Ocean and Coastal Management 163 (2018) 339–351

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Seasonal vessel activity risk to seabirds in waters off Baffin Island, Canada

Sarah N.P. Wong[a,*], Carina Gjerdrum[b], H. Grant Gilchrist[c], Mark L. Mallory[a,d]

[a] Department of Biology, Acadia University, Wolfville, NS, B4P 2R6, Canada
[b] Canadian Wildlife Service, Environment & Climate Change Canada, 45 Alderney Dr., Dartmouth, NS, B2Y 2N6, Canada
[c] Carleton University, Wildlife Research Division, Environment & Climate Change Canada, Raven Rd, Ottawa, ON, K1S 5B6, Canada
[d] Canada Fulbright Chair in Arctic Studies, University of Washington, Box 353650, Seattle, WA, 98195-3560, USA

ARTICLE INFO

Keywords:
Seabirds
Arctic
Marine distribution
Vessel activity
Anthropogenic risk

ABSTRACT

Millions of seabirds use the waters off Baffin Island. Considering current and future vessel activity in this region, it is important to understand where vulnerability to anthropogenic threats is highest to enable sound wildlife management and regulatory decisions. Using kernel density analysis on at-sea survey data spanning 1970 to 1983 and 2007 to 2016, we identified marine areas of high density for five of the most abundant species sighted: Dovekie *Alle alle,* Thick-billed Murre *Uria lomvia*, Black-legged Kittiwake *Rissa tridactyla*, Northern Fulmar *Fulmarus glacialis* and Black Guillemot *Cepphus grylle*, in summer (June–August) and fall (September–November). We quantified the level of vessel activity from vessel traffic data spanning 2011 to 2015. Overlapping these data layers, we identified regions where high vessel activity posed the highest risk to these species. Navy Board Inlet, Eclipse Sound, Frobisher Bay, Hudson Strait and the northern Labrador Shelf were consistently identified as areas of highest risk to multiple species of seabirds in summer and autumn. These waters not only encompass important summer foraging areas near colonies and post-breeding/migratory habitat but are also frequently navigated by vessels servicing busy communities. The level of vessel activity we found for the study area is relatively low compared to waters where many Arctic species overwinter (e.g., Thick-billed Murres off Newfoundland and Labrador). However, identifying current high-risk areas in Arctic waters is important for the conservation and management of Arctic seabirds as industrial and commercial development in this region expands and leads to higher levels of vessel activity.

1. Introduction

Seabirds spend most of their lives at sea where they are exposed to anthropogenic threats such as bycatch in fisheries (Hedd et al., 2016; Žydelis et al., 2013; Croxall et al., 2012), oiling from large scale events (Montevecchi et al., 2012; Piatt and Ford, 1996), chronic oiling (Fox et al., 2016; Wiese and Ryan, 2003), wind turbines (Furness et al., 2013; Garthe and Hüppop, 2004; Masden et al., 2009), offshore oil and gas platforms (Ronconi et al., 2015; Wiese et al., 2001), disturbance caused by vessel traffic (Ronconi and St. Clair, 2002; Schwemmer et al., 2011; Velando and Munilla, 2011), and at a larger scale, climate change (Keogan et al., 2018; Croxall et al., 2012). As the cumulative human impacts on the world's oceans increase (Halpern et al., 2015), researchers have begun mapping seabird vulnerability and risk from anthropogenic threats (Fox et al., 2016; Lieske et al., 2014; Renner and Kuletz, 2015). Risk is defined as the probability of adverse consequences (e.g. death, lower reproductive success), and is a product of the probability of occurrence and the expected ecological consequence (Michel et al., 2009; Renner and Kuletz, 2015). To identify marine regions of high anthropogenic risk, two things must be evaluated: species' sensitivity (degree to which a species responds to a pressure) and vulnerability (probability of being exposed to a pressure to which a species is sensitive) (Garthe and Hüppop, 2004; Zacharias and Gregr, 2005), both of which influence the expected ecological consequence.

Regions of high anthropogenic risk to seabirds have been identified in many parts of the world's oceans, but only recently have efforts been made to examine seabird vulnerability to human disturbance in the Arctic, where levels of human disturbance are currently considered to be low (Halpern et al., 2008). To date, most efforts examining vulnerability of seabirds to human activity in the Canadian Arctic have focused solely on a single stressor, marine pollution (Mallory et al. 2015; Braune et al. 2014; Provencher et al. 2014; Trevail et al., 2015), leaving a critical source of potential mortality, the cumulative anthropogenic risk of vessel-related threats, largely ignored. Declining sea ice in the Arctic has led to increased vessel activity in this region (*e.g.*, cargo, passenger, tanker, fishing) within the last 25 years (Pizzolato et al.,

* Corresponding author.
E-mail addresses: writesarahwong@yahoo.com, snpwong@dal.ca (S.N.P. Wong).

https://doi.org/10.1016/j.ocecoaman.2018.07.004
Received 15 October 2017; Received in revised form 23 May 2018; Accepted 3 July 2018
Available online 20 July 2018

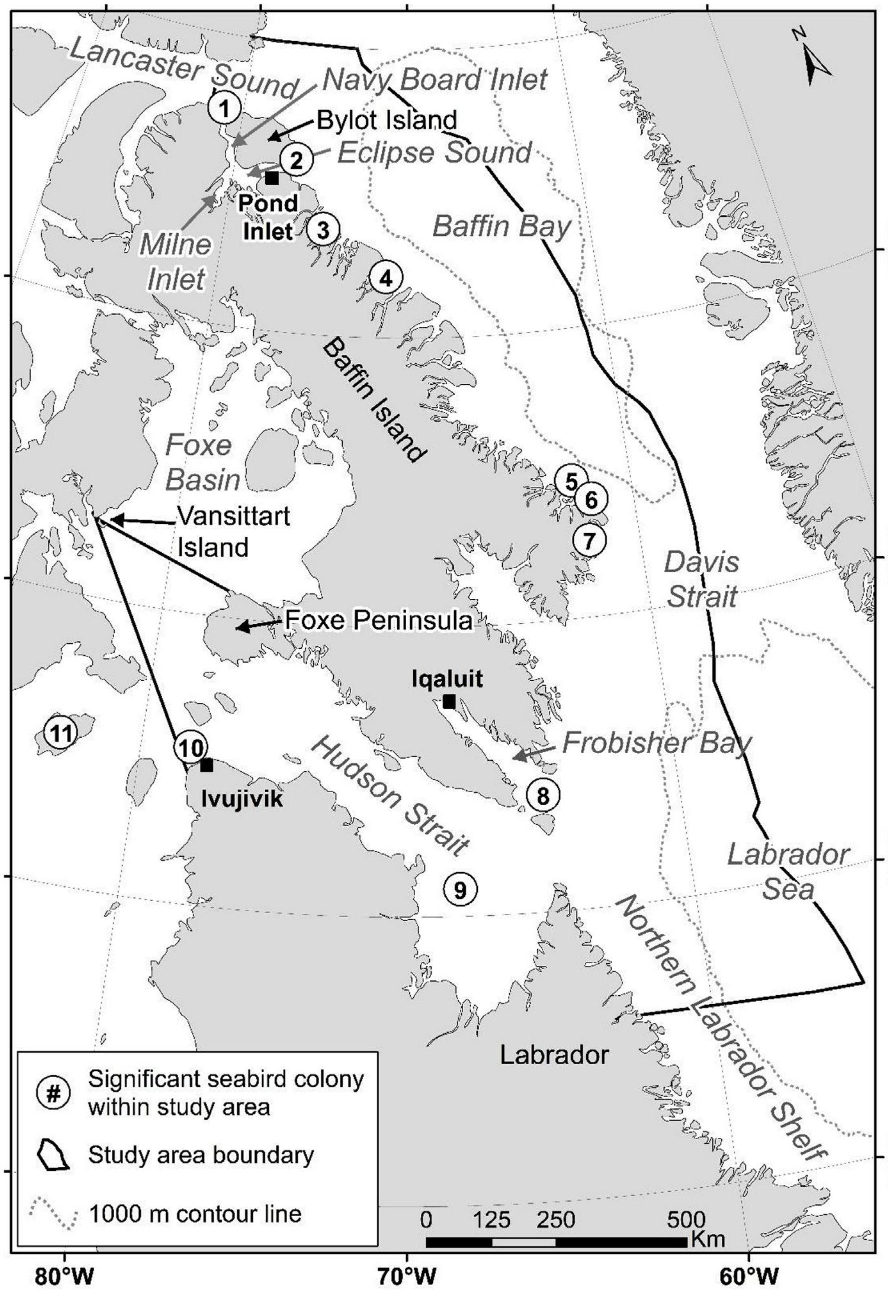


Fig. 1. Water bodies, ports of significance and important seabird colonies with study area.: 1) Cape Hay (Thick-billed Murre, Black-legged Kittiwake); 2) Cape Graham Moore (Thick-billed Murre, Black-legged Kittiwake); 3) Buchan Gulf (Northern Fulmar; 4) Scott Inlet (Northern Fulmar); 5) Cape Searle (Qaqulluit; Northern Fulmar); 6) The Minarets (Akpait; Thick-billed Murre, Black-legged Kittiwake, Northern Fulmar); 7) Exeter Island (Northern Fulmar); 8) Hantzsch Island (Thick-billed Murre, Black-legged Kittiwake); 9) Akpatok Island (Thick-billed Murre); 10) Digges Island (Thick-billed Murre); 11) Coats Island: (Thick-billed Murre).

2016), particularly from increased tourism and resource exploration (Pizzolato et al., 2014).

Increased levels of vessel activity in the Arctic should be of concern since high levels of vessel activity may increase the chances of accidental oil spills; the effects of a catastrophic oil spill on seabirds in Arctic waters is well-documented (Irons et al., 2000; Piatt and Ford, 1996). However, among the most important concerns of vessel traffic is the risk of chronic oiling (Fox et al., 2016; Vollard, 2017), which can lead to high levels of mortality (Wiese and Ryan, 2003) and reduced population growth rates (Wiese et al., 2004). Vulnerability to oiling is based on body size, distribution and life history traits (King and Sanger, 1979), and those species which spend a significant portion of their time on the water, such as alcids, are most susceptible to being oiled (King and Sanger, 1979). Risk of oily discharges from vessels in Canadian waters may increase with proximity to ports and harbours, as seen off the coast of British Columbia, Canada (Serra-Sogas et al., 2014) and is associated with higher levels of vessel activity (Bertazzon et al., 2014). As vessel activity increases in many parts of the Arctic (Huntington et al., 2015; Lasserre and Têtu, 2015; Pizzolato et al., 2016), and Arctic sea routes become more navigable (Aksenove et al., 2017; Smith and Stephenson, 2013; Stephenson et al., 2013), there is a growing need to identify areas with spatiotemporal overlap with seabirds.

Another concern within Arctic waters is the risk of incidental take in emerging fisheries (Chardine et al., 2000; Hedd et al., 2016). Arctic species such as Black-legged Kittiwake *Rissa tridactyla* and Northern Fulmar *Fulmarus glacialis* are particularly vulnerable to incidental take by fisheries, particularly longline operations (Mallory, 2006; Montevecchi, 2002; Žydelis et al., 2013). Other Arctic species, such as

Thick-billed Murre *Uria lomvia*, are at risk to incidental take in gillnet fisheries (Hedd et al., 2016). With the growth of the commercial Greenland Halibut *Reinhardtius hippoglossoides* fishery in the Canadian Arctic (DFO, 2014), researchers are trying to understand the spatio-temporal occurrence of bycatch in this fishery (Cosandey-Godin et al., 2015), but are already concerned about the high numbers of Northern Fulmars killed (Hedd et al., 2016).

Our study area focused on the waters off Baffin Island (Hudson Strait and off the eastern coast of Baffin Island) as these waters face some of the highest levels of vessel traffic in the Canadian Arctic and greatest rates of increase (Pizzolato et al., 2016). For example, vessel traffic in Hudson Strait has increased at approximately 4.5–5.5 transits/year from 1990 to 2015 (Pizzolato et al., 2016). While these waters are important for shipping, fishing and tourism, they are also important for seabirds; over 10 million breeding and non-breeding seabirds use the waters off Baffin Island in summer and autumn (Fort et al., 2013; Gaston et al., 2012; Mallory and Fontaine, 2004). Of the 30 species which breed in the area (Mallory and Fontaine, 2004), the most abundant include Thick-billed Murre (Gaston and Robertson, 2014), Northern Fulmar (Mallory, 2006), Black-legged Kittiwake (Mallory and Fontaine, 2004), Black Guillemot, *Cepphus grylle*, eiders *Somateria* spp., and Glaucous Gull *Larus hyperboreus* (Diemer et al., 2011; Mallory and Fontaine, 2004). Dovekie *Alle alle* are the most abundant during the non-breeding season (Fort et al., 2013).

The objectives of our study were to identify the marine areas of high seabird density within the waters off Baffin Island and to identify regions of risk where seabirds overlap with current vessel activity. We chose to include five species in the analysis (Dovekie, Thick-billed Murre, Black-legged Kittiwake, Northern Fulmar and Black Guillemot) as they are common in the area, represent different foraging niches, include coastal and pelagic species, and thus have varying sensitives to vessel-related threats. We used vessel traffic as a proxy for anthropogenic risk (Renner and Kuletz, 2015) and consider regions of high risk to be those where high vessel density overlaps with high concentrations of seabirds (Renner and Kuletz, 2015; Williams and O'Hara, 2010). Given the high use of these waters by seabirds, and recent and predicted future increases in anthropogenic activity in this area, identifying regions where seabirds are vulnerable to vessel traffic is critical.

2. Methods

2.1. Study area

The study area was defined as waters east of Baffin Island to the Canadian Exclusive Economic Zone, north to 75^0N, encompassing the mouth of Lancaster Sound to 82^0W, and south to 58^0N to include waters of Hudson Strait and cutting across Foxe Channel from Ivujivik to Vansittart Island to the top of Foxe Peninsula (essentially excluding Foxe Basin) (Fig. 1). No seabird surveys existed for Foxe Basin, thus our study area was confined to waters in which we had sufficient data for analysis. The bathymetry, seasonal ice patterns, presence of important currents like the Labrador and Baffin Island Currents, as well as vertical mixing all contribute to the primary production of this area (Ferland et al., 2011; Michel et al., 2015; Münchow et al., 2015; Tremblay et al., 2015), which supports seabird colonies at Digges, Coats and Akpatok islands (Thick-billed Murre) in Hudson Bay/Strait, The Minarets (Akpait; Thick-billed Murre, Black-legged Kittiwake, Northern Fulmar), and Cape Searle (Qaqulluit; Northern Fulmar) on Baffin Island, and Cape Hay and Cape Graham Moore (Thick-billed Murre, Black-legged Kittiwake) on Bylot Island (Fig. 1).

2.2. Data

2.2.1. Vessel activity data

Vessel traffic data were acquired from the Canadian Coast Guard for the period of 2011–2015 using an unclassified, multi-source data extraction, which contains an amalgamation of vessel traffic data from the following information systems: Vessel Traffic Management Information System (VTMIS identified by INNAV acronym), Long-Range Identification and Tracking (LRIT) and multiple sources of Automatic Identification System (AIS) data (terrestrial, ship-based, satellite and aircraft-based). Nearly all vessels, including pleasure craft, now carry various types of AIS systems, whereas some vessels are also mandated to carry LRIT and/or INNAV systems depending on vessel type and class, tonnage, country of registration and distances from Canada. Due to its remoteness, the Arctic suffers gaps in the electronic data, thus using a multi-source approach ensures better coverage in these remote locations and helps to cover transmission interruptions. By using a multi-source data extraction, positions of each vessel's track could come from one or more data sources. However, since each system emits at different times, the likelihood of duplicate hits is minimal.

Vessel activity was defined as any vessel, regardless of type and tonnage, transiting the study area and was measured using an estimated frequency of vessel tracks. Each vessel's position had a date and time stamp, which were used to extrapolate points into vessel tracks. For each vessel, consecutive positions (points) were joined into a single track if they were within six hours of each other. For consecutive positions where more than six hours had passed between locations, a new track for that vessel was assigned. Therefore, for each vessel's voyage, there might be more than one track. Single positions that were not within six hours of any preceding or proceeding position were excluded from the analysis. Six hours was chosen as the maximum amount of time between consecutive positions as it maximized the amount of locations that could be used (more hours between points resulted in more useable points) and minimized the number of tracks that fell over land (longer time periods between consecutive points resulted in tracks crossing land since the vessel could have changed course during that time). The resulting tracks were verified using Geographic Information Systems ArcGIS 10.1; tracks that fell over land were divided into separate tracks on either side of the landmass over which the track fell. Vessel track estimation was conducted in R version 3.3.2 (R Core Team, 2015).

2.2.2. Seabird data

Two databases of at-sea seabird surveys conducted in this region were used for the analysis: 1) Programme intégré de recherches sur les oiseaux pélagiques (PIROP), which contains survey data from 1970 to 1983, and 2) Eastern Canada Seabirds at Sea (ECSAS), which contains survey data from 2007 to 2016. Only data for summer (defined as June to August) and autumn (defined as September to November) were used as survey data collected during other months were limited. These two seasons reflect general phenology of Arctic seabirds where breeding is confined to summer and post-breeding migration occurs in autumn. All surveys were conducted from vessels of opportunity by trained observers, however there were some key differences in survey methods between the two data sets.

PIROP surveys were conducted by a single observer looking forward and scanning to a 90° angle from the port or starboard side. Scans were conducted with the naked eye and binoculars were only used to aid in species identification. Surveys were 10 min in length and observers conducted as many consecutive 10 min surveys as possible. All birds sighted were recorded. For each sighting, observers recorded the species (or genus/family if species could not be confirmed), flock size, and behavior (on water, ice, flying, or feeding). The more recent ECSAS surveys consisted of consecutive 5 min observation periods conducted by one observer (Gjerdrum et al., 2012). Observers scanned to a 90° angle from the port or starboard side but only recorded birds (species, flock size, and behavior) within a 300 m strip-width transect. A series of intermittent “snapshots” were used to enumerate flying birds, which often move faster than the ship and thus inflate estimates of local density (Tasker et al. 1984; Gaston et al. 1987). These scan intervals varied with ship speed (Gjerdrum et al., 2012). Linear densities

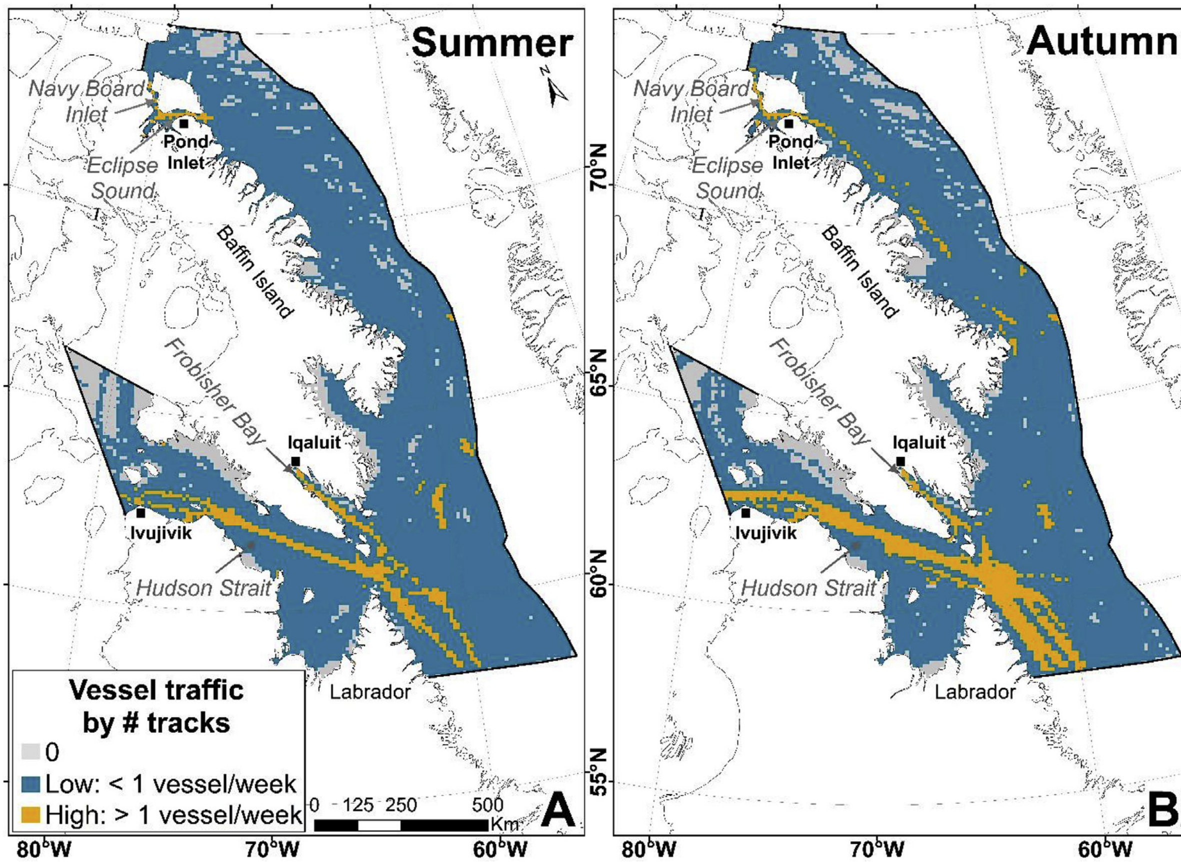


Fig. 2. Level of vessel activity from 2011 to 2015 in A) summer (June–August) and, B) autumn (September–November) defined by the number of vessel tracks within each 10 km by 10 km grid cell. Low = 1–60 tracks, or a vessel passed through the cell less than once a week, and High = over 60 tracks, or a vessel passed through the cell at least once a week within the study area (shown in grey). Vessel tracks were estimated from vessel locations separated by no more than 6 h.

(number of birds/km) are reported for all species to allow us to combine results from the PIROP and ECSAS datasets.

We examined the extent to which vessel traffic overlapped with Thick-billed Murres, Dovekies, Black-legged Kittiwakes, and Northern Fulmars in both summer and autumn, and Black Guillemots in just the summer as few sightings were recorded in autumn.

2.3. Analysis

To examine the distribution of vessels and seabirds, we overlaid a 10 by 10 km grid onto the study area. This size of grid cell ensured each cell contained multiple seabird surveys but remained small enough to give some spatial resolution to the results. To define the level of vessel activity in the study area, we summed the number of vessel tracks contained within each grid cell for each season (summer and autumn). Based on a visual inspection of the track frequency histograms, we defined a low level of vessel activity as any grid cell with between 1 and 60 tracks, and a high level of vessel activity as any grid cell with more than 60 tracks, which is roughly the equivalent to one vessel every week.

To identify marine areas of high density for each species, we used a kernel density estimation approach on the two data sets (PIROP and ECSAS). First, we summed the total number of linear kilometers surveyed and the total number of individuals for the species of interest recorded within each 10×10 km grid cell to calculate a density for each species for each data set and season. Only birds identified to species were included. We also summed the total number of seabirds recorded to obtain total seabird density. Kernel density analysis uses point data (in this case, density of each species per grid cell), and uses a non-parametric approach to estimate the probability density over a continuous smoothed surface. The resulting density of each cell is weighted by the distance from the starting features. A cell size of 10 km was chosen to match the grid cell size. We ran the analysis with bandwidths of 25, 50, 75 and 100 km, but based on visual inspection of the results, chose a bandwidth of 75 km as this value best fit the data without overgeneralizing the areas of high density. We used utilization distributions of 50% (50 UD) to delineate areas of high use for each database (Lascelles et al., 2016), for each species in each season and also for total seabird density. However, since we were interested in overall risk, we merged the 50 UD polygons from both data sets, resulting in one combined 50 UD map for each species (and total seabirds) by season. Recognizing that the risk map produced for total seabirds would be biased towards the most abundant species, we made a risk map that would give equal weight to the regions of high risk to our focal species. To do this, we combined the 50 UD maps for each of the focal species (five in summer, four in autumn) to produce a map highlighting high density areas for our species of interest in summer and autumn. We calculated kernels in ArcGIS 10.1.

To delineate regions where seabird species are most at risk to interactions with vessel activity, we overlaid the vessel activity layer first with the kernel density layer (50 UD) of each species separately, followed by the density layer for our five (four in autumn) focal species combined, and lastly with the density layer for all seabirds combined. Similar to the approach used by Renner and Kuletz (2015), we identified grid cells with the following combination of overlap: 1) high vessel activity + high marine seabird density (defined as 50 UD), 2) low vessel activity + high marine seabird density, 3) low marine seabird density (< 50 UD) and/or no vessel activity.

3. Results

3.1. Vessel activity

We used a total of 9269 estimated vessel tracks in summer and 10,522 in autumn to calculate the level of vessel activity in Canadian Arctic waters within Hudson Bay/Strait and off the coast of Baffin Island. The most common vessel length range was 51–100 m (36% summer, 40% autumn), followed by 101–150 m (18% summer, 25% autumn). For both seasons, the main types of vessels transiting were fishery (37% of all summer traffic, 39% of all autumn traffic), merchant (33% summer, 36% autumn) and tanker (11% summer, 9% autumn). In summer, most transits occurred in August (55%) followed by July (32%), and in autumn, most transits occurred in September (48%) followed by October (37%). Vessel traffic was highest in 2014 and 2015 for both seasons (summer: 25% and 31% respectively, autumn: 30% and 33% respectively) and lowest in 2011 and 2013 (summer: 8% and 11% respectively, autumn: 12% and 17% respectively). While the sea ice extent in the Arctic has declined over the last several decades (Comiso et al., 2017), the amount of vessel traffic did not match patterns of the inter-annual variability of minimum ice extent (https://nsidc.org/arcticseaicenews/charctic-interactive-sea-ice-graph/). For both summer and autumn, the highest levels of vessel activity (over one vessel transiting once a week) occurred through Navy Board Inlet and Eclipse Sound, Hudson Strait south along the northern Labrador Shelf and Frobisher Bay, with some high levels of vessel activity along the coast of Baffin Island in autumn (Fig. 2). High levels of vessel activity were more widespread in autumn compared to summer (Fig. 2), when sea ice is at its minimum extent.

3.2. Seabird distribution

Within the study area, 17,655 km (11,174 km summer, 6481 km autumn) of PIROP survey data were available from 1970 to 1983, and 12,006 km (7728 km summer, 4278 km autumn) of ECSAS survey data were available from 2007 to 2016 (Fig. 3). The bulk of summer surveys for PIROP occurred in August (76%), compared to July (20%) and June (4%), while summer surveys for ECSAS were distributed evenly between July (51%) and August (49%). Autumn surveys for PIROP and ECSAS occurred primarily in September (PIROP: 70%, ECSAS: 76%), compared to October (28% and 20%) and November (2% and 4%).

In summer, 176,849 birds were recorded for PIROP, which consisted mainly of Northern Fulmars (58,933 individuals; 33% of total), Black-legged Kittiwakes (29,836 individuals; 17%), Dovekies (19,704 individuals; 11%), Thick-billed Murres (16,737 individuals; 10%) (see Appendix 1 for full species summary table). There were 2394 Black Guillemots recorded (1% of total). For summer ECSAS surveys, 14,331 birds were recorded, similarly dominated by the same four species: Northern Fulmars (4922 individuals; 34% of total), Dovekies (3556 individuals; 25%), Thick-billed Murres (3157 individuals; 22%) and Black-legged Kittiwakes (1409 individuals; 10%). Only 110 Black Guillemots were recorded (0.8% of total).

In autumn, 79,852 birds were recorded for PIROP, including Northern Fulmars (29,554 individuals; 37% of total), Dovekies (18,995 individuals; 24%), Black-legged Kittiwakes (14,613 individuals; 18%) and Thick-billed Murres (4893 individuals; 6%). For autumn ECSAS surveys, 15,091 birds were recorded, comprised mainly of Dovekies (7257 individuals; 48% of total), Northern Fulmars (4934 individuals; 33% of total), Black-legged Kittiwakes (1308 individuals; 9%) and Thick-billed Murres (791 individuals; 5%).

The kernel density estimation of seabird distribution (Fig. 4) showed that Hudson Strait, the northern Labrador Shelf, Frobisher Bay, Eclipse Sound and Navy Board Inlet had consistently high densities of multiple species, particularly in autumn. High densities of Dovekies in summer were mainly in Baffin Bay and Davis Strait, along the coast of Baffin Island, which in autumn shifted southward to the northern Labrador Shelf (Fig. 4A). In summer, Thick-billed Murre densities were generally highest around the colonies and in autumn, densities were highest on the northern Labrador Shelf (Fig. 4B). Summer distribution of Black Guillemots was mainly in coastal areas, including Hudson Strait, Frobisher Bay and northern Labrador coast (Fig. 4C). Marine areas of high density for Black-legged Kittiwakes were widely distributed but also concentrated around colonies in summer, and with the exception of waters around Bylot Island, shifted southward in autumn to areas off the southern coast of Baffin Island and the northern Labrador Shelf (Fig. 4D). Finally, areas of high density for Northern Fulmars in summer were widely distributed, but then concentrated south of Davis Strait in autumn (Fig. 4E).

3.3. Seabird risk due to vessel activity

Vessel activity risk to Dovekies was high in small areas on the northern Labrador Shelf and mouth of Eclipse Sound in summer (Fig. 5A), and mainly at the mouth of Hudson Strait and on the northern Labrador Shelf in autumn (Fig. 6A). For Thick-billed Murres, high risk due to vessel activity occurred mainly in Hudson Strait, Frobisher Bay and Eclipse Sound in summer (Fig. 5B) and only on the northern Labrador Shelf in autumn (Fig. 6B). Black Guillemots were at high risk from vessel activity in Hudson Strait, close to the north coast of Labrador and the mouth of Eclipse Sound in summer (Fig. 5C). Vessel activity risk to Black-legged Kittiwakes and Northern Fulmars was high in Eclipse Sound and the northern Labrador Shelf in summer (Fig. 5D and E) and autumn (Fig. 6C and D).

Maps assessing the risk of overlap between marine areas of high seabird density and regions of high vessel activity consistently highlighted the same regions for multiple seabird species, including Hudson Strait, the northern Labrador Shelf, Frobisher Bay, Eclipse Sound, Navy Board Inlet and off Baffin Island. Overall risk to the focal species combined (Fig. 7) was high in Hudson Strait, the northern Labrador Shelf, Frobisher Bay, and Eclipse Sound in summer (Fig. 7A) and autumn (Fig. 7B). Regions of risk for all seabirds recorded was similar (Appendix 2) but did not identify Hudson Strait as being a region of high risk in summer (Appendix 2A) or autumn (Appendix 2B).

4. Discussion

Within the waters off Baffin Island, we identified regions where high densities of seabirds overlapped with high vessel activity in summer and autumn. In these regions of overlap, seabirds are at greatest risk of vessel interaction because their probability of exposure, and thus vulnerability is higher, compared to regions where vessel activity is low. Risks to species that do not congregate in dense flocks (low density), like Black Guillemots, may be still be elevated where they co-occur with high levels of vessel activity as their body size, behavior and life history traits render them vulnerable to vessel-associated threats such as oiling (e.g., Renner and Kuletz, 2015). Areas that were consistently considered high risk for multiple species included Hudson Strait, the northern Labrador Shelf, Frobisher Bay, Eclipse Sound and Navy Board Inlet (Figs. 5–7, Appendix 2). Previous work suggested that, broadly, Baffin Bay and Davis Strait posed the highest risk to seabirds due to the potential of high levels of anthropogenic activity (*e.g.* shipping, fishing) coupled with the occurrence of multiple species in these waters (Humphries and Huettmann, 2014). While our study did indeed find marine areas of high density within Davis Strait and Baffin Bay for many species (Fig. 4), risk of vessel activity to seabirds in this area was relatively low. This is due to the comparatively high level of vessel traffic in other, more localized areas, such as waters frequently navigated by vessels travelling to busy communities like Iqaluit, Pond Inlet, and those within Hudson Bay (Figs. 2, 5–7). These regions were also highlighted by Gaston et al. (2013) as waters posing the most anthropogenic threat to Thick-billed Murres during summer when they are foraging near their colonies.

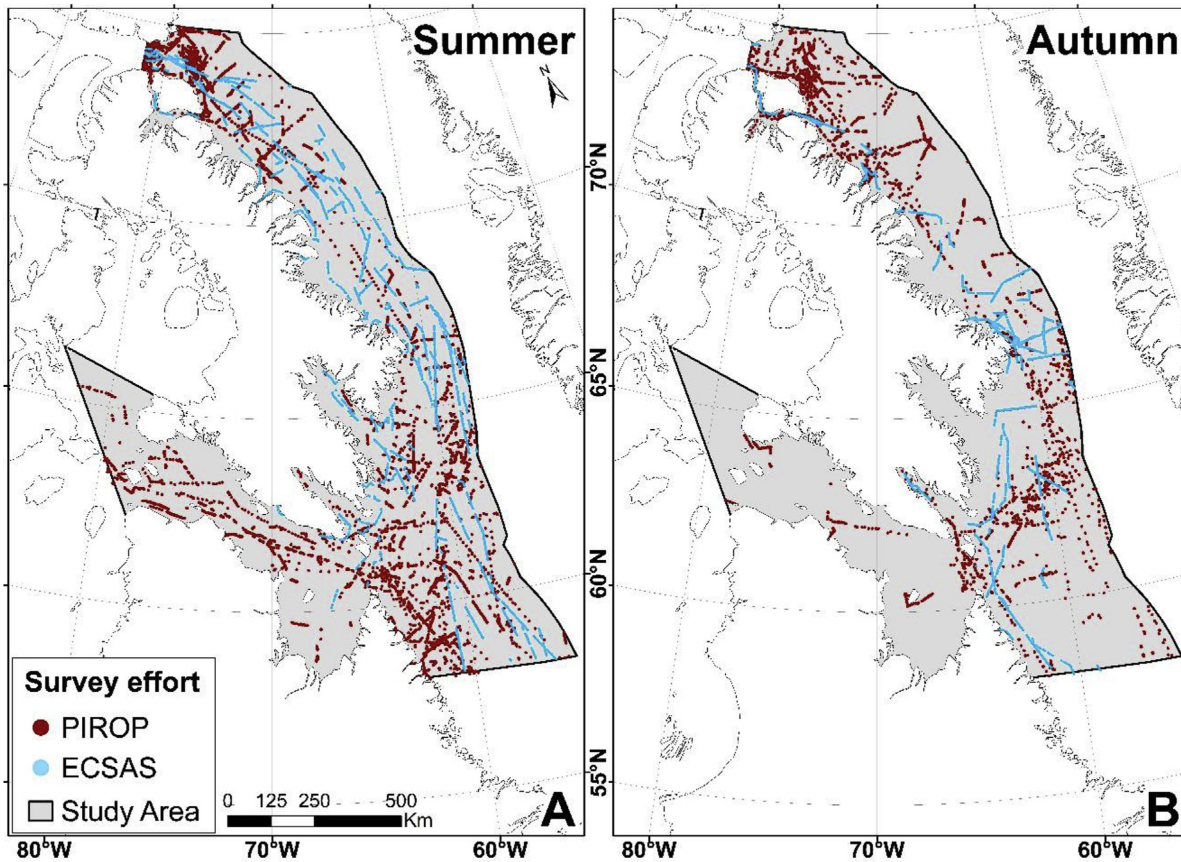


Fig. 3. Seabird survey effort for A) summer (June–August) and B) autumn (September–November). PIROP = Programme intégré de recherches sur les oiseaux pélagiques, 1970–1983, and ECSAS = Eastern Canada Seabirds at Sea, 2007–2016. Each dot represents the location of a 10-minute (PIROP) or 5-minute (ECSAS) continuous survey.

The largest threat that vessel activity poses to seabirds is mortality due to chronic oiling (Wiese and Robertson, 2004; Wiese and Ryan, 2003). Of the species we examined, chronic oiling would have the highest impact on alcids (Thick-billed Murres, Dovekies and Black Guillemots) (King and Sanger, 1979), which dive for their prey, spend more time on the surface of the water, and whose high levels of mortality due to oily discharges have been documented in subarctic waters of the North Atlantic (Wiese and Robertson, 2004; Wiese and Ryan, 2003; Wilhelm et al., 2009). The waters we identified as posing the largest risk to seabirds in our study area surround large colonies (see Fig. 1) of Thick-billed Murres, such as Akpatok Island in Hudson Strait, Coats and Digges islands within Hudson Bay, Hantzsch Island in Frobisher Bay, and Cape Graham Moore and Cape Hay on Bylot Island (Gaston et al., 2013; Mallory and Fontaine, 2004) where seabirds are foraging in the summer. In autumn, the northern Labrador Shelf and the mouth of Hudson Strait provide important habitat for Thick-billed Murres (Frederiksen et al., 2016; Gaston et al., 2011) and Dovekies (Fort et al., 2013) moving to their wintering areas (Fig. A.). Vessel activity in this region is high in autumn (Fig. 3) putting Thick-billed Murres and Dovekies at risk throughout the ice-free seasons (Figs. 6–7).

Another threat to seabirds associated with some types of vessel traffic is incidental take in fisheries. Northern Fulmars constitute the highest number of birds killed in longline fisheries in Arctic waters (Chardine et al., 2000), and bycatch rates of Northern Fulmars in gillnet and longline fisheries targeting Greenland halibut are high near colonies in Davis Strait and Baffin Bay (Hedd et al., 2016). Thick-billed Murres are also susceptible to incidental take in gillnet fisheries in Atlantic waters (Hedd et al., 2016). While our analysis did not specifically quantify the level of fishing vessel activity, fishing vessels were the most common vessel type in our vessel data. Furthermore, the Greenland halibut fishery in eastern Arctic waters has been expanding since 2001 (DFO, 2014) and with continued loss of Arctic sea ice, new and existing commercial and industrial fishing is predicted to grow (Christiansen et al., 2014). However, Greenland recently achieved MSC certification for its halibut fishery (Marine Stewardship Council, 2017), suggesting that efforts will be made to minimize all bycatch. Continued monitoring of fishing activity and seabird bycatch is thus recommended for these waters.

While our study identified marine areas where high vessel activity overlaps with high seabird densities in summer and autumn, our results should be interpreted with caution. First, due to the nature and diversity of data sources for the vessel traffic data, we extrapolated vessel tracks from points. Although we are unable to verify the accuracy of our vessel track estimates, we feel confident that this method is a good approximation of vessel activity in our study area and is appropriate given the large scale of the study area. Second, our delineation between high and low levels of vessel activity is an arbitrary threshold of relative risk (> 1 vessel per week as high). Our threshold would be considered low in other Arctic waters (Arctic Council, 2009; Humphries and Huettmann, 2014) and parts of Canadian waters, including the western North Atlantic (Simard et al., 2014), where many of these species spend their winters. Nonetheless, our approach identifies Arctic regions where seabird and human interactions are of most concern.

To put our work into a more global perspective of vessel activity risk to seabirds, we can compare the potential frequency of vessel encounters from our study to that documented in other regions. Within Arctic waters, most vessel activity occurs off Norway, Greenland, Iceland and the coasts of northwest Russia and the Bering Sea, where vessel activity can be at least 10 times greater than in our study area (Arctic Council, 2009; Humphries and Huettmann, 2014). For example,

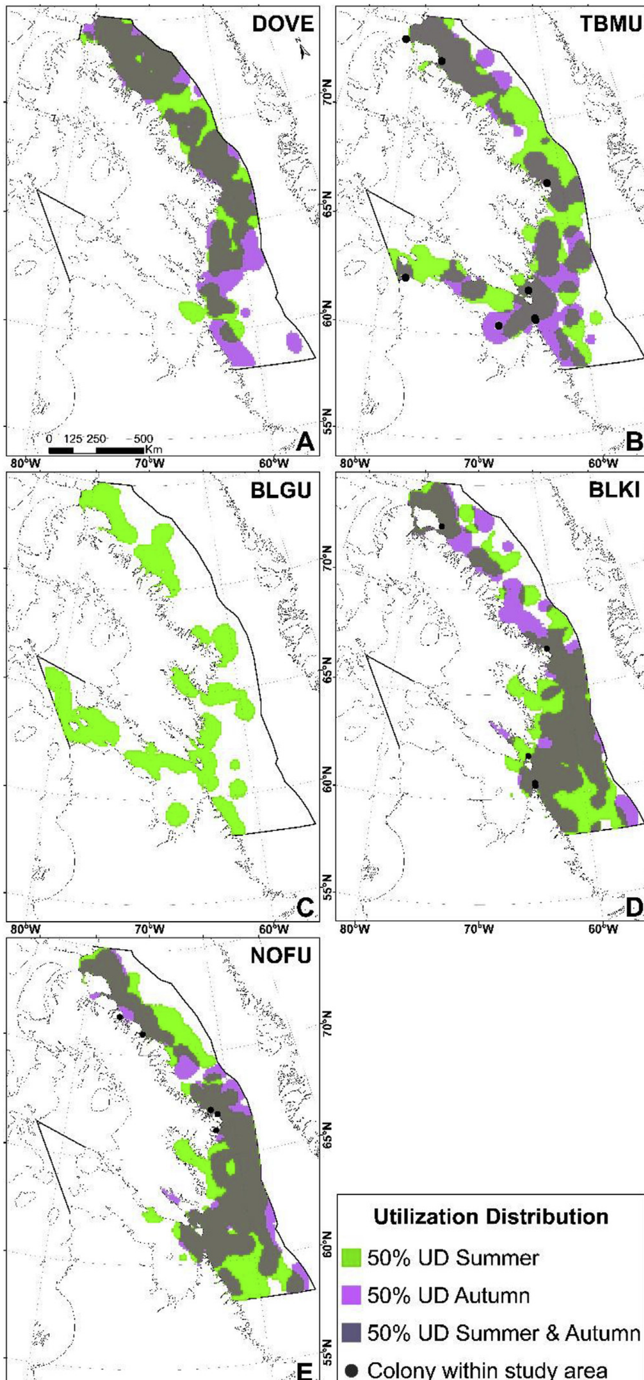


Fig. 4. Marine regions of high seabird density, defined as the 50% Utilization Distribution, in summer (green; June–August) and autumn (purple; September–November) and overlap of both season (grey) for A) Dovekie, B) Thick-billed Murre, C) Black Guillemot, D) Black-legged Kittiwake and E) Northern Fulmar from at-sea survey data collected between 1970 – 1983 and 2007–2016. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

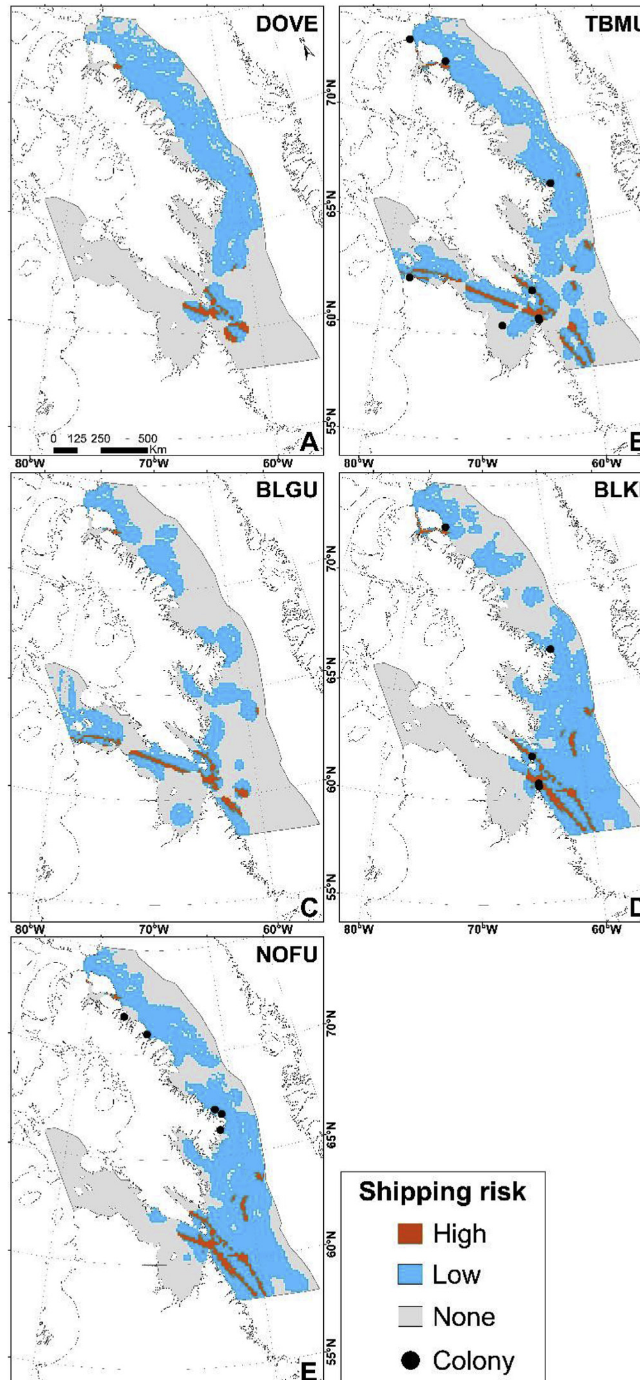


Fig. 5. Risk to selected species of seabirds where high vessel activity overlaps with marine areas of high density in summer (June–August) for A) Dovekie, B) Thick-billed Murre, C) Black Guillemot, D) Black-legged Kittiwake, E) Northern Fulmar. High risk = high vessel activity + high seabird density (defined as 50% Utilization Distribution), Low risk = low vessel activity + high seabird density, None = no vessel activity and/or low seabird density (< 50% Utilization distribution). Colonies within the study area are mapped.

vessel traffic through Bering Strait was estimated at 440 transits in 2013 (Huntington et al., 2015), amounting to an average of more than one vessel per day and likely much higher in summer and fall when vessel activity increases (Renner and Kuletz, 2015). Thus, the oiling risk of vessel traffic through Bering Strait is of concern given the large numbers of seabirds using this area (Humphries and Huettmann, 2014). Likewise, an estimated eight to nine vessels pass through the Aleutian Archipelago daily (Nuka Research & Planning Group, LCC. and Cape International, Inc., 2006), raising concerns of vessel activity risk to the millions of seabirds using those waters, particularly through the main Aleutian corridor of Unimak Pass (Renner and Kuletz, 2015).

Finally, temperate waters experience higher levels of vessel traffic (Simard et al., 2014) compared to the Arctic, including waters off Newfoundland and Labrador and Nova Scotia where many of the

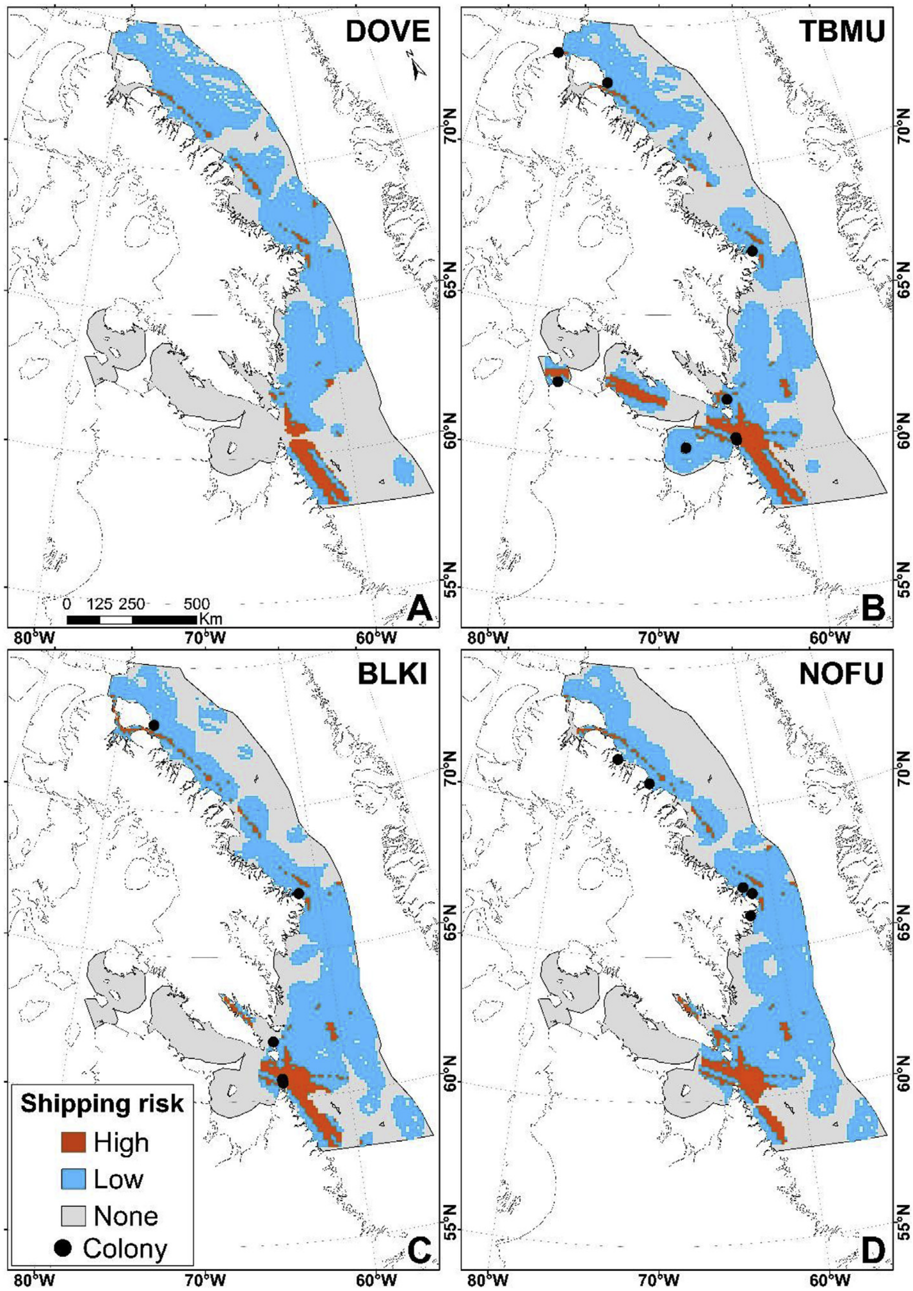


Fig. 6. Risk to selected species of seabirds where high vessel activity overlaps with marine areas of high density in autumn (September–November) for A) Dovekie, B) Thick-billed Murre, C) Black-legged Kittiwake, D) Northern Fulmar. High risk = high vessel activity + high seabird density (defined as 50% Utilization Distribution), Low risk = low vessel activity + high seabird density, None = no vessel activity and/or low seabird density (< 50% Utilization distribution). Colonies within the study area are mapped.

species we examined overwinter, including Thick-billed Murres (Frederiksen et al., 2016; Gaston et al., 2011), Dovekies (Fort et al., 2013; Mosbech et al., 2012), Black-legged Kittiwakes (Frederiksen et al., 2012) and Northern Fulmars (Mallory et al., 2008). For example, vessel traffic is particularly high along the south coast of the island of Newfoundland and over the Grand Banks, and these regions experience some of the worst chronic oil pollution problems in the world (Hedd et al., 2011; Wiese and Ryan, 2003). Mortality of murres due to chronic oiling in these waters is well documented (Wiese et al., 2004). Although recent studies suggest the number of birds found oiled are in decline (Wilhelm et al., 2009), many species are exposed to the additional risks associated with oil and gas infrastructure and fishing activities (Hedd et al., 2011). With predicted increases in vessel traffic in Arctic waters and emerging Arctic sea routes (Pizzolato et al., 2016; Smith and Stephenson, 2013), anthropogenic risks throughout the birds' annual cycle and their cumulative impacts need to be considered.

5. Conclusions

We identified Navy Board Inlet, Eclipse Sound, Frobisher Bay, Hudson Strait and the northern Labrador Shelf as areas where Arctic-breeding seabirds are at risk to vessel traffic in summer and autumn. As Arctic sea ice changes, more industrial development, commercial fishing, and shipping activity are expected in this region (Guy and Lasserre, 2016; Huntington et al., 2015; Pizzolato et al., 2016, 2014), which will put seabirds at greater risk to vessel incidents, chronic pollution and incidental take. Identifying regions where high seabird density and vessel activity overlap will allow us to better manage and

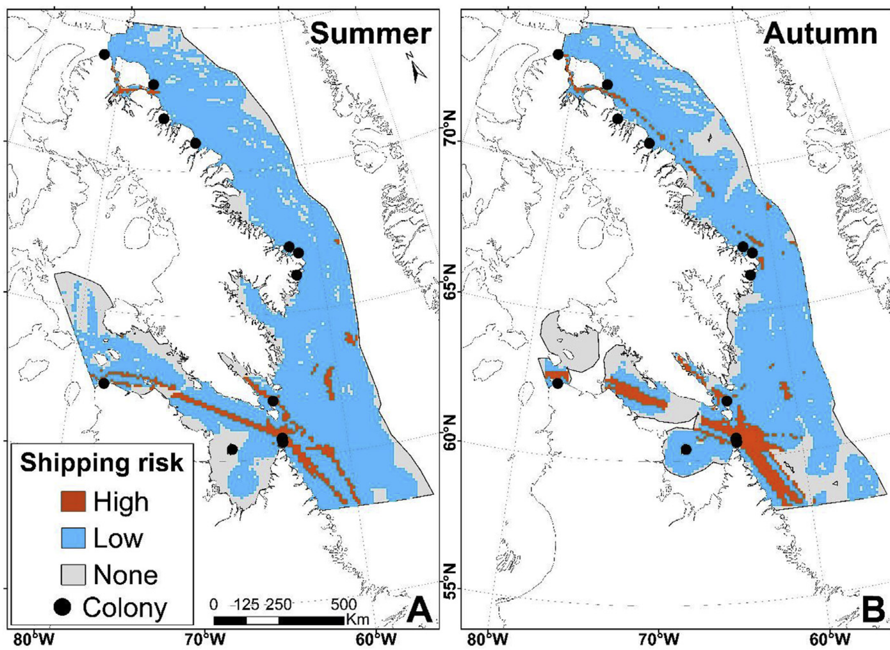


Fig. 7. Risk to the focal species (Dovekie, Thick-billed Murre, Black-Guillemot (summer only), Black-legged Kittiwake and Northern Fulmar) where high vessel activity overlaps with marine areas of high seabird density for A) summer and, B) autumn. High risk = high vessel activity + high seabird density (defined as 50% Utilization Distribution), Low risk = low vessel activity + high seabird density, None = no vessel activity and/or low seabird density (< 50% Utilization distribution). Colonies within the study area are mapped.

mitigate these interactions in advance of increased vessel activity.

Future work should examine individual anthropogenic risks (*e.g.*, fishing activity, chronic oiling) while considering species-specific sensitivities to each threat and determine whether the interaction with the activity (*e.g.*, commercial fishing) is having a negative effect on the population. Furthermore, as the distribution of seabirds shifts and/or expands with warming temperatures (Gaston and Woo, 2008), there is an ongoing need to monitor seabirds at sea to ensure areas where seabirds are vulnerable to anthropogenic threats remain updated. Together, this information can be used for marine spatial planning to ensure healthy seabird populations in the Arctic are maintained as human use of Arctic waters increases. Marine protected areas and fishery closure areas are just some tools available to protect marine wildlife but efforts should be made to evaluate how well current fishery closures (e.g. Disko Fan, Hatton Basin and Davis Strait Conservation Areas) and the future Lancaster Sound National Marine Conservation Area are protecting the species they have been established to protect. Identifying priorities for conservation, both from an ecosystem and human use perspective, while acknowledging each is dynamic, is needed to strike a balance for conservation planning in Arctic waters.

Acknowledgements

Thanks to the Canadian Coast Guard and H. Sherwood for providing access to and extracting the vessel data, and P. O'Hara for analytical advice. Seabird data were provided by the Canadian Wildlife Service at Environment and Climate Change Canada. Thanks to the many seabird observers that collected data over the years, particularly D. Brown. Funding and support were provided by Mitacs, W. Garfield Weston Foundation and Baffinland Iron Mines Coorporation. Many thanks to three anonymous reviewers, whose thoughtful comments and suggestions improved the manuscript.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.ocecoaman.2018.07.004.

Appendix 1. Summary of species recorded during at-sea surveys in waters off Baffin Island Strait for summer (June–August) and autumn (September–November) for two datasets: ECSAS (Eastern Canada Seabirds at Sea program) from 2007 to 2016 and PIROP (Programme intégré de recherges sur les oiseaux pélagiques) from 1970 to 1983. Species used in the analysis are highlighted in bold.

Family	Species		Database and season, count (%)[a]			
	Common name	Scientific name	PIROP summer	ECSAS summer	PIROP autumn	ECSAS autumn
Gavidae	Red-throated Loon	*Gavia stellata*	1 (< 0.1)	0	0	0
Procellariidae	**Northern Fulmar**	***Fulmarus glacialis***	**58,933 (33.3)**	**4922 (34.3)**	**29,554 (37.0)**	**4934 (32.7)**
	Cory's Shearwater	*Calonectris borealis*	3 (< 0.1)	0	0	34 (1.3)
	Great Shearwater	*Ardenna gravis*	6230 (3.5)	33 (0.2)	10 (< 0.1)	0
	Manx Shearwater	*Puffinus puffinus*	0	0	0	5 (< 0.1)
	Sooty Shearwater	*Ardenna grisea*	121 (0.1)	9 (0.1)	1 (< 0.1)	0
	Unidentified Shearwater		1 (< 0.1)	1 (< 0.1)	2 (< 0.1)	0
	Band-rumped Storm-petrel	*Oceanodroma castro*	10 (< 0.1)	0	0	0
Hydrobatidae	Leach's Storm-petrel	*Oceanodroma leucorhoa*	6 (< 0.1)	0	0	0
	Wilson's Storm-petrel	*Oceanites oceanicus*	184 (0.1)	0	0	0
	Unidentified Storm-petrel		50 (< 0.1)	1 (< 0.1)	0	0

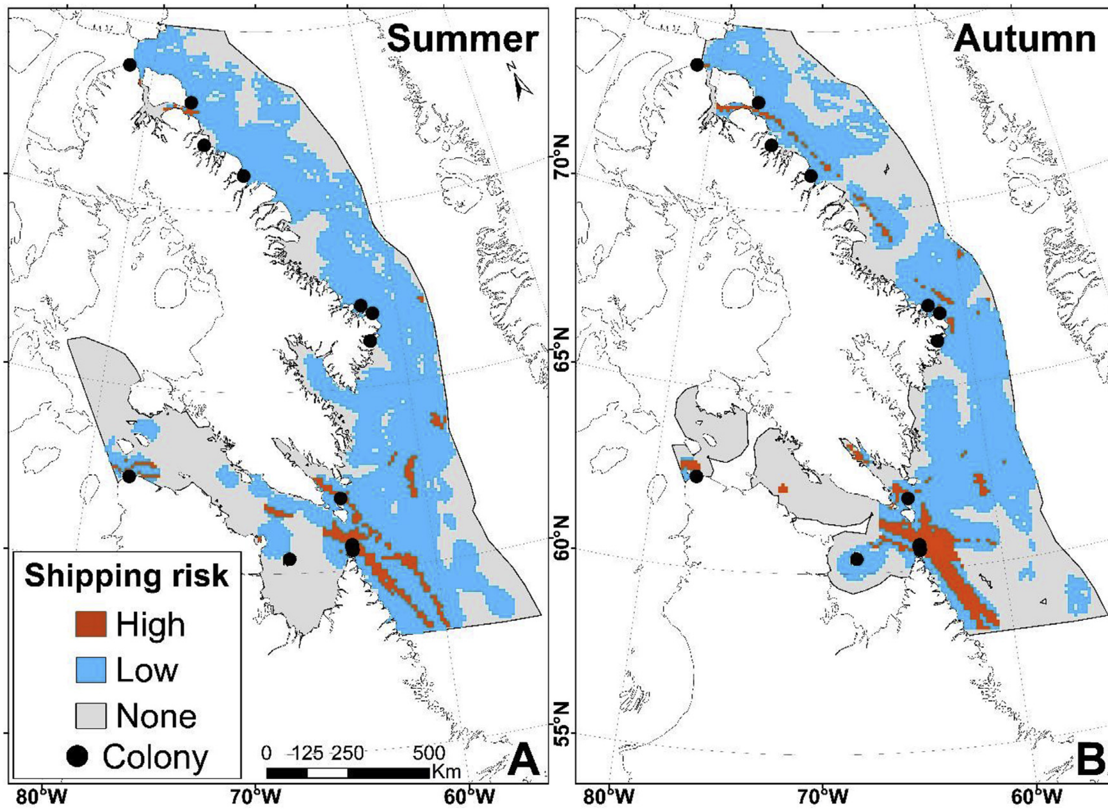
Sulidae	Northern Gannet	*Morus bassanus*	13 (< 0.1)	0	1 (< 0.1)	0
Phalacrocoracidae	Unidentified Cormorant		0	4 (< 0.1)	0	1 (< 0.1)
Anatidae	Common Eider	*Somateria mollissima*	514 (0.3)	8 (0.1)	3547 (4.4)	9 (0.1)
	King Eider	*Somateria spectabilis*	0	15 (0.1)	0	11 (0.1)
	Black Scoter	*Melanitta americana*	11 (< 0.1)	0	5 (< 0.1)	0
	Long-tailed Duck	*Clangula hyemalis*	1028 (0.6)	0	23 (< 0.1)	0
	Red-breasted Merganser	*Mergus serrator*	0	0	301 (0.4)	0
	Snow Goose	*Chen caerulescens*	175 (0.1)	0	33 (< 0.1)	0
	Unidentified Eider	*Somateria* spp.	2102 (1.2)	30 (0.2)	545 (0.7)	
Scolopacidae	Red Phalarope	*Phalaropus fulicarius*	13,404 (7.6)	141 (1.0)	81 (0.1)	0
	Red-necked Phalarope	*Phalaropus lobatus*	30 (< 0.1)	51 (0.4)	93 (0.1)	0
	Unidentified Phalarope	*Phalaropus* spp.	3044 (1.7)	240 (1.7)	54 (0.1)	8 (< 0.1)
Stercorariidae	Long-tailed jaeger	*Stercorarius longicaudus*	495 (0.3)	26 (0.2)	23 (< 0.1)	0
	Parasitic Jaeger	*Stercorarius parasiticus*	92 (0.1)	6 (< 0.1)	22 (< 0.1)	1 (< 0.1)
Stercorariidae	Pomarine Jaeger	*Stercorarius pomarinus*	448 (0.3)	23 (0.2)	98 (0.21)	15 (0.1)
	Great Skua	*Stercorarius skua*	15 (< 0.1)	0	3 (< 0.1)	2 (< 0.1)
	Unidentified Jaeger/Skua	*Stercorarius* spp.	323 (0.2)	9 (0.1)	14 (< 0.1)	0
Laridae	**Black-legged Kittiwake**	***Rissa tridactyla***	**29,836 (16.9)**	**1409 (9.8)**	**14,613 (18.3)**	**1308 (8.7)**
	Black-headed Gull	*Chroicocephalus ridibundus*	0	0	0	1 (< 0.1)
	Bonaparte's Gull	*Chroicocephalus philadelphia*	0	0	2 (< 0.1)	0
	Glaucous Gull	*Larus hyperboreus*	612 (0.3)	68 (0.5)	2341 (2.9)	469 (3.1)
	Great Black-backed Gull	*Larus marinus*	50 (< 0.1)	3 (< 0.1)	24 (< 0.1)	3 (< 0.1)
	Herring Gull	*Larus argentatus*	245 (0.1)	0	426 (0.5)	9 (0.1)
	Iceland Gull	*Larus glaucoides*	334 (0.2)	17 (0.1)	115 (0.1)	43 (0.3)
	Ivory Gull	*Pagophila eburnea*	295 (0.2)	2 (< 0.1)	429 (0.5)	0
	Laughing Gull	*Leucophaeus atricilla*	44 (< 0.1)	0	2 (< 0.1)	0
	Lesser Black-backed Gull	*Larus fuscus*	1 (< 0.1)	0	0	1 (< 0.1)
	Ross's Gull	*Rhodostethia rosea*	0	13 (0.1)	0	0
	Sabine's Gull	*Xema sabini*	189 (0.1)	4 (< 0.1)	41 (0.1)	1 (< 0.1)
	Thayer's Gull	*Larus thayeri*	109 (0.1)	3 (< 0.1)	113 (0.1)	0
	Arctic Tern	*Sterna paradisaea*	226 (0.1)	1 (< 0.1)	89 (0.1)	2 (< 0.1)
	Unidentified Gull		138 (0.1)	9 (0.1)	96 (0.1)	8 (< 0.1)
	Unidentified Tern	*Sterna* spp.	274 (0.2)	6 (< 0.1)	8 (< 0.1)	0
	Unidentified Gull/Tern		10 (< 0.1)	0	57 (0.1)	0
Alcidae	Atlantic Puffin	*Fratercula arctica*	74 (< 0.1)	7 (< 0.1)	101 (0.1)	4 (< 0.1)
	Black Guillemot	***Cepphus grylle***	**2394 (1.4)**	**110 (0.8)**	**562 (0.7)**	**34 (0.2)**
	Dovekie	***Alle alle***	**19,704 (11.1)**	**3556 (24.8)**	**18,995 (23.8)**	**7257 (48.1)**
	Common Murre	*Uria aalge*	387 (0.2)	26 (0.2)	344 (0.4)	4 (< 0.1)
	Thick-billed Murre	***Uria lomvia***	**16,737 (9.5)**	**3157 (22.0)**	**4893 (6.1)**	**791 (5.2)**
	Razorbill	*Alca torda*	20 (< 0.1)	1 (< 0.1)	0	0
	Unidentified Murre	*Uria* spp.	11,861 (6.7)	386 (2.7)	1510 (1.9)	47 (0.3)
	Unidentified Alcid		5784 (3.3)	34 (0.2)	289 (0.4)	113 (0.7)
Other			**290**[b]		**392**[c]	
All species			**176,849**	**14,331**	**79,852**	**15,091**

[a] % of total number for that database and season.

[b] Includes Canada Goose *Branta canadensis* (1), Wilson's phalarope *Phalaropus tricolor* (2), unidentified ducks (60), unidentified goose (3), unidentified pelacaniformes (3), unidentified waterfowl (36), unidentified seabird (187).

[c] Includes American Black Duck *Anas rubripes* (1), American Coot *Fulica americana* (1), Steller's Eider *Polysticta stelleri*, unidentified ducks (117), unidentified seabird (1), unidentified pelecaniforms (1), unidentified waterfowl (255).

Appendix 2. Risk to all species recorded during surveys where high vessel activity overlaps with marine areas of high seabird density for A) summer and, B) autumn. High risk = high vessel activity + high seabird density (defined as 50% Utilization Distribution), Low risk = low vessel activity + high seabird density, None = no vessel activity and/or low seabird density (< 50% Utilization distribution). Colonies within the study area are mapped.



References

Aksenove, Y., Popova, E.E., Yool, A., Nurse, A.J.G., Williams, T.D., Bertino, L., Bergh, J., 2017. On the future navigability of Arctic sea routes: high-resolution projections of the Arctic Ocean and sea ice. Mar. Pol. 75, 300–317. https://doi.org/10.1016/j.marpol.2015.12.027.

Arctic Council, 2009. Arctic Marine Shipping Assessment 2009 Report. Arctic. https://www.pmel.noaa.gov/arctic-zone/detect/documents/AMSA_2009_Report_2nd_print.pdf.

Bertazzon, S., O'Hara, P.D., Barrett, O., Serra-Sogas, N., 2014. Geospatial analysis of oil discharges observed by the national aerial surveillance program in the Canadian pacific ocean. Appl. Geogr. 52, 78–89. https://doi.org/10.1016/j.apgeog.2014.04.010.

Braune, B.M., Gaston, A.J., Gilchrist, H.G., Mallory, M.L., Provencher, J.F., 2014. A geographical comparison of mercury in seabirds in the eastern Canadian Arctic. Environ. Int. 66, 92–96.

Chardine, J.W., Porter, J.M., Wohl, K.D., 2000. Workshop on Seabird Incidental Catch in the Waters of Arctic Countries.

Christiansen, J.S., Mecklenburg, C.W., Karamushko, O.V., 2014. Arctic marine fishes and their fisheries in light of global change. Global Change Biol. 20, 352–359. https://doi.org/10.1111/gcb.12395.

Comiso, J.C., Meier, W.N., Gersten, R., 2017. Variability and trends in the Arctic Sea ice cover: results from different techniques. J. Geophys. Res. Oceans. 122, 6883–6900. https://doi.org/10.1002/2017JC012768.

Cosandey-Godin, A., Krainski, E.T., Worm, B., Flemming, J.M., 2015. Applying Bayesian spatiotemporal models to fisheries bycatch in the Canadian Arctic. Can. J. Fish. Aquat. Sci. 72, 186–197. https://doi.org/10.1139/cjfas-2014-0159.

Croxall, J.P., Butchart, S.H.M., Lascelles, B., Stattersfield, A.J., Sullivan, B., Symes, A., Taylor, P., 2012. Seabird conservation status, threats and priority actions: a global assessment. Bird Conserv. Int. 22, 1–34. https://doi.org/10.1017/S0959270912000020.

DFO, 2014. Integrated Fishery Management Plan Greenland Halibut (*Reinhardtius hippoglossoides*) Northwest Atlantic Fisheries Organization Subarea 0 Effective 2014.

Diemer, K.M., Conroy, M.J., Ferguson, S.H., Hauser, D.D.W., Grgicak-Mannion, A., Fisk, A.T., 2011. Marine mammal and seabird summer distribution and abundance in the fjords of northeast Cumberland Sound of Baffin Island, Nunavut, Canada. Polar Biol. 34, 41–48. https://doi.org/10.1007/s00300-010-0857-1.

Ferland, J., Gosselin, M., Starr, M., 2011. Environmental control of summer primary production in the Hudson Bay system: the role of stratification. J. Mar. Syst. https://doi.org/10.1016/j.jmarsys.2011.03.015.

Fort, J., Moe, B., Strøm, H., Grémillet, D., Welcker, J., Schultner, J., Jerstad, K., Johansen, K.L., Phillips, R.A., Mosbech, A., 2013. Multicolony tracking reveals potential threats to little auks wintering in the North Atlantic from marine pollution and shrinking sea ice cover. Divers. Distrib. 19, 1322–1332. https://doi.org/10.1111/ddi.12105.

Fox, C.H., O'Hara, P.D., Bertazzon, S., Morgan, K., Underwood, F.E., Paquet, P.C., 2016. A preliminary spatial assessment of risk: marine birds and chronic oil pollution on Canada's Pacific coast. Sci. Total Environ. 573, 799–809. https://doi.org/10.1016/j.scitotenv.2016.08.145.

Frederiksen, M., Moe, B., Daunt, F., Phillips, R.A., Barrett, R.T., Bogdanova, M.I., Boulinier, T., Chardine, J.W., Chastel, O., Chivers, L.S., Christensen-Dalsgaard, S., Clément-Chastel, C., Colhoun, K., Freeman, R., Gaston, A.J., González-Solís, J., Goutte, A., Grémillet, D., Guilford, T., Jensen, G.H., Krasnov, Y., Lorentsen, S.H., Mallory, M.L., Newell, M., Olsen, B., Shaw, D., Steen, H., Strøm, H., Systad, G.H., Thórarinsson, T.L., Anker-Nilssen, T., 2012. Multicolony tracking reveals the winter distribution of a pelagic seabird on an ocean basin scale. Divers. Distrib. 18, 530–542. https://doi.org/10.1111/j.1472-4642.2011.00864.x.

Frederiksen, M., Descamps, S., Erikstad, K.E., Gaston, A.J., Gilchrist, H.G., Grémillet, D., Johansen, K.L., Kolbeinsson, Y., Linnebjerg, J.F., Mallory, M.L., McFarlane Tranquilla, L.A., Merkel, F.R., Montevecchi, W.A., Mosbech, A., Reiertsen, T.K., Robertson, G.J., Steen, H., Strøm, H., Thórarinsson, T.L., 2016. Migration and wintering of a declining seabird, the Thick-billed Murre *Uria lomvia*, on an ocean basin scale: conservation implications. Biol. Conserv. 200, 26–35. https://doi.org/10.1016/j.biocon.2016.05.011.

Furness, R.W., Wade, H.M., Masden, E.A., 2013. Assessing vulnerability of marine bird populations to offshore wind farms. J. Environ. Manag. 119, 56–66. https://doi.org/10.1016/j.jenvman.2013.01.025.

Garthe, S., Hüppop, O., 2004. Scaling possible adverse effects of marine wind farms on seabirds: developing and applying a vulnerability index. J. Appl. Ecol. 41, 724–734.

Gaston, A.J., Robertson, G.J., 2014. A review of thick-billed murre banding in the Canadian arctic, 1950-2010. Arctic 67, 441–448. https://doi.org/10.14430/arctic4419.

Gaston, A.J., Woo, K., 2008. Razorbills (*Alca torda*) follow subarctic prey into the Canadian Arctic: colonization results from climate change? Auk 125, 939–942. https://doi.org/10.1525/auk.2008.07195.
Gaston, A.J., Collins, B.L., Diamond, A.W., 1987. The "Snapshot" count for estimating densitiesof flying seabirds during boat transects: a cautionary comments. The Auk 104, 336–338.
Gaston, A.J., Smith, P.A., Tranquilla, L.M.F., Montevecchi, W.A., Fifield, D.A., Gilchrist, H.G., Hedd, A., Mallory, M.L., Robertson, G.J., Phillips, R.A., 2011. Movements and wintering areas of breeding age Thick-billed Murre *Uria lomvia* from two colonies in Nunavut, Canada. Mar. Biol. 158, 1929–1941. https://doi.org/10.1007/s00227-011-1704-9.
Gaston, A.J., Mallory, M.L., Gilchrist, H.G., 2012. Populations and trends of Canadian arctic seabirds. Polar Biol. 35, 1221–1232. https://doi.org/10.1007/s00300-012-1168-5.
Gaston, A.J., Elliott, K.H., Ropert-Coudert, Y., Kato, A., Macdonald, C.A., Mallory, M.L., Gilchrist, H.G., 2013. Modeling foraging range for breeding colonies of Thick-billed Murres *Uria lomvia* in the Eastern Canadian Arctic and potential overlap with industrial development. Biol. Conserv. 168, 134–138. https://doi.org/10.1016/j.biocon.2013.09.018.
Gjerdrum, C., Fifield, D.A., Wilhelm, S.I., 2012. Eastern Canada Seabirds at Sea (ECSAS) Standardized Protocol for Pelagic Seabird Surveys from Moving and Stationary Platforms. Canadian Wildlife Service Technical Report Series No. 515. Atlantic Region vi + 37 pp.
Guy, E., Lasserre, F., 2016. Commercial shipping in the Arctic: new perspectives, challenges and regulations. Polar Rec. (Gr. Brit). 52, 294–304. https://doi.org/10.1017/S0032247415001011.
Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, John, F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R., 2008. A global map of human impact on marine ecosystems. Science 319, 948–952.
Halpern, B.S., Frazier, M., Potapenko, J., Casey, K.S., Koenig, K., Longo, C., Lowndes, j.S., Rockwood, R.C., Selig, E.R., Selkoe, K.A., Walbridge, S., 2015. Spatial and temporal changes in cumulative human impacts on the world's ocean. Nat. Commun. 6, 7615. https://doi.org/10.1038/ncomms8615.
Hedd, A., Montevecchi, W.A., Mcfarlane Tranquilla, L., Burke, C.M., Fifield, D.A., Robertson, G.J., Phillips, R.A., Gjerdrum, C., Regular, P.M., 2011. Reducing uncertainty on the Grand Bank: tracking and vessel surveys indicate mortality risks for common murres in the north-West Atlantic. Anim. Conserv. 14, 630–641. https://doi.org/10.1111/j.1469-1795.2011.00479.x.
Hedd, A., Regular, P.M., Wilhelm, S.I., Rail, J.F., Drolet, B., Fowler, M., Pekarik, C., Robertson, G.J., 2016. Characterization of seabird bycatch in eastern Canadian waters, 1998-2011, assessed from onboard fisheries observer data. Aquat. Conserv. Mar. Freshw. Ecosyst. 26, 530–548. https://doi.org/10.1002/aqc.2551.
Humphries, G.R.W., Huettmann, F., 2014. Putting models to a good use: a rapid assessment of Arctic seabird biodiversity indicates potential conflicts with shipping lanes and human activity. Divers. Distrib. 20, 478–490. https://doi.org/10.1111/ddi.12177.
Huntington, H.P., Daniel, R., Hartsig, A., Harun, K., Heiman, M., Meehan, R., Noongwook, G., Pearson, L., Prior-Parks, M., Robards, M., Stetson, G., 2015. Vessels, risks, and rules: planning for safe shipping in Bering Strait. Mar. Pol. 51, 119–127. https://doi.org/10.1016/j.marpol.2014.07.027.
Irons, D.B., Kendall, S.J., Erickson, W.P., Mcdonald, L.L., Lance, B.K., 2000. Nine years after the "Exxon Valdez" oil spill: effects on marine bird populations in Prince William Sound, Alaska. Condor 102, 723–737.
Keogan, K., Daunt, F., Wanless, S., Phillips, R.A., Walling, C.A., Agnew, P., Ainley, D.G., Anker-Nilssen, T., Ballard, G., Barrett, R.T., Barton, K.J., Bech, C., Becker, P., Berglund, P.A., Bollache, L., Bond, A.L., Bouwhuis, S., Bradley, R.W., Burr, Z.M., Camphuysen, K., Catry, P., Chiaradia, A., Christensen-Dalsgaard, S., Cuthbert, R., Dehnhard, N., Descamps, S., Diamond, T., Divoky, G., Drummond, H., Dugger, K.M., Dunn, M.J., Emmerson, L., Erikstad, K.E., Fort, J., Fraser, W., Genovart, M., Gilg, O., Gonzalez-Solis, J., Granadeiro, J.P., Gremillet, D., Hansen, J., Hanssen, S.A., Harris, M., Hedd, A., Hinke, J., Igual, J.M., Jahncke, J., Jones, I., Kappes, P.J., Lang, J., Langset, M., Lescroel, A., Lorentsen, S.H., Lyver, P.O., Mallory, M., Moe, B., Montevecchi, W.A., Monticelli, D., Mostello, C., Newell, M., Nicholson, L., Nisbet, I., Olsson, O., Oro, D., Pattison, V., Poisbleau, M., Pyk, T., Quintana, F., Ramos, J.A., Ramos, R., Reiertsen, T.K., Rodriguez, C., Ryan, P., Sanz-Aguilar, A., Schmidt, N.M., Shannon, P., Sittler, B., Southwell, C., Surman, C., Svagelj, W.S., Trivelpiece, W., Warzybok, P., Watanuki, Y., Weimerskirch, H., Wilson, P.R., Wood, A.G., Phillimore, A.B., Lewis, S., 2018. Global phenological insensitivity to shifting ocean temperatures amount seabirds. Nat. Clim. Change 8, 313–318. https://doi.org/10.1038/s41558-018-0115-z.
King, J.G., Sanger, G.A., 1979. Oil vulnerability index for marine oriented birds. In: Bartonek, J.C., Nettleship, D.N. (Eds.), Conservation or Marine Birds of North America. U.S. Fish and Wildlife Service, Wildlife Research Report 11:1-319, pp. 227–239.
Lascelles, B.G., Taylor, P.R., Miller, M.G.R., Dias, M.P., Oppel, S., Torres, L., Hedd, A., Le Corre, M., Phillips, R.A., Shaffer, S.A., Weimerskirch, H., Small, C., 2016. Applying global criteria to tracking data to define important areas for marine conservation. Divers. Distrib. 22, 422–431.
Lasserre, F., Têtu, P.-L., 2015. The cruise tourism industry in the Canadian Arctic : analysis of activities and perceptions of cruise ship operators. Polar Rec. (Gr. Brit). 51, 24–38. https://doi.org/10.1017/S0032247413000508.
Lieske, D.J., Fifield, D.A., Gjerdrum, C., 2014. Maps, models, and marine vulnerability: assessing the community distribution of seabirds at-sea. Biol. Conserv. 172, 15–28. https://doi.org/10.1016/j.biocon.2014.02.010.
Mallory, M.L., 2006. The Northern Fulmar (*Fulmarus glacialis*) in Arctic Canada: ecology, threats, and what it tells us about marine environmental conditions. Environ. Rev. 14, 187–216.
Mallory, M.L., Fontaine, A.J., 2004. Key marine habitat sites for migratory birds in Nunavut and the Northwest Territories. Occas. Pap. Can. Wildl. Serv., 109 93pp.. http://publications.gc.ca/collections/collection_2011/ec/CW69-1-109-eng.pdf.
Mallory, M.L., Akearok, J.A., Edwards, D.B., O'Donovan, K., Gilbert, C.D., 2008. Autumn migration and wintering of northern Fulmars (*Fulmarus glacialis*) from the Canadian high arctic. Polar Biol. 31, 745–750. https://doi.org/10.1007/s00300-008-0417-0.
Mallory, M.L., Braune, B.M., Provencher, J.F., Callaghan, D.B., Gilchrist, H.G., Edmonds, S.T., Allard, K., O'Driscoll, N.J., 2015. Mercury concentrations in feathers of marine birds in Arctic Canada. Mar. Pollut. Bull. 98, 308–313.
Marine Stewardship Council, 2017. World First as Greenland Halibut Fishery Gains MSC Certification. https://www.msc.org/newsroom/news/world-first-as-greenland-halibut-fishery-gains-msc-certification, Accessed date: 1 June 2017.
Masden, E.A., Haydon, D.T., Fox, A.D., Furness, R.W., Bullman, R., Desholm, M., 2009. Barriers to movement: impacts of wind farms on migrating birds. ICES J. Mar. Sci. 66, 746–753. https://doi.org/10.1093/icesjms/fsp031.
Michel, R.K., Bley, D.C., Leschine, T.M., Marcus, H.S., McCafferty, D., Mosley, A., North, R.C., Williams, M., 2009. Risk of Vessel Accidents and Spills in the Aleutian Islands: Designing a Comprehensive Risk Assessment. Special Report 293. The National Academies Press and Transportation Research Board, Washington, D.C. http://www.nap.edu/openbook.php?record_id=12443.
Michel, C., Hamilton, J., Hansen, E., Barber, D., Reigstad, M., Iacozza, J., Niemi, A., Seuthe, L., 2015. Arctic Ocean outflow shelves in the changing Arctic: a review and perspectives. Prog. Oceanogr. 139, 66–88.
Montevecchi, W.A., 2002. Interactions between fisheries and seabirds. In: Schreiber, E.A., Burger, J. (Eds.), Biology of Marine Birds. CRC Press, New York, pp. 527–557.
Montevecchi, W.A., Hedd, A., McFarlane Tranquilla, L., Fifield, D.A., Burke, C.M., Regular, P.M., Davoren, G.K., Garthe, S., Robertson, G.J., Phillips, R.A., 2012. Tracking seabirds to identify ecologically important and high risk marine areas in the western North Atlantic. Biol. Conserv. 156, 62–71. https://doi.org/10.1016/j.biocon.2011.12.001.
Mosbech, A., Johansen, K.L., Bech, N.I., Lyngs, P., Harding, A.M.A., Egevang, C., Phillips, R.A., Fort, J., 2012. Inter-breeding movements of little auks *Alle alle* reveal a key post-breeding staging area in the Greenland Sea. Polar Biol. 35, 305–311. https://doi.org/10.1007/s00300-011-1064-4.
Münchow, A., Falkner, K.K., Melling, H., 2015. Baffin island and west Greenland current systems in northern Baffin Bay. Prog. Oceanogr. 132, 305–317.
Nuka Research & Planning Group, LCC and Cape Interantional, I, 2006. Vessel traffic in the Aleutians Subarea. Report to Alaska Department of Environmental Conservation. 55p. http://dec.alaska.gov/spar/ppr/docs/060920vesselreport_s.pdf.
Piatt, J.F., Ford, G.R., 1996. How many seabirds were killed by the Exxon Valdez oil spill? Am. Fish. Soc. Symp. 18, 712–719.
Pizzolato, L., Howell, S.E.L., Derksen, C., Dawson, J., Copland, L., 2014. Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012. Clim. Change 123, 161–173. https://doi.org/10.1007/s10584-013-1038-3.
Pizzolato, L., Howell, S.E.L., Dawson, J., Laliberté, F., Copland, L., 2016. The influence of declining sea ice on shipping activity in the Canadian Arctic. Geophys. Res. Lett. 43, 12146–12154. https://doi.org/10.1002/2016GL071489.
Provencher, J.F., Mallory, M.L., Braune, B.M., Forbes, M.R., Gilchrist, H.G., 2014. Mercury and birds in Arctic Canada: effects, current trends and why we should be paying closer attention. Environ. Rev. 22, 1–12.
R Core Team, 2015. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/.
Renner, M., Kuletz, K.J., 2015. A spatial-seasonal analysis of the oiling risk from shipping traffic to seabirds in the Aleutian Archipelago. Mar. Pollut. Bull. 101, 127–136. https://doi.org/10.1016/j.marpolbul.2015.11.007.
Ronconi, R.A., St.Clair, C.C., 2002. Management options to reduce boat disturbance on foraging black guillemots (*Cepphus grylle*) in the Bay of Fundy. Biol. Conserv. 108, 265–271. https://doi.org/10.1016/S0006-3207(02)00126-X.
Ronconi, R.A., Allard, K.A., Taylor, P.D., 2015. Bird interactions with offshore oil and gas platforms: review of impacts and monitoring techniques. J. Environ. Manag. 147, 34–45. https://doi.org/10.1016/j.jenvman.2014.07.031.
Schwemmer, P., Mendel, B., Sonntag, N., Dierschke, V., Garthe, S., 2011. Effects of ship traffic on seabirds in offshore waters: implications for marine conservation and spatial planning. Ecol. Appl. 21, 1851–1860.
Serra-Sogas, N., O'Hara, P.D., Canessa, R., 2014. Modeling the distribution of illicit oily discharges detected by aerial surveillance in western Canadian marine waters. Mar. Pollut. Bull. 87, 76–87. https://doi.org/10.1016/j.marpolbul.2014.08.009.
Simard, Y., Roy, N., Giard, S., Yayla, M., 2014. Canadian year-round shipping traffic atlas for 2013: volume 1, east coast marine waters. Can. Tech. Rep. Fish. Aquat. Sci. 3091 (Vol.1)E. http://publications.gc.ca/collections/collection_2014/mpo-dfo/Fs97-6-3091-1-eng.pdf.
Smith, L.C., Stephenson, S.C., 2013. New Trans-Arctic shipping routes navigable by midcentury. PNAS 110, E1191–E1195. https://doi.org/10.1073/pnas.1214212110.
Stephenson, S.R., Smith, L.C., Brigham, L.W., Agnew, J.A., 2013. Projected 21st-century changes to Arctic marine access. Clim.Change. 118, 885–899. https://doi.org/10.1007/s10584-012-0685-0.
Tasker, M.L., Jones, P.H., Dixon, T., Blake, B.F., 1984. Counting seabirds at sea from ships: a review of methods employed and a suggestion for a standardized approach. The Auk 101, 567–577.
Tremblay, J.-É., Anderson, L.G., Matrai, P., Coupel, P., Bélanger, S., Michel, C., Reigstad, M., 2015. Global and regional drivers of nutrient supply, primary production and CO2 drawdown in the changing Arctic Ocean. Prog. Oceanogr. 139, 171–196.
Trevail, A.M., Gabrielsen, G.W., Kuhn, S., Van Franeker, J.A., 2015. Elevated levels of

ingested plastic in a high Arctic seabird, the Northern Fulmar (*Fulmarus glacialis*). Polar Biol. 38, 975–981. https://doi.org/10.1007/s00300-015-1657-4.
Velando, A., Munilla, I., 2011. Disturbance to a foraging seabird by sea-based tourism: implications for reserve management in marine protected areas. Biol. Conserv. 144, 1167–1174. https://doi.org/10.1016/j.biocon.2011.01.004.
Vollard, B., 2017. Temporal displacement of environmental crime: evidence from marine oil pollution. J. Environ. Econ. Manag. 82, 168–180. https://doi.org/10.1016/j.jeem.2016.11.001.
Wiese, F.K., Robertson, G.J., 2004. Assessing seabird mortality from chronic oil discharges at sea. Source J. Wildl. Manag. 68, 627–638.
Wiese, F.K., Ryan, P.C., 2003. The extent of chronic marine oil pollution in southeastern Newfoundland waters assessed through beached bird surveys 1984-1999. Mar. Pollut. Bull. 46, 1090–1101. https://doi.org/10.1016/S0025-326X(03)00250-9.
Wiese, F.K., Montevecchià, W.A., Davorenà, G.K., Huettmann, F., Diamond, A.W., Linkeàà, J., 2001. Seabirds at risk around offshore oil platforms in the North-west Atlantic. Mar. Pollut. Bull. 42, 1285–1290.
Wiese, F.K., Robertson, G.J., Gaston, A.J., 2004. Impacts of chronic marine oil pollution and the murre hunt in Newfoundland on Thick-billed Murre *Uria lomvia* populations in the eastern Canadian Arctic. Biol. Conserv. 116, 205–216. https://doi.org/10.1016/S0006-3207(03)00191-5.
Wilhelm, S.I., Robertson, G.J., Ryan, P.C., Tobin, S.F., Elliot, R.D., 2009. Re-evaluating the use of beached bird oiling rates to assess long-term trends in chronic oil pollution. Mar. Pollut. Bull. 58, 249–255. https://doi.org/10.1016/j.marpolbul.2008.09.018.
Williams, R., O'Hara, P.D., 2010. Modelling ship strike risk to fin, humpback and killer whales in British Columbia, Canada. J. Cetac. Res. Manag. 11, 1–8.
Zacharias, M.A., Gregr, E.J., 2005. Sensitivity and vulnerability in marine environments: an approach to identifying vulnerable marine areas. Conserv. Biol. 19, 86–97.
Žydelis, R., Small, C., French, G., 2013. The incidental catch of seabirds in gillnet fisheries: a global review. Biol. Conserv. 162, 76–88. https://doi.org/10.1016/j.biocon.2013.04.002.