



Using beached bird data to assess seabird oiling susceptibility

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ABSTRACT

Oil spills can cause severe impacts on seabirds, the extent of which varies by species. We investigated taxon-specific susceptibility using data from the *Nestucca* and *Tenyo Maru* oil spills in the northeast Pacific together with seasonally and spatially overlapping baseline beached bird abundance data collected over a 17-year time-period. Multivariate analyses revealed patterns of variation between spill and non-spill data, primarily driven by differences in the relative abundance of common murre (*Uria aalge*) and northern fulmars (*Fulmarus glacialis*). In subsequent susceptibility analyses, alcid (*Alcidae* spp.) carcasses were generally overrepresented in spill data, while gulls (*Larus* spp.), tubenoses (*Procellariiformes* spp.), and cormorants (*Phalacrocoracidae* spp.) were generally under-represented. We found that the baseline data had high variability, suggesting a need for many years of baseline data. We propose that where appropriate baseline data exists, this method can be employed to investigate the seabirds most vulnerable to oiling.

1. Introduction

Oil spills are one of the most catastrophic forms of marine pollution in nearshore marine ecosystems, as they can disrupt ecosystem processes via severe mortality of many species (Chilvers and Battley, 2019; Crain et al., 2009; Halpern et al., 2007). In particular, oil spills have well-documented impacts on seabirds (e.g., Burger and Fry, 1993; Munilla et al., 2011; Castège et al., 2004). These impacts range in scale from the individual bird (e.g., disrupted thermoregulation –Hartung, 1967) to entire populations (e.g., depressed breeding success– Barros et al., 2014). While oil spills are likely to have deleterious effects on all marine bird species, some species appear to be more susceptible to oil exposure and mortality than others (King and Sanger, 1979; Clark, 1984; Lorentsen and Anker-Nielsen, 1993; Wiese and Ryan, 2003; Camphuysen, 2007). Various methods have been employed to assess relative species susceptibility to oiling, including the development of indices of taxon-specific oiling vulnerability (Oiling Vulnerability Indices, or OVIs).

The development of OVIs was pioneered by King and Sanger (1979) in a landmark study assessing 176 marine bird species in the northeast Pacific. Subsequent authors have adopted the OVI approach, variously incorporating different numbers of factors, factor weights, and additive versus multiplicative formulae (e.g., Camphuysen, 1989; Wahl et al., 1981; Williams et al., 1995; Chilvers and Battley, 2019). In general,

these methods integrate factors related to natural history (e.g., habitat use, migratory pattern), life history and population dynamics (e.g., reproductive success, distribution) and conservation status (e.g., susceptibility to other population threats, conservation status assessed globally). The benefits of an index approach include the ability to create an assessment of likely risk for many species within a specified location (e.g., a large marine ecosystem). The drawbacks include that the indices necessarily reflect the decisions of the authors as to the importance of the factors incorporated (by deciding whether to weight all factors the same or to assign different weights). An independent evaluation of taxonomic patterns in oiling vulnerability would provide a means to assess the results OVIs deliver and could provide additional insight for resource management and protection/mitigation.

In this paper, we develop an approach complementary to that of OVIs by comparing taxon-specific spill and non-spill carcass deposition data within the northern California Current System. We used seabird carcass data from two spills, the *Nestucca* (Dec 1988, southern outer coast of Washington, US) and the *Tenyo Maru* (July 1991, northern outer coast of Washington, US). We compared observed patterns of taxonomic composition during those spills to baseline beached bird composition data. This baseline data, collected by a long-term citizen science program, was specific to the season and coastline affected for each spill (Fig. 1) Although this method cannot account for the behavior of live birds that might attract or repel them from oil at sea, effectively

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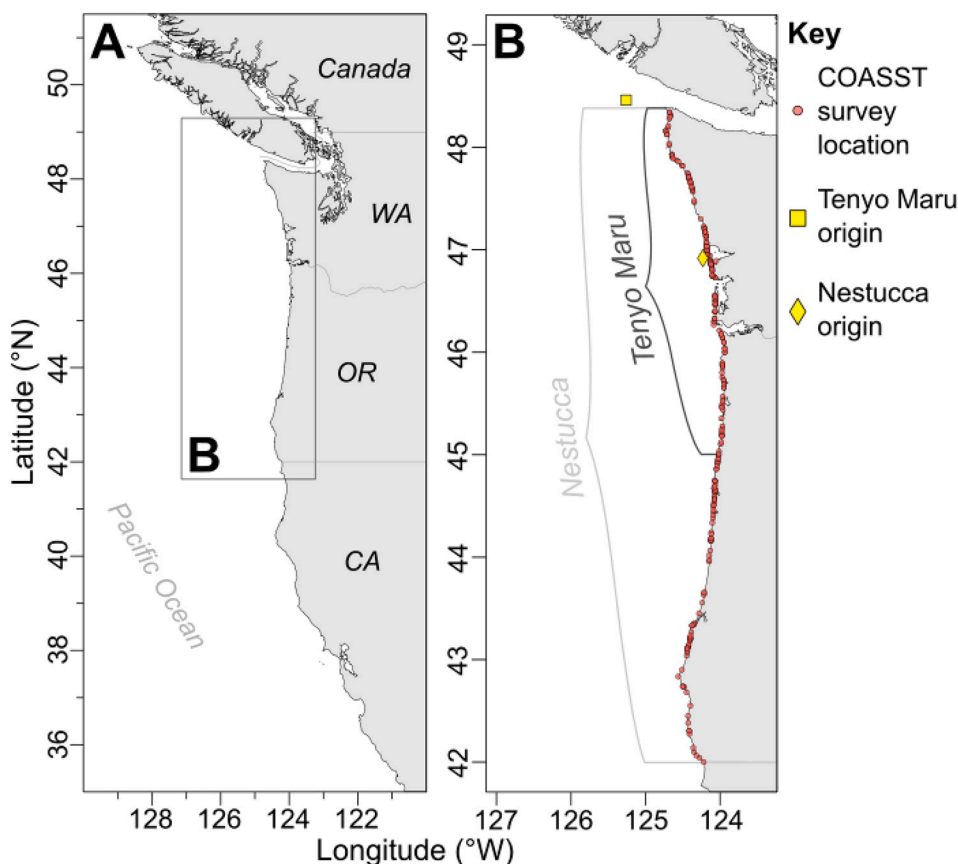


Fig. 1. Maps showing (A) the location of the study region within the northeast Pacific and (B) specific locations of spill occurrence and baseline beached bird monitoring sites. The zoomed in map of the study region (B) shows approximate spill points of origin, surveyed beach locations within the COASST program along the outer Washington and Oregon coastlines, and the coastline extent over which COASST surveys were queried to generate baseline estimates of species composition for each spill.

redistributing the local populations in the spill year, it is an otherwise valid comparison, as [Wiese \(2003\)](#) has shown no effect of oiling on carcass float duration.

Our goals in this work were firstly to identify whether overall spill taxonomic composition differed from baseline beached bird composition, considering the interannual variability in baseline composition; and secondly to identify which species were relatively over/underrepresented in the spill dataset as a means of categorizing taxon-specific susceptibility during these two spills. Finally, we compared these relative susceptibilities to the OVI scores for these same taxa presented in [King and Sanger \(1979\)](#) to highlight the similarities/differences of these approaches. We argue that baseline datasets, such as that utilized here, provide additional insight into oiling susceptibility by allowing for a data-informed approach independent from assumptions based on taxonomic traits.

2. Methods

2.1. Spill data

We used spill reports to assemble data on count and lowest possible

taxon of oiled beached bird carcasses (hereafter, carcasses) found following the *Nestucca* and *Tenyo Maru* oil spills ([Table 1](#)). Following the *Nestucca* spill, carcasses were collected in Washington State coastal areas from the day of the spill (22-Dec-1988) until late Jan-1989 ([Ford et al., 1991](#)). Survey efforts were coordinated by the Washington State Conservation Corps ([Ford et al., 1991; Burger, 1992](#)). Following the *Tenyo Maru* spill (22-Jul-1991), carcasses were recovered from Vancouver Island south to Lincoln City, Oregon (*Tenyo Maru* Trustee Council & U.S. Fish Wildlife Service 2000). Survey efforts were coordinated by the U.S. Fish and Wildlife Service, the State of Washington, the National Oceanic and Atmospheric Administration, and the Makah Tribe ([Summary of the Tenyo Maru oil spill restoration, 2006](#)).

2.2. Baseline data

Data from the Coastal Observation and Seabird Survey Team (COASST) were used to represent taxonomic patterns of baseline abundance, which we define here as taxon-specific carcass sightings by volunteer surveyors during non-spill years, with seasonal and geographic overlap with the spill in question. Established in 1999, COASST is a citizen science program housed at the University of

Table 1

For each spill, the date the spill occurred (Date), number of beached bird carcasses in the spill data (Spill Count), latitudinal range which the spill affected and for which we queried the COASST database (Lat. Range), days of the year for which we queried the COASST database (Day-of-year Range), number of beached bird carcasses in the queried subset of the COASST data set (COASST Count), and main data source for each spill (Spill Data Source).

Spill	Spill information		Baseline data (COASST)			Spill Data Source
	Date	Spill Count	Lat. Range (°N)	Day-of-year Range	COASST Count	
<i>Nestucca</i>	22-Dec-88	13,473	42.0–48.4	335–365, 1–14	10,927	Momot (1994)
<i>Tenyo Maru</i>	22-Jul-91	4300	45.0–48.4	181–225	4137	Tenyo Maru Trustee Council & U.S. Fish Wildlife Service (2000)

Washington in which expert-trained participants survey a known length of beach (Fig. 1) monthly for beached marine birds. Carcasses are scored for body condition, intactness, and the presence of oil or anthropogenic sources of entanglement. All carcasses are identified to the lowest possible taxon with the aid of a key (Hass and Parrish, 2013), photographed, individually marked to distinguish newly found birds from those previously found, and left on the beach. Identifications are subsequently verified by experts via measurements and photographs. Within the northern California Current large marine ecosystem encompassed by the COASST beached bird monitoring program, recorded chronic oiling rates are extremely low. This area has a median annual chronic oiling rate of 0.1%, ranging from 0.01% to 2.0% among years (2001–2019, $n = 656$ –10,144 birds per year). Within the seasonal and geographic bounds of each spill (i.e., the baseline data used to inform our analyses), oiled birds were only documented in the minority of years (*Nestucca*: 5 of 19 years; *Tenyo Maru*: 2 of 19 years), with recorded annual oiling rates ranging from 0 to 4% (2001–2019, $n = 70$ –5714 birds per year; COASST unpublished data).

While the COASST dataset does not include the years during which either spill occurred, the COASST dataset can provide a post hoc baseline of beached bird community composition. Although both spills had major impacts on local seabird populations in the short-term (*Tenyo Maru*: Thompson et al., 2003, Summary of the *Tenyo Maru* oil spill restoration, 2006.; *Nestucca*: Burger, 1993, Ford et al., 1991), there is little evidence to suggest that spills by themselves alter seabird populations in the long-term (Clark, 1984). However, factors like exposure to lingering oil and diet can affect recovery time (Esler et al., 2018). Additionally, we found no evidence to suggest that species composition derived from COASST data in the areas affected by either spill changed significantly over decadal timescales (Supplementary Material Table S1), suggesting that overall composition is relatively static.

For each spill analysis, the COASST dataset was restricted according to location and time of year to match the spatial and seasonal extent of the spill (Table 1). To account for the duration of carcass collection following each spill (*Nestucca*: primary response from 22-Dec to end of January- Ford et al., 1991; *Tenyo Maru*: primary response from 22-Jul to 29-Aug- National Oceanic and Atmospheric Administration, n.d.) and variation in beaching phenology over the year set encompassed by the baseline dataset, we defined a 45-day seasonal window centered on the day-of-year on which each spill occurred (Table 1). We explored smaller (30-day) and larger (60-day) windows but found that within-analysis proportional composition was largely unchanged (Supplementary Material Fig. S1). For each spill analysis we defined the “spill-region” of the baseline dataset as all COASST sites within the northern to southern extent of U.S. shorelines reported as oiled and from which oiled carcasses were recovered (Table 1). However, we did not incorporate the coastline of Vancouver Island, Canada into the analysis, despite oil and oiled carcasses arriving there, because there is no contemporaneous baseline dataset that matches the COASST data in spatial and temporal grain. Because the spatial coverage of COASST expanded into Oregon over time, we used data from 2002 (after which COASST spatial coverage changed by less than 0.1° latitude within the spill-regions) through 2018 (17 years) for both spill analyses.

2.3. Species and group-level data processing

Because there was little-to-no data on survey effort (e.g., number of searchers, beach length or area searched) for either spill, we were unable to compare the rate at which carcasses were found (i.e., carcasses per km) between spill and baseline data. Therefore, we focused on relative taxonomic composition— reasoning that the taxa that are relatively more prevalent in spill body count as opposed to in the baseline dataset are relatively more susceptible to oiling.

We conducted our analyses at two levels of taxonomic resolution: species level, and a variably higher taxonomic level we refer to as the “group level” (Table 2). Species-level analyses allowed us to analyze

data at the finest resolution possible but did not include the high proportion of carcasses not identified to species (e.g., in the *Nestucca* dataset ~9.1% of the total carcass count). Group-level analyses were based on semi-aggregated counts, which allowed for maximal inclusion of carcass counts (e.g., incorporating carcasses unknown to species but known to a higher taxonomic level) not presented at the species level. We ran the *Nestucca* data only at the group level, and the *Tenyo Maru* data at both the species and group levels.

In addition, raw counts from both spill and baseline datasets were processed to account for differences in identification and classification as follows. Several taxonomic categories were excluded a priori due to their ecology and/or scarcity: terrestrial birds, shorebirds, and waterfowl (except for scoters, *Melanitta* spp.); as well as all completely unidentifiable birds. Across both spill datasets, many gulls (*Larus* spp.) were not identified to species (*Nestucca*: 98.6% of all gulls; *Tenyo Maru*: 17.7%). Furthermore, within COASST, participants group all large (wing chord >33 cm) immature gulls into a single super-taxon (large immature gulls, Hass and Parrish, 2013), which account for 35% (*Nestucca* spill-region) to 59% (*Tenyo Maru* spill-region) of all reported gulls (*Larus* spp.) in the baseline datasets. Therefore, counts of gulls were excluded

Table 2

Species documented in either spill event analysis and relevant taxonomic groupings. Each group was included in both spill analyses unless otherwise indicated (TM = *Tenyo Maru*, N = *Nestucca*). For the *Tenyo Maru* species-level analysis, only species in bold were included; all remaining species did not meet thresholds for analysis inclusion based on rarity (threshold spill data: ≥ 1 individual; baseline data: ≥ 3 individuals in two or more years).

Family	Groups	Species
Alcidae	Auklets	Cassin's auklet (<i>Ptychoramphus aleuticus</i>), Parakeet auklet (<i>Aethia psittacula</i> , N only)
	Guillemots (TM only)	Pigeon guillemot (<i>Cephus columba</i>)
	Murrelets	Ancient murrelet (<i>Synthliboramphus antiquus</i> , N only), Marbled murrelet (<i>Brachyramphus marmoratus</i>)
	Murres	Common murre (<i>Uria aalge</i>)
	Puffins	Horned puffin (<i>Fratercula corniculata</i>), Rhinoceros auklet (<i>Cerorhinca monocerata</i>), Tufted puffin (<i>Fratercula cirrhata</i>)
Anatidae	Scoters	Black scoter (<i>Melanitta americana</i> , N only), Surf scoter (<i>Melanitta perspicillata</i>), White-winged scoter (<i>Melanitta deglandi</i>)
Diomedidae	Albatrosses (TM only)	Black-footed albatross (<i>Phoebastria nigripes</i>)
Gaviidae	Loons	Common loon (<i>Gavia immer</i>), Pacific loon (<i>Gavia pacifica</i> , N only), Red-throated loon (<i>Gavia stellata</i>)
Hydrobatidae	Storm petrels (TM only)	Fork-tailed storm petrel (<i>Oceanodroma furcata</i>)
Laridae	Gulls	American herring gull (<i>Larus smithsonianus</i> , N only), California gull (<i>Larus californicus</i> , TM only), Kittiwakes (<i>Rissa</i> spp., N only), Mew gull (<i>Larus canus</i>), Ring-billed gull (<i>Larus delawarensis</i> , N only), Western/Glaucous-winged gull (<i>Larus occidentalis</i> / <i>Larus glaucescens</i>)
		Caspian tern (<i>Hydroprogne caspia</i>)
		Brandt's cormorant (<i>Phalacrocorax penicillatus</i>), Double-crested cormorant (<i>Phalacrocorax auritus</i> , TM only), Pelagic cormorant (<i>Phalacrocorax pelagicus</i> , TM only)
		Western grebe (<i>Aechmophorus occidentalis</i>)
		Horned grebe (<i>Podiceps auritus</i>), Red-necked grebe (<i>Podiceps grisegena</i>)
Podicipedidae	Large Grebes (N only)	
	Small Grebes (N only)	
Procellariidae	Fulmars	Northern fulmar (<i>Fulmarus glacialis</i>)
	Shearwaters	Short-tailed shearwater (<i>Ardenna tenuirostris</i> , TM only), Sooty shearwater (<i>Ardenna grisea</i> , TM only)

from species-level analyses, but were combined (including kittiwakes, *Rissa* spp.) into a single group “gull” for group-level analyses.

Once these preliminary exclusions and groupings were made, 0.3% of the *Tenyo Maru* carcasses (14 of 4022) remained unidentified to species (and 2.4% of carcasses in the corresponding COASST baseline dataset), whereas 16% of the *Nestucca* carcasses (1911 of 11,913) remained unidentified to species (and 14.8% of carcasses in the corresponding COASST data). To maximize the inclusion of carcasses from the spill dataset in the analyses, and especially in cases where many carcasses were identified to a taxonomic level above that of our analysis (species for *Tenyo Maru*, group for *Nestucca*), we redistributed unknowns at a level one above the analysis to the next lower level according to the proportion of known carcasses within the dataset (see Supplementary Materials section 3). Redistribution had little effect on overall taxonomic composition (Supplementary Materials section 3), but became important in select taxa (e.g., grebes, *Aechmophorus* and *Podiceps* spp.) where the majority of spill dataset carcasses were categorized at family or sub-family levels. In these cases, redistribution allowed incorporation of the majority of the carcasses, ensuring the relative taxonomic proportions did not under-represent susceptibility to oiling (i.e., by effectively erasing the carcasses from the total count). All subsequent analyses were based on redistributed counts.

Taxonomic composition was initially examined by plotting proportional abundance (% count/total) by taxa (species for *Tenyo Maru*, group for *Nestucca*) for each spill analysis. To represent average baseline composition corresponding to each spill, we calculated the average proportion for each taxon present in the baseline data by averaging year-specific proportions across baseline data. In subsequent analyses, taxa with low/sporadic counts were excluded to avoid basing conclusions on the presence of only a small number of individual birds in either dataset (spill, baseline). To be included, taxa had to meet both of the following thresholds: spill: ≥ 1 individual; baseline: ≥ 3 individuals in two or more years. For the *Tenyo Maru* spill, species not meeting these thresholds (10 species, 194 carcasses, 4.5% of all carcasses; Supplementary Material Table S6) were omitted from species-level analyses but included in the group-level analyses, excepting large grebes (which included only western grebe, *Aechmophorus occidentalis*) which were still too rare even at the group level. Within the *Nestucca* dataset, guillemots (which included only pigeon guillemot, *Cephus columba*) were the only group excluded based on rarity. After processing, counts were converted to a proportion of the total for each oil spill and each baseline year, resulting in a dataset of proportional species composition.

2.4. Statistical analysis

2.4.1. Ordination and clustering of spill and baseline datasets

We explored annual variation in taxonomic composition among baseline data and the placement of the spill dataset year among the baseline years via a series of multivariate analyses (including ordination and cluster analyses). This enabled us to identify the degree to which the spill dataset differed from its baseline and to identify taxa driving any differences. To determine the similarity between spill and non-spill years, we calculated distance matrices using Jaccard's distance (Jaccard, 1901) in the vegan package in R (Oksanen et al., 2015). Jaccard's distance was used as it is less affected than other distance metrics (e.g., symmetrical distance metrics like simple matching) by “double absences” (i.e., zero counts for a taxon in multiple years; in our analyses, ~12.0% *Nestucca* group level- to 18.5% *Tenyo Maru* species level- of taxa/year combinations had a value of zero, leading to double absences) which may otherwise have skewed measures of similarity among years (Legendre and Legendre, 2013).

We applied Principal Coordinates Analyses (PCoAs) to the spill-specific multivariate distance matrices to visualize relative differences, and potential clustering, in species composition among all years (i.e., a single spill year and multiple baseline years). We explored the number of dimensions needed to adequately represent patterns of taxonomic

composition using the percent variation explained for each individual axis and the overall percent variation explained for a given n-dimensional representation. Taxa driving patterns in variability among years were identified by calculating the coefficient of determination, R^2 , between an individual taxon's proportional abundance among years (response) and the axis scores (predictors) resulting from the PCoA. A permutation test was then applied to determine the likelihood that the observed variation explained (R^2) by the axis scores could have occurred by chance (i.e., if there was no relationship with that taxon's proportional abundance). Based on the results of the permutation test we plotted vectors for taxa whose correlation with axis scores was significantly ($\alpha = 0.05$) higher than expected, as an indication of taxa responsible for major modes of taxonomic variation.

We further explored whether years displayed distinct clustering using Ward's Minimum Variance method (Ward, 1963), which aims to group similar points via minimization of the sum of within-cluster distances for a desired number of clusters. We used silhouette width (Rousseeuw, 1987) to determine how many clusters were present in the data. Silhouette width measures how well an observation belongs to a cluster based on distances to observations contained within the cluster to which it is assigned, relative to the next nearest alternative cluster; where widths close to one are well clustered, and widths approaching zero are indicative of points that lie between two or more clusters (Menardi, 2011). We evaluated mean silhouette width for $k = 2$ –10 clusters, and the optimum number of clusters was chosen as the value of k maximizing mean silhouette width. For the optimum number of clusters, we also examined the silhouette width for each individual point to identify how well it belonged to its assigned cluster. Cluster analyses were visualized via dendrograms to illustrate grouping structure and to identify whether the spill data, or any baseline datum, would be considered an outlier relative to remaining data for consideration in subsequent analyses. All multivariate analyses were performed in R version 4.0.4 (R Core Team, 2021).

2.4.2. Susceptibility analysis

We compared the proportion of each taxon observed during the spill against proportions observed across the baseline data. Baseline proportions among years were processed via bootstrap resampling to calculate the mean and 95% confidence interval of the mean proportion for each taxon. We also calculated whether proportional abundances in each baseline year were above or below that recorded during the oil spill for each species.

To explore patterns of taxonomic over-/under-representation, we calculated an index of *relative representation* as the ratio of proportional abundance recorded during the oil spill, P_{spill} , to the bootstrapped baseline mean proportion, \overline{P}_{base} .

$$\text{Relative representation} = \frac{P_{spill}}{\overline{P}_{base}}$$

For this index, a value above (below) one indicates that that taxon was over- (under-) represented in the oil spill relative to the baseline. We took the log of this ratio such that equivalent proportions (i.e., $P_{spill}/\overline{P}_{base} = 1$) are close to zero, and over-/under-represented species take positive/negative values, respectively. This also has the advantage that resulting values are symmetric according to the degree of over/under-representation (i.e., oil spill proportions double or half that of the baseline are equally distant, ± 0.693 , from the equivalence value of zero when the log-ratio is used).

To examine relative variability in proportional species composition among baseline years, we also identified the number of years for which baseline proportional abundance was exceeded by proportional abundance observed during the corresponding spill. This was then converted to the proportion of years by dividing by the total number of baseline years ($n = 17$). We treat the resulting index, $p(P_{spill} > \overline{P}_{base})$, as a measure of *reliability* given interannual variability in the baseline data, with

values close to 0 and 1 indicative of high confidence that a species was under/over-represented in the spill, respectively. Values close to 0.5 convey low *reliability* as corresponding taxa were just as likely to be under-represented as over-represented when examining the spill proportion against any individual baseline year.

Finally, we performed two types of sensitivity analyses to quantify the degree to which our conclusions may have been affected by extremes in our datasets. To account for potential effects of unusual years, we ran all analyses with and without baseline years that had been identified as outliers following multivariate cluster analyses. Second, because proportions are not independent among taxa, there is a risk that susceptibility analyses could have been unduly influenced by dominant taxa (i.e., over-representation by a particularly abundant species may mask signals for less abundant species). To account for this, we re-ran susceptibility analyses in stages, sequentially removing the taxon with the highest perpendicular Euclidean distance from equivalence (i.e., the theoretical point where oil spill and baseline proportions are equal) as this data point is most likely to skew results among remaining taxa. We tracked changes in our indices of *relative representation* and *reliability* through sequential taxon removals and identified whether changes would affect our overall conclusions regarding taxon susceptibility. All species susceptibility analyses were performed in Python 3.9.0 (Python Core Team, 2021).

3. Results

3.1. Community composition during spills

Community composition for spill and corresponding baseline datasets can be described as a Pareto curve (Wood and Wood, 2005), wherein a few taxa overwhelmingly dominated the pattern, with a steep

fall off to a long tail of less abundant taxa (Fig. 2). However, the dominant species were not entirely consistent between spill analyses, or when comparing spill and relevant baseline data within an analysis. In both spills, common murres (*Uria aalge*) accounted for more than 50% of all carcasses (Fig. 2). Spill-specific differences in taxonomic representation were also evident, with puffins (*Fratercula* and *Cerorhinca* spp.) and murrelets (*Synthliboramphus* and *Brachyramphus* spp.) being relatively prevalent in the *Tenyo Maru* spill, but almost completely absent in the *Nestucca* spill; and the opposite being true of grebes and scoters (Fig. 2). Demonstrable differences between spill and the relevant baseline data composite included procellariids (*Procellariidae* spp.), cormorants (*Phalacrocoracidae* spp.), and gulls, which were relatively abundant in baseline datasets, and relatively rare in both spills (Fig. 2).

3.2. Ordination and clustering of spill and baseline datasets

To examine the interannual variability of spill-specific baseline communities and to locate the spill dataset relative to the baseline years, we used PCoAs based on proportional taxonomic composition. Over half (55–60%) of the variance in annual community composition was explained by the first two axes (Fig. 3), with subsequent axes resulting in minimal additional variance explained (3rd axis: +10–13%, 4th axis: +7.5–8.5%; Supplementary Material Section 5). For both spill analyses, most years were situated along a single cross-axis gradient described by opposing dominance ($\alpha = 0.05$) of common murres (*Tenyo Maru*) and fulmars (including only the species northern fulmar—*Fulmarus glacialis*, in both *Tenyo Maru* and *Nestucca*; Fig. 3; Supplementary Material Table S7). Annual exceptions to the dominant gradient were apparent in both analyses and consisted of a loose grouping of mostly consecutive years (*Tenyo Maru*: 2011–2013, *Nestucca* 2014–15 and 2018) creating a secondary dimension, and variably characterized by shearwaters

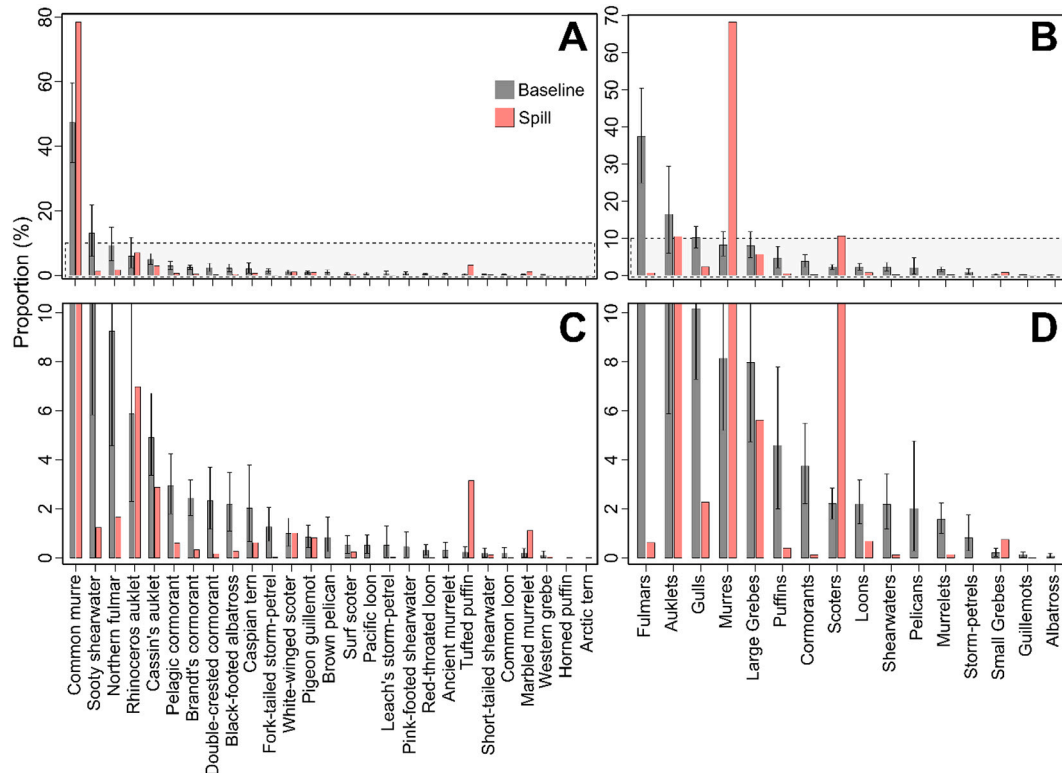
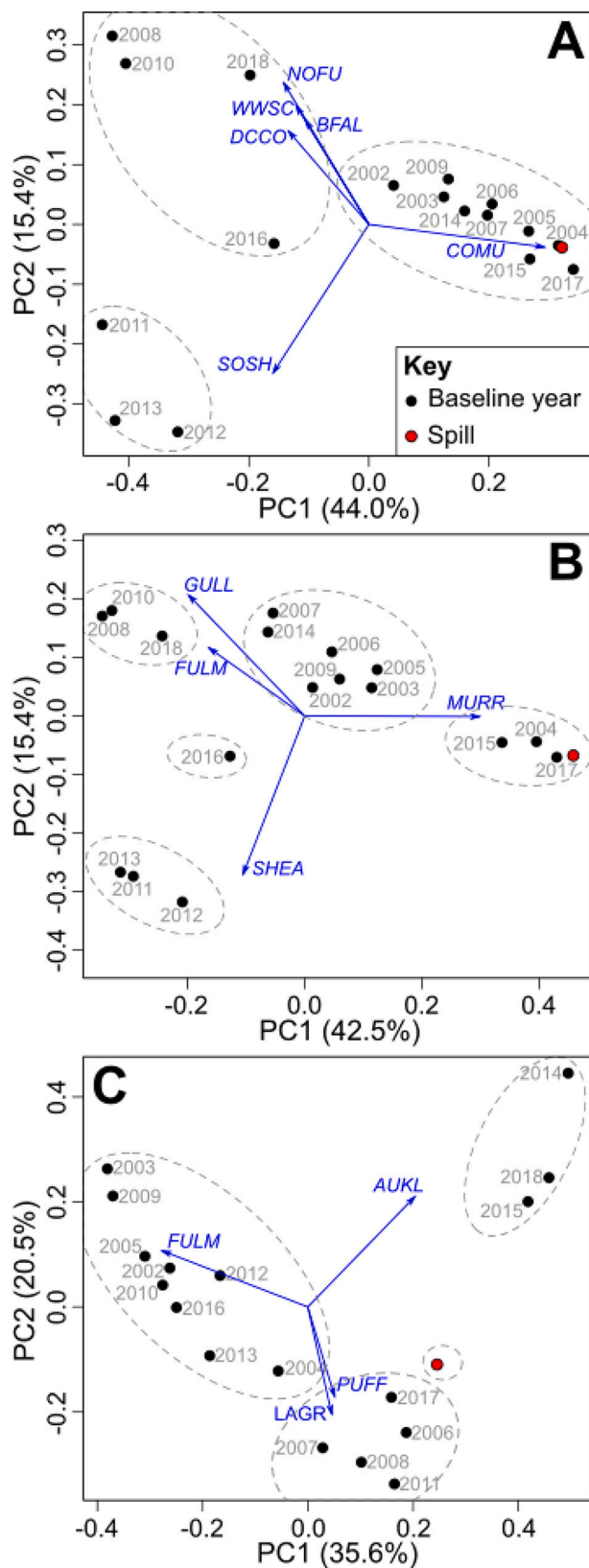


Fig. 2. Taxonomic composition of baseline and spill beached bird datasets in decreasing rank order according to baseline taxon abundance. Plotted are the proportional composition (count/total expressed as a %) by species for the *Tenyo Maru* spill (A) and by group for the *Nestucca* spill (B). For each spill, the corresponding baseline proportions representing the average proportion calculated across available baseline years are plotted, along with error bars representing the 95% confidence intervals of bootstrapped mean proportion among years. Lower panels represent a detailed view, truncated at 10% for the *Tenyo Maru* (C) and *Nestucca* (D) taxonomic compositions to show rarer taxa.



(caption on next column)

Fig. 3. Principal Coordinates Analyses (PCoA) plots showing ordinations of spill and baseline taxonomic composition data for the *Tenyo Maru* spill at the species (A) and group (B) levels, and for the *Nestucca* spill at the group level (C). Percent variation explained along each axis is given in parentheses. Clusters of similar years identified via hierarchical clustering are indicated by dashed ovals. Vectors showing taxonomic loadings are illustrated for those taxa for which variability was significantly ($\alpha = 0.05$) explained by principal axis scores assessed via permutation test. COMU/MURR: Common murre, BFAL: Black-footed albatross, NOFU/FULM: Northern fulmar, WWSC: White-winged scoter, DCCO: Double-crested cormorant, SOSH: Sooty shearwater, GULL: gulls, SHEA: Shearwaters, AUKL: Auklets, PUFF: Puffins, LAGR: Large Grebes.

(*Ardenna* spp.; *Tenyo Maru*) or auklets (*Ptychoramphus* and *Aethia* spp.) *Nestucca*; Fig. 3). In both analyses, taxonomic composition of the spill data fell within the extremities of the primary gradient, aligning with the dominant baseline species: towards common murres for the *Tenyo Maru* spill, and against northern fulmars for both spills (Fig. 3).

We applied hierarchical clustering to the multivariate ordination firstly to reveal clusters indicative of 'modes' in taxonomic composition; and secondarily to examine whether the spill year could be considered as an expression of one of those modes or characterized as an outlier. Clustering structure was best described with 3 (*Tenyo Maru* -species), 5 (*Tenyo Maru* - group) or 4 (*Nestucca* - group) clusters determined based on average silhouette widths (although clustering strength was moderate: 0.32–0.39; see Supplementary Material Fig. S3) and visualized in Fig. 3 as circled year sets. Although clustering easily identified off-gradient years, including outliers, it also partitioned the dominant gradient into 2–3 clusters (Fig. 3). The *Nestucca* spill year was characterized as an outlier, whereas the *Tenyo Maru* spill year was strongly grouped with other baseline years (silhouette width 0.5–0.6, Supplementary Material Fig. S3 and Table S8). Finally, despite the addition of taxa (e.g., gulls) at the group level *Tenyo Maru* analysis, the pattern of ordination remained largely unchanged (Fig. 3 A vs B). Gulls were strongly aligned with fulmars as a driving group and identified by a single cluster, whereas years dominated by murres (which included only common murre) formed an opposing and distinctive cluster, and both were separated from intervening years.

3.3. Susceptibility analysis

We examined taxonomic oiling susceptibility using a 2-axis data visualization (Fig. 4). The abscissa shows *relative representation*, or our index of the degree to which taxon-specific proportional abundance in the spill year exceeded (or not) that of the baseline dataset, while the ordinate represents our index of *reliability* in that conclusion. These graphs describe a continuum which can be simply parsed into three regions. The upper right corner includes taxa which proportionally occur order(s) of magnitude more in the spill relative to the baseline and exceed the baseline in a high proportion of years (e.g., high representation and *reliability*). The lower left corner includes taxa that occur order(s) of magnitude more in the baseline relative to the spill, and whose spill proportion falls below the baseline in a high proportion of years (e.g., low representation and high *reliability*). In the middle are taxa for which patterns of susceptibility are variable based on inclusion/exclusion of dominant taxa in the dataset and possibly length of the baseline dataset.

Only a small number of taxa were over-represented on average in spill datasets relative to their baselines, namely common murres, puffins, and murrelets for the *Tenyo Maru* spill analysis, with the latter two only becoming apparent at the group level; and murres, scoters and small grebes (*Podiceps* spp.) for the *Nestucca* spill analysis (Fig. 4). In contrast, across both spills analyses, procellariids, cormorants, loons (*Gavia* spp.), and gulls were under-represented in spill datasets relative to average baseline proportions (Fig. 4). Taxa of indeterminate status (i.e., neither over- nor under-represented) were taxonomically inconsistent between spill analyses.

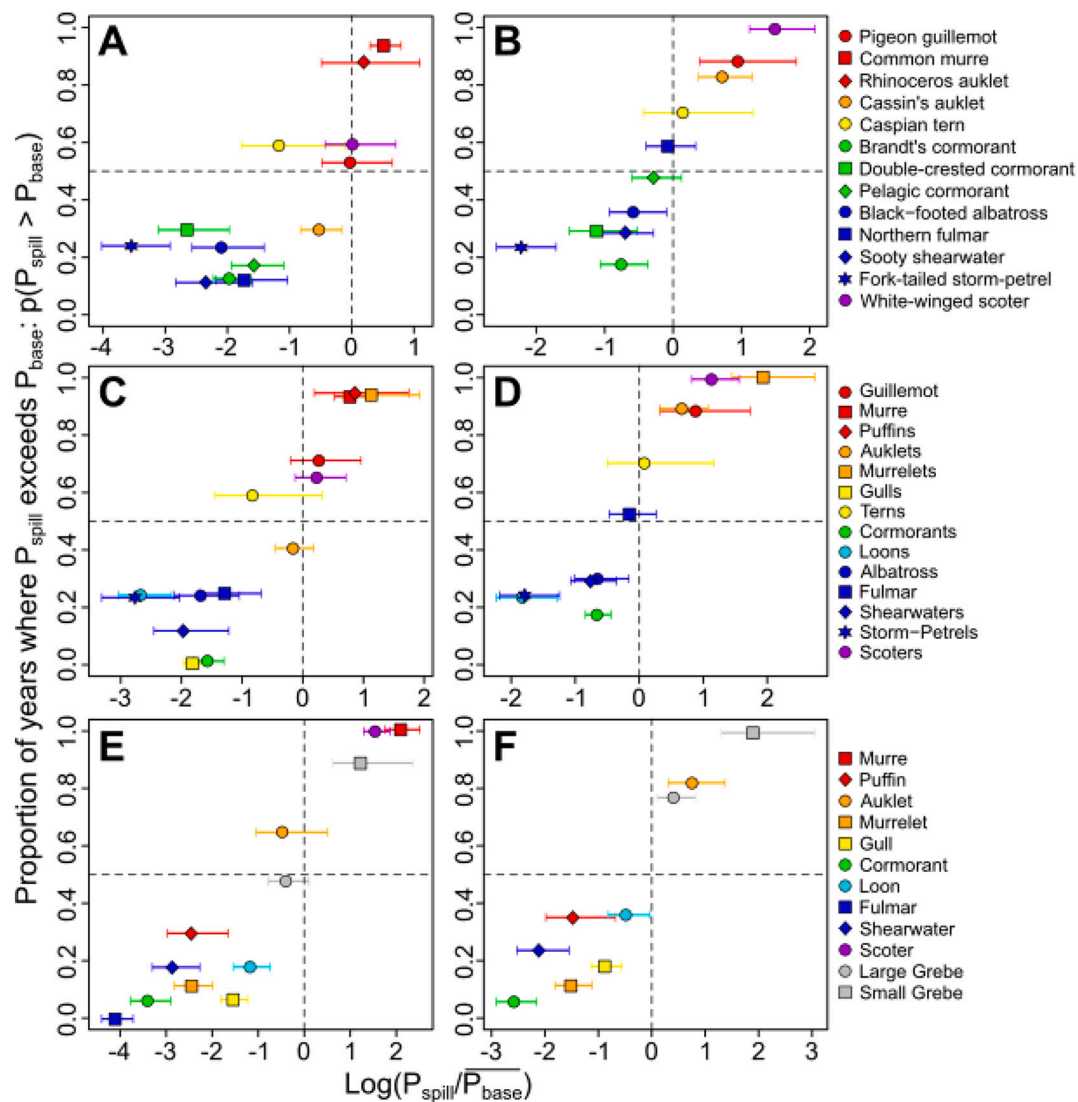


Fig. 4. Bi-plots of relative representation ($\log(\frac{P_{spill}}{P_{base}})$) and reliability ($p(P_{spill} > P_{base})$) metrics for the *Tenyo Maru* spill at the species (A & B) and group levels (C & D) and for the *Nestucca* spill at the group level (E & F). Alternate panels for each spill show metrics calculated before (A, C, E) and after (B, D, F) removal of potentially influential taxa whose influence may have masked patterns in taxonomic. Taxa removed were: *Tenyo Maru* at the species level: Common murres and Rhinoceros auklets (A – B); *Tenyo Maru* at the group level: Murres, Puffins, and Gulls (C – D), *Nestucca* at the group level: Murre, Fulmars, and Scoters (E – F).

Our *reliability* index indicated that most taxa had some chance of the spill year proportion exceeding at least one baseline year (Fig. 4). Notable exceptions were gulls and cormorants for the *Tenyo Maru* group-level analyses and fulmars for the *Nestucca* analyses. Overall, this suggests that for the most over-represented taxa during each spill, years with higher proportional abundance in the baseline may only occur once per decade.

The apparent difference in *reliability* for cormorants in the *Tenyo Maru* spill analysis between species (*reliability* = 0.1–0.3; Fig. 4A) and group-level (*reliability* = 0; Fig. 4C) analyses arose due to species-specific absences in alternating baseline years (pelagic cormorant *Phalacrocorax pelagicus*: 2 years; Brandt's cormorant- *Phalacrocorax penicillatus*: 2 years; double-crested cormorant- *Phalacrocorax auritus*: 5 years), resulting in some years where the spill exceeded the baseline. When aggregated across the species group, all baseline years became nonzero and always exceeded that observed during the spill.

When numerically dominant taxa were sequentially removed, *relative representation* changed considerably for the *Tenyo Maru* analyses (Fig. 4) with five species (~38.46%) and three groups (~21.43%) changing signs from relatively susceptible to relatively immune, or vice

versa (Fig. 4; see Supplementary Material Figs. S5–S8 for full sensitivity results). *Nestucca* analyses were also influenced by the inclusion of numerically abundant taxa, but to a lesser extent, with three groups (loons, large grebes, and auklets) changing sign upon taxon removal (Fig. 4, and Supplementary Material Figs. S5–S8). Taken together, this suggests that the occurrence of particularly dominant taxa may mask signals presented by less abundant species when using analyses based on proportions.

4. Discussion

4.1. Main findings

Our analyses demonstrate the value of long-term beached birds monitoring programs for taxon-specific impact assessment of oil spills. Although the composition of beached birds following two major spills along the outer coast of Washington State arguably fell within the space described by the baseline dataset (Fig. 3), there was selective over/under-representation among particular taxa suggesting differential susceptibility to oiling (Fig. 4). Such spill-mediated shifts in taxonomic

composition have been found in other taxa (e.g., in phytoplankton, Parsons et al., 2015; and bacteria, Engel et al., 2017).

Species that tend to have high carcass counts in spills are often singled out as being highly vulnerable (e.g., murre in the *Exxon Valdez* spill - Piatt et al., 1990). By contrast, our approach focuses on taxa that are highly over- and under-represented in spills regardless of raw carcass count. This brings out relatively rare taxa that appear to have a higher susceptibility to oiling, (e.g., marbled murrelets, *Brachyramphus marmoratus*, and tufted puffins, *Fratrula cirrhata* in our analyses, Figs. 2 and 4), which might otherwise be overlooked because of the predominance of majority taxa.

4.2. Spills occurring in the same location but different seasons

Not surprisingly, there was a classic Pareto curve (Wood and Wood, 2005) evident in both the baseline and spill datasets (Fig. 2). Although the *Tenyo Maru* spill originated further offshore than the *Nestucca* spill, oil from both spills quickly spread along the entire outer coastline of Washington State, reaching variably into Oregon (Fig. 1). While differences in the species diversity of the spill datasets may have been influenced by the offshore-onshore distribution of the spill origin, inter-spill differences in the associated baseline dataset patterns are likely indicative of seasonally driven relative abundance (*Tenyo Maru* - summer; *Nestucca* - winter), and/or seasonally specific mortality of specific species, as a function of life history and natural history. For instance, locally breeding common murre predominated in the summer baseline datasets and experience a beaching peak following the end of the breeding season (Parrish et al., 2007), whereas seasonal immigrant northern fulmars predominated during the winter (Fig. 2) following dispersal south from the Gulf of Alaska (Hatch et al., 2010). However, within the spill datasets, murre were overwhelmingly dominant, upwards of 70% of the total (Fig. 2), suggesting that - at least for this species - oil susceptibility may not depend on season.

4.3. Comparison with oil vulnerability indices

To address the paucity of spatio-temporally relevant independent data needed to describe relative susceptibility directly following major spills in the northeast Pacific, King and Sanger (1979) developed a trait-based approach to assessing the relative vulnerability of marine-associated birds known as the Oil Vulnerability Index, or OVI. Their approach used a 1–5 (low-to-high) scale to rank the importance of each of 20 factors variously describing status and trends in species' abundance and distribution in addition to a range of natural history and life history traits.

The OVI approach has since been adapted across a range of subsequent oil vulnerability analyses (e.g., Camphuysen, 1998; Wahl et al., 1981; Williams et al., 1995; Wiese and Ryan, 2003; Chilvers and Battley, 2019) as well as vulnerability to other anthropogenic mortality sources (e.g., wind farms - Garthe and Hüppop, 2004). Factor numbers have varied, as has factor weighting (e.g., Anker-Nilssen, 1987; Williams et al., 1995). Additional factor types have typically included susceptibility to anthropogenic mortality sources, including oil; and conservation status assessments (e.g., Webb et al., 2016).

The utility of King and Sanger's (1979) work is the ability to create a single set of OVI scores for a wide range of species, which can then be applied to any number of spill, or spill scenario, situations throughout the northeast Pacific (e.g., Wahl et al., 1981), and more broadly (e.g., the North Sea - Camphuysen, 1989; New Zealand - Chilvers and Battley, 2019). The drawbacks were, and are, variable data quality across all species and necessary reliance on expert opinion as a raw data stand-in.

King and Sanger (1979) favored individual traits (9) over population (3) factors, and also included five factors focused specifically on exposure to oil. In general, mortality factors other than oiling (3) and factors related to population size were less influential in generating their higher OVI scores, both because of the skew in factor number, and because

these latter factors tended to have lower scores (e.g., 1–3) assigned to them. Furthermore, because individual traits and oiling exposure scores tended towards identical within family, OVI rankings produced phylogenetic clustering.

Our data suggest that there is an effect of phylogeny as more closely related taxa tended to be clustered together (most apparent in the *Tenyo Maru* species level analysis; Fig. 4A). One exception are the alcids (*Alcidae* spp.), which ranged across our susceptibility categories, especially in the winter spill (Fig. 4E). Despite this singular difference, we suggest an interpretation of this general similarity is that shared traits expressed in the ecology and behavior of related species do matter in placing individual birds in harm's way and may trump population and broader-scale conservation factors, at least as assessed at the local (immediate to spill) level.

However, our results also suggest that there are differences between the OVI for northeast Pacific taxa (i.e., King and Sanger, 1979) and a spill-specific baseline data-driven approach, both in the relative placement of taxa (i.e., the rank order of species or higher taxonomic groupings), and in seasonal shifts in apparent susceptibility. Alcids, scoters, and grebes emerged as the most susceptible taxonomic groups in our analysis (Fig. 4). King and Sanger (1979) also ranked alcids (scores of 70+ out of 100) and scoters (score of 72) as highly vulnerable, although this was not particularly the case with grebes (scores of 44–56). In general, alcids tend to score as highly vulnerable in OVIs, regardless of geolocation (Wahl et al., 1981; Camphuysen, 1989; Camphuysen, 1998; Williams et al., 1995; Webb et al., 2016; Webb et al., 1995; Tasker et al., 1990; Wiese and Ryan, 2003). Scoters are also highly susceptible (Camphuysen, 1989; Camphuysen, 1998; Williams et al., 1995; Webb et al., 2016; Webb et al., 1995; Tasker et al., 1990). By contrast, grebes tend to be relatively unsuceptible (but see Williams et al., 1995; Webb et al., 1995).

At the individual species level, differential results between the approaches are more apparent. At the scale of the northeast Pacific, King and Sanger (1979) ranked marbled murrelets as the most vulnerable alcid, and common murre as the least. Wahl et al. (1981), working in an adjacent geography - the Puget Sound within Washington State - scored rhinoceros auklets (*Cerorhinca monocerata*), pigeon guillemots, and common murre as most vulnerable. We found that murre were consistently the single most susceptible species (see also Wiese and Ryan, 2003), whereas murrelets were among the most variable taxa in terms of winter (low susceptibility) to summer (extremely high susceptibility) shifts.

At the other end of the scale, the procellariids (fulmars, shearwaters, storm-petrels - which included only fork-tailed storm-petrels, *Oceanodroma furcata*, and albatrosses - which included only black-footed albatrosses, *Phoebastria nigripes*) were consistently among the least susceptible groups in our analysis (Fig. 4). Although King and Sanger (1979) did rank shearwaters and albatrosses as relatively less vulnerable, with scores well below their vulnerability threshold of 61, they ranked storm-petrels as quite vulnerable (scores of 63–67). In general, procellariids are considered less vulnerable to oiling than many other groups, albeit with taxon- and location-specific exceptions (e.g., fulmars: Camphuysen, 1989; shearwaters: Williams et al., 1995, Tasker et al., 1990).

Other major groups were variably similar in ranking between our analysis and King and Sanger (1979), with differences often emerging as a function of spill, and presumably season. That is, our results indicate that some groups may experience differential susceptibility: cormorants shifting from medium to low susceptibility from summer to winter; and loons displaying the opposite pattern (Fig. 4).

Fox et al. (2016), examining risk of oiling of 12 taxon groups in an area of the northern British Columbia, Canada coastline found grebes and pigeon guillemots to be relatively at risk, but also listed large and small gulls, and cormorants as having a relatively high oiling risk, whereas our work indicated these taxa as relatively safe (Fig. 4). We suggest these differences arise not only from methodological differences

(mapping overlays versus beached carcass counts) but also from the fact that their highest risk of chronic oiling was consistently located immediately adjacent to the shoreline, effectively placing all nearshore species at higher risk than those with more shelf-wide distributions. Adapting this approach to spill tracks may create more coincident results.

In sum, we suggest that both the mapping and OVI approaches can provide excellent predictions of relative risk, whereas our post-hoc beached bird method allows for a more comparative, control-treatment, approach. Because long-term beached bird baseline data is lacking for many spill locations (e.g., Jones et al., 1970; Paine et al., 1996), and at-sea marine bird data are variably available, an OVI approach may be more globally useful.

4.4. Caveats of this method

We found that the baseline dataset is a dynamic assemblage of species, where taxonomic composition varies year over year, and occasionally across stanzas of years (e.g., *Tenyo Maru* 2011–2013, Fig. 3). While spill years are found within the margins, or extremities, of the entire baseline set, they are not necessarily outliers. Although this may indicate that the taxonomic distribution of mortality following a spill is not necessarily that different from at least a portion of the baseline, another interpretation is that other forcing factors are provoking significant shifts in the mortality distribution across the species present in the system, and that those factors are variably evident across years. Significant mortality factors in the northeast Pacific within the past twenty years that have differentially affected marine bird species with concomitant shifts in the frequency distribution of beach-cast carcasses include harmful algal blooms (Jones et al., 2017) and the marine heat-wave (Jones et al., 2018; Piatt et al., 2020). The northeast Pacific has undergone regime shifts (Overland et al., 2008) and different phases of El Niño Southern Oscillation (Wang et al., 2019) between the *Nestucca* spill and today, with the - untested - potential to permanently shift the taxonomic distribution of seabirds.

Our baseline data were collected after the spills had occurred, eliminating the possibility of a simple before-after design (e.g., McDonald et al., 2000; Roth and Baltz, 2009). To address this potential source of bias, we compared taxa composition over the first half of the COASST baseline data (2002–2010) with the taxa composition over the second half (2011–2018; Supplementary Material Table S1). We found no significant difference between the two time periods, suggesting that species composition and baseline mortality factors in the spill-regions did not change substantially. However, we cannot confirm that individual taxa did not change significantly due to factors other than the spill within the study interval.

Where baseline data are available, either the spill or baseline data may be lacking effort control (e.g., number of searchers, area searched, person-hours spent searching), as was the case for the spill data used here. If effort control metadata are missing, our approach of using proportion data may be appropriate, with full acknowledgment that taxa proportions are interdependent (Douma and Weedon, 2019). Dominant taxa can “swamp” the analysis, making it difficult to assess patterns in less prevalent taxa. We addressed this by sequentially removing the most dominant taxa and observing how this affected the susceptibility of less prevalent taxa (Fig. 4, Supplementary Material Figs. S5–S8).

4.5. Conclusion

In summary, we propose the use of rigorous beached bird data as a valid baseline against which to assess the impacts of anthropogenic forcing on marine bird populations, including oil spills; and argue that baseline datasets created a posteriori to an event in question can be appropriate. However, we also caution that the creation of a credible baseline dataset can take years to decades, and may require dozens of data collection sites, to encompass the variability inherent in the system.

Nevertheless, we advocate for more long-term, rigorous beached bird datasets collected and maintained for the purpose of determining the impacts of anthropogenic forcing on marine systems. Where such baseline data are available, our method can serve as a valuable tool alongside OVIs to provide a spatial and seasonal view of which seabirds are most vulnerable to spills.

CRedit authorship contribution statement

Jazzmine K. Waugh: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, Visualization. **Timothy Jones:** Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – review & editing, Visualization. **Julia K. Parrish:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marpolbul.2022.113437>.

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