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A preliminary spatial assessment of risk: Marine birds and chronic oil pollution on Canada's Pacific coast

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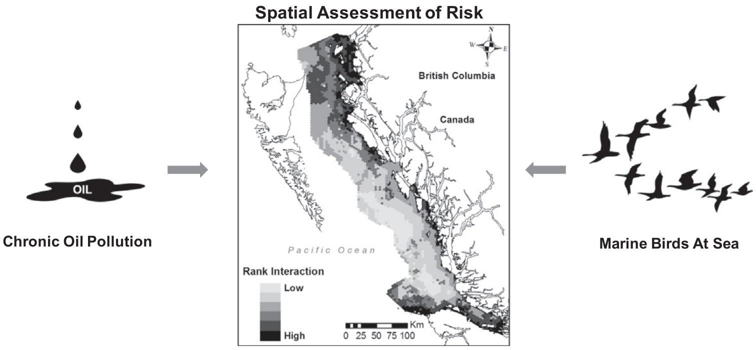
HIGHLIGHTS

- On Canada's Pacific coast, the effects of chronic oil pollution are poorly known.
- This study evaluates the spatial risk of oil exposure to marine birds.
- Two areas of highest potential risk were identified in the study area.
- Individual marine bird species identified at most risk varied taxonomically.
- Further improvement of marine bird and chronic oil pollution information is needed.

GRAPHICAL ABSTRACT



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ABSTRACT

Chronic oil pollution poses substantial risks to marine birds and other marine wildlife worldwide. On Canada's Pacific coast, the negative ecological consequences to marine birds and marine ecosystems in general remain poorly understood. Using information relating to oil spill probability of occurrence, areas of overall importance to marine birds, and the at-sea distribution and density of 12 marine bird species and seven bird groups, including multiple Species at Risk, we undertook a spatial assessment of risk. Our results identify two main areas important to marine birds potentially at higher risk of exposure to oil. For individual bird species or species groups, those predicted to have elevated bird densities near the mainland and the northeast coast of Vancouver Island were identified as being at higher potential risk of exposure. Our results, however, should be considered preliminary. As with other anthropogenic stressors, in order to better understand and subsequently mitigate the consequences of chronic oil pollution on marine birds, improved information relating to marine birds and the occurrence of oil spills on Canada's Pacific coast is needed.

1. Introduction

The planet's oceans, particularly continental shelf ecosystems, are increasingly subject to a number of anthropogenic stressors (Halpern

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et al., 2008). Canada's Pacific coast is no exception, with the entire continental shelf already subjected to a litany of human activities (e.g., Ban et al., 2010), many of which are anticipated to increase (e.g., shipping traffic, Nuka Research, 2013). In addition to driving biodiversity losses (e.g., declines in species richness and population sizes), these human activities influence whole-ecosystem properties, including structure, function, and resilience (Chapin III et al., 2000; Worm et al., 2006).

Although a large number of human activities occur in marine ecosystems, oil pollution is among the more serious threats. Oil enters the world's marine ecosystems by way of natural processes (i.e., natural seeps) and through anthropogenic activities, including land-based run-off, routine marine operations, drilling platforms, and ship and pipeline spills (NRC, 2003; GESAMP, 2007; Morandin and O′Hara, 2016). Anthropogenic releases may be intentional, the result of negligence, or accidental (Bertazzon et al., 2014). Of these, large volume or “catastrophic” oil spills typically result in significant attention (e.g., Bourne et al., 1967; Vermeer and Vermeer, 1975; Piatt et al., 1990) despite estimates that oil pollution resulting from “day to day” activities contributes more oil to marine ecosystems than do shipping accidents (NRC, 2003; GESAMP, 2007). These small-scale oil discharges, also known as chronic oil pollution, almost never trigger a formal response in Canada and elsewhere (i.e., in terms of cleanup and other efforts to mitigate potential impacts), primarily because they are small and occur frequently over extensive and remote areas.

In addition to contributing more oil to marine environments, the cumulative ecological impacts from small-scale discharges may be greater than impacts arising from large-scale catastrophic spills (Camphuysen, 1989; NRC, 2003). Although oil in marine environments is broadly deleterious to marine organisms, marine birds are among the most prominent and abundant taxa injured or killed (Burger and Fry, 1993). Small-scale discharges may result in similar or even greater cumulative bird mortalities than the larger, catastrophic oil spills (e.g., Camphuysen, 1989; Burger 1992, 1993a). And although there is clear evidence that rates are generally declining worldwide (e.g., GESAMP, 2007; Serra-Sogas et al., 2008; O′Hara et al., 2009; Camphuysen, 2010; Lagring et al., 2012), operational oil pollution remains a serious environmental threat (GESAMP, 2007; Vollaard, 2014).

Based on spatial patterns detected in Beached Bird Surveys (BBS - systematic surveys of beaches for documenting rates of oil fouled beach-cast bird carcasses; O′Hara et al., 2009; Camphuysen, 2010) and in aerial surveillance (aircraft borne surveillance for oil pollution; O′Hara et al., 2013), there is evidence that declining rates occur in coastal areas where enforcement activities are concentrated. Furthermore, operational discharges may be displaced to areas or times where enforcement activities are less concentrated (Vollaard, 2014; for a general reference on criminal displacement theory see Weisburd et al., 2006). Indeed, Gullo (2011) detected no change in non-compliance with federal and international oil pollution regulations (i.e., MARPOL 73/78 is the International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978) in port-state inspections, despite increased enforcement efforts by US federal agencies, although these rates should be interpreted with caution as it appears the author did not correct for number of inspections each year. The potential displacement of illegal discharges is particularly troubling for much of the isolated coastal regions of Canada and the rest of the world where enforcement efforts are generally low to non-existent.

On Canada's Pacific coast, there is a documented history of marine birds being oiled (e.g., Vermeer and Vermeer, 1975; Burger 1993b; Stephen and Burger, 1994; O′Hara et al., 2009). The ecological consequences, however, have not been quantified, primarily due to limitations associated with interpreting information from BBS (O′Hara and Morgan, 2006). Given the presence of globally significant populations of marine birds on Canada's Pacific coast, including Species at Risk, the co-occurrence of chronic oil pollution with marine bird species warrants investigation.

In general, efforts to understand and mitigate the socio-ecological consequences of human activities typically require knowledge relating to a given human activity and a given ecosystem component. Spatially explicit quantitative risk assessments, by definition, are composed of two core components (often expressed as probabilities): (1) the likelihood of a stressor (e.g., oil spills) occurring in an area; and (2) the socio-ecological consequences or costs, should the specific stressor occur. Where information regarding both components is available, spatial risk assessments are a key approach to examining potential consequences of anthropogenic activities in marine ecosystems.

A spatially-explicit approach that focuses on the consequence component of risk assessment involves the overlay of spatial probability of occurrence of potential stressors with the spatial distributions of response organisms considered sensitive to those stressors (often referred to as “receptors”; see US EPA, 1998 for example). This approach essentially addresses vulnerability of organisms, which is defined here as the likelihood of exposure to the stressor, and assumes that these organisms are negatively affected or sensitive when exposed (sensu Zacharias and Gregr, 2005). Examples include the spatial assessment of ship strike risk to whales using both whale species and marine vessel densities (e.g., Vanderlaans et al., 2008; Williams and O′Hara, 2010), and seabird bycatch in fisheries using information on seabird species distributions and fishing effort (e.g., Fischer et al., 2009). Notably, however, this approach is considered a first step in estimating the potential consequences of exposure, in large part because understanding of the interaction and the potential outcomes of the interaction between organisms and stressors is necessary to fully assess risk on a spatial basis.

In this study, we assess the risk of exposure for marine birds to chronic oil pollution in coastal British Columbia (BC) using a spatially explicit semi-quantitative approach. Our objectives: (1) identify vulnerable areas predicted to experience elevated probabilities of small-scale oil spills co-occurring with elevated marine bird densities for 19 species or species groups and for marine birds on a cumulative or overall basis; and (2) rank marine birds or groups based on their risk of exposure to chronic oil pollution. Here, the probability of marine birds being oiled is the variable of interest although we note that the proximity of small-scale oil discharges to a given marine bird is only one determinant of risk. In this study, risk is therefore approximated by multiplying the predicted probability of a small-scale oil discharge with the predicted probability of occurrence of marine birds in a given area. Herein, we rely on oil spill predictions from a spatial model developed by Bertazzon et al. (2014) based on oil spill data collected by the National Aerial Surveillance Program (Transport Canada) in Canada's Pacific Exclusive Economic Zone (EEZ). Marine bird spatial predictions for 12 marine bird species and seven groups (representing 24 species) were modified from Fox et al. (in review).

2. Methods

The study area, referred to here as the Queen Charlotte Basin, comprises approximately 36,000 km^2 of BC's coastal region. The boundaries were chosen to match mutually shared spatial extents of predicted small oil discharges (modified from Bertazzon et al., 2014) and predicted marine bird densities (Fox et al., in review). The Queen Charlotte Basin includes four major bodies of water: Dixon Entrance, Hecate Strait, Queen Charlotte Sound, and Queen Charlotte Strait (Fig. 1a). The Queen Charlotte Basin and surrounding region hosts numerous seabird colonies, including Triangle Island within the Scott Islands, which is Canada's largest Pacific coast seabird colony (Fig. 1a).

2.1. Marine bird information

Marine bird predictive surfaces were generated from systematic line transect survey information collected in the Queen Charlotte Basin. Marine bird surveys took place in spring (April and May 2007; June 2008), summer (August 2005, 2006, 2008), and fall (October and November

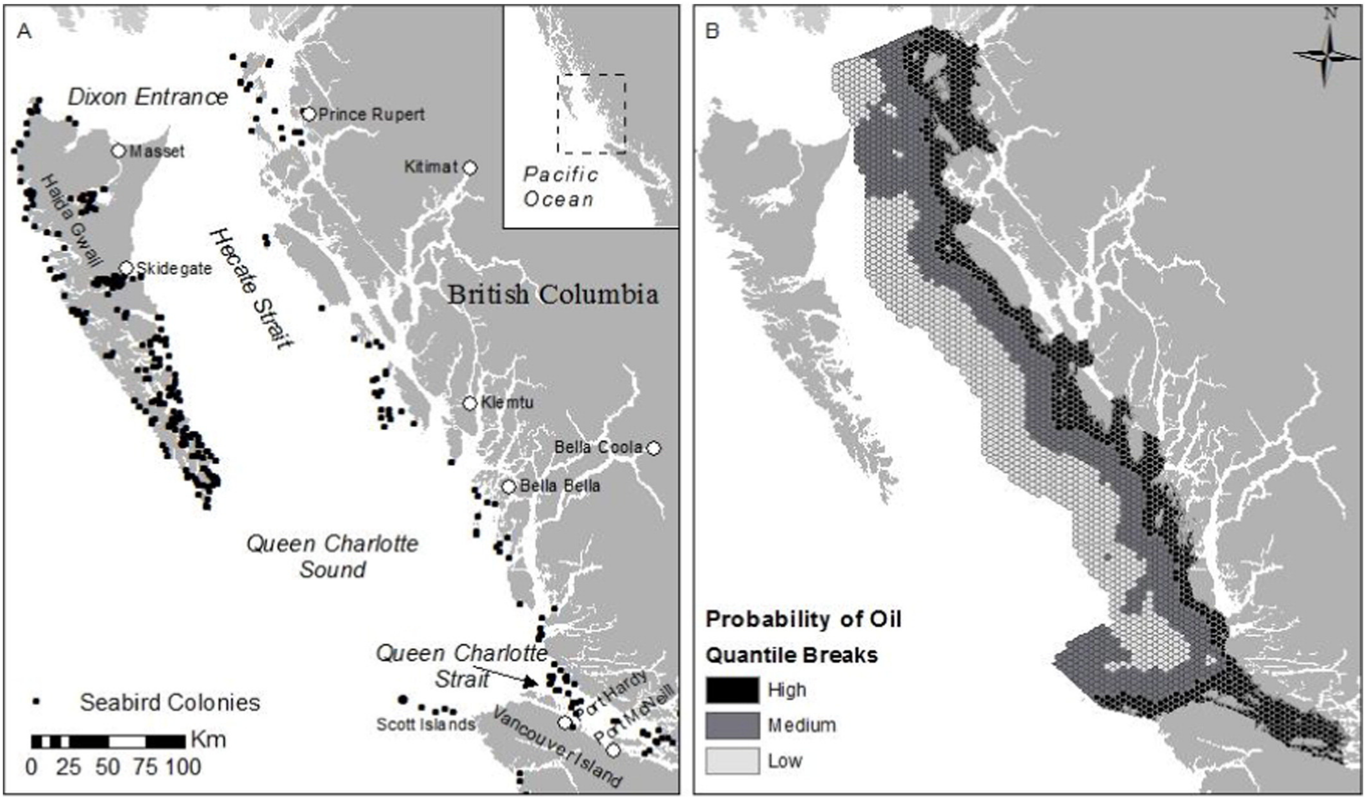

Fig. 1. (a). Locations of seabird colonies (source: Environment and Climate Change Canada), towns and water bodies in study area and adjacent areas and (b) probability of small-scale oil discharges (modified from Bertazzon et al. 2014), ranked from high, medium, and low using quantile breaks in coastal British Columbia, Canada.

2007). Within the marine bird study area, 4729 km of planned transect and 824 km of 'on passage' transect were realized. Density along 1 km transect segments were estimated using Multiple Covariate Distance Sampling (MCDS) in the software program Distance 6.0 release 2 (Thomas et al., 2010), the package MRDS v2.1.4 (Laake et al., 2013) and the software program R v3.0.2 (R Core Team, 2013). Using estimated density per transect segment as the response variable and 27 static, dynamic, and climatological environmental variables, model ensembles for 12 marine bird species and seven groups (representing 24 species; Table 1) were derived using four machine learning algorithms (RandomForests, TreeNet, Multivariate Adaptive Regression Splines, and Classification and Regression Trees) in Salford Systems Predictive Modeler v7.0 (San Diego, CA, USA).

For this study, predicted marine bird density surfaces were reduced to the mutually shared spatial extent of the predicted small oily discharge surface (Bertazzon et al., 2014) using ArcGIS10 (ESRI, Redlands, CA, USA). For marine bird species or groups and for the overall importance prediction, a hexagonal grid (13.9 km^2) was used. The estimated density (birds per km^2) of individual marine bird species or groups were transformed into three categories using quantile breaks (terciles valued 1–3). Predictive estimated density models were used to generate an estimate of combined overall importance based on marine bird species or group richness and density. The overall importance of marine birds was estimated by (1) normalizing estimated density (density values per hexagonal grid cell range from 0 to 1 for all species) and subsequently adding all marine bird species or group modified densities; and (2) modifying the overall normalized density values into the three quantile breaks. For full details on marine bird model predictive model ensembles and the overall predicted density of marine birds, used here as a proxy to identify potential areas important to marine birds, see Fox et al. (in review). For survey design details, see Williams and Thomas (2007), Thomas et al. (2007) and Best et al. (2015).

2.2. Oil information

A prediction layer for oil discharges in BC was created based on global and regional spatial regression models developed by Bertazzon et al. (2014), who associated small oily discharges detected and documented by NASP with human marine activities (e.g., recreational activities, commercial traffic, fisheries etc.). In their study, Bertazzon et al. (2014) grouped predictor variables into two alternative global models to reduce multicollinearity among variables within each model. Model 1, whose predictors included vessel type (vs. vessel age in model 2), was found to perform the best, based on AIC, log-likelihood, and McFadden pseudo-R^2 (Bertazzon et al. 2014).

The Bertazzon et al. (2014) study area was divided into three regions based on results from the global model and expert opinion, and model 1 (henceforth "oil model") was rerun, resulting in better performance within each region, based on adjusted McFadden pseudo-R^2 (Bertazzon et al. 2014). For this study, region 1 is most representative of the study area. The oil model was subsequently modified by using inverse distance weighting (IDW) to (1) interpolate predictions within the hexagonal grid (13.9 km^2); and to (2) extrapolate 25 km westward; before (3) reducing the study area to match the overlapping spatial extent of the modified oil model's oil discharge study area and the bird study area used by Fox et al. (in review). Lastly, the oil model was modified by altering the predicted occurrence of small oily discharges (0–1) into three quantile break categories representing low (1), medium (2), and high (3) probability of small oil discharges (Fig. 1b). We note that this model predicted incidence rate (i.e., accounting for surveillance effort as an offset), accounting for approximately 17% of the spatial variability in incidence rate. Nevertheless, categorization of predicted

Table 1
Associated taxonomic and conservation status for marine bird species in this study. Information was derived from line transect surveys in coastal British Columba, Canada (2005–2008). Abbreviations: breeding population (Br), non-breeding population (Nb), migrant (M; species occurring regularly on migration at particular staging areas or concentration spots), International Union for the Conservation of Nature (IUCN), Committee on the Status of Endangered Wildlife in Canada (COSEWIC), British Columbia (BC) and not assessed (NA). For the provincial conservation status (BC), where there were a range of conservation ranks provided for a given species, the lower conservative status is reported.

Taxonomic order, family & common name	Scientific name	Global - IUCN	National - COSEWIC	Provincial - BC
Anseriformes Anatidae				
Black Scoter	*Melanitta americana*	Near threatened (2013)	NA	Nb: Vulnerable (2015)
Surf Scoter	*Melanitta perspicillata*	Least concern (2012)	NA	Br: Vulnerable, Nb: Apparently secure (2015)
White-winged Scoter	*Melanitta deglandi*	Least concern (2013)	NA	Br: Apparently secure (2015)
Charadriiformes Alcidae				
Ancient Murrelet	*Synthliboramphus antiquus*	Least concern (2012)	Special concern (2014)	Br: Imperiled, Nb: Apparently secure (2015)
Cassin's Auklet	*Ptychoramphus aleuticus*	Near threatened (2015)	Special concern (2014)	Br: Vulnerable, Nb: Apparently secure (2015)
Common Murre	*Uria aalge*	Least concern (2015)	NA	Br: Imperiled, Nb: Vulnerable (2015)
Marbled Murrelet	*Brachyramphus marmoratus*	Endangered (2012)	Threatened (2012)	Br: Vulnerable, Nb: Vulnerable (2015)
Pigeon Guillemot	*Cepphus columba*	Least concern (2012)	NA	Br: Apparently secure (2015)
Rhinoceros Auklet	*Cerorhinca monocerata*	Least concern (2012)	NA	Br: Apparently secure (2016)
Tufted Puffin	*Fratercula cirrhata*	Least concern (2012)	NA	Br: Imperiled, Nb: Apparently secure (2014)
Charadriiformes Laridae				
California Gull	*Larus californicus*	Least concern (2012)	NA	Br: Imperiled (2015)
Glaucous-winged Gull	*Larus glaucescens*	Least concern (2015)	NA	Br: Apparently secure (2015)
American Herring Gull	*Larus smithsonianus*	Least concern (2014)	NA	Br: Secure (2015)
Thayer's Gull	*Larus thayeri*	Least concern (2015)	NA	M: Secure (2015)
Black-legged Kittiwake	*Rissa tridactyla*	Least concern (2012)	NA	Nb: Critically imperiled (2015)
Bonaparte's Gull	*Larus philadelphia*	Least concern (2012)	NA	Nb/Br: Secure (2015)
Mew Gull	*Larus canus*	Least concern (2015)	NA	Br: Apparently secure (2015)
Sabine's Gull	*Xema sabini*	Least concern (2015)	NA	M: unranked (2009)
Charadriiformes Scolopacidae				
Red-necked Phalarope	*Phalaropus lobatus*	Least concern (2012)	Special concern (2014)	Br: Vulnerable (2015)
Gaviiformes Gaviidae				
Common Loon	*Gavia immer*	Least concern (2012)	Not at risk (1997)	Br: Secure (2015)
Pacific Loon	*Gavia pacifica*	Least concern (2012)	NA	Br: Apparently secure, Nb: Vulnerable (2015)
Red-throated Loon	*Gavia stellata*	Least concern (2012)	NA	Br: Apparently secure (2015)
Yellow-billed Loon	*Gavia adamsii*	Near threatened (2015)	Not at risk (1997)	Nb: Imperiled (2015)
Pelecaniformes Phalacrocoracidae				
Brandt's Cormorant	*Phalacrocorax penicillatus*	least concern (2012)	NA	Br: Critically imperiled, Nb: Apparently secure (2015)
Double-crested Cormorant	*Phalacrocorax auritus*	least concern (2012)	Not at risk (1978)	Br: Vulnerable (2015)
Pelagic Cormorant	*Phalacrocorax pelagicus*	Least concern (2012)	NA	Br: Apparently secure (2015)
Podicipediformes Podicipedidae				
Horned Grebe	*Podiceps auritus*	Vulnerable (2015)	Special concern (2009)	Br: Apparently secure (2015)
Red-necked Grebe	*Podiceps grisegena*	Least concern (2015)	Not at risk (1982)	Br: Secure (2015)
Western Grebe	*Aechmophorus occidentalis*	Least concern (2012)	Special concern (2014)	Br: Critically imperiled, Nb: Imperiled (2015)
Procellariiformes Diomedeidae				
Black-footed Albatross	*Phoebastria nigripes*	Near threatened (2014)	Special concern (2007)	Nb: Vulnerable (2015)
Procellariiformes Hydrobatidae				
Fork-tailed Storm-petrel	*Hydrobates furcatus*	Least concern (2012)	NA	Br: Apparently secure (2015)
Leach's Storm-petrel	*Hydrobates leucorhous*	Least concern (2012)	NA	Br: Apparently secure (2015)
Procellariiformes Procellariidae				
Northern Fulmar	*Fulmarus glacialis*	Least concern (2015)	NA	Br: Critically imperiled, Nb: Apparently secure (2015)
Pink-footed Shearwater	*Ardenna creatopus*	Vulnerable (2012)	Threatened (2004)	Nb: Vulnerable (2015)
Flesh-footed Shearwater	*Ardenna carneipes*	Least concern (2012)	NA	Nb: Vulnerable (2015)
Short-tailed Shearwater	*Ardenna tenuirostris*	Least concern (2012)	NA	M: Unranked (2015)
Sooty Shearwater	*Ardenna grisea*	Near threatened (2015)	NA	M: Unranked (2015)

rates into quantiles is useful as an index for relative probability of occurrence.

2.3. Spatial assessment of risk

In order to identify areas predicted to experience elevated probabilities of chronic oil pollution and elevated marine bird densities, the spatial overlap between marine birds and small oily discharges were mapped overall and on a species- or group-specific basis. We used a semi-quantitative risk assessment tool to assess risk of exposure to chronic oil pollution for marine birds in our study area, as simple quantitative approaches are considered an improvement over standard qualitative approaches (Cox et al., 2005; but see Cox, 2008 and Levine, 2012). In our risk matrix (Fig. 2), the likelihood of an oil spill (the stressor) occurring interacts with the predicted marine bird density (the socio-ecological consequence).

Vulnerability was determined by the product of predicted marine bird species or group density (quantile breaks; valued 1–3) and the predicted occurrence of small oily discharges (quantile breaks; valued 1–3). Overall vulnerability was similarly determined using the same predicted occurrence of small oily discharges, but multiplied by the overall importance of marine birds (quantile breaks; valued 1–3). Both probabilities were scaled and categorized so that they impact the overall risk function with equal weight. Using this approach, the extent of spatial overlap was then mapped for individual species and groups, in addition to the overall vulnerability of marine birds.

For each bird species or group, risk of exposure was estimated using the following equation, where P_{1-3} represents the percent of the population (based on quantile breaks; valued 1–3) in the study area that overlap spatially with areas where the predicted occurrence of chronic oil pollution is low (1), medium (2), and high (3) in the study area:

$$\text{Risk of exposure} = (1 * P_1) + (2 * P_2) + (3 * P_3) \quad (1)$$

3. Results

Areas of predicted high overall marine bird importance are unevenly distributed across the study area, and include a large area of northern Hecate Strait and Dixon Entrance, with smaller areas of high importance concentrated around the Scott Islands, much of Queen Charlotte Strait, and along the margins adjacent to land, particularly on the North and Central Coasts (Fig. 3a). Similarly, the modified prediction of oil occurrence from Bertazzon et al. (2014) indicates that the highest probability areas for oil occurrence are adjacent to the land, including all of the Queen Charlotte Strait and areas directly adjacent to the Scott Islands (Fig. 1b). Although probability of oil occurrence is predicted to decline with distance from the coast, bands of medium probability of occurrence extend through the northern section of Hecate Strait and Queen Charlotte Sound, near the Scott Islands (Fig. 1b). The interaction between overall marine bird importance and predicted oil occurrence identifies two specific areas of highest potential risk: (1) northern Hecate Strait and eastern Dixon Entrance, particularly adjacent to the mainland; and (2) adjacent to the Scott Islands and extending south into Queen Charlotte Strait (Fig. 3b). An additional, although smaller area identified as high risk is directly adjacent to the mainland Central Coast (Fig. 3b).

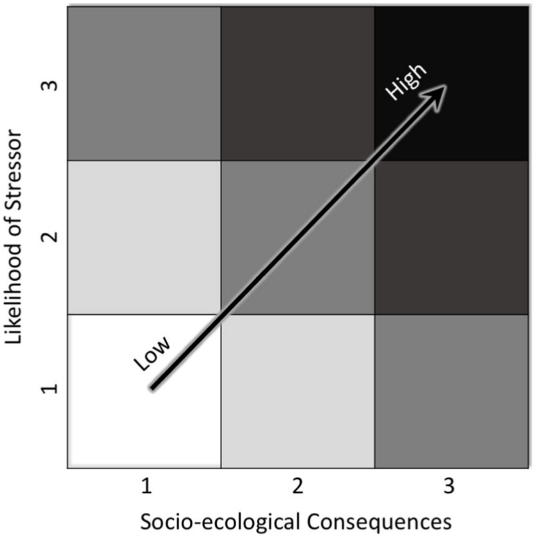

Fig. 2. Spatial risk assessment framework (Risk = Likelihood × Socio-ecological Consequence) that establishes the relative degree of risk from low to high based on the likelihood of a stressor occurring and the estimated socio-ecological consequences should the stressor occur.

For individual marine bird species or groups, quantile rank density is reported in panels for 12 species and seven groups (Fig. 4). Adjacent panels display predicted "risk", where areas of spatial overlap between marine birds and oil occurrence are predicted to occur, with shading reflecting the multiplicative output of quantile rank marine bird density (low, medium, high) and probability of oil occurrence (low, medium, high; Fig. 4). Those with highest potential exposure varied across guilds, with the top five highest ranked species or groups being large gulls, cormorants, Pigeon Guillemot, grebes, and small gulls (ranked 1–5; Table 2). Species or groups with lowest potential exposure also varied across guilds and included more pelagic species: Ancient Murrelet, Pink-footed Shearwater, dark shearwaters, Tufted Puffin, and Fork-tailed Storm-petrel (ranked 15–19; Table 2).

In terms of the comparison between exposure risk rankings and the Oil Vulnerability Index (OVI) developed by King and Sanger (1979) for marine birds in the Northeast Pacific Ocean, of the top five identified as having the highest exposure risk, only Pigeon Guillemot was similarly ranked in terms of OVI value (Table 2). For the remaining top four exposure risk ranked species or groups, OVI rankings were low (Table 2).

4. Discussion

In this study, we identify two areas of highest potential risk of exposure to marine birds: (1) northern Hecate Strait and eastern Dixon Entrance, particularly adjacent to the mainland; and (2) Queen Charlotte Strait and waters adjacent to the Scott Islands, which are off northern Vancouver Island. However, we note that the assessment of areas of overall importance to marine birds (developed by Fox et al. (in review) was not inclusive of all species present in the region and, further, that the areas identified as important should be anticipated to be dynamic (e.g., seasonal and interannual change). In terms of individual species and groups identified as most at risk, grebe and cormorant groups, large and small gull groups, and the alcid Pigeon Guillemot were ranked as the most at risk of exposure to small-scale oil discharges. There appeared to be no taxonomic trend in terms of rank exposure. However, species or groups that are more pelagic (e.g., Tufted Puffin and shearwaters) were assessed as being at the lowest risk of exposure, whereas species and groups with elevated densities near the mainland coast and the northeast coast of Vancouver Island were ranked among the highest risk of exposure. We emphasize that these estimates are relative (i.e., within species or group) rankings of exposure for species or groups estimated to occur within the spatial extent of the oil spill model. These estimates do not represent the full spatial extent of exposure, and this is particularly the case for species whose distribution is largely offshore.

In coastal BC – and similarly in other coastal waters around the world – oil spill probability can be readily estimated in a given area due to the existence of information relating to oil discharges from commercial vessels. Further, because these vessels may be tracked using the Automatic Identification System, vessel density in an area can be used as a predictor for oil spill occurrence (e.g., Bertazzon et al., 2014). However, estimating the potential consequences stemming from these oil discharges is far more difficult due to a number of uncertainties including density of organisms at risk of being oiled in a given area at a specific time. For example, areas of concentrations for marine organisms at risk of being oiled were not included in the Pacific Region for the Canadian nationwide risk assessment for oil spills conducted by Transport Canada (WSP, 2014).

Logically, the two components of a spatial risk assessment should be integrated with similar weighting; otherwise risk assessments will be biased towards the component with higher values. However, combining these components without biases can be problematic, particularly when the components vary temporally and spatially, in addition to being

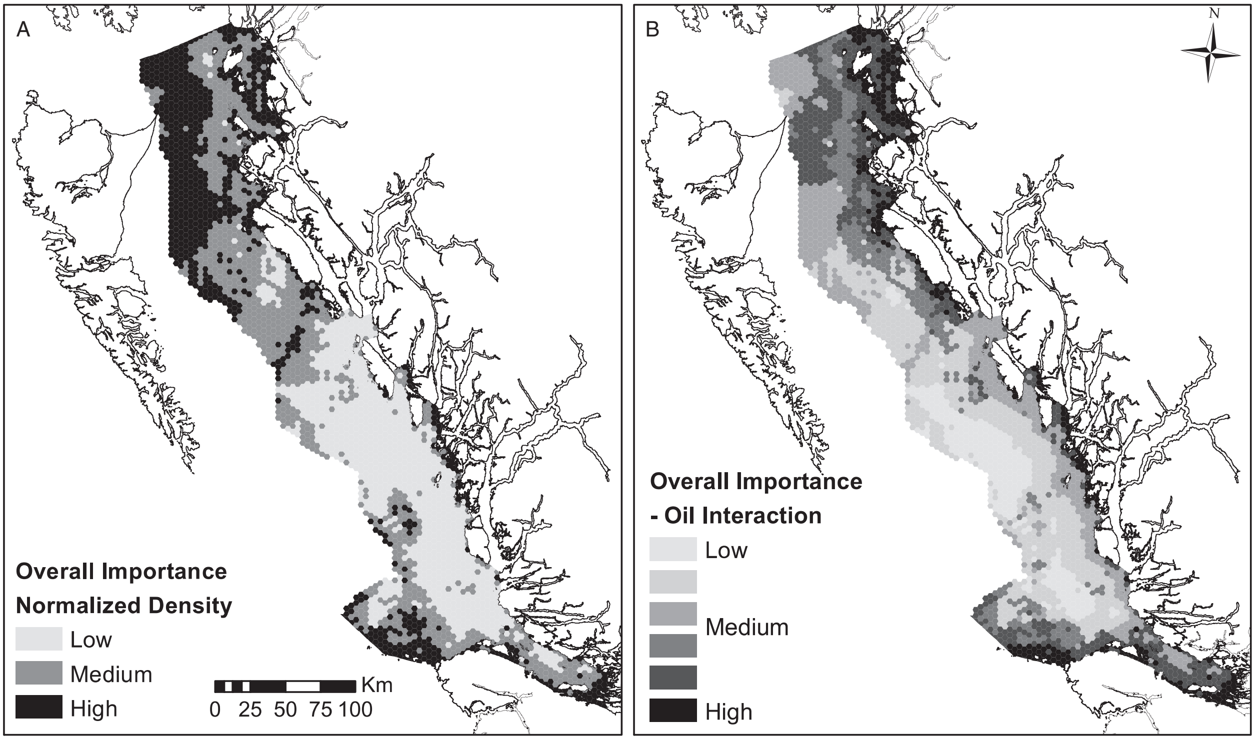

Fig. 3. (a). Overall importance (normalized density) of 12 marine bird species and seven bird species groups ranked from high, medium and low using quantile breaks and (b) interaction between marine bird overall importance and probability of small-scale oil discharges in coastal British Columbia, Canada.

subject to uncertainty. Further, understanding the effects (or responses) of exposure can be very complex, ranging from inference at the organism-level using simple assumptions or models, to the population-level, with much more complicated extrapolations across varying levels of organization (Suter, 2007). Here we present a spatially explicit semi-quantitative approach that combines exposure (likelihood of a small scale oil spill occurring) and potential consequences (as proxied by marine bird densities). By reducing estimated oil spill occurrence probabilities and marine bird densities to quantiles (i.e., probability functions for low, medium, and high probabilities or densities), we reduce our uncertainty and weight equally exposure and consequence components of our risk analyses. This approach provides new insights, including the identification of areas and marine bird species or groups of potentially elevated concern.

We chose a semi-quantitative approach to assess risk because it is intuitive and easy to interpret. However, although we standardized both input variables to ensure equal weighting (i.e., similar ranges and distributions), we acknowledge that concerns have been raised about likelihood-consequence matrix approaches to risk assessment and their interpretation, including range compression, low resolution, and lack of integration of uncertainty (e.g., Cox 2008; Levine 2012). To address these concerns to some degree, we intentionally maintained a low resolution in our variables and final product categorizations to assess risk of exposure to chronic oil pollution for marine birds. However, we emphasize that care must be taken when interpreting our results, particularly because we do not include uncertainty in our risk assessments.

Our study departs from standard approaches for assessing risk of exposure to small-scale oil discharges for marine birds, which typically relies on evidence of oiling found on beach-cast carcasses and stricken live birds, and oil found in nearby coastal substrates (e.g., Bourne 1976a, 1976b; Camphuysen, 1989; Camphuysen and Heubeck, 2001; Wiese and Robertson, 2004; Wilhelm et al., 2009). Although BBS are a useful and cost-effective way to monitor oil pollution, data collected may be biased towards species that tend to occur relatively close to the survey beaches as bird carcasses stay afloat for a short period of time only (Weise 2003; see Weise and Robertson (2004) as an example of a marine area represented by BBS data collected in Newfoundland, Canada). Stricken individuals can also fly or swim to shore, but we believe that this would be a relatively small component contributing to the estimated impacts from oil pollution based on BBS data. In BC, there are large coastal regions that are too remote or too difficult to access to be included in a BBS. Considerable numbers of marine birds and a wide variety of other marine taxa also occur offshore of those areas of BC (e.g., Kenyon et al., 2009). Consequently, the numbers of marine birds and the number of species impacted are likely underestimated in BC BBS records, an issue which is acknowledged by BBS organizers and researchers basing studies on BBS data (e.g., Wiese and Robertson, 2004; O′Hara and Morgan, 2006).

The Oil Vulnerability Index (OVI), as defined by King and Sanger (1979) and others, is a useful metric for ranking vulnerability to oil pollution among marine bird species. Our ranking approach fundamentally differs from the OVI in that the OVI incorporates factors reflecting both vulnerability and sensitivity to oil exposure as we have defined them here. These include range and distribution, population dynamics, behaviour, and seasonal exposure to oil pollution (King and Sanger, 1979). Scores are based on these factors with total scores being used to rank vulnerability among species. In our view, a key drawback of the OVI is that rankings are undoubtedly influenced by species that typically show up in BBS, and subsequently influence the selection of focal species based on their prevalence in BBS records (e.g., Camphuysen, 1989). Our approach, which focuses on the likelihood of exposure based on spatial coincidence or co-occurrence, identifies species or groups at high risk of exposure that may not have large OVIs (e.g., large and small gulls, grebes, and cormorants). Not mutually exclusive, our approach could be complementary to assessments and analyses based on the OVI or its extension, the Area Vulnerability Score (see Williams et al., 1995; Begg et al., 1997). As an example, future analyses could integrate the OVI factors reflecting sensitivity to oil exposure with our estimates of likelihood of exposure based on spatial coincidence.

We note that our estimates of vulnerability do not reflect important variability among and within species. Among species, for example, exposure to oil pollution likely varies with foraging behaviour, with species that spend time diving or on the water's surface considered to be at greater risk of exposure than species that forage while flying (e.g., Camphuysen, 1998). Within species, vulnerability can also vary with phenology; for example, post-breeding moult can result in flightlessness, making individuals more vulnerable to exposure to oil pollution during this period (Stone et al., 1995). Lastly, we assume all birds are equally sensitive once exposed to oil, although evidence

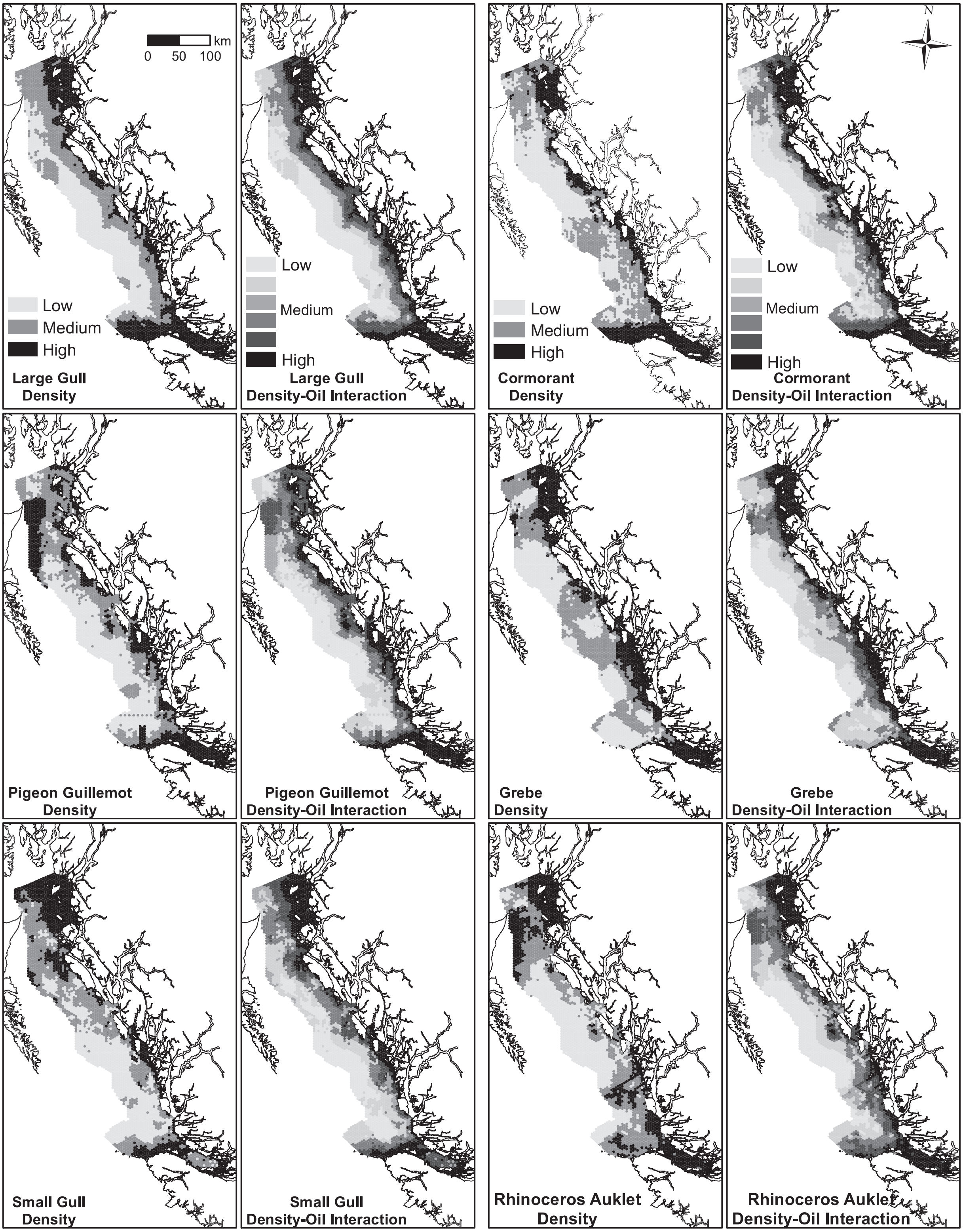

Fig. 4. Predicted marine bird species or species group density (number of birds per km^2) and marine bird-oil interaction, based on oil spill probability ranked as low, medium, and high in coastal British Columbia, Canada.

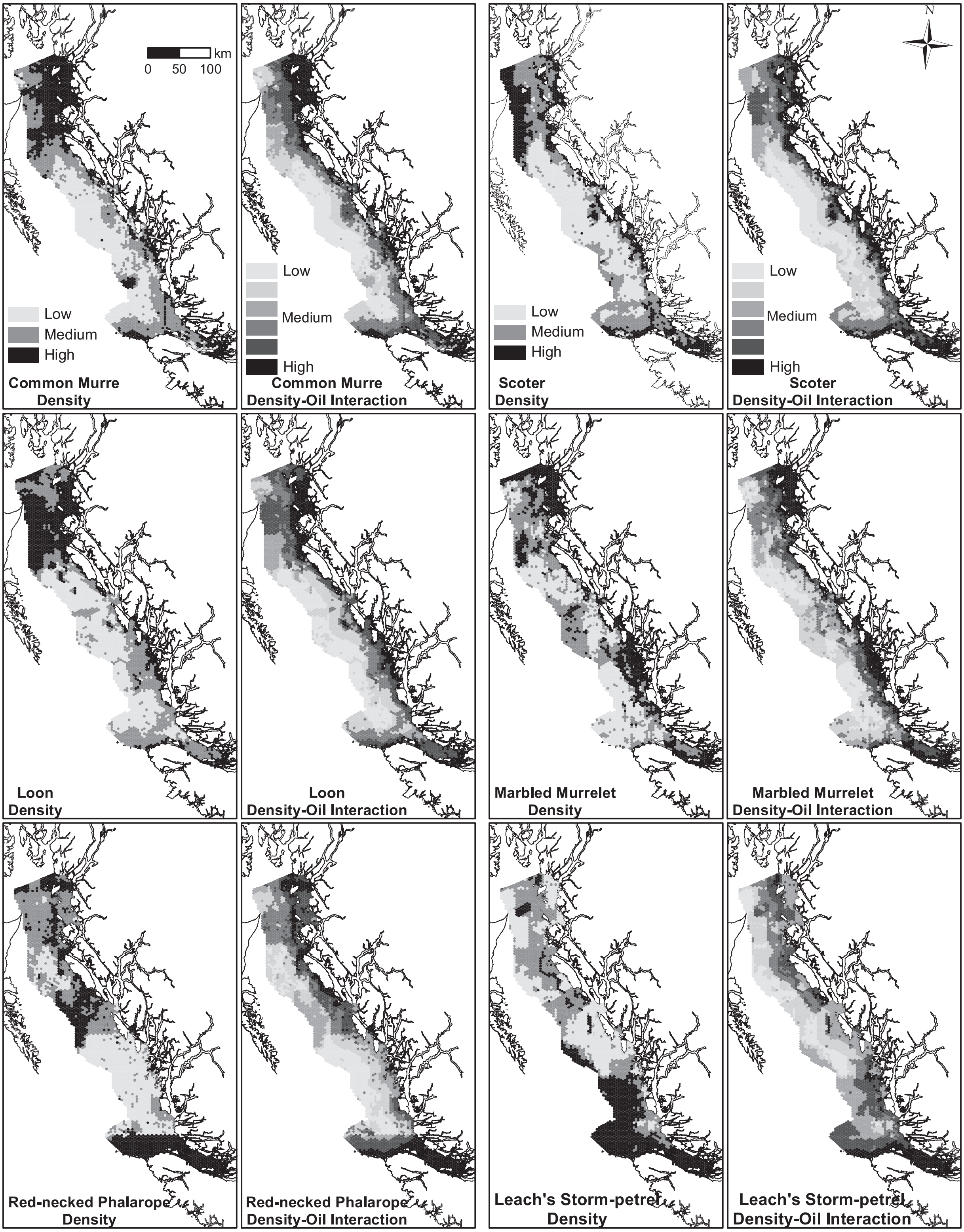

Fig. 4 (*continued*).

suggests that the response of individual species varies (e.g., Camphuysen, 1998; Wiese and Ryan, 2003; Robertson et al., 2014). Some of this variability may be captured by one or more OVI factors, which could also be integrated into our approach.

Canada's Pacific coast is already subject to significant anthropogenic pressures (Ban and Alder 2008), several of which are projected to increase (e.g., climate change; IPCC, 2014, shipping traffic; Nuka Research, 2013). With a number of Pacific coast marine bird species already considered to be at elevated risk of extinction under Canada's Species at Risk Act (SARA) and other legislation (e.g., the US Endangered Species Act), an additional number listed as priority species for assessment, and future predictions of population declines and extinctions

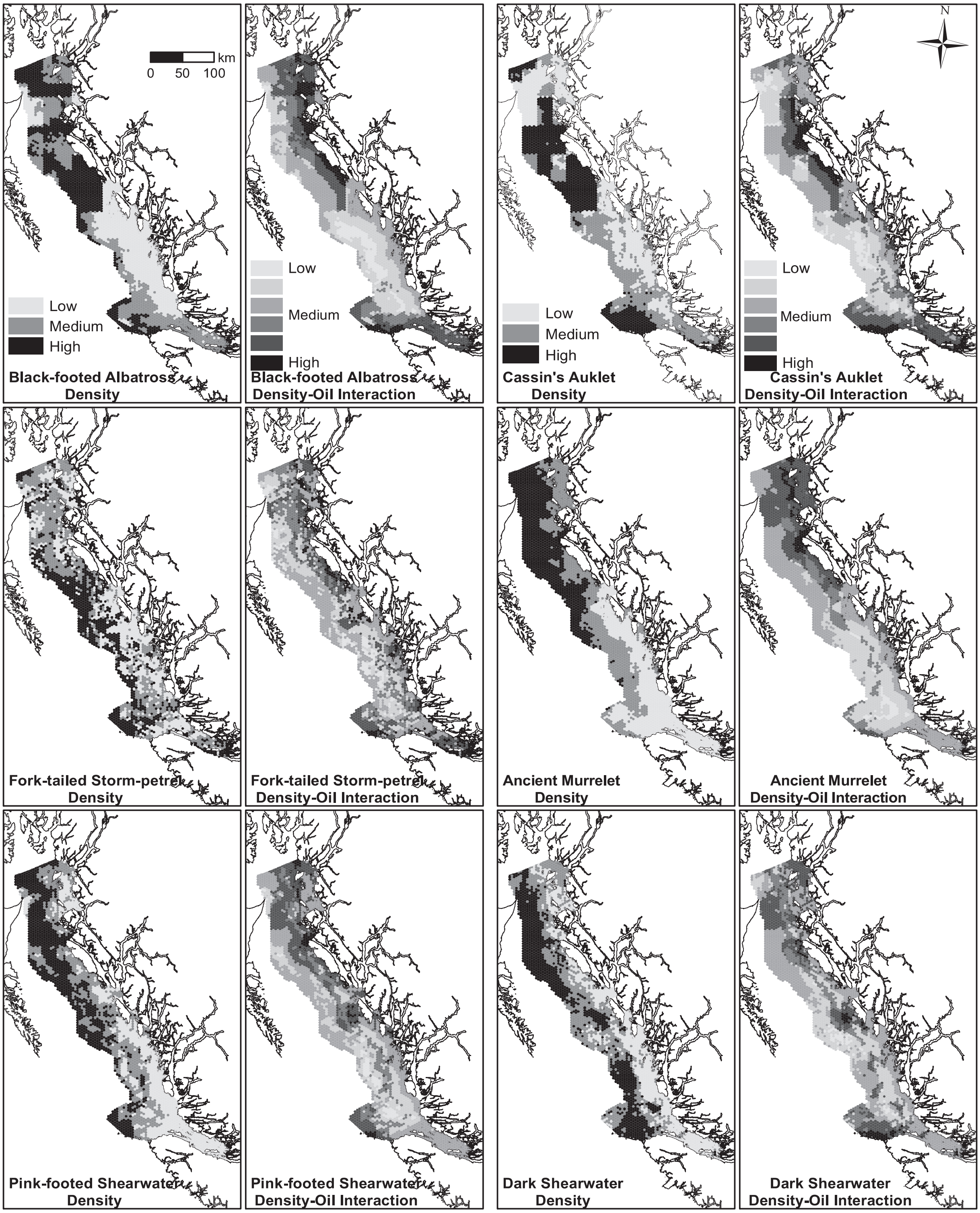

Fig. 4 (*continued*).

(Şekercioğlu et al., 2004), efforts to improve and continuously update our understanding of the ecological consequences of these various anthropogenic pressures are crucial. Although our findings should be considered preliminary, our evaluation is the first semi-quantitative assessment of the spatial risk of oil exposure to marine bird birds on Canada's Pacific coast. As more information becomes available, further improvement of marine bird and chronic oil pollution information is needed, including an expansion of research to other coastal regions.

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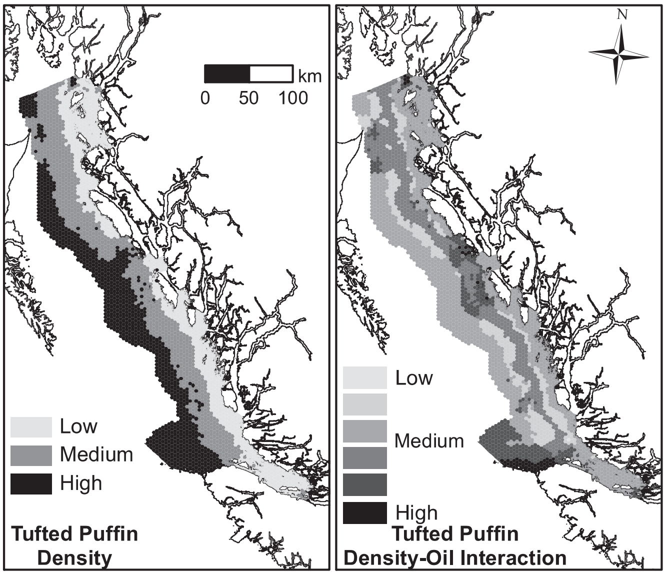

Fig. 4 (*continued*).

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Table 2

Mean predicted density of marine bird species or groups ± standard error (SE), percent of marine bird population (quantile rank value 1–3) predicted to occur in oil spill areas (quantile rank low, medium, high), and rank exposure (see Methods) in coastal British Columbia. SE represents SE of the marine bird predicted density across the study area but not uncertainty associated with the ensemble model itself or underlying source data. King and Sanger (1979) Oil Vulnerability Index (OVI) values and respective ranking are also included for comparative purposes. *Indicates that information involving flying birds is included in these estimates.

Common name	Mean predicted density (birds/km^2) ± SE	Predicted population in oil risk areas (%)			Exposure risk		King & Sanger (1979)	
		Low	Medium	High	Value	Rank	OVI	Rank
Large Gull (California, Glaucous-winged, Herring, and Thayer's)*	63.5 ± 1.3	20.2	30.0	49.8	229.6	1	43.5	18
Cormorant (Brandt, Double-crested, and Pelagic)	1.9 ± 0.1	21.6	28.9	49.6	228.0	2	57.3	12
Pigeon Guillemot	9.4 ± 0.3	23.1	29.6	47.4	224.3	3	82	3
Grebe (Eared, Horned, Red-necked, and Western)	7.5 ± 0.6	24.1	28.2	47.7	223.6	4	49.3[a]	15
Small Gull (Bonaparte's, Mew, Sabine's, and Black-legged Kittiwake)*	9.0 ± 0.3	23.6	29.6	46.7	223.1	5	44.25	17
Rhinoceros Auklet	52.7 ± 2.7	23.6	31.3	45.1	221.5	6	74	4
Common Murre	141.8 ± 5.5	24.4	30.9	44.8	220.4	7	70	8
Scoter (White-winged, Surf, and Black)	9.6 ± 0.7	25.7	28.6	45.7	220.0	8	72	6
Loon (Common, Pacific, Red-throated, and Yellow-billed)	7.36 ± 0.1	25.6	30.4	44.0	218.4	9	54.8	13
Marbled Murrelet	4.0 ± 0.2	26.4	29.1	44.5	218.0	10	84	1
Red-necked Phalarope*	82.0 ± 9.6	27.3	31.2	41.5	214.2	11	62	11
Leach's Storm-petrel*	6.8 ± 0.2	30.9	34.0	35.1	204.1	12	63	10
Black-footed Albatross*	0.5 ± 0.0	35.5	31.6	32.9	197.4	13	50	14
Cassin's Auklet	15.0 ± 0.3	35.2	32.4	32.4	197.2	14	84	2
Fork-tailed Storm-petrel*	69.4 ± 4.8	36.9	31.7	31.4	194.6	15	67	9
Ancient Murrelet	29.0 ± 0.5	39.8	31.7	28.4	188.3	16	74	5
Pink-footed Shearwater*	0.8 ± 0.0	39.1	34.3	26.6	187.5	17	47	16
Dark Shearwater (Flesh-footed, Short-tailed, Sooty Shearwater)*	68.1 ± 1.3	40.0	34.0	26.1	186.1	18	35[b]	19
Tufted Puffin	0.5 ± 0.0	42.9	34.3	22.8	179.9	19	72	7

[a] Eared Grebe was not included.

[b] Flesh-footed Shearwater was given an OVI of 1.

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