Using foraging range and colony size to assess the vulnerability of breeding seabirds to oil across regions lacking at-sea distribution data

O'Hanlon, Nina J.; Bond, Alexander l; Masden, Elizabeth A.; Boertmann, David; Bregnballe, Thomas; Danielsen, Jóhannis; Descamps, Sébastien; Petersen, Aevar; Strøm, Hallvard; Systad, Geir; James, Neil A.

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Abstract

With the projected increases in shipping activity and hydrocarbon extraction globally, there is an increased risk of negative ecological impacts from oil pollution on the marine environment, including seabirds. Oil Vulnerability Indices (OVIs) are a common approach to assess seabird species vulnerability to oil pollution, and to identify where species are most at risk, typically across regional spatial scales and for a relatively limited number of species. This approach generally requires comprehensive data on at-sea distributions and densities, however for many regions these data are limited. We present a simplified OVI to assess seabird species vulnerability to oil pollution. To create the spatial component of the OVI we used a predictive foraging radius approach, using existing colony size and foraging range data, to project at-sea distributions of seabird populations during the breeding season. We demonstrate this approach over a large spatial scale, the eastern North Atlantic, which includes areas where seabird at-sea data are lacking. Our results reveal areas off west Greenland, Iceland and Norway where seabirds are most vulnerable to oil pollution during the breeding season, largely driven by large colonies of auks. We also identify locations along the coast of mainland Norway, Iceland and Scotland, where seabirds are particularly at risk to oil pollution associated with major shipping routes. Identifying areas where species are most at risk can help inform where, and which, measures should be put in place to mitigate the impacts of oil pollution, such as protecting and avoiding high risk areas, for example, through adopting dynamic Areas to be Avoided (ATBAs). Our simplified OVI combined with the predictive foraging radius approach can adapted to other regions globally that lack seabird-at-sea distribution data, to other marine wildlife, and to assess the risk from hydrocarbon extraction and other anthropogenic threats, including fishing activities and offshore renewable developments.

Key words: Atlantic; marine birds; oil vulnerability index; pollution

Lay Summary

- Identifying where seabirds are most at risk to oil pollution can help us take appropriate measures to protect them, such as avoiding oil extraction and major shipping routes in these areas.
- Oil Vulnerability Indices (OVIs) are commonly used to assess seabird vulnerability to oil pollution. However, mapping this vulnerability requires at-sea distribution and density data, which are often lacking.
- The predictive foraging radius approach uses colony size and foraging range data to estimate seabird at-sea density distribution data.
- We combined this approach with a simplified OVI to map breeding seabird vulnerability to oil pollution across the eastern North Atlantic.
- This approach revealed that seabirds were most vulnerable to oil pollution off east Greenland, west Iceland and Norway, where large, auk colonies are located.
- By combining mapped seabird vulnerability to oil with vessel density, we also identified locations off Norway, Iceland and Scotland where seabirds are at particular risk to oil pollution from shipping.

Introduction

Globally, shipping traffic is increasing, and this increase is projected to continue (Sardain et al. 2019, Gunnarsson 2021). This is especially true in the Arctic where a reduction in sea-ice has led to increasing political and commercial interest in the Arctic's resources as opportunities arise for new shipping routes, such as the Northern Sea Route, and access to unexploited hydrocarbon resources, especially oil (Miller and Ruiz 2014, Wilkinson et al.

2017). However, an increase in shipping and hydrocarbon extraction activity also increases the risk of negative ecological impacts, for example, through shipping or extraction accidents, pipeline leaks, sub-surface well blowouts and accidental or deliberate discharge of hydrocarbons during transportation (Clark 2001, Wilkinson et al. 2017). In the North Sea, the volume of oil input into the ocean has declined over recent decades due to measures put in place to reduce oil pollution (Camphuysen and Heubeck 2015, Carpenter 2019, Camphuysen 2022). However, there is still a considerable risk of oil pollution given the volume of shipping traffic and hydrocarbon extraction sites in the North Sea and elsewhere in the eastern North Atlantic (Camphuysen and Vollaard 2015).

Seabirds are among the most threatened group of birds, with 28% of species categorised as globally threatened (Paleczny et al. 2015, BirdLife International 2021), and populations facing numerous threats, including pollution (Croxall et al. 2012, Dias et al. 2019). Seabirds are long-lived, and their population growth rates are highly sensitive to changes in adult survival (Sæther and Bakke 2000). Seabirds are therefore particularly vulnerable to oil pollution, which can affect survival rates (Piatt and Ford 1996, Votier et al. 2005, Munilla et al. 2011). Although large (acute) oil spills and disasters can result in high mortality of individuals, and gain more attention, persistent chronic oil pollution, largely from illegal and incidental discharges from shipping and offshore hydrocarbon installations, has a greater impact on seabirds (Wiese and Robertson 2004, O'Hara and Morgan 2006, Camphuysen 2007, Ronconi et al. 2015). Seabirds can also be impacted indirectly by oil pollution through displacement from foraging habitats and reduced food availability where prey are affected (Peterson et al. 2003, Velando et al. 2005).

Given the predicted increase in shipping activity we need to assess the vulnerability of seabirds to oil pollution, and to highlight locations of high risk. Here we define vulnerability as the potential for harm due to a species behaviour or demography, whilst risk is defined as the potential for harm due to the presence of a threat. The most common approach to achieve this is through calculating an index based on species-specific behaviours and life history traits; for vulnerability to oil, this is an Oil Vulnerability Index (OVI; King and Sanger 1979, Williams et al. 1994). This requires data on seabird demography to determine how quickly a population may recover from an oil spill, and on how a species' behaviour may influence their vulnerability to oil. These species-specific indices can be combined with species' distributions and densities to create a map to identify specific locations where seabirds are most vulnerable to oil-related anthropogenic activities (Webb et al. 2016). Typically, the spatial component of these OVIs are calculated from data collected from vessel or aerial based at-sea surveys (Williams et al. 1994, Skov et al. 2002, Webb et al. 2016). Although seabird at-sea surveys can obtain information on the distribution and density of a large number of individuals and species throughout the year, across relatively large areas, coverage is patchy in time and space due to the logistical and financial costs involved (Stone et al. 1995, Dunn 2012). An alternative approach is to use species distribution models (SDM) to overcome uneven coverage in data collection (Waggitt et al. 2020). However, this still relies on some level of distributional data to inform the SDMs, as well as adequate data on environmental conditions that influence seabird at-sea distributions. Tracking data can also be used to create distribution maps and provide data to SDMs, especially over discrete areas and smaller suites of species (Augé et al. 2018, Carneiro et al. 2020, Fauchald et al. 2021, Ronconi et al. 2022). However, despite the large, and increasing, amount of tracking data available, both for the breeding and non-breeding season (Lascelles et al. 2016, Oppel et al. 2018, Davies et al. 2021), data are still limited for many species and locations. To overcome the need for extensive at-sea survey data, the predictive foraging radius approach provides a simple method to estimate breeding seabird distributions for regions with limited at-sea data (Grecian et al. 2012, Soanes et al. 2016, Critchley et al. 2018). This approach uses data on species-specific maximum foraging ranges to project the predicted density of individuals around a breeding colony based on the size of that colony. Scaling this up across all colonies and species within an area of interest results in a community projected density map, which can then be used in combination with OVI scores to map vulnerability to oil pollution. This approach has previously been implemented effectively to identify important at-sea foraging areas and potential marine protected areas, at local and country-level scales, as well as examining the effectiveness of marine protected areas (Grecian et al. 2012, Soanes et al. 2016, Critchley et al., 2018).

The eastern North Atlantic holds internationally important numbers of seabirds due to high marine productivity (Wong et al. 2014, BirdLife International 2017). Within this region, community-level OVI data exist for some locations and seabird species to varying degrees, with comprehensive information available for some territorial waters at the national level (i.e., Norway and the UK, Webb et al. 2016; Systad et al. 2018). However, not all jurisdictions have methods for assessing risks to seabirds from oil, and there is no regional assessment in the eastern North Atlantic. This is due to a scarcity of data on behavioural and demographic traits used in generating indices for under-studied seabird species, particularly Arctic breeders, and limited year-round information on at-sea seabird distributions and densities from vessel and aerial surveys (i.e. for Iceland, Petersen 2007). However, it remains important to understand how anthropogenic activities might affect species in these locations.

Here, we demonstrate how the predictive foraging radius approach (Grecian et al. 2012, Soanes et al. 2016, Critchley et al. 2018) can be used to assess where seabirds may be most at risk to oil pollution over a large region of the eastern North Atlantic Ocean, an area where seabirds, especially pelagic species, concentrate, during the breeding season. To our knowledge this is the first time this approach has been used to assess the risk of an anthropogenic stressor over such a wide geographic area and taxonomic breadth of species. By applying this approach, we can identify which species and areas are most at risk to chronic and acute oil pollution across the eastern North Atlantic, during the breeding season, to inform marine spatial planning and management recommendations.

Methods

We focused on the eastern North Atlantic Ocean, including the sea regions of Denmark, the Faroe Islands, east Greenland, Iceland, Norway including Svalbard and Jan Mayen, the Republic of Ireland, and the United Kingdom (Figure 1). For the eastern North Atlantic, data are available on seabird foraging radii, shipping lanes, and seabird abundance, allowing us to test key assumptions of our approach. We included the tubenoses (Procellariidae, Hydrobatidae), cormorants (Phalacrocoracidae), gannets (Sulidae), phalaropes (Charadriidae: *Phalaropus* spp.), skuas (Stercorariidae), gulls and terns (Laridae), and auks (Alcidae) following Gaston (2004). We also included loons (Gaviidae), sea ducks, mergansers (Anatidae: Mergini), and grebes (Podicipedidae), as these species spend a large proportion of the year at sea (Gaston, 2004). All seabird species known to breed in the region were included (del Hoyo et al. 2018), totalling 62 species (Table 1). Throughout, we followed the taxonomic treatment of Birds of the World (Billerman et al. 2020) and Birdlife International (del Hoyo and Collar 2014).

Calculating OVI scores

We used the updated OVI for the UK continental shelf, named the Seabird Oil Sensitivity Index (SOSI; Webb et al. 2016), as the basis for developing a community-level OVI over a large geographical area (see O'Hanlon et al. 2020 for the rationale of this approach). The SOSI for the UK continental shelf incorporates eight factors to assess the vulnerability of species to oil incidents that inform: 1) how likely individuals are to be affected by oil due to their behaviour (two factors); 2) how vulnerable a population/species is (three factors); and 3) how quickly a population/species might recover from an oil incident (three factors; Webb et al. 2016).

Species-specific OVI scores for eastern North Atlantic seabirds

To be relevant to the North Atlantic we replaced the three factors relating to the vulnerability of a population/species (factors 4-6 in the SOSI; Webb et al. 2016) with a single factor, the species' global IUCN Red List status (Birdlife International 2021), which was strongly correlated for UK species and is a suitable extension to other areas with a similar suite of species (O'Hanlon et al. 2020). For our main analysis we used this global measure of conservation status to allow the modified OVI to be used globally with comparable OVI scores. However, this means that the regional and local conservation importance of a species is not considered. Therefore, we also calculated the OVI scores substituting a species global IUCN Red List status with its European Red List status that can be used where determining vulnerability of species is required for national management (Table S3).

The resulting six factors were scored on a scale of 0.2 to 1.0, from low to high sensitivity (Webb et al. 2016): 1) Proportion of time spent sitting on the sea; 2) Percentage of tideline corpses contaminated with oil; 3) Habitat flexibility; 4) Global IUCN Red List status; 5) Potential annual productivity; and 6) Adult annual survival rate (Table 2).

We therefore also modified the SOSI equation (Webb et al. 2016) to calculate the OVI for species *i* as:

Equation 1.

$$OVI_i = (F_1 \times F_2)^{1-\frac{F_3}{F_3+0.5}} \times (F_4)^{1-\frac{\left(\frac{F_5+F_6}{2}\right)}{\left(\frac{F_5+F_6}{2}\right)+0.5}}$$

Where F_z are the factors described in Table 2 (z = 1-6). This equation is based on the recommendations by Certain et al. (2015) to appropriately combine factors that directly control the vulnerability of individuals to a pressure (primary factors, i.e. time spent on the sea and habitat flexibility) to factors that aggravate existing vulnerability (aggravation factors, i.e. conservation status and demographic rates such as adult survival). This approach aims to reduce the effect of assumptions associated with factors not being independent or additive, and to account for hierarchy between primary and aggravation factors (Certain et al. 2015).

Country specific values were not available for F_2 (percentage of tideline corpses contaminated with oil). To explore whether removing this factor influenced the community-level OVI (OVI_j, Equation 4), we created two additional OVI maps: the first one omitting F_2 from the OVI calculation (Equation 2), and the second, replacing F_2 with F_1, so using F_1 x F_1 (Equation 3), as F_1 is strongly correlated to F_2 (O'Hanlon et al. 2020).

Equation 2.

$$OVI_i = (F_1)^{1-\frac{F_3}{F_3+0.5}} \times (F_4)^{1-\frac{\left(\frac{F_5+F_6}{2}\right)}{\left(\frac{F_5+F_6}{2}\right)+0.5}}$$

Equation 3.

$$OVI_i = (F_1 \times F_1)^{1-\frac{F_3}{F_3+0.5}} \times (F_4)^{1-\frac{\left(\frac{F_5+F_6}{2}\right)}{\left(\frac{F_5+F_6}{2}\right)+0.5}}$$

Seabird at-sea distribution and density data for mapping risk

To identify locations where seabirds may be most vulnerable to oil pollution, we combined the calculated species-specific OVI scores with data on seabird at-sea distributions estimated from following the predictive foraging radius approach (Grecian et al. 2012, Soanes et al. 2016, Critchley et al., 2018). Seabird colony locations and populations sizes were obtained from national seabird censuses for Denmark, Greenland, Republic of Ireland, Norway (including Svalbard and Jan Mayen), and the UK. For each species we used the most recent data available for Greenland (1980-2018), Republic of Ireland (1999-2010), Svalbard (1980-2018), Jan Mayen (1980-2018), and the UK (1999-2019). For mainland Norway, we used the maximum colony size for the last five years of available data for each species (between 2005-2018). For Denmark, we used the maximum size of each colony between 2005 and 2017 (most species), between 2010 and 2015 (Common Murre *Uria aalge* and Razorbill *Alca torda*) or between 2005 and 2018 (Mew Gull *Larus canus*, Great Cormorant *Phalacrocorax carbo* and Sandwich Tern *Thalasseus sandvicensis*). We used colony data for Greenland between 1980 and 2018, which excluded the estimates from 37 colonies (which involved a total of 959 breeding pairs) from the east coast of Greenland, which were surveyed before 1980 and therefore not useful for calculating a contemporary OVI. National databases of seabird breeding data at the colony level were not available for the Faroe Islands and Iceland, therefore seabird colony data were obtained from the literature and unpublished data from more recent surveys (Supplementary Material, Table S4).

We obtained breeding colony information for 31 of 62 species (Table 1). Suitable breeding location and population size data for seaducks, loons, grebes and phalaropes were not available for all countries, therefore these species could not be included in the community-level OVI. As the foraging radius approach focuses on the breeding season, most of the species for which we could not determine their spatial distribution, breed inland and typically spend less time in the marine environment during this period.

To generate species-specific at-sea density distributions applying the predictive foraging radius approach we used the R script provided by Critchley et al. (2018), which predicts the total number of individuals in every 5 × 5 km grid square across the region based on foraging range (Table 1), colony location and size (Table S3). To map seabird vulnerability to oil, for all species combined, based on these predicted at-sea density distributions, we used the following equation used by Webb et al. (2016).

Equation 4.

$$OVI_j = \sum_{i1}^{iS} \frac{\widehat{D}_{ij}}{1 - OVI_i}$$

Where OVI_j = overall OVI score at location *j*, $\widehat{D}_{ij}$ = density of species *I* (number/5 km²) at location *j*, OVI_i = OVI score for species *i*.

As we did not obtain seabird colony data from all countries surrounding the southern region of the eastern North Atlantic, we cropped the area of interest to only include sea areas where we had accounted for all breeding birds that may forage within this region. We created two breeding season community-level OVI maps that included the species-specific OVI_i scores that used the conservation status at a) the global and b) the European scale.

An example to identify areas of risk from oil pollution

To provide an example of how the community-level OVI can be used to identify areas where seabirds are at risk to a specific source of oil pollution we overlaid the community-level OVI map, using the global IUCN Red List status, with spatial data on vessel density from the relevant time of year. Locations where areas of high vessel density overlapped with areas of high seabird vulnerability were identified as areas where seabirds are most at risk to oil pollution from current shipping activity, using data from 2018 as an example. While the transportation of oil via tankers poses the greatest potential risk for an acute oil pollution incident, chronic oil pollution from illegal and incidental discharge of oil can occur from various vessel, and in most cases the source of such discharges cannot be linked to specific vessel types (GESAMP 2001, Camphuysen 2007). Furthermore, most oil slicks occur along the major shipping lanes where vessel density is highest (Anon. 1995, Camphuysen 2007). We therefore used monthly data on vessel density, for all vessel types, across the region of interest, downloaded from EMODnet (https://web.archive.org/web/20210121162105/https://www.emodnet-humanactivities.eu/view-data.php).

As we only had predicted at-sea density estimates for the breeding season, we used mean monthly vessel density data for March to September 2018, with density measured as the total hours of vessel time in each 1 km^2 cell each month (Vessel density was significantly correlated for this period across years 2017 – 2022, range $r > 0.92$). Using the *Raster* package in R (Hijmans 2022) we calculated the mean vessel density for each cell by summing across the monthly rasters; vessel density data were not available for southeast Greenland. To calculate the mean vessel density within each grid square of the community-level OVI we carried out a spatial join in R.

Following Renner and Kuletz (2014), we estimated the potential risk to seabirds of oil pollution from sea vessels using the following calculation in the *Raster Calculator* function in ArcMap, where sigma is the standard deviation:

Equation 5.

$$Risk = \frac{Vessel\ Density}{\sigma\ (Vessel\ Denisty)} \times \frac{OVI_j}{\sigma\ (OVI_j)}$$

This identifies particularly high-risk locations where areas of higher-than-average vessel density overlapped with areas of higher-than-average seabird vulnerability. Mapping these values on a log scale reveals areas of lower and intermediate risk (Renner and Kuletz 2015).

Results

Species-specific OVI scores for eastern North Atlantic seabirds

We calculated OVI scores for 62 seabird species in the eastern North Atlantic, with scores ranging from high vulnerability (0.843 – Atlantic Puffin *Fratercula arctica*) to low vulnerability (0.041 – Red-necked Phalarope *Phalaropus lobatus*) (Table 1, Table S2). The most vulnerable seabird species were Atlantic Puffin, Yellow-billed Loon *Gavia adamsii*, Velvet Scoter *Melanitta fusca*, and Balearic Shearwater *Puffinus mauretanicus* (OVI scores:

0.592-0.843). The top 16 species most vulnerable to oil are all species that spend a greater proportion of time on the sea surface (loons, grebes, auks, seaducks) compared to those species with lower OVI scores (gulls, terns, skuas, phalaropes; Table 1).

Seabird at-sea distribution and density data for mapping risk

We collated colony size and location information for 31 species (Table 1) to calculate predicted at-sea density distributions across the eastern North Atlantic (Figure 2a) and map seabird vulnerability to oil (Figure 2b; using the global IUCN Red List status) during the breeding season. The two resulting maps are very similar (strong positive correlation: $r = 0.94$); with areas of highest seabird density being the areas where seabirds are most vulnerable to oil. This was attributed to the influence of species density in how the seabird vulnerability map was calculated (Equation 4), despite the calculation putting greater emphasis on those species that are most vulnerable to oil pollution (Certain et al. 2015, Webb et al. 2016).

There was also a positive correlation between the predicted at-sea seabird density map and the seabird vulnerability map using the European IUCN Red List status ($r = 0.74$, Figure S2), and between the two seabird vulnerability maps (0.93). Neither omitting or replacing F_2 (Percentage of tideline corpses contaminated with oil) with F_1 (Proportion of time spent sitting on the sea) had any noticeable effect on the resulting seabird vulnerability maps (Figure S2), with a significant positive relationship between these modified maps and the original seabird vulnerability map ($r > 0.99$).

Across the region, during the breeding season, seabirds are most at risk to oil pollution off Ittoqqortoormiit, east Greenland, around western Iceland, along the northern coast of

Norway, and around the west and southeast of Svalbard (Figure 2b). Seabirds are also at risk around Jan Mayen, the Faroe Islands, and northern Scotland. As would be expected during the breeding season, the lower risk areas were those away from the coastline, outside the maximum foraging ranges of most species.

An example to identify areas of risk from oil pollution

Obtaining data on at-sea vessel density demonstrated how the community-level OVI can be used to highlight where seabirds may be most at risk from specific sources of oil pollution. Calculating risk from combining the vessel density and seabird vulnerability map (Equation 5) revealed particularly high-risk areas located along the coast of Norway and discrete coastal locations off Iceland and Scotland, likely associated with busy ports (Figure 3a). By visualising the data on the log scale, areas of lower and intermediate risk were revealed, which included most coastal regions where seabirds will be present during the breeding season (Figure 3).

Discussion

At the geographic scale of the eastern North Atlantic, the community-level OVI revealed areas off the east coast of Greenland, along the coast of Norway, the western part of Iceland, as well as to a lesser extent Svalbard, Jan Mayen, the Faroe Islands, and north-eastern Scotland, where seabirds may be at greatest risk to acute and chronic oil pollution during the breeding season. This result is largely driven by large colonies of auks, a group highly vulnerable to oil pollution based on their behaviour; specifically, very large colonies of Thick-billed Murre *Uria lomvia*, Little Auk *Alle alle* and Atlantic Puffin, and, to a lesser extent, Common Murre and Razorbill (Fauchald et al. 2015, Boertmann et al. 2020). As well as being highly vulnerable to oil pollution, these species have moderately large maximum foraging ranges (Table 1), compared to sympatric species that are less vulnerable to oil pollution (cormorants, skuas, gulls, terns). The area of particular high risk off Ittoqqortoormiit, east Greenland, is attributed to two Thick-billed Murre colonies and a number of very large Little Auk colonies (Boertmann et al. 2020).

Calculating species-specific OVI scores using the European rather than global IUCN Red List category only resulted in a small difference in the resulting seabird vulnerability maps (Figure S2). As our focus was to assess seabird vulnerability to oil pollution over a large spatial scale, we did not create a community-level OVI based on the national red list status of species. However, in some situations it will be important to consider local conservation status. For example, although the Thick-billed Murre is classified as Least Concern at the global and European level, it is classified as threatened at the national level in Greenland, Iceland, Norway, and Svalbard (Table S3).

OVI scores for eastern North Atlantic seabirds

The first step in assessing seabird vulnerability to oil pollution is to establish how vulnerable different species are through selecting a suite of factors to calculate OVI scores. Our OVI is relatively simple with six contributing factors. For a more representative OVI, we could have included additional factors including ability to withstand oiling (Burger and Gochfield 2002), foraging behaviour, for example, the time individuals spend foraging at sea versus on land for species such as gulls and terns (Schreiber and Burger 2001), and at-sea aggregation behaviour (Stone et al. 1995, Reid et al. 2001). However, adequate data available to score these factors accurately for most species and locations are lacking, which presents a danger of creating a false sense of precision in OVI values. Using a simpler approach is more straightforward to apply consistently to different regions globally.

Even with six factors, data to score all these factors were not available for all species. Where we could not use species-specific information, we used values from taxonomically and ecologically similar species. This is unlikely to alter our assessment of vulnerability as small differences between similar species will likely be accounted for in the binning of values to produce species-specific OVI scores.

A sensitivity analysis revealed that the factors that determine how likely individuals will be affected by oil due to their behaviour (factors 1-3) had the greatest influence on species-specific OVI scores (O'Hanlon et al. 2020). For many species and countries, data do not exist to provide accurate parameter values on the proportion of time spent on the sea and proportion of oiled beached corpses: with data on the latter being difficult to collect in regions where there are large stretches of coastline and few people. However, although the proportion of tideline corpses contaminated with oil can differ geographically, the ranking of oiling rates for species are generally similar (Camphuysen 1998). Therefore, using the best data available from surrogate species or locations may be appropriate. We also did not account for potential spatial or temporal variation in foraging behaviour. Although the proportion of time individuals spend on the sea surface is largely driven by species-specific behaviour, this may vary over time and space due to food availability and weather conditions, particularly for species that have flexible foraging strategies (Finney et al. 1999, Hamer et al. 2007, Nevalainen et al. 2019). While this variation in behaviour may influence a species OVI score, it is unlikely to have a large effect on the resulting vulnerability maps given the greater overall influence of seabird density. Factors relating to how quickly a species might recover from an oil incident (factors 5-6 in this study) had a relatively low influence on OVI scores;

indicating that spatial and temporal variation in demographic rates will not significantly influence the final species-specific OVI scores (O'Hanlon et al. 2020).

When assessing seabird vulnerability to oil, monthly maps are useful to understand temporal variation in seabird densities and distributions (Webb et al. 2016). Foraging ranges can change seasonally (Schreiber and Burger 2001), and annually (Ponchon et al. 2014, Christensen-Dalsgaard et al. 2018), however, such information is lacking on a general basis, therefore we could not create monthly maps. A single map also does not account for spatial or temporal variation in phenology for species breeding across large geographical extents, where extrinsic factors such as weather, ice extent and food availability can drive phenology (Burr et al. 2016). Therefore, when interpreting the vulnerability maps it is important to be aware of variation in breeding phenology of species depending on the location and time of year of an oil pollution incident.

Assessing areas of risk to seabirds from specific oil pollution sources

To demonstrate how our community-level OVI could be used to assess risk of seabirds to a specific source of oil pollution we used vessel density, as a proxy for the probability of chronic oil pollution from shipping (Renner and Kuletz 2014). Our results revealed high risk areas at discrete locations along the coasts of Norway, as well as to a lesser extent off Iceland and Scotland. Larger areas where seabirds are at intermediate and lower risk to shipping related oil pollution included most coastal areas where seabirds breed. Although there will be some spatial variation in vessel traffic among years, vessel density largely reflects major shipping routes where chronic oil pollution from illegal or incidental discharges from vessels typically occur (Anon. 1995, Camphuysen 2007, Rodrigue 2020).

Limitations of using the foraging radius approach

There are several limitations with using the predictive foraging radius approach to map seabird vulnerability to oil. This approach only considers breeding adults, not juveniles, immatures or non-breeding adults, which might make up to 50% of some populations (Carneiro et al. 2020). It also requires data on colony size and maximum foraging range for all species. For half of the species we identifed as using the marine environment within the eastern North Atlantic, we were unable to collate adequate data on breeding distributions and numbers to include in the community-level OVI, as these species are typically less colonial and often breed away from the coast and so are not included in all seabird monitoring schemes. We have included the species-specific OVI scores of these species in the event that this data becaomes available in the future.

Another consideration is that the foraging ranges of species and individuals can be colony-specific, and be influenced by colony size (e.g. Patterson et al. 2022), the density of conspecifics and other species within the region, and local food availability, as well as habitat features and dynamic environmental conditions that species might target for foraging (Wakefield et al. 2017, Critchley et al. 2019). For many colonies in the eastern North Atlantic, specific foraging ranges, and details on influencing environmental conditions, are currently unknown. Despite these limitations, at-sea distributions estimated using the predicted foraging range approach correlate well with those generated from at-sea survey and tracking data, indicating that this approach is valid where these data are not available (Grecian et al. 2012, Critchley et al. 2019).

The predicted seabird distributions created using the foraging radius approach are therefore influenced by data precision and accuracy. Some jurisdictions have relatively comprehensive data on seabird colonies from national censuses, however these may not always be current or reflect recent population changes. Therefore, caution should be taken given recent declines in seabird populations. As the colony data for Iceland and the Faroe Islands were inferred from national population estimates and estimated colony sizes of the largest or most important colonies, we have lower confidence in the predicted seabird distributions around these countries. For Ivory Gulls *Pagophila eburnea*, Iceland Gulls *Larus glaucoides*, and Ross's Gulls *Rhodostethia rosea*, we also had to use the maximum breeding season foraging ranges of similar species (Table 1). Therefore, although the map does not reflect current absolute distribution and vulnerability of seabirds to oil, it does provide a relative indication of which areas need the greatest focus with regards to oil pollution during the breeding season. Furthermore, a benefit of the foraging radius approach is that it can easily be updated when new data become available.

To assess the year-round risk of seabirds to oil pollution it is necessary to include the non-breeding season, when individuals are no longer constrained to their breeding colonies, and many species are more pelagic in their distribution (Frederiksen et al. 2012, Fayet et al. 2017). This is particularly important as certain species or individuals may be at greater risk to oil pollution when not attending the colony, for example, auk species where chicks leave the colony before being able to fly, and adults which have periods of flightless moult (Harris and Wanless 1990, Harris, Wanless, and Jensen 2014). Within this analysis we also did not include seaducks due to a lack of data on breeding colonies/locations from some parts of the region, however, at-sea concentrations of moulting individuals (Einarsson and Gardarsson 2004, Boertmann and Mosbech 2012), will be particularly vulnerable to oil pollution during this flightless period.

Conclusions

Obtaining up-to-date seabird at-sea data to map vulnerability to anthropogenic stressors such as oil pollution is challenging where data from vessel and aerial surveys are limited (Camphuysen 2007, Dunn 2012). We highlight how the predictive foraging range approach provides a useful alternative where at-sea distribution data are lacking, and there are limited resources to obtain these data, but where sources of acute and chronic oil pollution, from shipping and hydrocarbon extraction activity, are likely to increase in future (Reeves et al. 2014, European Environment Agency 2017, Gunnarsson 2021).

To obtain a more accurate and robust understanding of where seabirds are at risk to oil pollution and other threats, improved data collection is vital for species and locations where data on at-sea distributions, demography and behaviour are currently limited. Until this has been achieved the approach we took here will be useful for other regions where data on at-sea distributions are limited, but where some information on colony size and locations exists. Given the influence of the factors used to score the OVI, this approach can be used for under-studied species, using information from surrogate species or expert opinion to score factors.

Our results emphasise the need for preventative measures, specifically better regulation and enforcement of legislation to eliminate illegal and incidental discharges of oil from vessels especially along coastal areas where breeding seabirds are particularly at risk (Camphuysen 2007). Given the projected increase in global shipping traffic, especially in the Arctic, identifying areas of high seabird vulnerability to oil can help inform decisions on where the development of new shipping routes should be limited or avoided, such as the implementation of dynamic Areas to be Avoided (ATBAs), which have been adopted by the

International Maritime Organization (IMO) to protect such areas of high ecological importance (Camphuysen 2007, Huntington et al. 2019, Pirotta et al. 2019)

We focused on seabird vulnerable to oil pollution but this approach can be easily modified to explore other potential anthropogenic threats such as over-fishing and marine renewable energy installations (Garthe and Hüppop 2004, Certain et al. 2015), and to assess the vulnerability of marine mammals to such threats.

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Table 1. OVI scores of widespread migrant and breeding seabird species present in the eastern North Atlantic, maximum foraging ranges for species included in the spatial OVI. See Table S2 for species-specific factor scores used to calculate the OVI scores. Species are listed by descending OVI score, using the global IUCN Red List status.

Common name	Scientific name	IUCN Red List status (Global) [1]	Status	OVI Score	Max. foraging range (km)
Atlantic Puffin	*Fratercula arctica*	VU	Breeding	0.843	383 [3]
Yellow-billed Loon	*Gavia adamsii*	NT	Breeding	0.703	-
Velvet Scoter	*Melanitta fusca*	VU	Breeding	0.657	-
Balearic Shearwater	*Puffinus mauretanicus*	CR	Migrant	0.592	-
Common Murre	*Uria aalge*	LC	Breeding	0.585	339 [3]
Thick-billed Murre	*Uria lomvia*	LC	Breeding	0.585	168 [6]
Horned Grebe	*Podiceps auritus*	VU	Breeding	0.570	-
Stelle’’s Eider	*Polysticta stelleri*	VU	Breeding	0.570	-
Long-tailed Duck	*Clangula hyemalis*	VU	Breeding	0.570	-
Common Loon	*Gavia immer*	LC	Breeding	0.563	-
Razorbill	*Alca torda*	LC	Breeding	0.563	314 [3]
Black Guillemot	*Cepphus grylle*	LC	Breeding	0.563	15 [4]
Little Auk	*Alle alle*	LC	Breeding	0.563	110 [6]
Common Eider	*Somateria mollissima*	NT	Breeding	0.542	-
Arctic Loon	*Gavia arctica*	LC	Breeding	0.538	-
Red-throated Loon	*Gavia stellata*	LC	Breeding	0.511	-
Black-legged Kittiwake	*Rissa tridactyla*	VU	Breeding	0.436	229 [3]
European Shag	*Gulosus aristotelis*	LC	Breeding	0.435	24 [3]
King Eider	*Somateria spectabilis*	LC	Breeding	0.420	-
Great Cormorant	*Phalacrocorax carbo*	LC	Breeding	0.345	50 [4]
Black-necked Grebe	*Podiceps nigricollis*	LC	Breeding	0.336	-
Harlequin Duck	*Histrionicus histrionicus*	LC	Breeding	0.336	-
Common Scoter	*Melanitta nigra*	LC	Breeding	0.336	-
Manx Shearwater	*Puffinus puffinus*	LC	Breeding	0.333	1219 [3]
Great Skua	*Catharacta skua*	LC	Breeding	0.319	219 [4]
Red-necked Grebe	*Podiceps grisegena*	LC	Breeding	0.300	-
Great Crested Grebe	*Podiceps cristatus*	LC	Breeding	0.300	-
Goldeneye	*Bucephala clangula*	LC	Breeding	0.300	-
Great Black-backed Gull	*Larus marinus*	LC	Breeding	0.299	60 [4]
Greater Scaup	*Aythya marila*	LC	Breeding	0.287	-
Northern Fulmar	*Fulmarus glacialis*	LC	Breeding	0.282	664 [3]

Northern Gannet	*Morus bassanus*	LC	Breeding	0.282	709 [4]
Common Gull	*Larus canus*	LC	Breeding	0.272	50 [4]
Red-breasted Merganser	*Mergus serrator*	LC	Breeding	0.270	-
Sooty Shearwater	*Ardenna grisea*	NT	Migrant	0.266	-
Goosander	*Mergus merganser*	LC	Breeding	0.260	-
Arctic Jaeger	*Stercorarius parasiticus*	LC	Breeding	0.255	75 [4]
Long-tailed Jaeger	*Stercorarius longicaudus*	LC	Breeding	0.255	-
Black-headed Gull	*Larus ridibundus*	LC	Breeding	0.255	40 [4]
Ivory Gull	*Pagophila eburnea*	NT	Breeding	0.254	92 [5]
Lesser Black-backed Gull	*Larus fuscus*	LC	Breeding	0.239	181 [4]
Mediterranean Gull	*Larus melanocephalus*	LC	Breeding	0.231	20 [4]
European Herring Gull	*Larus argentatus*	LC	Breeding	0.227	92 [4]
Yellow-legged Gull	*Larus michahellis*	LC	Migrant [2]	0.227	-
Great Shearwater	*Ardenna gravis*	LC	Migrant	0.211	-
Common Tern	*Sterna hirundo*	LC	Breeding	0.205	30 [4]
Cor’’s Shearwater	*Calonectris borealis*	LC	Migrant	0.203	-
Pomarine Jaeger	*Stercorarius pomarinus*	LC	Breeding	0.203	-
Little Tern	*Sternula albifrons*	LC	Breeding	0.198	11 [4]
Roseate Tern	*Sterna dougallii*	LC	Breeding	0.195	30 [4]
Sabin’’s Gull	*Xema sabini*	LC	Migrant	0.194	92 [5]
Sandwich Tern	*Thalasseus sandvicensis*	LC	Breeding	0.171	54 [4]
Arctic Tern	*Sterna paradisaea*	LC	Breeding	0.162	30 [4]
Little Gull	*Hydrocoloeus minutus*	LC	Breeding	0.161	-
Iceland Gull	*Larus glaucoides*	LC	Breeding	0.138	92 [5]
Glaucous Gull	*Larus hyperboreus*	LC	Breeding	0.138	92 [5]
Leac’’s Storm-petrel	*Hydrobates leucorhous*	VU	Breeding	0.133	1154 [3]
Ros’’s Gull	*Rhodostethia rosea*	LC	Breeding	0.121	-
European Storm-petrel	*Hydrobates pelagicus*	LC	Breeding	0.089	365 [3]
Black Tern	*Chlidonias niger*	LC	Breeding	0.084	-
Red Phalarope	*Phalaropus fulicarius*	LC	Breeding	0.048	-
Red-necked Phalarope	*Phalaropus lobatus*	LC	Breeding	0.041	-

[1] LC Least Concern; VU Vulnerable; NT Near Threatened; EN Endangered; CR Critically Endangered (BirdLife International, 2021). [2] Very small breeding numbers in south England. [3] Oppel et al. 2018. [4] Critchley et al. 2018; [5] Foraging range not available therefore we used the maximum froaging range of the European Herring Gull; [6] Jovani et al. 2015.

Table 2. Factors used in our oil vulnerability index (OVI) modified from Webb et al. (2016) to use across a large geographical area, the eastern North Atlantic, including how each factor was scored on a scale of 0.2 to 1.0, from low to high vulnerability to oil.

Factor	Category scores					Data sources
	0.2	0.4	0.6	0.8	1.0	
F1. Proportion of time spent sitting on the sea	0.00 – 20.00%	20.01 – 40.00%	40.01 – 60.00%	60.01 – 80.00%	80.01 – 100.00%	For species in the UK SOSI framework, values were taken from Webb et al. (2016), obtained from European Seabird at Sea data for the UK continental shelf area between 1995 and 2015. For species outside the UK (n = 9), we used values from ecologically similar species (Table S2).
F2. Percentage of tideline corpses contaminated with oil	0.00 – 20.00%	20.01 – 40.00%	40.01 – 60.00%	60.01 – 80.00%	80.01 – 100.00%	For species in the UK SOSI framework, values were taken from Webb et al. (2016), rescaled from Williams et al. (1994). For species outside the UK (n = 9), we used values from ecologically similar species (Table S2).
F3. Habitat flexibility	Tend to forage over large marine areas with little known association with specific features				Tend to feed on very specific habitat features.	Values for species in the UK SOSI were taken from Webb et al. (2016), based on scores used by Furness et al. (2013). Habitat flexibility is a measure of a species' ability to locate and forage in alternative habitats, including on land, with specialist species that occupy habitats within a restricted geographical extent being more vulnerable to oil pollution than species which can range over extensive areas and habitats (Webb et al. 2016). For species not included in these studies we determined their habitat flexibility scores based on their habitat use and foraging ecology as described in the literature (Supplementary Table S1).
F4. Global IUCN Red List status	Least Concern	Near Threatened	Vulnerable	Endangered	Critically Endangered	Values were based on each species' global IUCN Red List status (Birdlife International 2019). These can be substituted to a species European or country-specific (where available) status depending on the scale of interest.
F5. Potential annual productivity (maximum and mean clutch size & age at first breeding)	Large clutch size and low age of first breeding				Small clutch size and delayed age of first breeding	Data for UK species were obtained from Horswill and Robinson (2015). Data for other species were taken from the literature. Where data could not be found we used the scores of ecologically similar species (Table S2). Potential annual productivity scores were categorised as outlined in
F6. Adult annual survival rate	⩽ 0·75	> 0·75 – 0·80	> 0·80 – 0·85	> 0·85 – 0·90	> 0·90	Webb et al. (2016), rescaled from Williams et al. (1994). Where data were available from multiple sources, we used the mean value. Adult annual survival rates scores were rescaled from Garthe and Hüppop (2004) and Furness et al. (2013).

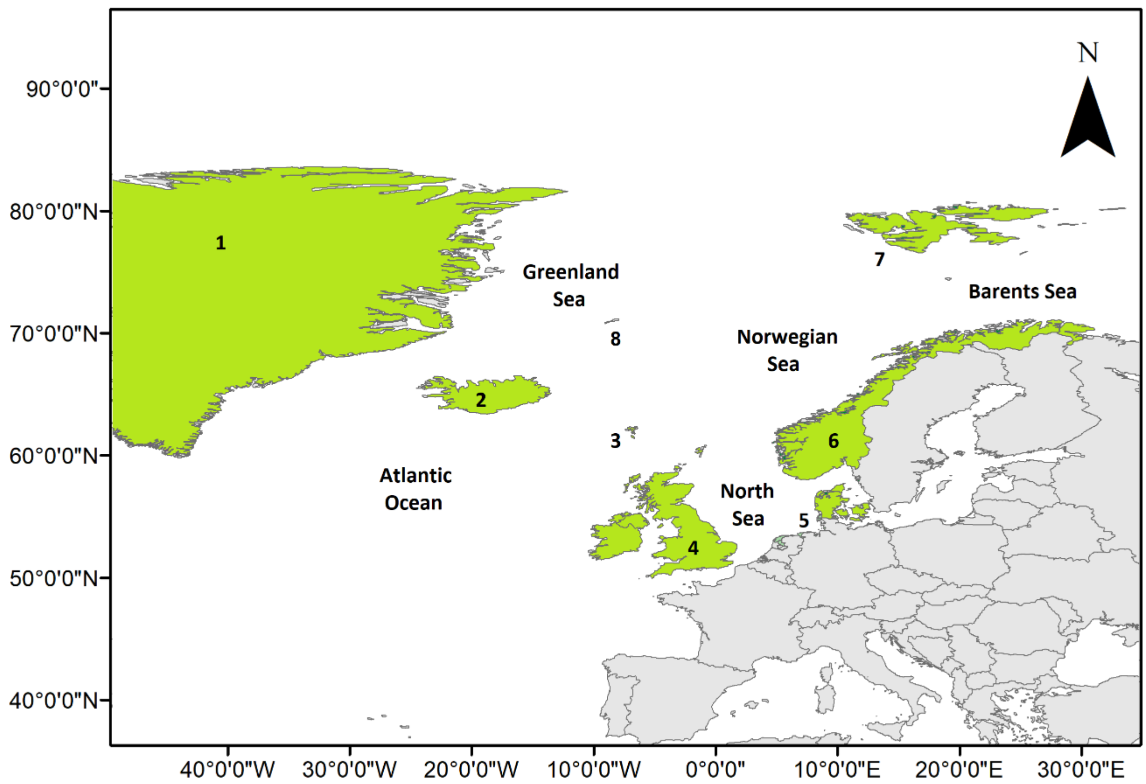

Figure 1. Countries where data on seabirds were obtained to create the spatial oil vulnerability index. 1–- East Greenland, 2 – Iceland, 3 – Faroe Islands, 4 – United Kingdom and the Republic of Ireland, 5 – Denmark, 6 – Norway, including Svalbard (7) and Jan Mayen (8).

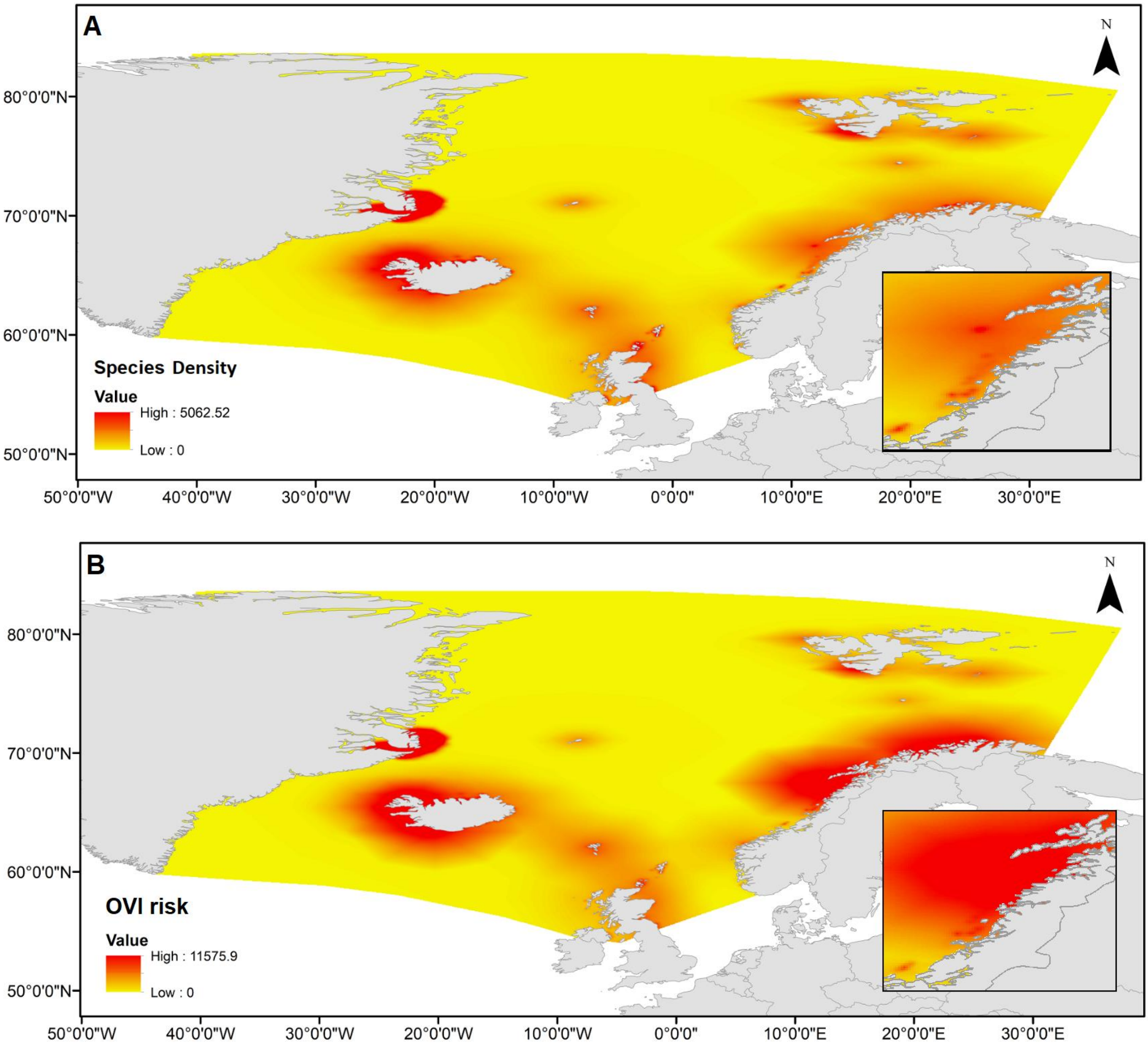

Figure 2. Eastern North Atlantic showing a) the predicted density of 31 seabird species (individuals / 5 km^2) and b) the spatial distirbution of Oil Vulnerability Index (OVI) risk calculated from the predicted seabird densities and the oil vulnerability scores, using global IUCN Red List classifications. Inserts show the resolution of the data at a zoomed in stretch of the Norway coast.

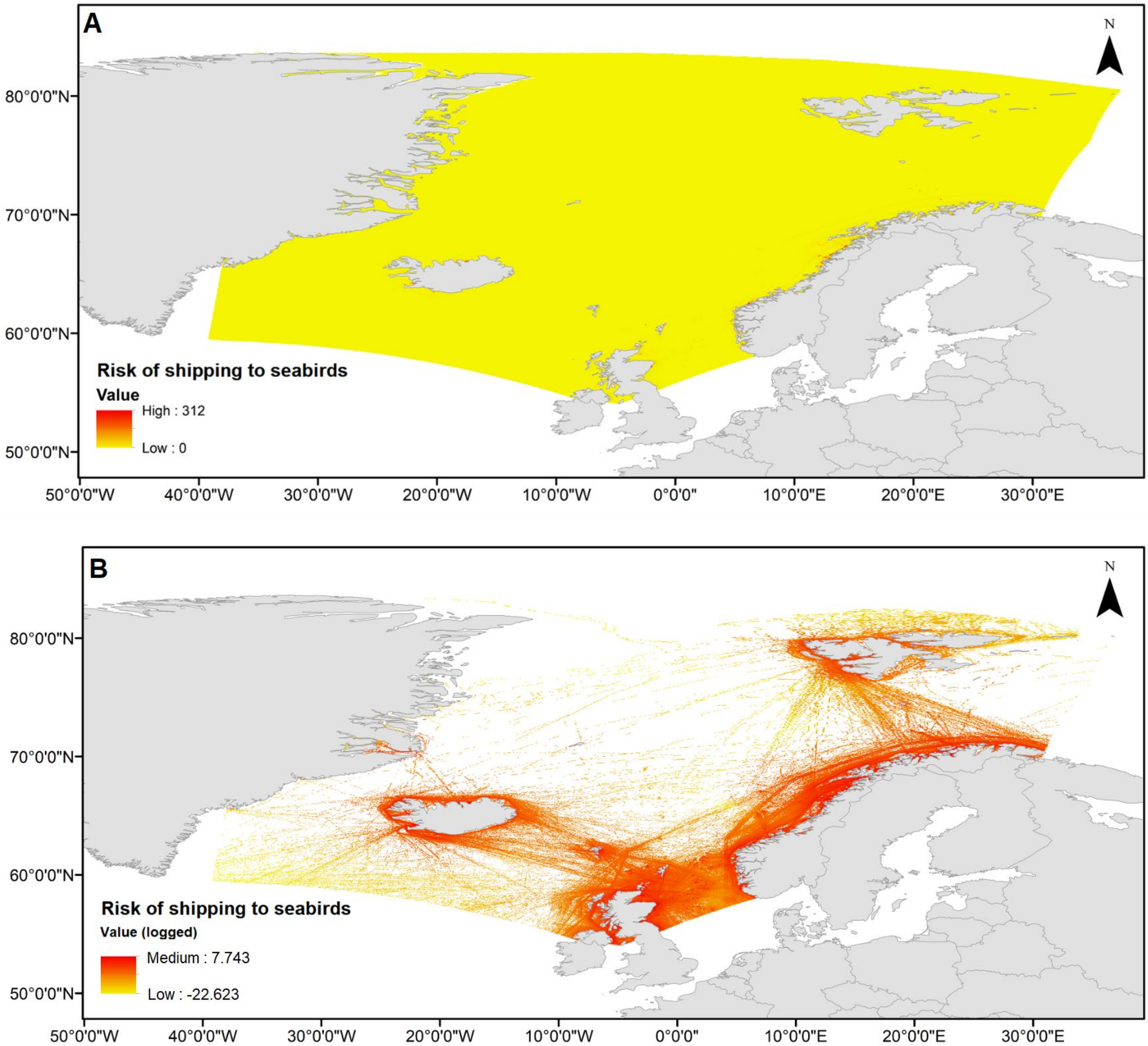

Figure 3. Risk of shipping to seabirds during the breeding season, calculated from vessel density (March to September 2018) and the spatial distribution of Oil Vulnerability Index (OVI) risk, using global IUCN Red List classifications (see Equation 5 in main text). The figures display the same data a) on the linear scale to identify the highest risk areas, largely near large ports and along the coast of Norway, and b) on the log scale to reveal lower and intermediate risk areas (Renner and Kuletz 2015).