-density krill patches, and show higher feeding rates and less acrobatic lunges when targeting higher-density patches (Goldbogen et al. 2015). A second study demonstrates that blue whales switch foraging strategies in response to variation in prey density to conserve oxygen and maximize energetic efficiency (Hazen et al. 2015). Some models defining krill densities that correspond to when blue whales should leave a patch are available for blue whales (Goldbogen et al. 2011); however, these thresholds are biased upwards given that models ignore the fact that blue whales may feed around the clock (Doniol-Valcroze et al. 2011) and thus do not account for the energy acquired during the night. Clearly, bio-energetic models integrating these phenomenon along with seasonally-changing activity budgets that include feeding during the night, realistic species-specific biomasses, densities and energy contents, are needed to determine the thresholds beyond which a prey patch may no longer be of interest to a blue whale.

Predicting the location of krill and blue whale aggregations

As well as the small-scale factors that determine what constitutes a profitable krill patch, the medium- to large-scale distribution of krill patches in recurrent and predictable areas is of crucial concern to these nomadic foragers. The distribution of krill or whale densities alone may help address habitat suitability. However models using a validation dataset and incorporating prey densities and other static and dynamic environmental correlates along with whale densities are likely to be the most informative for understanding where these recurrent and predictable feeding areas are likely to occur (see Doniol-Valcroze et al. 2012; Maps et al. 2015).

Abrupt topography has been identified as a feature of the habitat often associated with krill aggregations, both in the SLE and GSL and elsewhere (e.g, Sameoto 1976; Simard et al. 1986; Simard and Lavoie 1999; Croll et al. 2005; McQuinn et al. 2015). This combined with modelling studies (e.g., Sourisseau et al. 2006; Maps et al. 2014; Lavoie et al. 2015) and what is known about zooplankton spatial dynamics (Mackas et al. 1985; Genin 2005), suggest that the spatiotemporal variability of the circulation, topography and krill swimming behaviour contribute to the patchy distribution of krill (see Simard 2009; Maps et al. 2015). Until recently, models of krill transport assumed that krill particles needed to stay at depth to remain in the GSL (e.g., Sourisseau et al. 2006). By following modelled finite-time Lyapunov exponents (FTLE), Maps et al. (2015) demonstrated that surface circulation features such as currents are, in contrast to previous beliefs, not an obstacle to the accumulation of zooplankton biomass in the GSL but instead have an important role in forming krill aggregations. These authors showed that krill, either entirely within the surface layer or migrating between the surface and their daytime depth (DVM), converged to specific areas that were not necessarily along slopes. Lavoie et al. (2015) used coupled 3D hydrodynamic and krill modeling over a 5-year cycle to evidence the control of krill distribution and aggregation in the SLE and GSL by large-scale oceanographic and meteorological processes. These included two main seasonal circulation patterns driven by local wind forcing and transport at Cabot Strait and at the Strait of Belle Isle, extratropical storms passing over the SLE and GSL, and contribution of the transport in the surface layer (where krill are found at night). These findings are important because they allow us to better understand the presence of foraging blue whales other than in areas of abrupt topography (Doniol-Valcroze et al. 2012).

Modeling Approaches

Initial attempts to predict habitat suitability for blue whales in eastern Canada were made using a combination of blue whale sightings and environmental correlates, not including krill aggregations (i.e., related to topography, SST, and primary productivity) (Abgrall 2009). This analysis was conducted using presence-only data from the IWC whaling records along with (mostly opportunistic) sightings around Newfoundland to make predictions for the entire eastern Canadian region. With the caveat that this database was strongly biased by including only a handful of sightings in the SLE and GSL where most blue whales are currently reported, this analysis identified the GSL and waters off the southern coast of Newfoundland as the most suitable habitats for blue whales, with other core habitat also being identified along the coastlines of northeast Newfoundland and coastal Labrador, and farther offshore, following the steep continental slope (Abgrall 2009). Blue whale distribution in these waters was found to be best characterized by areas of deep water and steep seabed slope. When challenged with a small set of new sightings records that were not used in the original analysis, the habitat suitability model proved to be fairly accurate, with 7 of 11 blue whale sightings falling into the 15% of habitat that was considered as core by Abgrall (2009).

This dataset, with the addition of the newer blue whale sightings, was used in a Species Distribution Model (or SDM) (Moors-Murphy et al. 2017). The SLE and GSL were excluded from the analysis but it was expanded to include the Scotian Shelf. Variants of the environmental variables used previously were included in the model along with the geographic location of blue whales to identify spatial relationships. After accounting for sampling biases, i.e., absence of whales in potential suitable habitat due to lack of survey effort, and overrepresentation in regions with high sampling efforts (e.g., the Gully or areas near those with important commercial fishing), the model identified sea surface temperature during summer and ocean depth, and to a lesser extent chlorophyll magnitude during spring, as important correlates to blue whale distribution. In general, deep water areas along the continental slopes of the Scotian Shelf and the Grand Banks, the Laurentian Channel, as well as shallower areas on the western Scotian Shelf and the shelf off southern Newfoundland were considered habitat of medium to high suitability (Figure 13; Moors-Murphy et al. 2017). Deep water regions beyond the shelf break exhibited low to very low habitat suitability for blue whales; however, they were also areas where survey effort was poor or non-existent.

In the SLE, a blue whale presence-only model coupled with a reduced set of environmental variables highlighted topographical features as important explanatory variables for foraging blue whale distribution, and indicated that plateaux and deep areas with relatively flat bottoms were also exploited by feeding blue whales at certain times of the tidal cycle (Figure 5a; Doniol-Valcroze et al. 2012). The authors cautioned about habitat suitability models tending to identify false positives and not discriminating well between potential and actual high-quality habitats when dynamic features of the habitat (e.g., 3D currents, fronts) and information on krill vertical and horizontal distribution are not included in models (Doniol-Valcroze et al. 2012). Unfortunately, an analysis incorporating krill distribution in a habitat suitability model was not possible at the time this document was produced, but will be conducted to refine habitat suitability predictions.

Until recently, data on krill distribution and densities in eastern Canada were extremely limited, except in the SLE at the head of the Laurentian Channel where repeated hydroacoustic surveys were conducted (e.g., Simard et al. 1986; Simard and Lavoie 1999). Over the past few years however, there has been extensive hydroacoustic survey efforts in the SLE and GSL in particular, but also on the Scotian Shelf and in southern Newfoundland, to document krill seasonal distribution and densities, transport and aggregation mechanisms, and production (e.g., Gagné et al. 2013; Plourde et al. 2014; Maps et al. 2014; 2015; McQuinn et al. 2015; McQuinn et al. 2016). Coupled with a new capacity to distinguish between krill species using multi-frequency hydroacoustic signals (McQuinn et al. 2013b), this has allowed us to refine our understanding of krill ecology and distribution down to the species level, and identify environmental correlates to krill aggregations (Plourde et al. 2016).

A habitat model coupling static and dynamic features of the physical and biological environment with acoustically-estimated krill biomasses in the SLE and GSL indicated that static (bathymetry, slope) and dynamic (sea surface temperature, surface chlorophyll a, surface height) environmental variables contributed to explain a significant percentage of the deviance in krill biomass spatial distribution in this region (Plourde et al. 2016). While optimal environmental conditions associated with high krill biomass varied among species and seasons (Plourde et al. 2016), the strong contribution of dynamic environmental variables to the model regardless of species or seasons emphasizes the key role of bio-physical processes in controlling krill distribution.

Modelling results for total krill biomass (sum of all species) were then used to predict the probability of finding dense krill aggregations in waters of eastern Canada and northeastern US, including the SLE and GSL, the Scotian Shelf, the Newfoundland shelf, and the Gulf of Maine--Bay of Fundy area, both in the spring (May, June) and summer (July, August, September) over a 5 year period (2009-2013) (Plourde et al. 2016). Overall, cells with at least one dense krill aggregation predicted to occur represented only 10% of the entire spatial domain. Among these cells, ‘Significant Areas of Krill’ (SAK, i.e., with a >50% probability of occurrence) represented 32% and 27% of locations in the spring and fall, respectively, indicating that while dense krill aggregations may form elsewhere, krill aggregations identified as SAK are likely to be more predictable or recurrent. Based on these predictions, SAK formed continuums in the SLE and GSL regions in the spring, notably in the lower SLE and along the Gaspé Peninsula into the southern GSL, along the coast in the northern GSL, and around Anticosti Island (Figure 14a). At that time of year, there were also large SAK predicted in the eastern GSL (head of Esquiman channel), on the eastern Scotian Shelf, in the outer Bay of Fundy and in western Gulf of Maine, with smaller SAK spread along the slope of deep channels of the continental shelf and on the western Scotian Shelf. In summer, several SAK observed in the spring in the lower SLE, in the GSL and in the Gulf of Maine/ Bay of Fundy were smaller and more discontinuous than in the spring. However, larger SAK were predicted off southern Newfoundland, on the eastern Scotian Shelf and in the Gully (Figure 14b; Plourde et al. 2016). The small fraction of cells predicted to have SAK over the entire spatial domain (2.2%) emphasizes the highly dynamic nature of dense krill aggregations in Canadian waters (Plourde et al. 2016) that result from the complex bio-physical coupling between krill swimming behaviour and physical processes (Sourisseau et al. 2006; 2008; Maps et al. 2014; Maps et al. 2015, Lavoie et al. 2015).

ACOUSTIC HABITAT

Blue whales, like other marine mammals, rely on acoustic signaling and passive listening to complete their normal activities (Dreher and Evans 1964; Payne and Webb 1971; Richardson et al. 1995). Human activities may interfere with the behaviour of marine mammals both by direct interference (physical disturbance), or through the noise they generate (Nowacek et al. 2007; Clark et al. 2009; Parsons 2012; Pirotta et al. 2015).

Noise associated with human activities is ubiquitous in the world oceans, and has dramatically changed their acoustic landscape (McDonald et al. 2006; Hildebrand 2009; Frisk 2012). Effects of acute sounds associated with seismic surveys, military sonars and construction activities have been intensively studied (see reviews in Nowacek et al. 2007; Southall et al. 2007; Tyack 2008; Clark et al. 2009; NMFS 2016). However, of more recent and particular concern is the chronic exposure to shipping noise, which has contributed largely over the past 50 years to an overall increase in low-frequency ambient ocean noise of at least 10 dB from preindustrial conditions to present, through an increase in the world fleet and ship gross size (Hildebrand 2009; Chapman and Price 2011; Frisk 2012). Effects of shipping and other chronic forms of ocean noise have more in common with habitat degradation or loss (Barber et al. 2009; Clark et al. 2009) than with a dose-response relationship that may characterize other forms of disturbance such as when animals are faced with high-amplitude, acute noise sources (Richardson et al. 1995).

The St. Lawrence is a major commercial seaway to Central Canada and the U.S. Midwest, and available data on commercial shipping shows considerable traffic in the SLE and GSL, and in areas closer to coastal waters off Newfoundland and Nova Scotia (Simard et al. 2014). However, shipping is poorly documented along the coast of Labrador and in > 100 km offshore areas, although merchant traffic in this northern area is known to be limited. Seismic survey coverage has been extensive in blue whale habitat, and continues to develop in the southern GSL, and near the shelf edge of Nova Scotia and Newfoundland (Moors-Murphy et al. 2017). All this activity is likely to raise ambient noise and interfere with normal activity of marine mammals, including blue whales, by reducing their communication space (e.g., Clark et al. 2009; Gervaise et al. 2012; Hatch et al. 2012; Aulanier et al. 2016).

A recent study examined the quality of the acoustic environment of blue whales at the low frequencies they use in their communication and which is in the bandwidth where shipping noise is the highest. Commercial traffic position and transit routes in the SLE and GSL, monitored via an Automatic Identification System (AIS) and for the months of July and January were combined with in-situ–measured ship source levels (SL) to estimate the insonification area using a simulation approach, with a sound propagation modeling configured with the environmental conditions (Aulanier et al. 2016). The amount of noise radiated by shipping in the blue whale call frequency band was validated with in situ measurements. Shipping noise statistics were calculated for 10 depth layers to map the shipping noise level cumulative distribution function (cdf). The cdf was then used to estimate the risk of exceeding or staying below given noise thresholds, so to identify at-risk and quiet areas. The results indicate that shipping masks the two main call types of blue whales and reduces their communication space, with effects increasing with proximity to shipping lanes and density of traffic (Aulanier et al. 2016). In the Laurentian Channel shipping noise exceeded ambient levels 95% of the time. The highest shipping noise quartile spread to the entire study area except shallow waters. Using thresholds commonly assumed to cause behavioural responses to continuous noise in cetaceans (i.e., SPL of 110 dB and 120 dB re 1 uPa RMS (Southall et al. 2007; Hatch et al. 2012) as a proxy for indicating degradation of habitat and potential masking effects and interference with normal behaviour, the authors conclude that the amount of habitat exposed to this risk and location of high-risk area change depending on depth, frequency and season (Figure 15). Overall, the risk of exceeding the lowest of the two threshold might exist up to 30% of the time at ranges up to about 20 km from shipping lanes (Figure 15 a and b). The radius of effects declines to 5 km or less when using the upper threshold (Figure 15 c and d). Consequences of this increase in ambient noise for the receiving whales at 25 m and 75 m, the probable depths of feeding whales

(Doniol-Valcroze et al. 2011; 2012), vary with location of the emitting whale and call type. A reduction of blue whale acoustic space can be less than 10% during 80% of the time in the Laurentian Channel for A-call, or more than 90% during 90% of the time for D calls. Relatively close to ship traffic in areas of lower traffic, masking is less frequent, but can be almost total when a ship is passing (Aulanier et al. 2016).

This study indicates that masking in most of the SLE and GSL is considered low for blue whale A-calls, but severe for D-calls. The following considerations can be taken into account in future studies. First, since blue whales are not uniformly distributed but concentrate in particular areas (e.g. slopes, basins), particular attention should be put to the intersection of these used areas with the high exposure areas. Second, this study focused on the merchant traffic, but there is also non-commercial traffic in the SLE that is not accounted for in this analysis if they were not equipped with the AIS system. This focus on merchant traffic was selected on purpose since source level measurements indicate that the contribution of small vessels (< 50 m) to low-frequency shipping noise is much lower (by ~ 30 dB, Gervaise et al. 2012) than that of merchant ships. A very large non-commercial fleet (~ one thousand transits) would be needed to contribute the same amount of low-frequency noise as a single merchant ship. However, this small-vessel traffic would reduce the amount of quiet times. Therefore it would be advised in future studies to consider effects from small vessel traffic on insonification time and on their relative contribution at frequencies higher than those considered in this study.

QUANTITY AND QUALITY OF HABITAT

We are unable to quantify the total amount of habitat necessary for a blue whale to complete its annual cycle, or for the population to maintain itself or fully recover. Uncertainty associated with the energetics of foraging on various densities of prey of various qualities and at different depths, and associated effects on body condition and vital rates preclude this exercise at this time. As we have demonstrated, there is a lot more to the quality of a foraging habitat than just total biomass of krill (e.g., Doniol-Valcroze et al. 2011; McQuinn et al. 2013a; 2016), and we should refrain from estimating habitat quality and potential for recovery based on total krill biomass alone.

ACTIVITIES MOST LIKELY TO DESTROY HABITAT PROPERTIES

Activities likely to result in the destruction of the biophysical functions, features and attributes of important habitats identified here are summarized in Table 1. Some of the activities that may lead to such effects are discussed below.

While there is a constant debate as to whether climate change should be included or not with other human activities with a potential to affect or destroy habitat functions, features and attributes, there is a need to consider other threats in the perspective of this ongoing process. In the Southern Ocean for example, krill abundance showed a significant decline between 1976 and 2002, a trend that has been associated with a decrease in sea ice cover (Atkinson et al. 2004). Projections based on various climate change scenarios suggest a decrease of 20% in the optimal habitat range of Antarctic krill in the late 21st century (Hill et al. 2013). In the northwest Atlantic, blue whales feed on different species of krill that have different energy content, vertical distribution, and preferred temperatures (Gavrilchuk et al. 2014; McQuinn et al. 2015; this document). The Arctic krill is a cold-water species that reaches the southern margin of its distribution range in the SLE and GSL (Simard 2009; McQuinn et al. 2015; 2016). The region is warming and several highly anomalous warm years have been observed since 2010 (Galbraith et al. 2015), potentially resulting in a decrease of arctic krill biomass since 2009 (McQuinn et al. 2016). Giving that scenarios of future climate changes predict that eastern

Canadian waters will get warmer (Loder and Zang 2015), one could foresee a gradual decrease in Arctic krill habitat quality in the future.

Fishing activities

Currently, there is a moratorium on commercial krill fishing in eastern Canada. Studies of krill distribution, production and transport in the St. Lawrence system indicate that biomasses of krill observed in the SLE and GSL are interconnected (Sourisseau et al. 2006; 2008; Maps et al. 2014; Gagné et al. 2013; Lavoie et al. 2015). By reducing local krill biomass and patchiness, krill exploitation is most likely to affect krill availability, in terms of biomass and density, in other sectors.

Blue whales are capital breeders, provisioning their offspring using energy stores accumulated earlier (Houston et al. 2007). It is estimated that blue whales require on average 3.3% of their body mass in krill daily during the feeding period in order to successfully complete their yearly cycle (Wiedenmann et al. 2011). In other species such as right whales, reproductive success has been linked to prey abundance and amount of energy reserves (Greene and Pershing 2004; Leaper et al. 2006; Miller et al. 2011). In Antarctic blue whales, reduction of prey abundance and its link to foraging and reproductive success is predicted to be non-linear, suggesting there is a threshold below which negative effects accelerate (Wiedenmann et al. 2011).

There is only a limited understanding, based largely on modelling exercises, of what constitutes an attractive food patch for a blue whale, and of the threshold beyond which exploitation is no longer profitable. A study in the Antarctic has modelled the potential effect of an increased krill fishery on blue whale survival and reproductive success, and has identified 110 $g \cdot m^{-3}$ as the threshold value below which blue whales are predicted to reject krill swarms (Wiedenmann et al. 2011). This value is similar to that obtained for blue whales in the Pacific (Goldbogen et al. 2011), although another study proposed a much lower threshold value of 100 krill per m^3 (or 12 $g \cdot m^{-3}$) for inefficient foraging in Pacific blue whales feeding on a krill species of a size similar to *Thysanoessa rachii* (Hazen et al. 2015). As acknowledged by the authors, the model applied was relatively simplistic. For example, it assumed that whales fed only during the day, while SLE data indicate that blue whales in this region feed around the clock (Doniol-Valcroze et al. 2011). The model also did not account for all the complexity in krill aggregations and their spatial distribution as they included only the densest swarms, and did not incorporate factors that might mitigate the impact of the fishery on blue whales. In the SLE, blue whales have been observed feeding on krill densities much lower than 110 $g \cdot m^{-3}$ (McQuinn et al. 2016).

We recommend using these thresholds with extreme caution. Profitability depends on many factors, including prey depth and prey energetic quality (Goldbogen et al. 2015) and thus, it is unclear whether these results apply to blue whales in the northwest Atlantic, given different prey species, vertical distribution, biomass and energetic quality. Blue whales in some areas of the Pacific feed at depths on average much greater than those reached by blue whales in other foraging areas such as the SLE and GSL (Doniol-Valcroze et al. 2012; McQuinn et al. 2013a). In addition, a fishery may not need to reduce krill biomass below these thresholds in order to affect blue whale foraging and capacity to build their energy reserves. By lowering local biomass density, fisheries may reduce the time for a blue whale to deplete a krill patch below its optimal efficiency threshold, shortening foraging time and forcing the animal to find alternate prey patches earlier than in a non-exploitation scenario.

Shipping and other industrial activities contributing to raise ambient noise levels

As reviewed above, anthropogenic noise has the potential to interfere with normal activities of blue whales. While in Canadian waters, blue whales face two main sources of sound that may increase ambient noise and reduce their capacity to feed, find mates, or navigate. These include vessel-generated noise, a chronic source of noise, and seismic activity associated with oil and gas exploration, a more acute sound source. While ship traffic occurs over vast areas in eastern Canadian waters (Simard et al. 2014; Aulanier et al. 2016), seismic surveys and oil and gas exploration is currently limited to the southern GSL, the Scotian Shelf and waters around Newfoundland and Labrador (e.g., Moors-Murphy et al. 2017). The capacity of seismic surveys to considerably raise ambient noise over long-distance is well documented (Clark et al. 2009; Guerra et al. 2011). The degree of habitat degradation associated with this activity in Canadian waters is currently unknown. However, given that most of this activity is concentrated along the continental shelf and near or in the Laurentian Channel in the southern GSL, the potential for it to result in degradation of the acoustic environment of blue whales is high.

A study conducted in the SLE and GSL indicates that ship traffic reduces the quality of the acoustic environment of blue whales, and reduces their communication space. In proximity with shipping lane and when traffic volume is high, this effect maybe nearly continuous (Aulanier et al. 2016). Shipping lanes are largely located near, or within, areas where blue whales aggregate or transit in the SLE, western part of the GSL, and at the Laurentian fan off southwestern Newfoundland. The spatial and temporal zone of influence of shipping noise in the Critical Habitat of blue whales, if designated, should be examined to determine the importance of this threat. Consequences of this chronic increase in ambient noise, and thresholds above which they impair normal activities of blue whales, are currently unknown.

Whale-watching activities

Vessel traffic may disrupt normal activities of marine mammals in addition to exposing them to collision risks (Richardson et al. 1995; Laist et al. 2001; Nowacek et al. 2007; Clark et al. 2009; Parsons 2012; Pirotta et al. 2015). Whale-watching is a form of vessel traffic in which boat operators and tourists specifically seek to interact with marine mammals. This activity is a lucrative business that has developed rapidly and widely worldwide over the past decades (O'Connor et al. 2009). In eastern Canada, there is a well-established whale-watching industry in the SLE and to a lesser extent along the Gaspé peninsula in the nwGSL, which targets, among other species, blue whales. There are also ongoing research programmes, where scientists must get close to the animals to conduct their research.

Behavioural responses to vessels and whale-watching activities have been documented in a variety of marine mammal species, and were found to vary widely between studies (e.g., Richardson et al. 1995 and Parsons 2012 for reviews), most likely as a result of context of exposure. Indeed, a variety of factors may influence the severity of observed behavioural responses including characteristics of the sound source (e.g., vessel speed, manoeuvres, number of vessels, configuration around the whale, acoustic output, etc.) and those of the whale including its current activity, age, and prior exposure to the stimuli (Gill et al. 2001; Wartzok et al. 2004; Southall et al. 2007; Ellison et al. 2012). Repeated or persistent behavioural disruptions may carry energetic costs potentially having long-term consequences on vital rates through loss of foraging opportunities, or a reduction in the capacity to detect mates, predators, and sense their environment as a result of loss of acoustic space (e.g., Bejder et al. 2006; Williams et al. 2006; Lusseau and Bejder 2007; Clark et al. 2009; Christiansen et al. 2013a, b; Symons et al. 2014).

The degree of exposure of blue whales to whale-watching activities and to research vessel activities, and consequences on surface and foraging behaviour have been documented for blue whales in the SLE (de Albuquerque Martins 2012; Lesage et al. 2017). Vessels, of which 80 to 94% were related to whale-watching (the rest being transiting ships or research vessels), were present around blue whales on average 59% (SD = 31%) of the observation time and 74% of the surface intervals in the two studies. Their presence within a 2,000 m radius from a whale affected surface time, the number of blows per breathing sequence, and dive time (Lesage et al. 2017); these metrics progressively declined with increasing proximity of vessels to the whale at the beginning of the breathing sequence. At distances ≤ 400 m, vessels induced a 49% shortening of surface time and a 51% reduction in the number of breaths taken, which reduced dive duration by 36% (Lesage et al. 2017). Blue whales in the SLE spend most (average 68%, SD = 14%) of their time foraging (Doniol-Valcroze and Lesage, DFO, Mont-Joli, unpubl. data), transit time is incompressible and invariant among individuals (Goldbogen et al. 2011), and foraging depth is fixed by where krill densities are located. It follows that the observed reduction in dive duration directly affects the time spent in the food patch. It was predicted, using optimal foraging models developed for SLE blue whales (Doniol-Valcroze et al. 2011), that these lost feeding opportunities corresponded to a 35-42% reduction in foraging time for food patches located at depths of 50 to 100 m (Lesage et al. 2016).

Therefore, we can conclude that whale-watching activities, and by extension research-related activities can reduce blue whale access to foraging habitat which in this case is krill at depth, by altering blue whale normal behaviour and limiting their foraging time at depth. The potential for destruction of habitat function increases with vessel proximity. Compensatory mechanisms available to blue whales to cope with disturbance, and the threshold beyond which they may affect their body condition and vital rates are currently unknown. The severity of effects likely depends on the persistence of the activity, the relative importance of daytime and nighttime feeding, as well as the energy return from feeding on prey patches of various qualities and depths. Currently, threshold levels leading to destruction of habitat functions by deprivation of sufficient access to food patch is unknown.

SUMMARY AND CONCLUSIONS

Blue whales feed while in Canadian waters and their distribution is linked to aggregations of krill. Arctic krill (*Thysanoessa* spp.) and northern krill (*Meganyctiphanes norvegica*) are their two main prey, but the species consumed varies seasonally and among individuals, and likely also geographically. As a result, habitats important for blue whales were identified using information on where blue whales were seen (recent or historical) and where prey aggregations were observed or predicted to occur.

Given the evidence provided above and summarized in Figure 16 and using the bounding box approach, four areas were identified as important foraging/feeding and socializing areas for blue whales (Figure 17):

1) The Lower SLE and nwGSL, where multiple data sources indicate that a near-continuum of habitat suitable to foraging blue whales occur in the shelf, slope and deep waters of the Lower SLE and nwGSL between Tadoussac and Mingan along the north shore, and the Gaspé Peninsula along the south shore, including banks in offshore waters. It is estimated that 20 up to perhaps 100 blue whales use areas within this region each year, with some using it year-round.
2) The nearshore waters south and southwest of Newfoundland, where the presence of blue whales nearly year round is indicated by opportunistic but regular blue whale sightings, and by PAM and ice entrapment data. This area is also predicted to be favorable to blue whales

based on modelled suitable habitat for blue whales and krill aggregation occurrence. This region is one where whaling was historically an important activity.

3) The Mecatina Trough area, including the head of the Esquiman Channel, where recent blue whale sightings have been scarce due to limited survey efforts, but where krill aggregations have been observed, and where blue whale presence, along that of krill aggregations are predicted to be high. This region is also one where whaling was historically important. Seasonality of use of this area remains uncertain, although there is probably higher use during the ice-free period.

4) The continental shelf edge off Nova Scotia, Newfoundland and the Grand Banks, where blue whale sightings are regularly reported during sporadic survey efforts, where calls are detected by PAM stations, and where krill aggregations and blue whale occurrence are predicted to be high. This region, including canyons, is important for blue whales, probably year-round.

Two areas were identified as migration corridors: the Honguedo and Cabot Strait (Figure 16, 17) which respectively provide access to the SLE and nwGSL, and to the GSL as a whole. Blue whales most likely need to use several of the important habitats within these areas to fulfill their biological needs. As a result, access corridors and habitat they connect need to be considered equally important for the population.

Wintering areas of blue whales in the northwest Atlantic are poorly defined. Satellite telemetry, PAM, and whaling data suggest that it is relatively diffuse, and includes the Gulf of St. Lawrence, northwestern Newfoundland, and Scotian Shelf, as well as the mid-Atlantic Bight off the U.S. coast, and warm and deep oceanic waters off this area. Whether breeding occurs in this region is unknown.

Important features and attributes of these areas are provided in Table 2 and include sufficient quantity and quality of prey, free access to transit corridors, enough physical space to freely maneuver, water of sufficient quality to not result in loss of function, and an acoustic environment that does not interfere with communication, passive detection of prey or navigation, or impede use of important habitat by blue whales or their prey. Activities likely to destroy the habitats' functions are, to the extent known, those that would result in reduced prey availability or accessibility, acoustic disturbance, environmental contamination, and physical disturbance (Table 1).

It is unknown if the important habitats identified here are sufficient to achieve the population objectives of the Recovery Strategy for Northwest Atlantic blue whales.

SCHEDULE OF STUDIES

Most of our understanding of the foraging ecology of blue whales in the western North Atlantic comes from the SLE and nwGSL. Although it can be assumed that euphausiids remain the primary focus of foraging efforts of blue whales in other regions and throughout the year, the species targeted are likely to vary between regions within eastern Canadian waters, and among seasons.

There is evidence for blue whales vacating what appears to be a suitable foraging habitat off northwest Anticosti near Mingan. This conflicting observation emphasizes the complexity of the foraging energetics of blue whales and underscores several data gaps, including the characteristics making an area attractive to blue whales, minimum energy requirements for successful reproduction, amount and annual recurrence of disturbance that blue whale can sustain before their body condition and fitness are affected. A better understanding of area-specific diet and foraging energetics may also bring perspective and help predict effects of climate variability on blue whale distribution, survival and recovery.

There also remains considerable uncertainty about the relative proportion of the population occurring in Canadian waters and in its various regions, about the relative importance of deep oceanic waters located off the shelf break both for feeding and breeding or calving, and location and limits of wintering areas. Whether mating occurs in Canadian waters is uncertain; the recording of tonal calls, which are thought to be produced by males in a breeding display context, raises questions about this additional function for habitats in Canadian waters. There is also a need to increase research efforts in offshore waters and other areas where blue whale sightings have been limited, but where the occurrence of krill aggregations or blue whales is predicted to be high.

Areas of research, including monitoring, that might help answer the important questions listed above, and further our understanding of whether habitat is sufficient for blue whale recovery include, but are not limited to the following:

- Conduct genetic analyses to determine stock structure for blue whales in the North Atlantic.
- Maintain long-term photo-identification efforts to monitor trends in use of the various areas of the Canadian waters.
- Quantitatively integrate blue whale densities with static and dynamic environmental variables, including krill species, depth and densities, to discriminate among potential habitat and those that are more likely to be exploited. It is also important to challenge these models continuously when new information on blue whale or environmental components becomes available.
- Monitor temporal trends in krill biomass and relative availability per species in the SLE and GSL, and increase multi-frequency hydroacoustic survey effort in other areas such as the Scotian Shelf and waters around Newfoundland.
- Promote the use of satellite telemetry and acoustic monitoring to document habitat use year-round, and in remote sectors such as those located near the continental shelf break or the deep-ocean waters near the New England seamounts.
- Monitor spatial, inter-individual and temporal changes in diet of blue whales.

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Table 1. Activities that have the potential of affecting functions, features or attributes of habitats important to blue whales in the western North Atlantic.

Threat	Activity	Effect Pathway	Function Affected	Feature Affected	Attribute Affected
Reduced prey availability	Capture and removal of prey species (e.g., a plankton fishery) Other activities that are detrimental to habitat of prey	Reduction in abundance and availability of prey	Feeding and foraging	Quantity and quality of prey	Krill stocks (*Thysanoessa* spp. and *Meganyctiphanes norvegica*) sufficient to support the population
Acoustic disturbance	Vessel traffic Acute and chronic in-water and/or land-based industrial sounds (e.g. pile driving, production drilling etc.) Seismic surveys using airgun arrays Military and commercial low and mid-frequency sonars	Interference with hearing and communication or alterations from normal behaviour Acoustic disturbance resulting in loss of habitat availability or function	Feeding and foraging Reproduction, socializing, resting	Acoustic environment	Ambient noise levels that allow efficient acoustic social communication and do not impede use of important habitat by blue whales
Environmental contaminants	Deposit of deleterious substances into marine environment (multiple sources could include ocean dumping, industrial developments and persistent vessel discharges in and around critical habitat)	Loss of prey or reduction in prey quality Indirect species and ecosystem level effects may also occur	Feeding and foraging Reproduction, socializing and resting	Prey quantity and quality Water and air quality	Sufficient water quality to sustain prey species and maintain access to area of prey aggregations Air quality at levels not causing adverse health effects for prey or blue whales
Physical disturbance	Vessel traffic in close proximity to whales	Reduction of physical space available to whales	Feeding and foraging Reproduction, socializing, resting	Physical space	Enough space to maneuver in vertical and horizontal planes, and not alter normal behaviour at and below the surface

Table 2. Essential functions, features and attributes of habitat considered important to blue whales in the western North Atlantic.

Life stage	Function	Feature(s)	Attribute(s)
All Adult females and calves Adult males and females	Feeding/Foraging Rearing Courtship/mating	Prey (*Thysanoessa* spp. and *Meganyctiphanes norvegica*) Features contributing to krill aggregations and primary productivity, such as spatiotemporal variability of the circulation, including surface currents, topography and krill swimming behaviour	Krill in densities and of quality adequate to support life cycle and the population (e.g., in the SLE and GSL, krill aggregations at depth < 100 m from the surface)
All Adult females and calves Adult males and females	Feeding/Foraging Rearing Courtship/mating Transit/Migration	Acoustic Environment	Received sound levels below a level that would impact acoustic social communication, passive detection of prey or navigation, or impede use of important habitat by blue whales or their prey.
All Adult females and calves Adult males and females	Feeding/Foraging Rearing Courtship/mating Transit/Migration	Physical Space	Enough space to maneuver in vertical and horizontal planes, and not alter normal behaviour at and below the surface
All Adult females and calves Adult males and females	Feeding/Foraging Rearing Courtship/mating Transit/Migration	Water and Air	Sufficient water quality to sustain prey species, and air quality to not cause adverse health effects or result in loss of function
All Adult females and calves Adult males and females	Feeding/Foraging Rearing Courtship/mating Transit/Migration	Access corridor	Free access to obliged transit corridors leading to the Estuary or the Gulf of St. Lawrence (e.g., Cabot Strait, Honguedo Strait)
Adult females and calves	Rearing	Water Temperature	Oceanographic and atmospheric processes providing the Gulf Stream with its properties

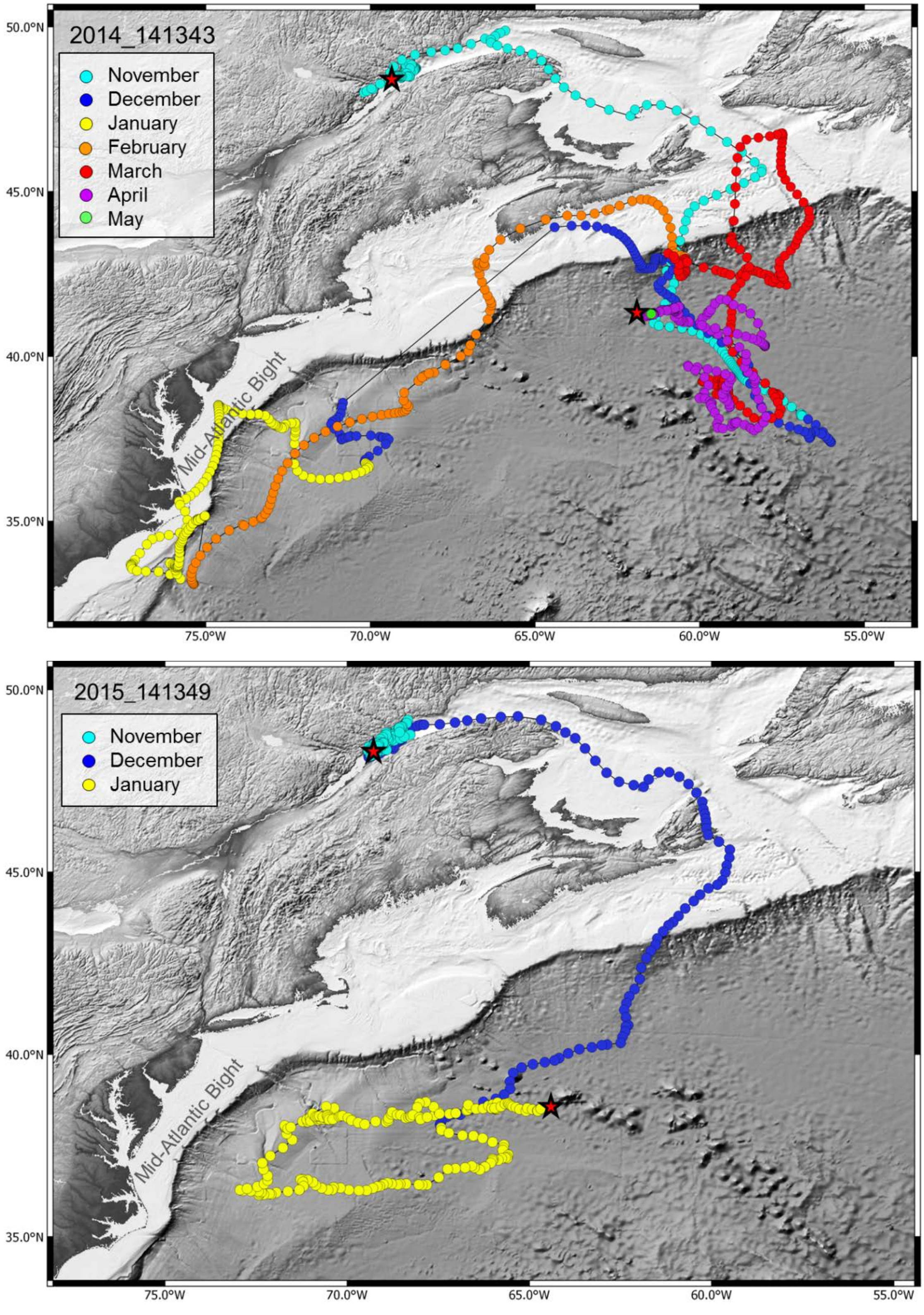


Figure 1. Seasonal movements of two female blue whales tagged in November of 2014 (B244 Upper panel) and 2015 (B197 Lower panel) in the St. Lawrence Estuary, Quebec. Stars indicate where tag was deployed in the St. Lawrence Estuary, and where transmissions ceased (1 May 2015 and 30 January 2016, respectively) off the mid-Atlantic Bight. (Source: Lesage et al. 2016)

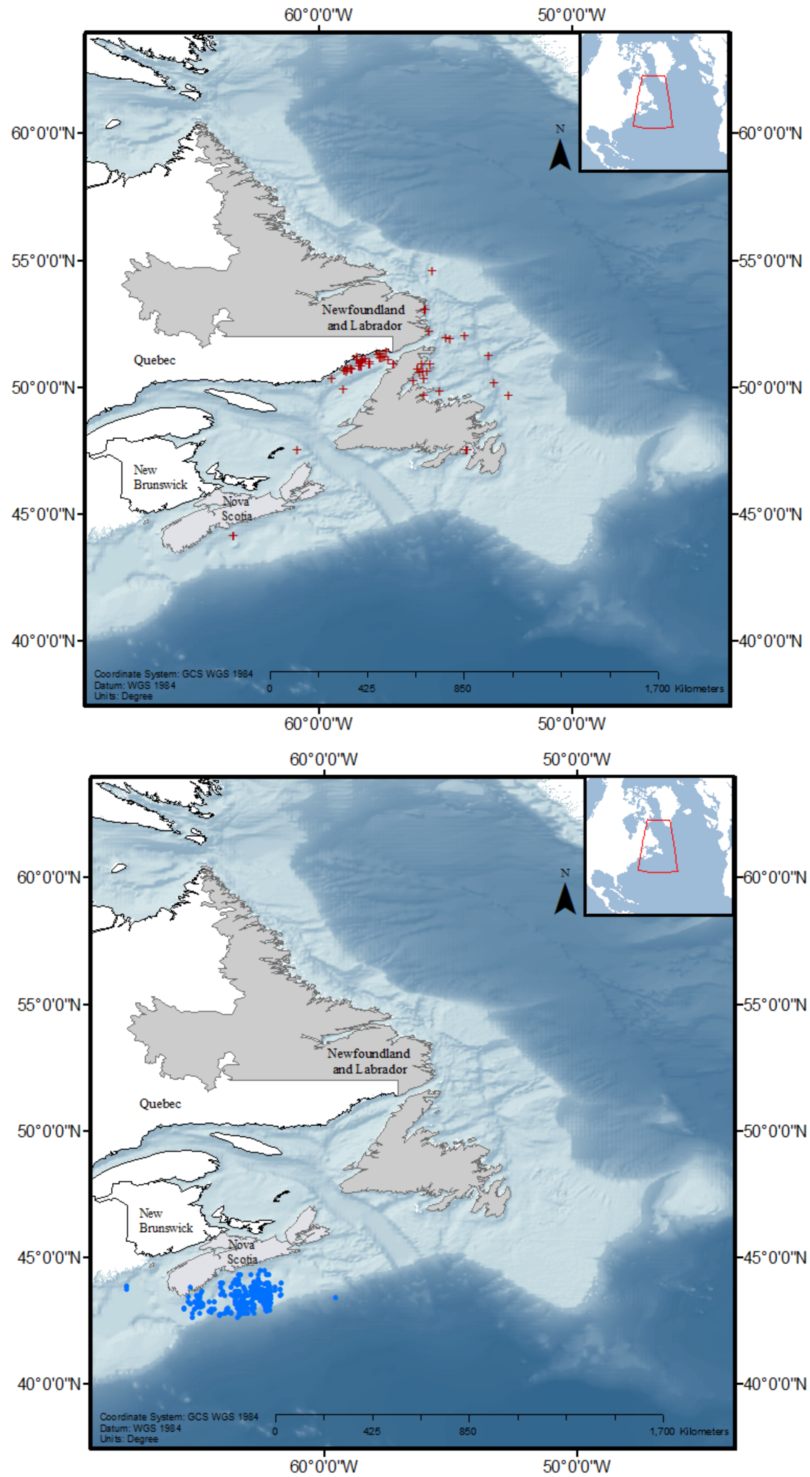


Figure 2. Blue whale catch (top panel) and sighting (lower panel) records from whaling operations occurring in Newfoundland and Labrador between 1927-1958 (top panel), and off Nova Scotia between 1966-1969 (lower panel). Data for Nova Scotia was obtained from Blandford whaling station logs as compiled in Sutcliffe and Brodie (1977). Records for Newfoundland and Labrador were obtained from the International Whaling Commission database. Note this information is incomplete. For instance, locations for kills made in the northwestern Gulf of St. Lawrence are not shown (Source: Moors-Murphy et al. 2017).

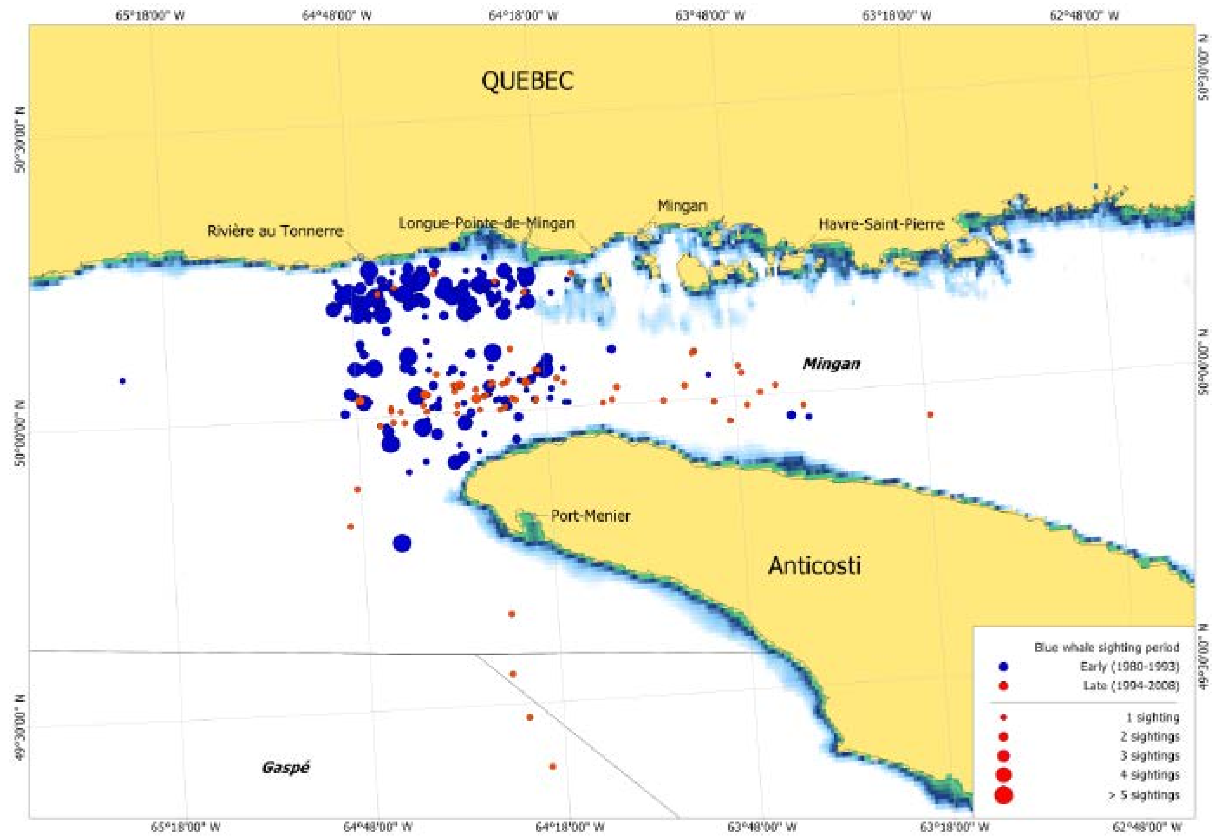


Figure 3. First sightings of identified blue whales observed in the periods of 1980-1993 (blue circles) and 1994-2008 (red circles). (Source: Ramp and Sears 2013).

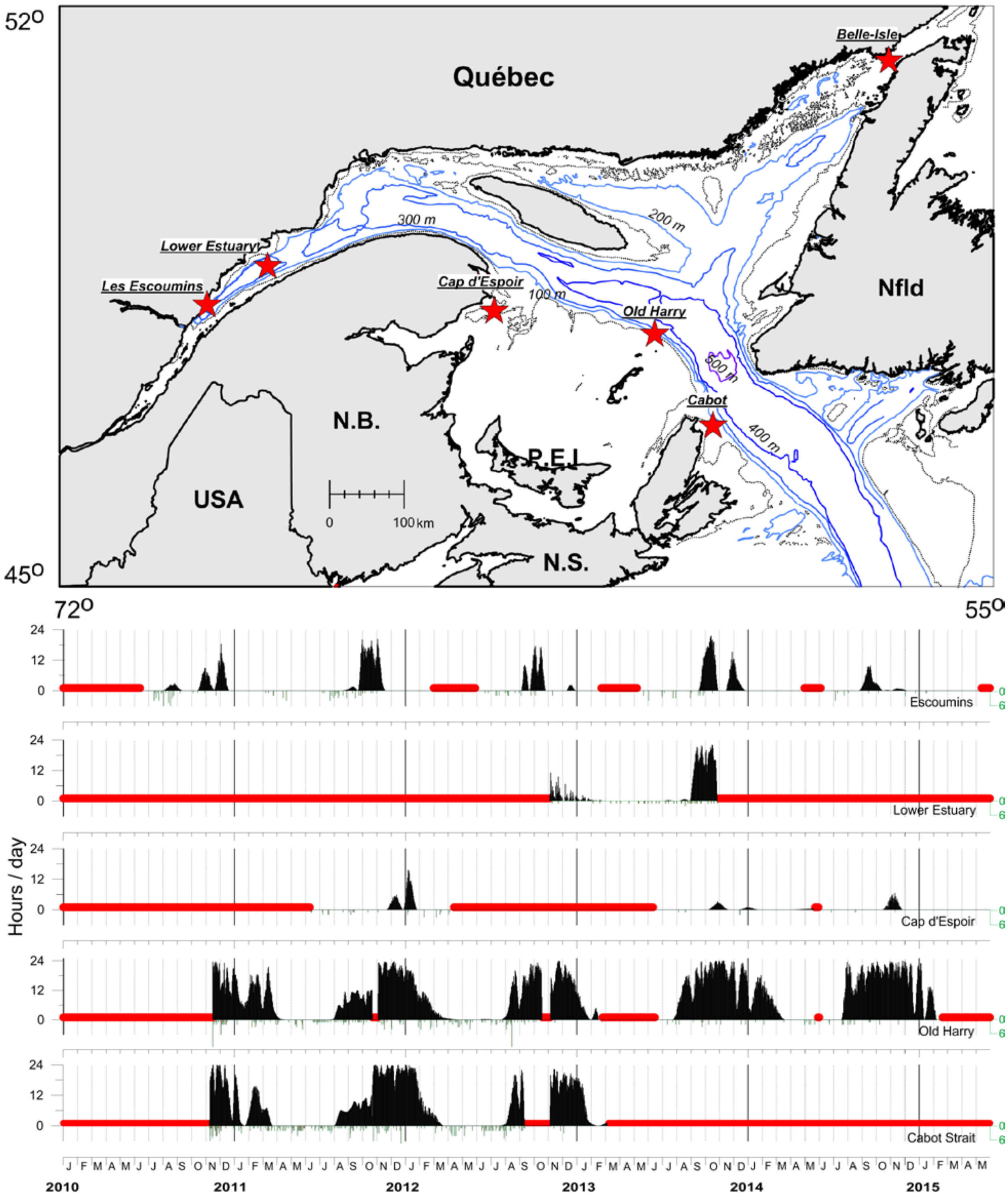


Figure 4. Distribution of passive acoustic monitoring stations in the Estuary and Gulf of St. Lawrence (top panel) with corresponding blue whale detections at each of the locations (lower panel). No blue whale calls were detected at the Belle Isle location during the period of deployment (Nov 2011 to Dec 2012) (Source: Simard et al. 2016).

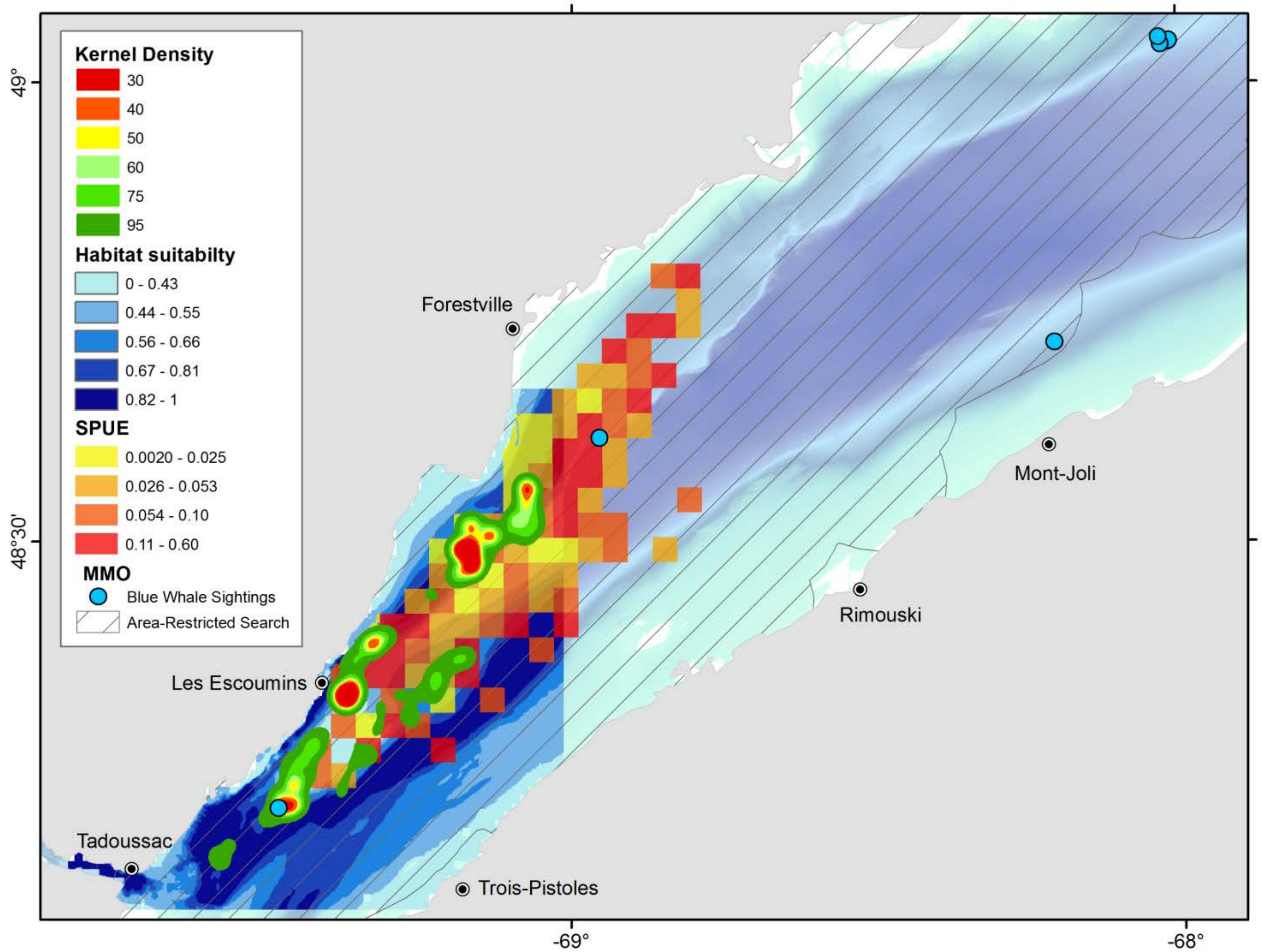


Figure 5. Areas most likely occupied by blue whales in the St. Lawrence Estuary, estimated using (a) a habitat suitability model (darker blue shading indicating a greater suitability) and kernel densities of foraging blue whales (green to red shades: Doniol-Valcroze et al. 2012), (b) area-restricted search behaviour from individual satellite tagged blue whales (smallest convex polygons in black; Lesage et al 2016), (c) blue whale raw observations from systematic ship-based surveys (blue dots: McQuinn et al. 2016), and (d) effort-corrected blue whale densities from non-systematic vessel-based surveys (shaded red to yellow: Ramp and Sears 2013).

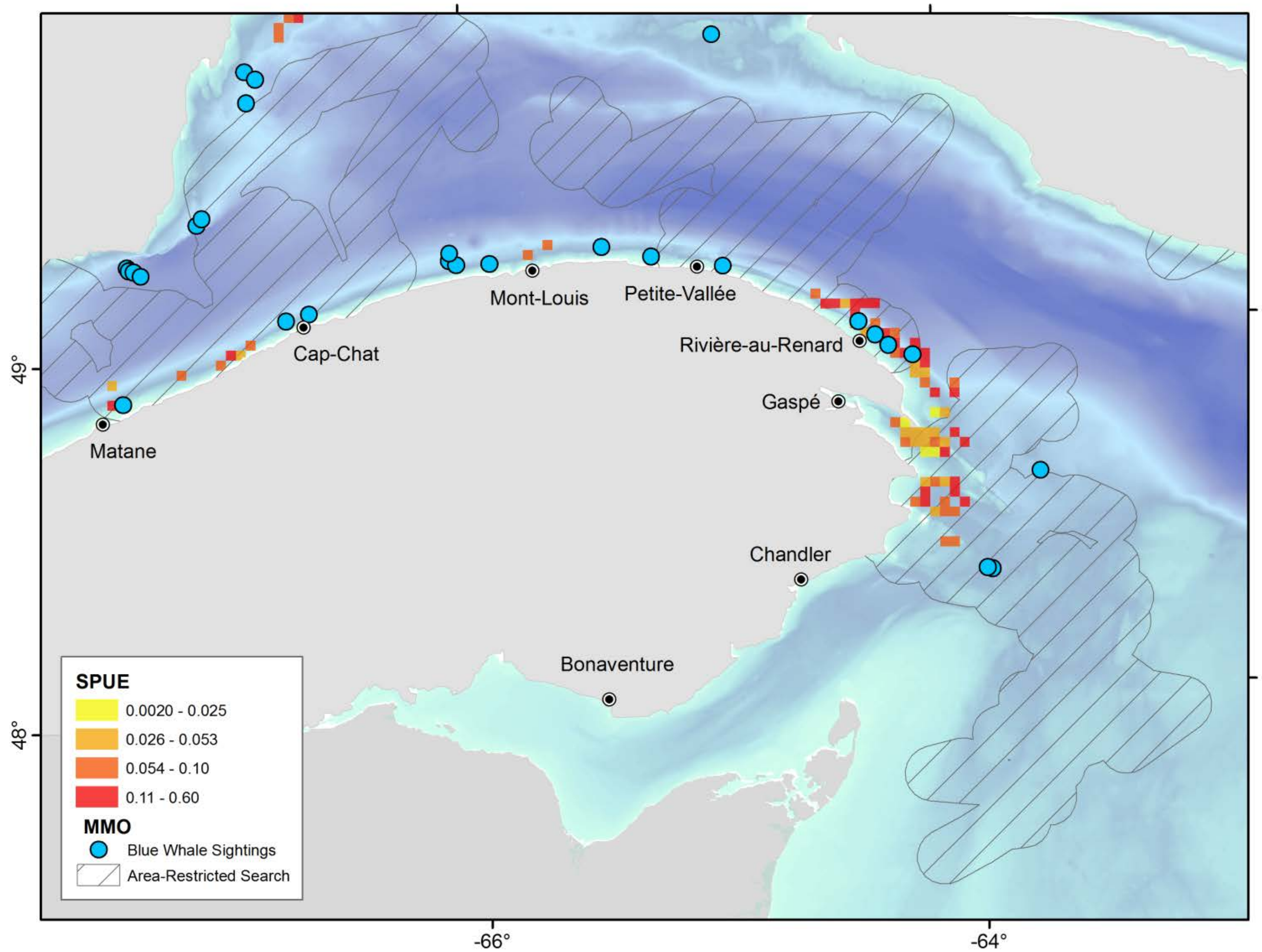


Figure 6. Areas most likely occupied by blue whales in the Gaspé Peninsula region, estimated using (a) area-restricted search behaviour by individual satellite tagged blue whales (smallest convex polygon in black; Lesage et al. 2016), (b) blue whale raw observations from systematic vessel-based surveys (blue dots: McQuinn et al. 2016), and (c) effort-corrected blue whale densities based on non-systematic vessel-based surveys (Ramp and Sears 2013).

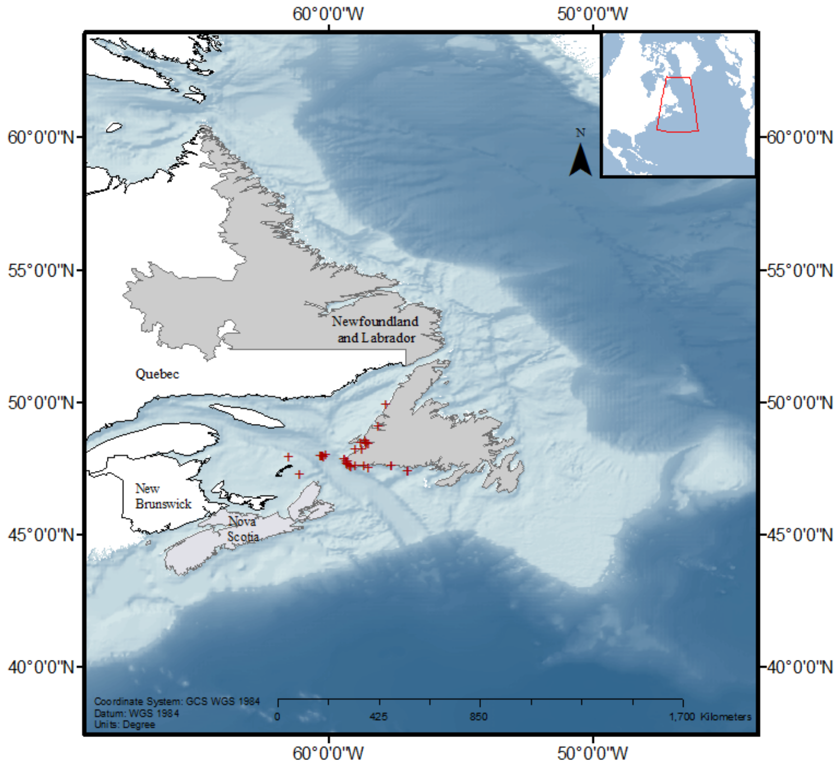


Figure 7. Reported blue whale ice entrapment records (red crosses) off Newfoundland from 1974 to 2015. The black box surrounds the entrapments recorded in 2014 (N=9). Three adult blue whales were seen swimming near the 2014 entrapped whales. (Source: Moors-Murphy et al. 2017).

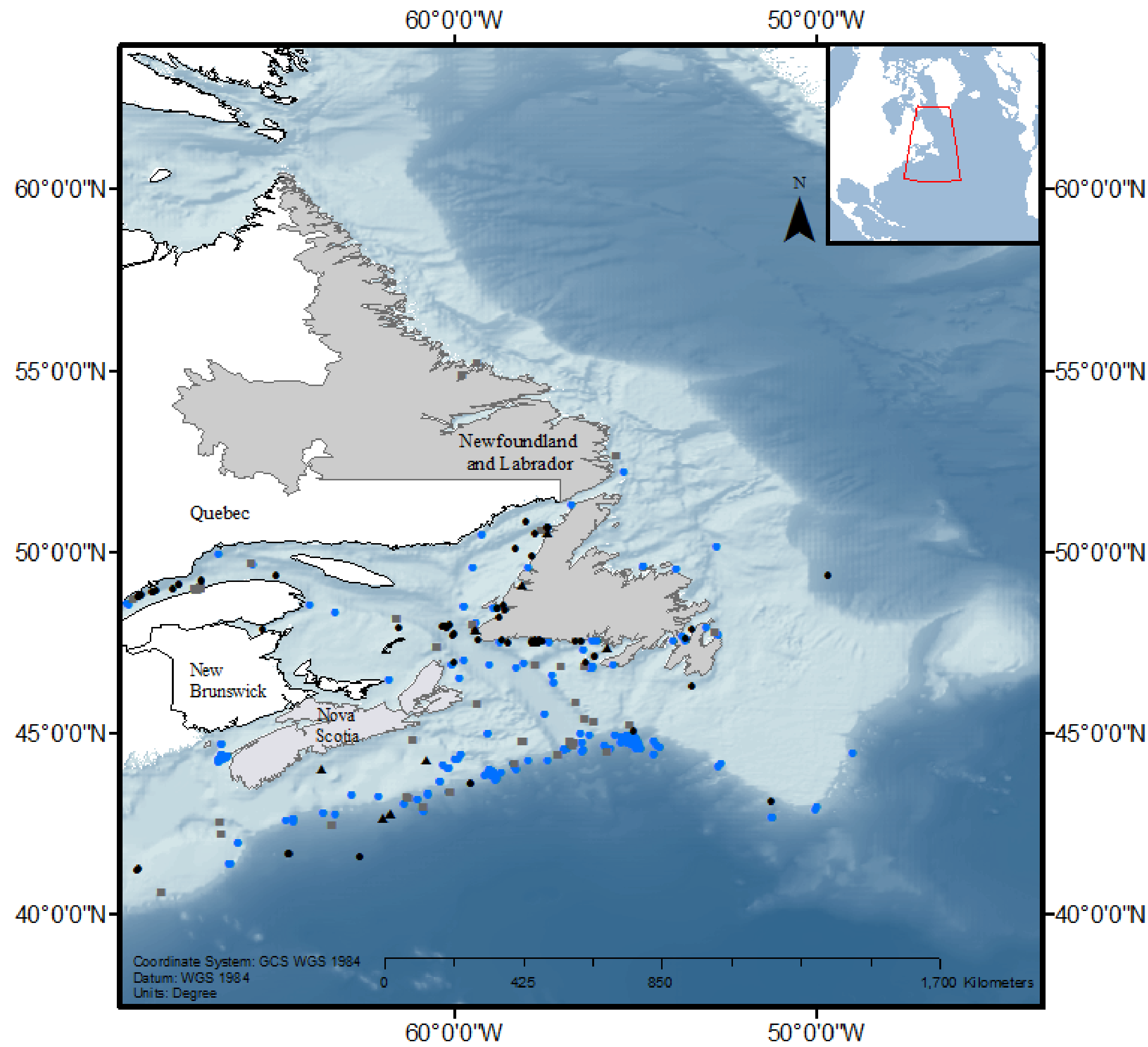


Figure 8. Locations of reported live blue whale sightings in the Gulf of St. Lawrence, Nova Scotia, Newfoundland and Labrador regions between 1975- 2015 in spring (black circles; N = 55), summer (blue circles; N = 218), fall (grey squares; N = 65) and winter (N = 8). These sightings were obtained from five sources: (1) the Department of Fisheries and Oceans (DFO Maritimes and DFO Newfoundland and Labrador regions' cetacean sightings databases), (2) the Ocean Biogeographic Information System (OBIS), (3) the Whitehead Lab at Dalhousie University, (4) the Eastern Canada Seabirds at Sea (ECSAS) database, and (5) the "Song of the Whale" initiative (R/V Song of the Whale 1993-2013, International Fund for Animal Welfare c/o MCR International. (Source: Moors-Murphy et al. 2017).

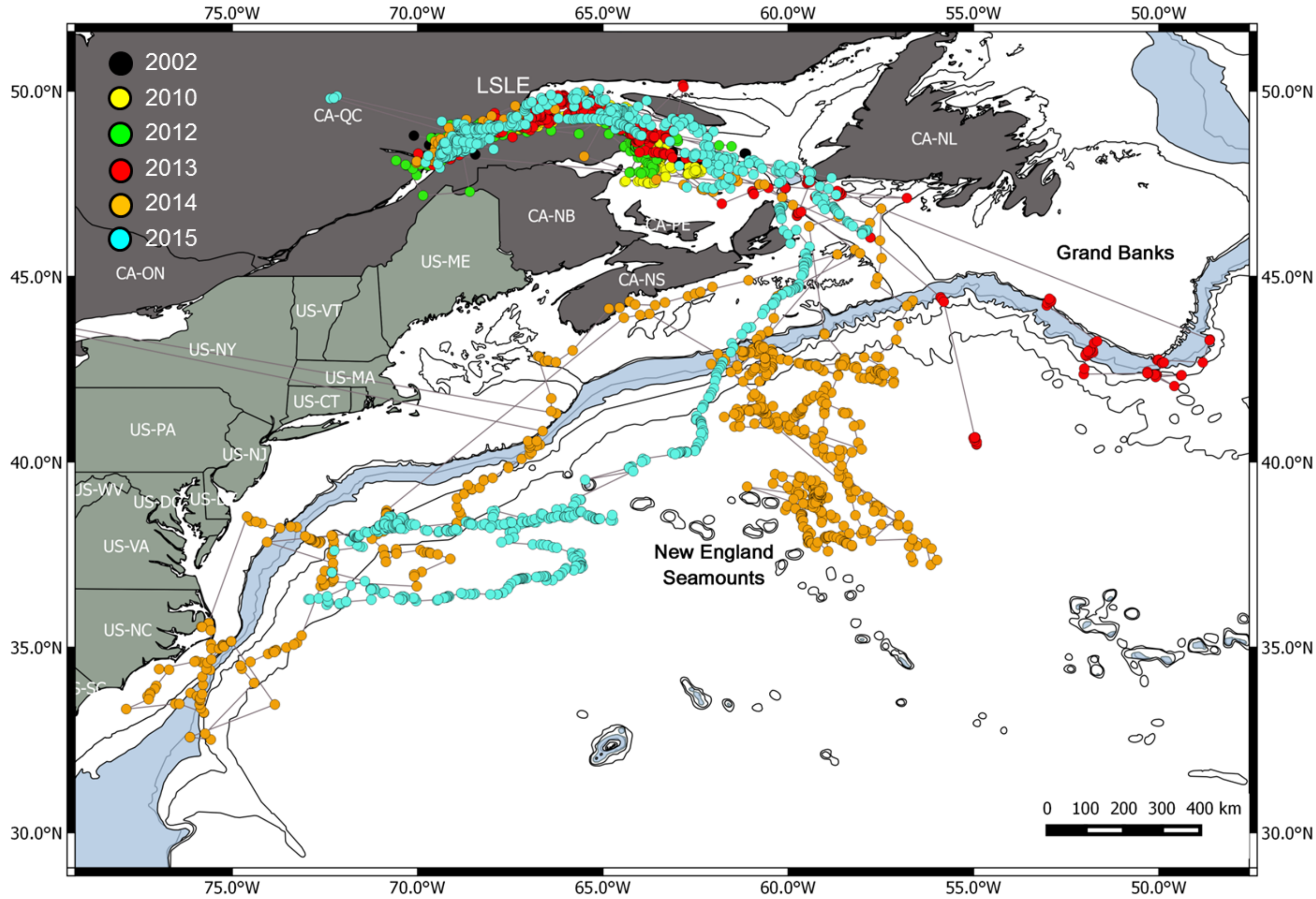


Figure 9. Argos raw satellite tracks from 23 blue whales tagged in the Estuary and Gulf of St. Lawrence, Quebec in 2002 (n = 1), 2010 (n = 2), 2012 (n = 5), 2013 (n = 8), 2014 (n = 2), and 2015 (n = 5). Shaded blue polygon depicts the continental shelf slope (depth 500–2500). (Source: Lesage et al. 2016)

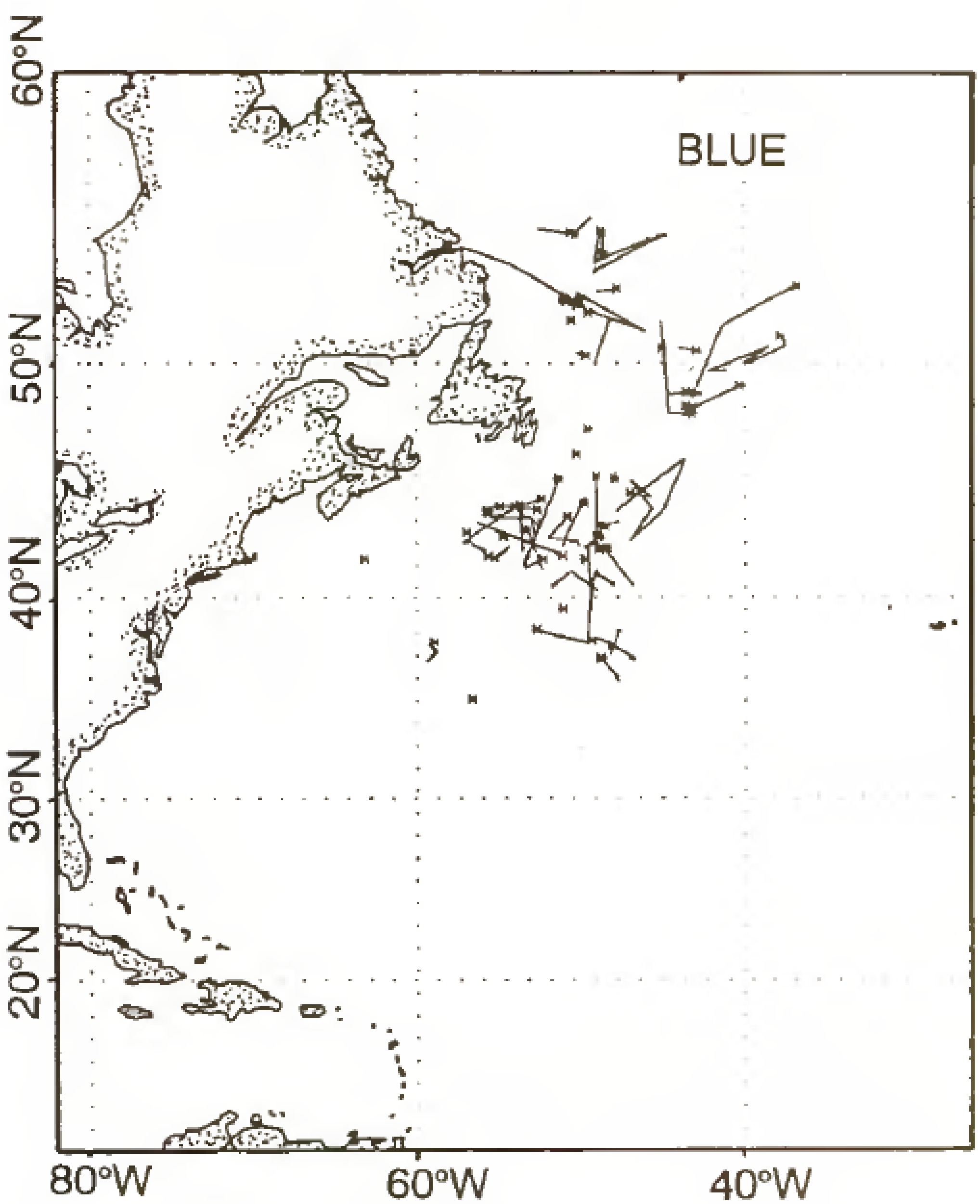


Figure 10. Movement tracks and single call locations of blue whales in September 1993 obtained from passive hydrophone arrays that were part of the US Navy's Integrated Undersea Surveillance System (IUSS). (Source: Clark 1995).

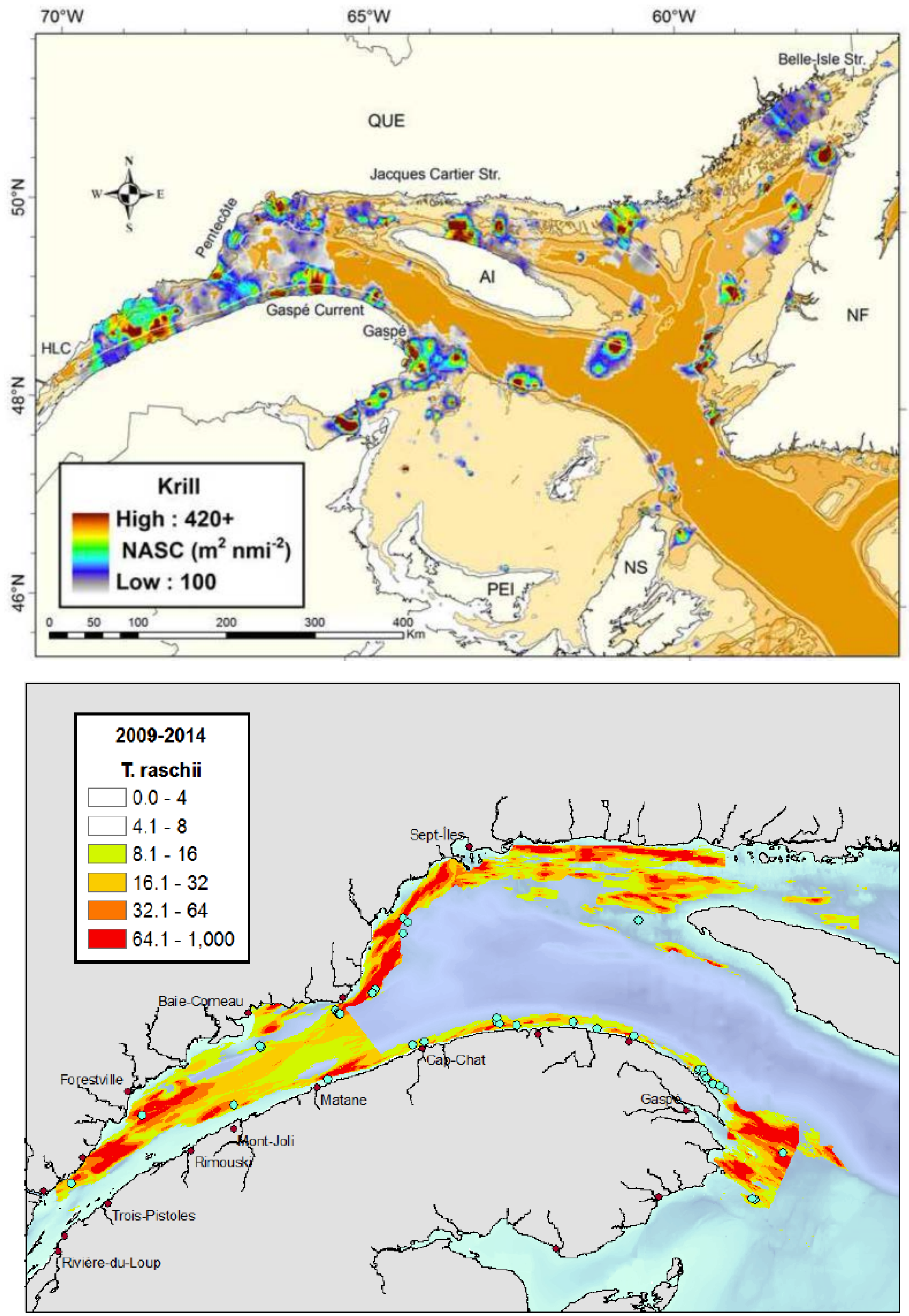


Figure 11. Composite distribution of krill aggregations collected in the Estuary and Gulf of St. Lawrence from 2000-2014 using multi-frequency hydroacoustic surveys. (Source: McQuinn et al. 2015; 2016).

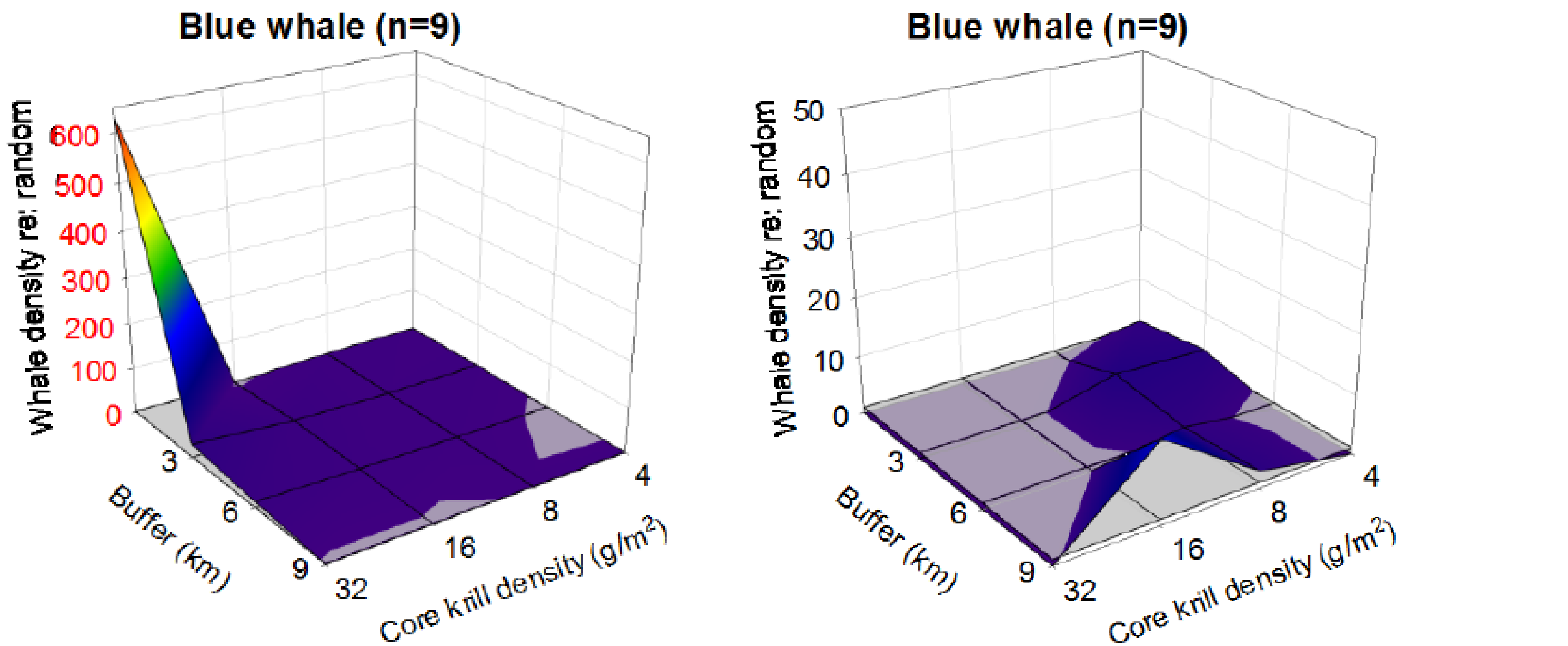


Figure 12. Association index estimated as the ratio of blue whale density within a T. raschii (left panel) or M. norvegica (right panel) prey patch core located in 0-80 m depth, and each of its associated spatial buffers relative to a random density distribution. (Source: McQuinn et al. 2016).

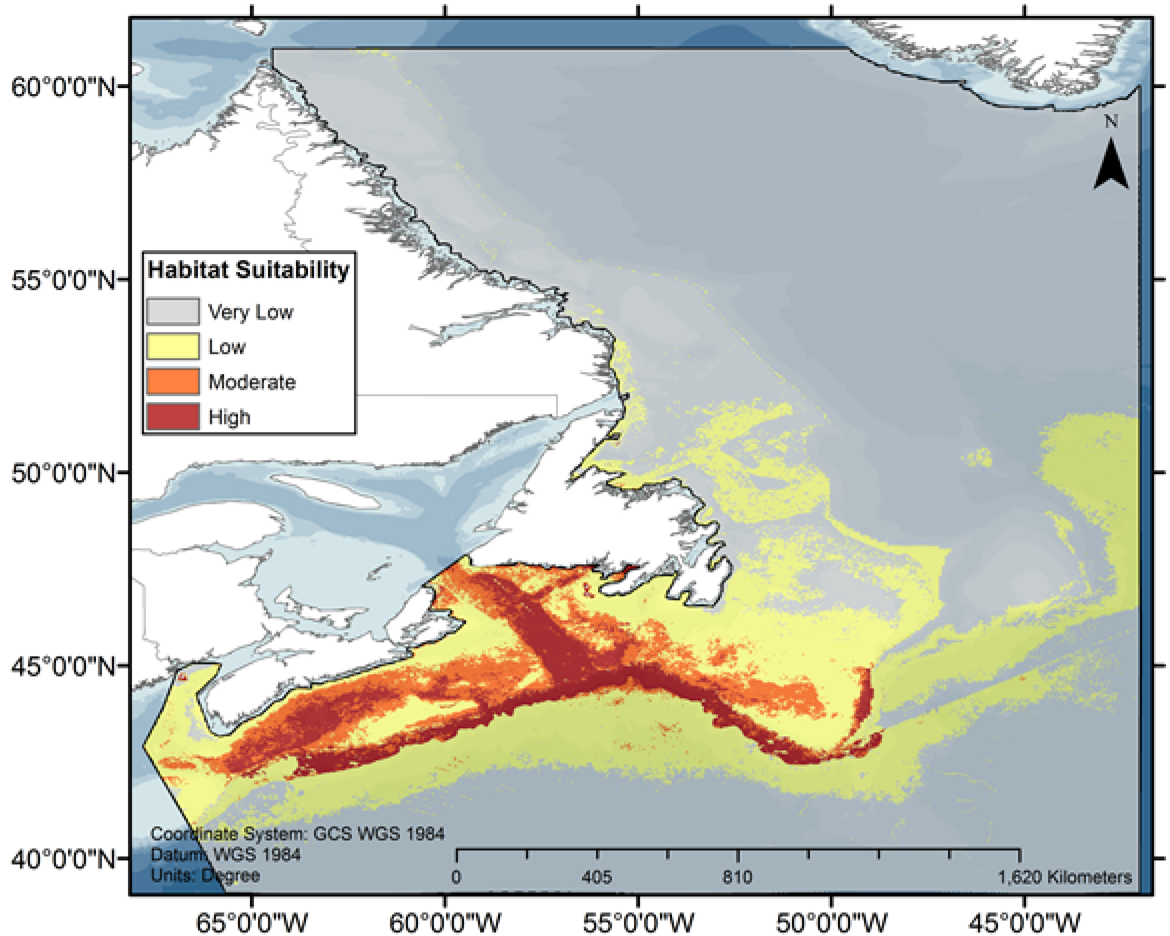


Figure 13. Summer (June-August) habitat suitability for blue whales predicted using a MaxEnt Species Distribution Model (SDM) and five environmental correlates applied to presence-only data obtained from opportunistic sightings and more systematic survey effort. Black line indicates the boundaries of the study area (3,251,342 km^2) (the analysis did not include the Gulf of St. Lawrence). Color shading from red, orange to yellow indicates a change from high, moderate to low suitability (source: Moors-Murphy et al. 2017).

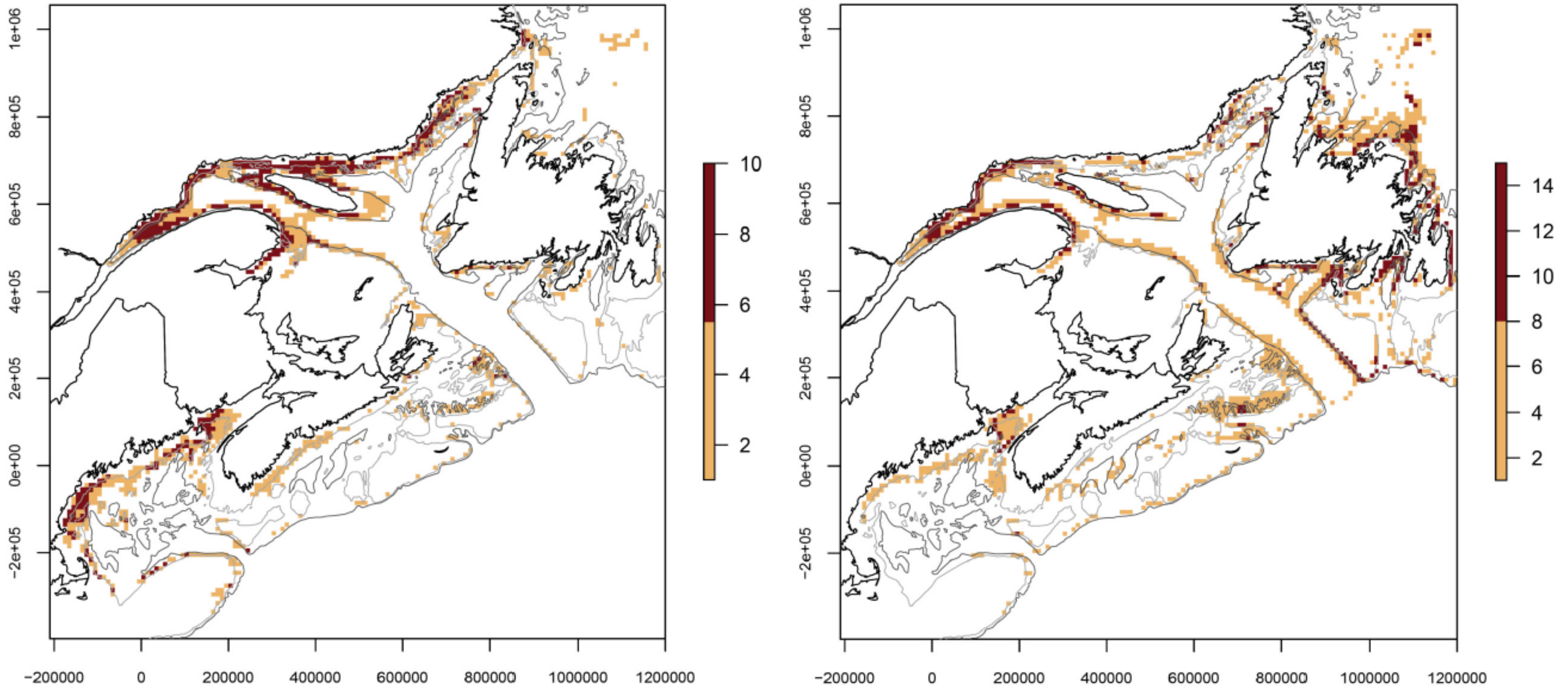


Figure 14. Predicted euphausiid aggregations in spring (left panel) and summer (right panel). Locations with a probability greater than 50% for a dense krill aggregation (biomass >95th percentile) to occur (red) and defined as Significant Areas of Krill (SAK) in spring 2009-2013. Predictions were performed with the GAM. Dark grey line: 200 m isobaths. Light grey line: 100 m isobaths. (Plourde et al. 2016)

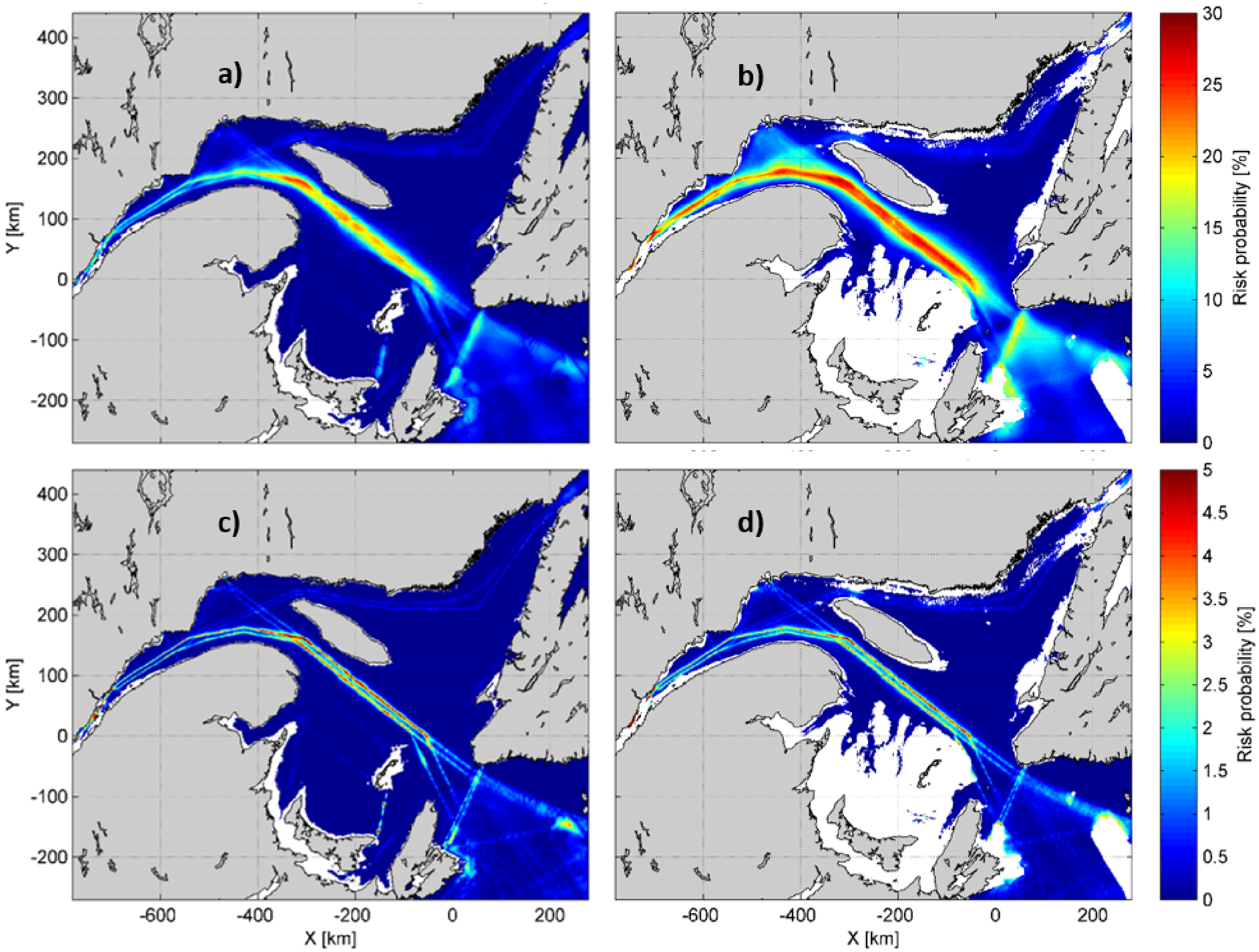


Figure 15. Risk that 16 Hz shipping noise in July 2013 is higher than a, b) 90 dB re 1uPa at 25 or 75 m depths, and c, d) 100 dB re 1uPa at 25 and 75 m depths. Not the change in the colour bar between the top and bottom panels. The two noise thresholds correspond to broadband SPLs of 110 and 120 dB re 1 Pa RMS when not expressed in one-third octave band. (Source: Aulanier et al. 2016).

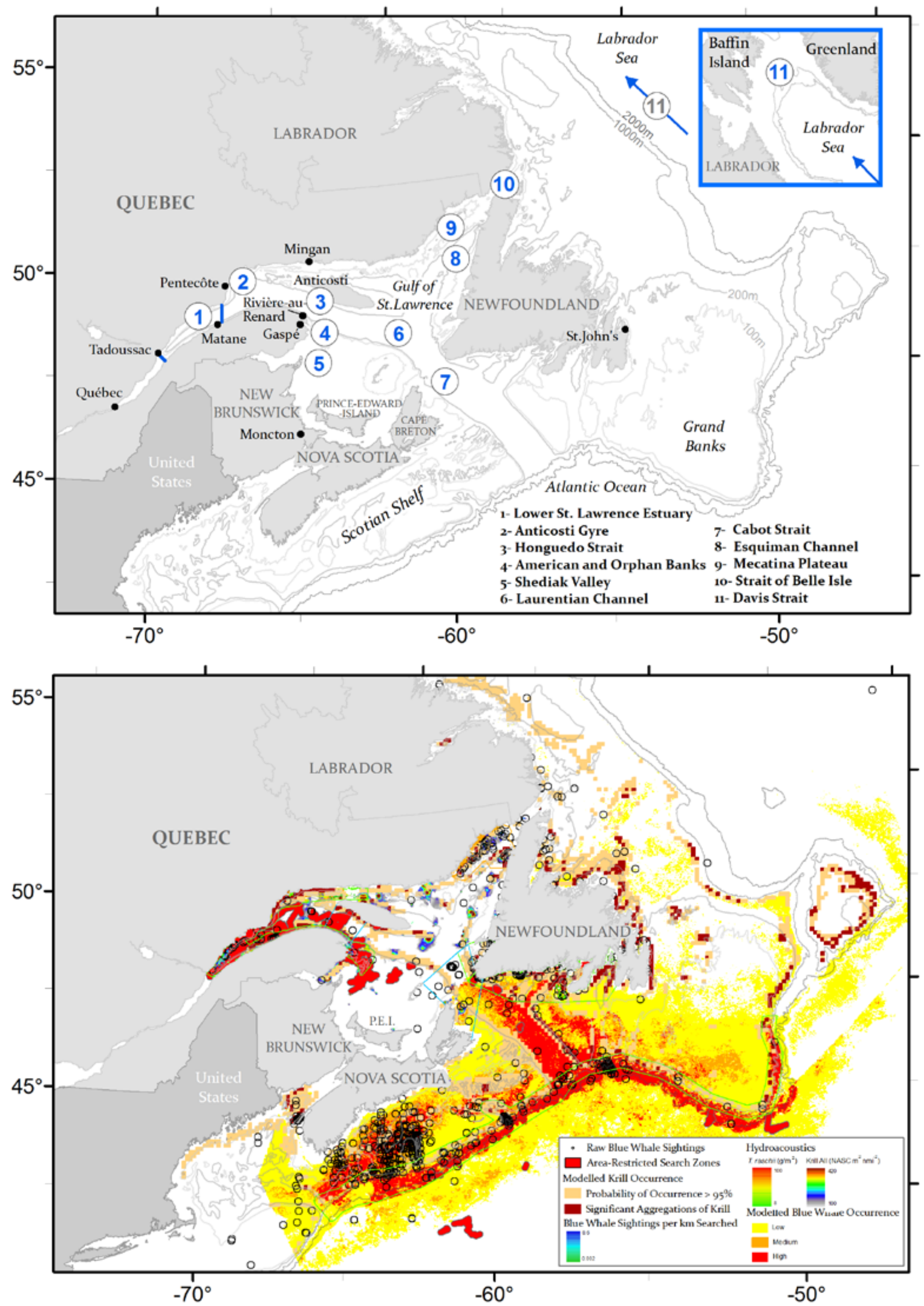


Figure 16. Study area (top panel) and the information available for evaluating the relative importance of various areas in Canadian waters for the blue whale (lower panel). Data come from blue whale sightings either raw or effort-corrected, area of restricted search from individually satellite-tracked blue whales, measured or predicted krill aggregations, and predicted areas of blue whale occurrence. An interactive pdf of this map is presented in appendix.

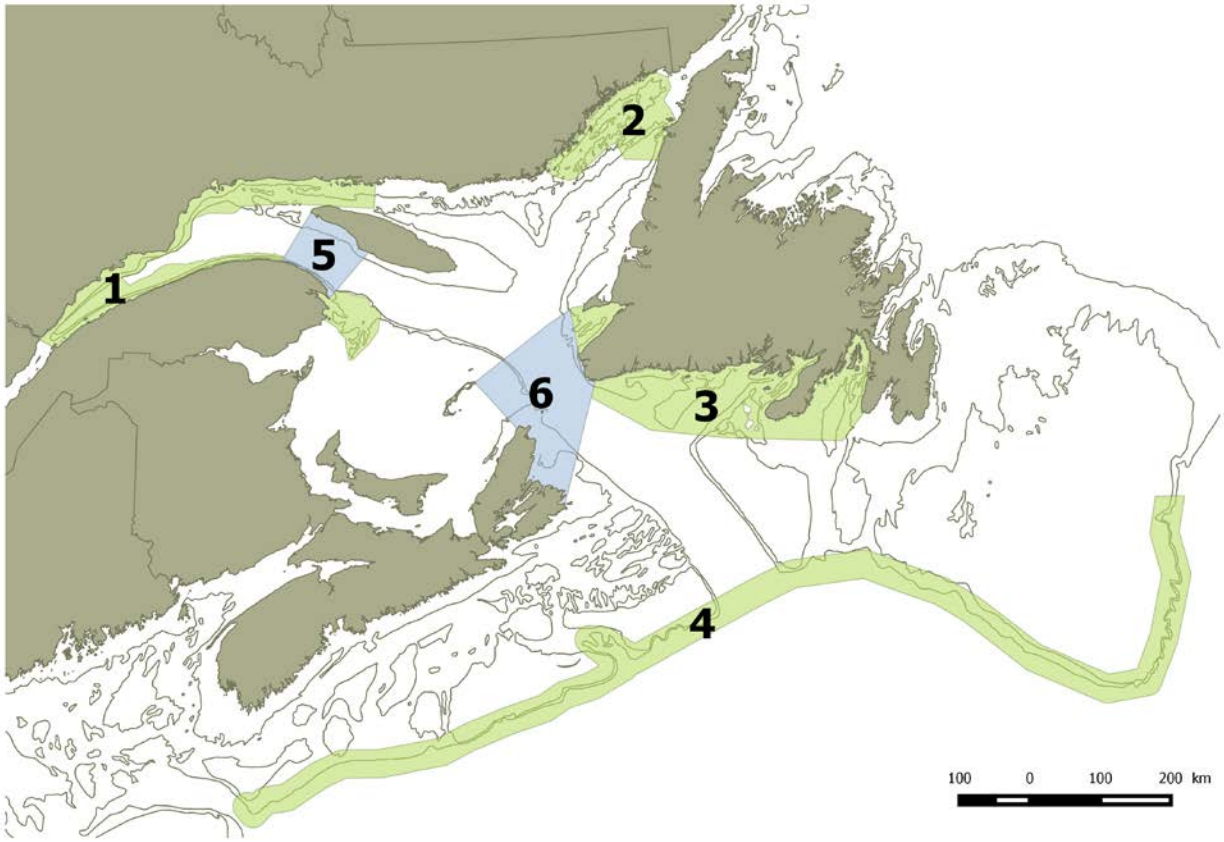
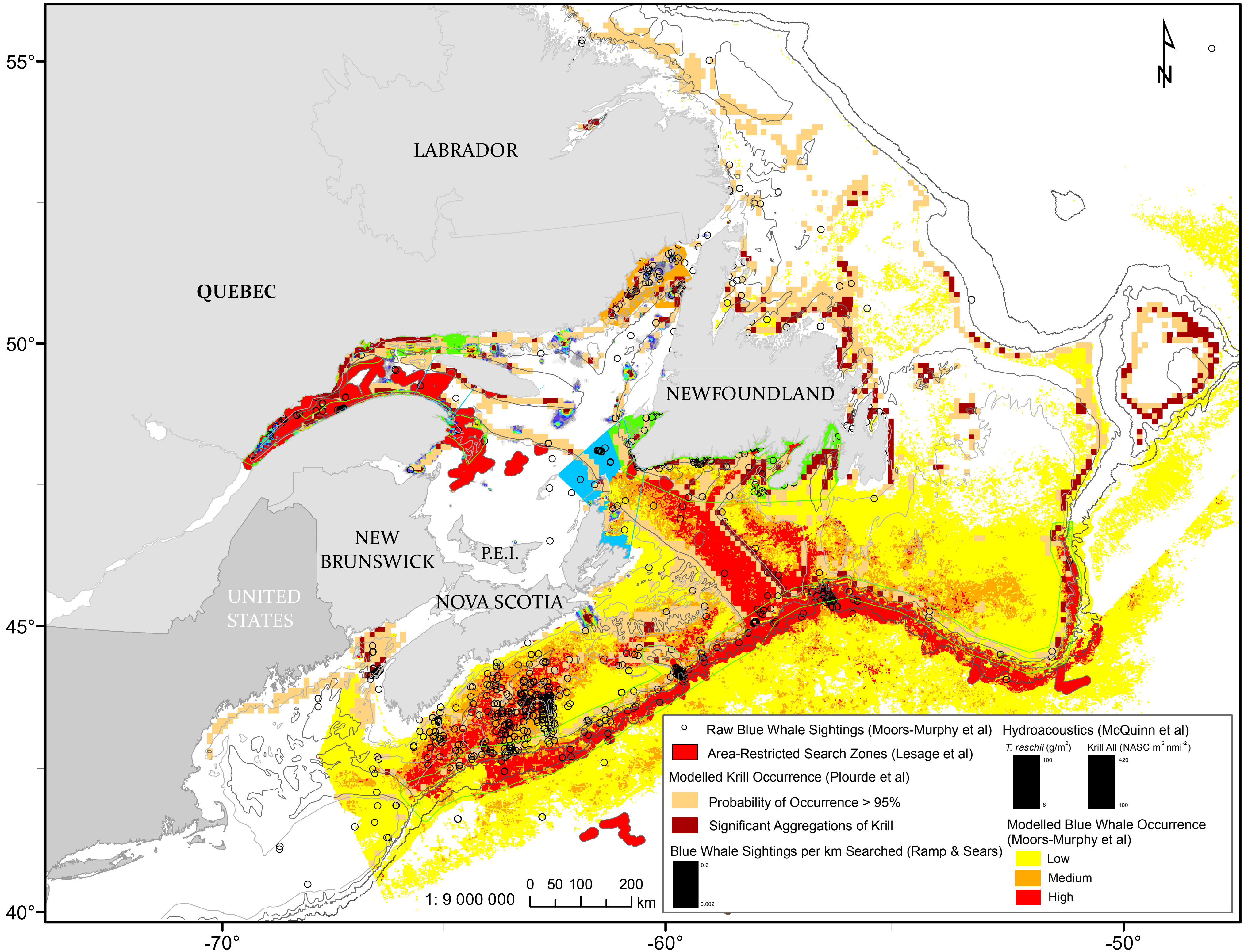


Figure 17. Polygons delimit areas important to blue whales for foraging (green) and transit (blue): (1) lower St. Lawrence Estuary – northwestern Gulf of St. Lawrence, (2) Mecatina Trough, (3) south and southwestern Newfoundland, (4) continental shelf edge, (5) Honguedo Strait, (6) Cabot Strait. Part of the wintering area, off and in the mid-Atlantic Bight, is not show.

APPENDIX

Map showing the relative importance of Blue Whale habitats. To visualize the data, double-click the vocatmap to open in Acrobat. Select the double diamonds in the navigation tools on the left panel. The different data layers can be selected or deselected. Polygons delimit areas important to blue whales for foraging (green) and transit (blue) (see also Figure 16), (On next page)



55°
50°
45°
40°
-70°
-60°
-50°
LABRADOR
QUEBEC
NEWFOUNDLAND
NEW BRUNSWICK
P.E.I.
NOVA SCOTIA
UNITED STATES
N
0 50 100 200
km
1: 9 000 000
Raw Blue Whale Sightings (Moors-Murphy et al)
Area-Restricted Search Zones (Lesage et al)
Modelled Krill Occurrence (Plourde et al)
Probability of Occurrence > 95%
Significant Aggregations of Krill
Blue Whale Sightings per km Searched (Ramp & Sears)
0.6
0.002
Hydroacoustics (McQuinn et al)
T. raschii (g/m²)
100
8
Krill All (NASC m² nmi⁻²)
420
100
Modelled Blue Whale Occurrence (Moors-Murphy et al)
Low
Medium
High