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Research article

Collision and displacement vulnerability to offshore wind energy infrastructure among marine birds of the Pacific Outer Continental Shelf

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ABSTRACT

Marine birds are vulnerable to collision with and displacement by offshore wind energy infrastructure (OWEI). Here we present the first assessment of marine bird vulnerability to potential OWEI in the California Current System portion of the U.S. Pacific Outer Continental Shelf (POCS). Using population size, demography, life history, flight heights, and avoidance behavior for 62 seabird and 19 marine water bird species that occur in the POCS, we present and apply equations to calculate Population Vulnerability, Collision Vulnerability, and Displacement Vulnerability to OWEI for each species. Species with greatest Population vulnerability included those listed as species of concern (e.g., Least Tern [*Sternula antillarum*], Marbled Murrelet [*Brachyramphus marmoratus*], Pink-footed Shearwater [*Puffinus creatopus*]) and resident year-round species with small population sizes (e.g., Ashy Storm-Petrel [*Oceanodroma homochroa*], Brandt's Cormorant [*Phalacrocorax penicillatus*], and Brown Pelican [*Pelecanus occidentalis*]). Species groups with the greatest Collision Vulnerability included jaegers/skuas, pelicans, terns and gulls that spend significant amounts of time flying at rotor sweep zone height and don't show macro-avoidance behavior (avoidance of entire OWEI area). Species groups with the greatest Displacement Vulnerability show high macro-avoidance behavior and low habitat flexibility and included loons, grebes, sea ducks, and alcids. Using at-sea survey data from the southern POCS, we combined species-specific vulnerabilities described above with at-sea species densities to assess vulnerabilities spatially. Spatial vulnerability densities were greatest in areas with high species densities (e.g., near-shore areas) and locations where species with high vulnerability were found in abundance. Our vulnerability assessment helps understand and minimize potential impacts of OWEI infrastructure on marine birds in the POCS and could inform management decisions.

1. Introduction

Offshore wind energy development is a promising alternative energy source for coastal communities in the Western United States. The U.S. Bureau of Ocean Energy Management (BOEM) has recently considered renewable energy proposals within U.S. Pacific Outer Continental Shelf (POCS) waters off the coast of Oregon and California (Trident Winds LLC, 2016). Minimizing negative interactions of offshore wind energy infrastructure (OWEI) with marine species is an important step towards a sustainable offshore energy future (Musial and Ram, 2010). Marine bird species are among the most threated species of birds, due in part to their exposure to cumulative anthropogenic threats including fisheries bycatch, pollution, habitat loss, and invasive species at terrestrial nesting grounds (Croxall et al., 2012). The construction of OWEI could pose additional threats for marine birds including collision with infrastructure and/or displacement from important foraging, resting, and commuting habitats.

Herein, we quantified population, collision, and displacement vulnerability to OWEI for 81 marine bird species common to the California Current System portion of the POCS (i.e., not including Hawaii). The California Current System ecologically defines this marine region where these species breed, forage, and/or over-winter (Checkley and Barth, 2009, Fig. 1). The vulnerability values generated for these 81 marine bird species were based on species' life history traits, population sizes, demography, habitat use, disturbance sensitivity, and conservation status. The vulnerability values generated in this assessment can be used by resource managers to evaluate potential impacts associated with the construction and long-term operation of OWEI within the POCS.

This assessment was inspired by similar studies that evaluated bird

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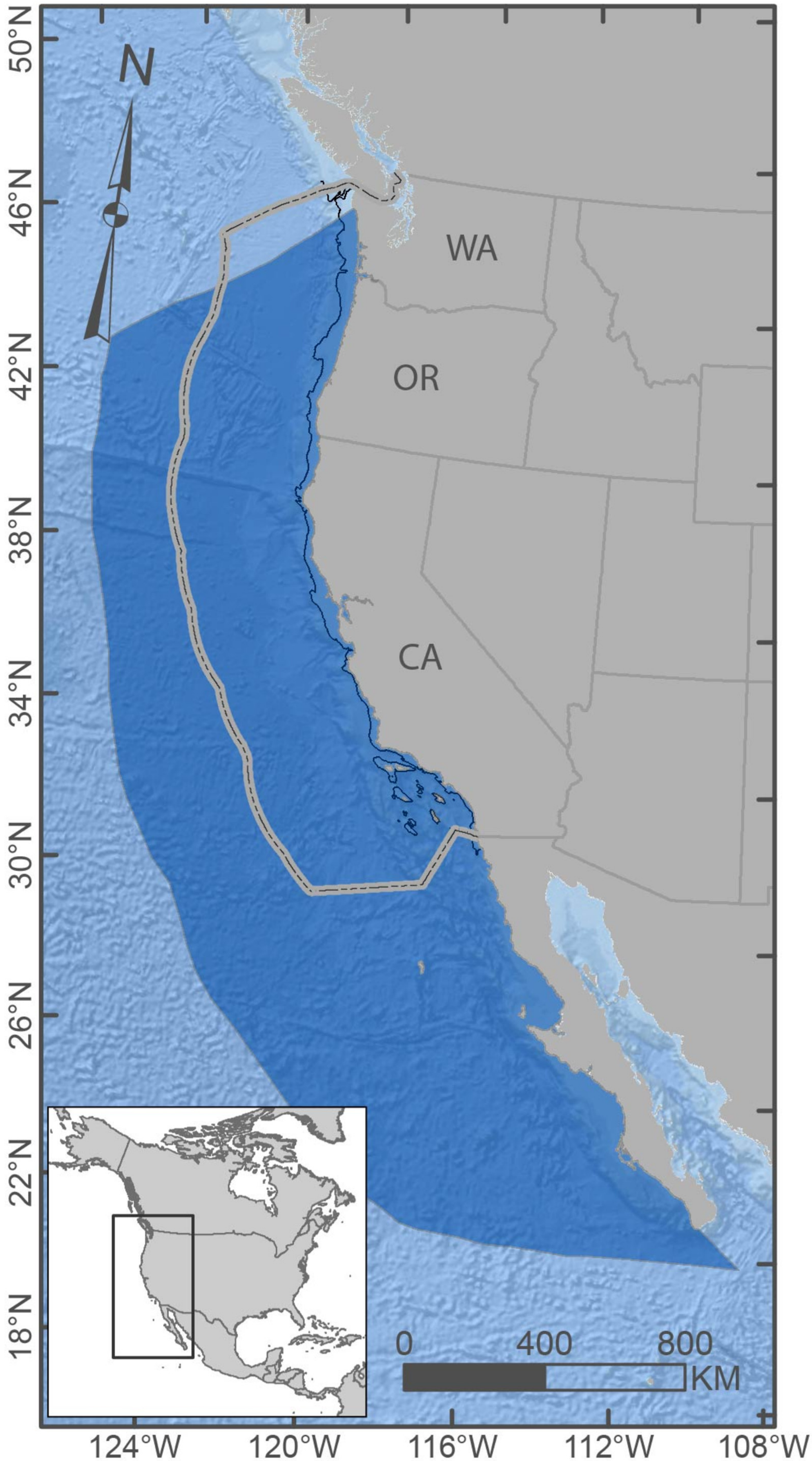

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Fig. 1. Map of the west coast of North America showing California (CA), Oregon (OR), Washington (WA), and the extent of the U.S. west coast Pacific Outer Continental Shelf (POCS) region (200 nm from coastline, tan and black line outline) in relation to the California Current Large Marine Ecosystem (dark blue shading; NOAA IEA: http://www.noaa.gov/iea/regions/california-current-region/index.html). Black line indicates the continental shelf break (200 m water depth).

vulnerability to OWEI in the North Sea and eastern Atlantic Ocean (Desholm, 2009; Furness and Wade, 2012; Furness et al., 2013; Garthe and Hüppop, 2004), and western Atlantic Ocean (Robinson Willmott et al., 2013). Herein, we update these methodologies based on our current understanding of OWEI impacts on marine birds and provide the first vulnerability assessment of the POCS species assemblage. Unlike previous assessments in Europe, but similar to the Robinson Willmott et al. (2013) assessment of the Atlantic Outer Continental Shelf, our assessment precedes OWEI development in the POCS and proactively facilitates planning that could minimize negative interactions between marine birds and OWEI in this region.

2. Species selection

In this assessment, we included all marine birds that occur regularly in the POCS (Appendix Table A1). The list of species considered was generated from aerial at-sea surveys (Adams et al., 2014; Briggs et al., 1981, 1983, 1987, 1992; Mason et al., 2007), plus additional species known to be present (e.g., Black Skimmer [*Rynchops niger*], Tufted Puffin [*Fratercula cirrhata*], Yellow-billed Loon [*Gavia adamsii*], Hawaiian Petrel [*Pterodroma sandwichensis*]), but are rarely encountered during surveys cited above. We will use the phrase “species group” when discussing vulnerabilities or characteristics that apply to more than one species of a genus or taxonomic group (e.g. – "loon species group" when refering to the avoidance behavior of the four loon species found in the POCS). Shorebirds, raptors, and passerines that occur offshore within the POCS were not considered herein.

3. Vulnerability calculations

We quantified three types of vulnerability among seabirds in the POCS: Population Vulnerability (PV), Collision Vulnerability (CV), and Displacement Vulnerability (DV; Table 1). For all metrics used in the PV, CV, and DV calculations, we searched available literature to determine appropriate values for each species. When available literature sources provided conflicting data, we gave preference to the most relevant source (e.g., the study that had been done within the region, most recently, etc.). If no sources were available to estimate a metric value for a given species, we used data from similar species. When such compensations were made, we incorporated a level of uncertainty to create a range of possible metric values (described in following sections). Metric values for each species should be interpreted with caution and revised when new, relevant information is published. All metric values and source citations used in this study are available via USGS ScienceBase (Adams et al., 2017; see Data Accessibility). PV, CV, and DV scores are calculated independently and are not directly comparable to each other.

3.1. Population Vulnerability (PV)

Factors related to demography, population size, and at-sea range can influence a species vulnerability to OWEI on a population level. We used six metrics to calculate Population Vulnerability (PV) for each of the 81 species: global population size (POP), annual occurrence in the POCS (AO), percent of the population present in the POCS (POCSpop), threat status (TS), annual adult survival (AS), and breeding score (BR; equation (1)). The metrics POP, POCSpop, TS, and AS were valued from 1 to 5. The metrics AO and BR were valued from 1 to 2 and included as weighting factors for POCSpop and AS, respectively.

$$\text{Population Vulnerability(PV)}=(POP \pm POPu) + (\text{AO} \times (\text{POCS}pop \pm \text{POCS}popu)) + TS + (BR \times (AS \pm ASu)) \quad (1)$$

where

POP = Global Population Size, *AO* = Annual Occurrence in the POCS, *POCSpop* = Proportion of Species' Population found in POCS, *TS* = Threat Status, *BR* = Breeding Score, *AS* = Adult Survival, *u* = uncertainty (see section 3.4).

3.1.1. Global population size (POP)

We used American Bird Conservancy (ABC, 2012), Birdlife International (2014), and additional sources, to estimate Global Population Size (POP). We assigned POP values from 1 to 5, where

1 = > 3,000,000 individuals
2 = 1,000,001–3,000,000 individuals
3 = 500,001–1,000,000 individuals
4 = 100,000–500,000 individuals
5 = < 100,000 individuals.

3.1.2. Proportion of population in POCS (POCSpop)

We derived local population size estimates (POCSpop) from at-sea surveys for California, Oregon, and Washington (Briggs et al., 1981, 1983, 1987, 1992), Birdlife International (2014), ABC (2012), and additional sources. When counts of breeding pairs only were recorded (e.g., Ainley et al., 1990) the estimated number of non-breeders in the population was added to the breeding pair counts using breeder to non-breeder population ratios (Manuwal, 1972).

We calculated the POCSpop by dividing by POCS population size by POP. We binned POCSpop into numerical range categories (1–5), where

1 = < 1%
2 = 1–33%
3 = 34–66%
4 = 67–99%
5 = > 99%.

Table 1
Organization, abbreviations, and definitions for metrics used to calculate Population (PV), Collision (CV), and Displacement Vulnerability (DV; data available: https://www.sciencebase.gov/catalog/item/58f7fadae4b0b7ea5451fc5c).

Population Vulnerability		Collision Vulnerability		Displacement Vulnerability	
POP	Global Population Size	NFA	Nocturnal Flight Activity	MAd	Macro-Avoidance of Wind Turbines
POCSpop	Proportion of POP in POCS	DFA	Diurnal Flight Activity	HF	Habitat Flexibility
TS	Threat Status	MAc	Macro-Avoidance of Wind Turbines		
AS	Adult Survival	RSZt	Percent Time in RSZ		
BR	Breeding Score in POCS				
AO	Annual Occurrence (mos. in POCS)				

3.1.3. Annual occurrence in the POCS (AO)

We estimated the number of months per year that each species resides within the POCS (AO) based on aerial seabird surveys (Adams et al., 2014; Briggs et al., 1981, 1983, 1987, 1992), eBird sightings (eBird, 2015), and additional sources (see Adams et al., 2017). AO was valued from 1 to 2 and used as a weighting factor for POCSpop; for example, if a species spends more time in the POCS annually (AO = 2), POCSpop carried twice the weight of a species that only spends a few months annually in the POCS (AO = 1), thus

1 = 1–4 months spent in the POCS each year
1.5 = 5–8 months spent in the POCS each year
2 = 9–12 months spent in the POCS each year.

3.1.4. Threat status (TS)

We used the International Union for Conservation of Nature (IUCN) species threat status (International Union for Conservation of Nature, 2014) and the U.S. Fish and Wildlife national threat status lists (U.S. Fish and Wildlife Service, 2014a) to determine Threat Status (TS). Where available, we evaluated threat status values from U.S. Fish and Wildlife Service Birds of Conservation Concern (U.S. Fish and Wildlife Service, 2012), California Endangered Species Act (California Department of Fish and Wildlife, 2015), California Department of Fish and Wildlife Bird Species of Special Concern list (Shuford and Gardali, 2008), Oregon Department of Fish and Wildlife (Oregon Department of Fish and Wildlife, 2014), and Washington State Department of Fish and Wildlife State Sensitive and Candidate Species (Washington Department of Fish and Wildlife, 2015, Table 2). For species that migrate through the POCS, but breed in another country, we also considered TS values from all countries where the species is found (Canada, Mexico, Chile, New Zealand, and Japan). In lieu of TS values based solely on breeding distribution or U.S. geopolitical boundaries, we suggest that the greatest TS value, regardless of source (Adams et al., 2017, Table 2), conservatively reflected the full geographical and ecological threat level for a given species (Hyrenbach et al., 2000; Nevins et al., 2009).

3.1.5. Adult survival (AS)

Adult annual survival rate (AS) is indicative of life history characteristics among birds (Sæther et al., 1996). Species with greater AS generally will comprise populations that are more susceptible to declines resulting from increased adult mortality (Desholm, 2009). We evaluated AS for each species and determined a binned value from 1 to 5, where AS

1 = < 0.75
2 = 0.75–0.80
3 = 0.81–0.85
4 = 0.86–0.90
5 = > 0.90.

3.1.6. Breeding score (BR)

The vulnerability of collision and displacement associated with OWEI is exacerbated for breeding birds whose offspring may also be affected. Therefore, we incorporated Breeding Score (BR) to weight AS. For example, if a species breeds or feeds its young within the POCS (BR = 2), its AS rank was weighted more than a species that does not breed in the POCS (BR = 1), thus

1.0 = Species is unlikely to be foraging to feed young in the POCS
1.5 = Some individuals of species will forage for young in the POCS
2.0 = Species is known to regularly forage to feed young in the POCS.

3.2. Collision vulnerability (CV)

Site-specific, quantitative wind turbine/bird-collision-risk-modeling (e.g., Band, 2012; Johnston et al., 2014; Masden and Cook, 2016; Tucker, 1996) has incorporated detailed flight characteristics, bird morphology, visual and radar observations, landscape features, turbine dimensions, and other factors to assess and predict bird collision rates with energy infrastructure. To calculate Collision Vulnerability (CV), we selected four non-site-specific metrics used in collision-risk-models and adopted by Desholm (2009), Furness and Wade (2012), Furness, et al. (2013), Garthe and Hüppop (2004), and/or Robinson Willmott et al. (2013): diurnal and nocturnal flight activity, flight-height (defined as time spent in the rotor sweep zone), and macro-avoidance (Equation (2)). For species in the POCS that didn't have data associated with these metrics, data on similar species were used.

$$\text{Collision Vulnerability(CV)} = ((NFA \pm NFAu) + (DFA \pm DFAu))/2 + (RSZt \pm RSZtu) + (MAc \pm MAcu) \quad (2)$$

NFA = Nocturnal Flight Activity, DFA = Diurnal Flight Activity, $RSZt$ = Percent time spent in Rotor Sweep Zone, MAc = Macro-Avoidance, u = Uncertainty.

3.2.1. Nocturnal flight activity (NFA) and diurnal flight activity (DFA)

OWEI avoidance behavior, and consequently collision vulnerability, can differ during day and night for some bird species (Band, 2012; Krijgsveld et al., 2009; Marques et al., 2014; Peterson et al., 2006). We used information from the Birds of North America accounts, previous OWEI vulnerability assessments (Furness and Wade, 2012; Furness et al., 2013; Garthe and Hüppop, 2004; Robinson Willmott et al., 2013), and additional sources to determine NFA and DFA. Because vision for birds during crepuscular periods is thought to be comparable to

Table 2
Regional Threat Status (TS) values and sources used for each species; Population Vulnerability was calculated using the greatest TS from these five regional assessments.

TS	International	United States	California	Oregon	Washington
	IUCN 2014[a]	USFWS 2014[b], USFWS 2012[c]	CESA 2015[d], Shuford and Gardali 2008 [e]	ODFW 2014[f]	WDFW 2015[g]
1	Least Concern	No Ranking	No Ranking	No Ranking	Monitored
2	Near-Threatened	Petitioned/Pacific Region BCC[c]	BSSC[e], Taxa to Watch	Vulnerable Sensitive	Sensitive
3	Vulnerable	Candidate	BSSC[e]	Critical Sensitive	Candidate
4	Endangered	Threatened	Threatened	Threatened	Threatened
5	Critical	Endangered	Endangered	Endangered	Endangered

[a] International Union for Conservation of Nature.
[b] US Fish and Wildlife Service national threat status list.
[c] Birds of Conservation Concern (BCC).
[d] California Endangered Species Act.
[e] California Bird Species of Special Concern (BSSC).
[f] Oregon Department of Fish and Wildlife Sensitive, Threatened, or Endangered Species.
[g] Washington Department of Fish and Wildlife State Sensitive Species and State Candidate Species.

nighttime vision (Stienen et al., 2007), we included time spent in crepuscular flight with NFA for species that are active during these periods (e.g., alcids and pelicans; del Hoyo et al., 1996). For migrating passerines, and perhaps some seabird species, collision risk can increase at night (Hüppop et al., 2016; Marques et al., 2014). The proportion of time spent flying during day and night for some species can also vary with season and latitude, thus potentially influencing their collision risk. However, supporting evidence for these variations in vulnerability associated with nocturnal versus diurnal flight activity is sparse and we thus were not able to incorporate such variations into our equation.

To calculate CV (Equation (2)), we averaged NFA and DFA for each species. The equation herein was modified slightly from our previous calculations in Adams et al. (2017), where NFA was given 2 × the weight of DFA. The NFA and DFA values represent ranges of time spent flying during day or night (0–100%), where

1 = 0–20%
2 = 21–40%
3 = 41–60%
4 = 61–80%
5 = 81–100%.

3.2.2. Percent time spent in the rotor sweep zone (RSZt)

The percent time a bird spends flying within the rotor sweep zone (RSZt) of the turbine blades will influence its risk of collision. We evaluated previously reported flight heights among marine birds (Furness and Wade, 2012; Furness et al., 2013; Garthe and Hüppop, 2004; Robinson Willmott et al., 2013) and new data on flight heights among seabirds in the UK (e.g., Bradbury et al., 2014; Johnston et al., 2014) and in the eastern Pacific (Ainley et al., 2015), to estimate RSZt. We found considerable variation in reported flight-height values, especially for birds with > 20% RSZt. Therefore, we binned data into three range categories (instead of 5) based on RSZt. To keep the range of metric values between 1 and 5, the three bin values were 1, 3, and 5, where RSZt

5 = > 20%
3 = 5–20%
1 = < 5%.

3.2.3. Macro-avoidance (MAc)

The ability of a bird to maneuver around a wind turbine (i.e., avoidance) is important for assessing collision vulnerability and has been a major focus of post-construction studies at existing OWEI sites (e.g., Blew et al., 2008; Cook et al., 2014; Krijgsveld et al., 2011; Plonczkier and Simms, 2012). We recognize three broad types of avoidance behavior: macro-avoidance, meso-avoidance and micro-avoidance. Macro-avoidance refers to a bird's ability to change its flight course to avoid entering a wind farm area, quantified as the difference between actual and expected collision rates (Cook et al., 2014). We reviewed macro-avoidance data from visual and radar observations at existing OWEI sites to determine Macro-Avoidance (MAc) for POCS species or, when data was not available, for similar species (Adams et al., 2017). Although we acknowledge that some species can exhibit meso-avoidance (a change in flight direction within a wind farm area) and micro-avoidance (last-minute flight movements to avoid a specific turbine) behavior (Cook et al., 2014), we did not have enough information on meso- and micro-avoidance rates for POCS species to incorporate it into our analysis.

In contrast with avoidance, some species may be attracted to OWEI by increased prey availability (shearwaters, fulmars, storm-petrels; Baird, 1990; Burke et al., 2012), availability of new, artificial roosting habitat (gulls, cormorants, and pelicans; Peterson et al., 2006; Ronconi et al., 2014; Vanermen et al., 2014; Dierschke et al., 2016), or by attraction to artificial light at night (alcids, shearwaters, storm-petrels, and sea ducks; Burke et al., 2012; Hamer et al., 2014; Ronconi et al., 2014). Apart from the few current studies and new compilation efforts of these behaviors (e.g. Dierschke et al., 2016), attraction of marine birds to OWEI is not well understood (Wade et al., 2016). Although attraction may be considered negative MAc, studies reporting attraction behaviors at OWEI were considered too inconclusive to be incorporated into our MAc calculations.

We estimated MAc as a range of percentages (i.e., rates) describing OWEI avoidance. Greater rates of avoidance indicate lower risk of collision, and therefore, corresponds with a smaller MAc value.

1 = > 40% avoidance
2 = 30–40% avoidance
3 = 18–29% avoidance
4 = 6–17% avoidance
5 = 0–5% avoidance.

MAc values are inverse of MAd, macro-avoidance value calculated for the displacement calculation (Section 3.3.1).

3.3. Displacement vulnerability (DV)

OWEI also can cause barrier effects and habitat loss for seabirds (Busch and Garthe, 2016; Cook et al., 2014; Vanermen et al., 2014). Herein, we accounted for such effects in our estimation of Displacement Vulnerability (DV). We calculated DV (Equation (3)) based on metrics that could influence species-specific chances for displacement caused by OWEI. For species in the POCS that didn't have data associated with these metrics, data on similar species were used.

$$\text{Displacement Vulnerability(DV)} = (MAd \pm MAdu) + (HF \pm HFu) \quad (3)$$

where

MAd = Macro-Avoidance, HF = Habitat Flexibility, u = uncertainty

3.3.1. Macro-avoidance (MAd)

Macro-avoidance (MAd) is the difference between collision rates (e.g., based on observational and radar studies) and the expected number of collisions given no avoidance behavior occurs for all individuals of a species (Cook et al., 2014). We used MAd values generated from avoidance rates at existing OWEI. In contrast with Collision Vulnerability (Section 3.2.3), for DV, a greater MAd corresponded with a greater value, thus

1 = 0–5% avoidance
2 = 6–17% avoidance
3 = 18–29% avoidance
4 = 30–40% avoidance
5 = > 40% avoidance.

3.3.2. Habitat flexibility (HF)

We considered species with greater habitat flexibility (HF; i.e., ability to feed on a variety of food sources or forage within multiple habitat types) to be less-likely affected by OWEI than species that forage on specific prey or in specific habitats (Busch and Garthe, 2016; Masden et al., 2010). We reviewed descriptions of feeding behavior from the Birds of North America species accounts, del Hoyo et al. (1992, 1996) and additional sources (see Adams et al., 2017) to determine HF values. Where

1 = Species uses a wide range of foraging habitats, or are opportunistic foragers with the ability to switch among prey types based on availability, 2–4 = Species show some grade of behavior between 1 and 5, or
5 = Species have very habitat- and prey-specific requirements with little flexibility in foraging range, foraging behavior, habitat selection, or diet.

3.4. Uncertainty

There exists inherent uncertainty when estimating marine bird vulnerability to OWEI (Masden et al., 2014; Wade et al., 2016). Because values for most metrics have associated uncertainty, we assigned uncertainty to be low (10%), medium (25%), or high (50%) depending on the quality and number of data sources examined, how recent the data sources were, and the range of values published that informed each metric value. For example, if avoidance behavior data wasn't available from a species and instead data from a similar species was used for the MAc and MAd metric value, the highest level of uncertainty (50%) was assigned to that value. We multiplied the percent uncertainty for each metric value by 4 (the difference between the greatest [5] and least possible metric values [1]) to generate the following three uncertainty scalers:

$50\% = 0.50 \times 4 = 2.0$
$25\% = 0.25 \times 4 = 1.0$
$10\% = 0.10 \times 4 = 0.4.$

The uncertainty scaler was added to and subtracted from the metric to create a range of possible values. Uncertainty values were capped to stay within the 1–5 value range. For each species, we report Population Vulnerability (PV), Collision Vulnerability (CV), and Displacement Vulnerability (DV) along with upper and lower values to create a bracketed range of PV, CV, and DV for each species (Equations (1)–(3)). For example, Brown Pelican (*Pelecanus occidentalis*) has a HF value of 4 with an uncertainty of 50% (2.0 uncertainty scaler). To calculate HF lower: Brown Pelican HF – HF uncertainty = HF lower = 4 - 2 = 2. To calculate HF upper: Brown Pelican, HF + HF uncertainty = 5 + 2 = 7, thus HF upper is capped at 5 (maximum value allowed). We applied this method to all metric values that have uncertainty before calculating upper and lower limits for PV, CV, and DV. The magnitude of change in vulnerability score and rank as a function of uncertainty was determined by evaluating the range in ranks of lower, best estimate, and upper values for each species.

4. Spatial vulnerability calculations

To provide a spatial example of cumulative species vulnerability to OWEI, we applied vulnerability values to at-sea species distributions to evaluate spatial variability in seabird vulnerability at sea off southern California (the southern portion of the POCS). We used seasonally-averaged seabird density data collected from offshore Cambria, CA to the California-Mexico border (Mason et al., 2007; Takekawa et al., 2008). Nine at-sea aerial surveys were completed from 1999 to 2002, with three surveys during each oceanographic season: spring (May), fall (September), and winter (January). Forty-eight of 81 species in our vulnerability assessment were observed by Mason et al. (2007) and 21 broader species groups were also observed (e.g., shearwaters recorded during surveys were identified when possible, but were recorded as the broader species group “unidentified shearwaters” when species identification was not possible; Appendix Table A1). We calculated the mean species and mean species-group densities for all surveys within each 5×5 min grid cell in the study area.

To incorporate vulnerability spatially, best estimate values (BE; i.e., not including uncertainty) of CV and DV were multiplied by each species' PV (Equations (4) and (5)), because population-level impacts ultimately determine the magnitude of collision and displacement effects (Dierschke et al., 2016). To calculate the resulting Population Collision Vulnerability (PCV) and Population Displacement Vulnerability (PDV), we removed Annual Occurrence (section 3.1.3) from the PV calculation because the proportion of the year spent within the POCS is accounted for in the seasonal at-sea distribution data for the species.

$$\text{PCV} = \text{BE Collision Vulnerability} \times \text{BE Population Vulnerability}[-\text{AO}] \tag{4}$$

$$\text{PDV} = \text{BE Displacement Vulnerability} \times \text{BE Population Vulnerability}[-\text{AO}] \tag{5}$$

Thus, PCV and PDV represent species-specific population-level vulnerability to collision and displacement, respectively. For broader species groups (e.g., “unidentified shearwaters”) we generated species-group PCV and PDV by taking the weighted average (by POCSpop) among species included within the group.

We then multiplied PCV and PDV scores for each species and species-group by its mean density within the 5 × 5' survey bin to create PCV Density and PDV Density for each species and species group (Equations (6) and (7); Appendix Table A1). Lastly, we summed these vulnerability-density values for all species in each grid cell and mapped them in three vulnerability-density categories: Low (lower 50% of values across all grid cells), Medium (50–75%), and High (upper 25%).

$$\text{For each 5x5 survey grid cell: } \Sigma^{spp}(\overline{Density} * PCV) = \text{PCV Density} \tag{6}$$

$$\text{For each 5x5 survey grid cell: } \sum^{spp}(\overline{Density} * PDV) = \text{PDV Density} \tag{7}$$

5. Results

The best-estimate Population, Collision, and Displacement Vulnerability values for each species are shown in Table 3. The species-specific metric values used to calculate these three vulnerability values are listed in Adams et al. (2017) (Equations (1)–(3)), Table 3, Fig. 2).

5.1. Vulnerability calculations

Species with greatest PV were taxonomically diverse and included Ashy Storm-Petrel (*Oceanodroma homochroa*), Brown Pelican, Least Tern (*Sternula antillarum*), Brandt's Cormorant (*Phalacrocorax penicillatus*), Marbled Murrelet (*Brachyramphus marmoratus*), and Pink-footed Shearwater (*Puffinus creatopus*; Table 3). Greatest CV was found in jaegers/skuas, pelicans, terns and gulls; alcids and loons had lowest CV (Table 3). Species groups with greatest DV were loons, grebes, sea ducks, and alcids; species groups with lowest DV were medium-large gulls, jaegers, and skuas (Table 3).

5.2. Uncertainty

PV sensitivity to uncertainty ranged from 0 (Rhinoceros Auklet [*Cerorhinca monocerata*] and Ashy Storm-Petrel) to 45 (Laysan Albatross [*Phoebastria immutabilis*]). Procellariiformes and gulls had the greatest sensitivity to PV uncertainty. CV sensitivity to uncertainty ranged from 1 (Parasitic Jaeger [*Stercorarius parasiticus*]) to 42 (Red Phalarope [*Phalaropus fulicarius*] and Leach's Storm-Petrel [*Hydrobates leucorhous*]). Procellariiformes, sea ducks, and cormorants had the greatest sensitivity to CV uncertainty. DV sensitivity to uncertainty ranged from 3 (Glaucous-winged Gull [*Larus glaucescens*]) to 50 (Manx Shearwater [*Puffinus puffinus*], Sooty Shearwater [*Adrenna grisea*], Northern Fulmar [*Fulmarus glacialis rodgersii*], and Leach's Storm-Petrel). Procellariiformes, grebes, and terns had the greatest sensitivity to DV uncertainty.

5.3. Spatial vulnerability calculations

The mapped PCV Density and PDV Density for all species and species groups quantified off southern California by Mason et al. (2007) provides a spatial example of species vulnerability to OWEI. Locations with contrasting vulnerability categories (e.g., survey bins with high PCV-density but low PDV-density, or vice versa) were more commonly found offshore. Both PCV and PDV Densities were greatest in near-shore

Table 3
Final best estimate, upper, and lower for Population Vulnerability (PV), Collision Vulnerability (CV), and Displacement Vulnerability (DV) for each species. BE = Best Estimate value, Rank = rank order of value compared with other values, Rank range = the range of all PV, CV, DV ranks for the species.

Species	Alpha code	Population Vulnerability				Collision Vulnerability				Displacement Vulnerability			
Common Name		Lower (rank)	BE (rank)	Upper (rank)	Rank Range	Lower (rank)	BE (rank)	Upper (rank)	Rank Range	Lower (rank)	BE (rank)	Upper (rank)	Rank Range
Brant	BRAN	9 (42)	13 (38)	17 (39)	4	6 (21)	7 (36)	10 (58)	37	6 (10)	9 (1)	10 (1)	9
Common Merganser	COME	5.6 (73)	6 (81)	12.4 (75)	8	5 (28)	8 (29)	11 (42)	14	3 (58)	5 (58)	7 (70)	12
Red-breasted Merganser	RBME	6.6 (64)	8 (73)	12.4 (75)	11	5 (28)	8 (29)	10.4 (57)	29	3 (58)	5 (58)	8 (39)	19
Harlequin Duck	HADU	10.1 (31)	14 (32)	18.4 (30)	2	5 (28)	7 (36)	10 (58)	30	7.6 (3)	9 (1)	9.4 (19)	18
Surf Scoter	SUSC	7 (60)	12 (47)	18 (32)	28	3.5 (50)	7 (36)	11.5 (40)	14	6 (10)	9 (1)	10 (1)	9
White-winged Scoter	WWSC	4.5 (79)	8 (73)	13.5 (64)	15	4 (40)	7 (36)	11 (42)	6	5 (23)	8 (15)	10 (1)	22
Black Scoter	BLSC	6.5 (65)	10 (59)	14.5 (55)	10	4 (40)	7 (36)	11 (42)	6	6 (10)	9 (1)	10 (1)	9
Long-tailed Duck	LTDU	6.5 (65)	6.5 (80)	10.9 (80)	15	4 (40)	5.5 (52)	8.5 (65)	25	7.6 (3)	9 (1)	9.4 (19)	18
Red-throated Loon	RTLO	9.5 (38)	13 (38)	16.5 (43)	5	3 (56)	5.5 (52)	8.9 (64)	12	8.2 (1)	9 (1)	9.4 (19)	18
Pacific Loon	PALO	8 (50)	11.5 (53)	15 (52)	3	3 (56)	4 (68)	8.4 (71)	15	6.6 (7)	9 (1)	10 (1)	6
Common Loon	COLO	12.6 (13)	15.5 (24)	17.4 (38)	25	3 (56)	3.5 (69)	7.9 (76)	20	8.2 (1)	9 (1)	9.4 (19)	18
Yellow-billed Loon	YBLO	12.6 (13)	16 (20)	18 (32)	19	3 (56)	3.5 (69)	7.9 (76)	20	6.6 (7)	9 (1)	10 (1)	6
Horned Grebe	HOGR	7 (60)	9 (65)	15 (52)	13	3 (56)	6.5 (43)	12.5 (32)	24	6.6 (7)	9 (1)	9.4 (19)	18
Red-necked Grebe	RNGR	8.1 (47)	10 (59)	13.9 (60)	13	3 (56)	6 (46)	12 (34)	22	5.6 (20)	8 (15)	8.4 (35)	20
Eared Grebe	EAGR	5 (77)	7 (78)	11.4 (78)	1	3 (56)	6 (46)	12 (34)	22	4 (35)	8 (15)	10 (1)	34
Western Grebe	WEGR	12.1 (17)	16.5 (17)	21.9 (10)	7	3 (56)	6 (46)	12 (34)	22	4 (35)	8 (15)	10 (1)	34
Clark's Grebe	CLGR	11.1 (24)	15.5 (24)	22.5 (8)	16	3 (56)	6 (46)	12 (34)	22	4 (35)	8 (15)	10 (1)	34
Laysan Albatross	LAAL	11.2 (23)	12 (47)	13.2 (68)	45	4.5 (34)	8 (29)	13 (14)	20	4 (35)	6 (40)	8 (39)	5
Black-footed Albatross	BFAL	11.1 (24)	16.5 (17)	19.9 (21)	7	4.5 (34)	8 (29)	13 (14)	20	4 (35)	6 (40)	8 (39)	5
Short-tailed Albatross	STAL	14.6 (8)	19 (7)	21 (15)	8	3.5 (50)	7.5 (35)	13 (14)	36	4 (35)	6 (40)	8 (39)	5
Northern Fulmar	NOFU	8.6 (44)	11 (55)	13.4 (67)	23	4 (40)	5 (61)	7.4 (80)	40	5 (23)	6 (40)	6.4 (73)	50
Murphy's Petrel	MUPE	8 (50)	13 (38)	16 (46)	12	5 (28)	7 (36)	10 (58)	30	5 (23)	6 (40)	8 (39)	17
Mottled Petrel	MOPE	8.1 (47)	12 (47)	13.9 (60)	13	4 (40)	6 (46)	11 (42)	6	4 (35)	6 (40)	8 (39)	5
Hawaiian Petrel	HAPE	14.1 (9)	16.5 (17)	18 (32)	23	4 (40)	6 (46)	11 (42)	6	4 (35)	8 (15)	10 (1)	34
Cook's Petrel	COPE	11 (27)	15.5 (24)	18 (32)	8	4.5 (34)	6.5 (43)	11 (42)	9	4 (35)	6 (40)	8 (39)	5
Pink-footed Shearwater	PFSH	16.1 (4)	20 (5)	21.5 (11)	7	3 (56)	5 (61)	11 (42)	19	4 (35)	6 (40)	8 (39)	5
Flesh-footed Shearwater	FFSH	10.1 (31)	12.5 (43)	15.9 (49)	18	3.5 (50)	5.5 (52)	11 (42)	10	4 (35)	6 (40)	8 (39)	5
Buller's Shearwater	BULS	8.6 (44)	12 (47)	14.4 (57)	13	3 (56)	5 (61)	11 (42)	19	4 (35)	6 (40)	8 (39)	5
Sooty Shearwater	SOSH	10 (33)	14 (32)	16.4 (44)	12	4 (40)	5 (61)	7.4 (80)	40	5 (23)	6 (40)	6.4 (73)	50
Short-tailed Shearwater	SRTS	6.5 (65)	8.5 (71)	10.4 (81)	16	3 (56)	5 (61)	11 (42)	19	4 (35)	6 (40)	8 (39)	5
Manx Shearwater	MASH	9.6 (35)	11 (55)	16 (46)	20	4 (40)	5 (61)	9 (63)	23	5 (23)	6 (40)	6.4 (73)	50
Black-vented Shearwater	BVSH	12.6 (13)	17 (13)	19.4 (26)	13	3 (56)	5 (61)	11 (42)	19	4 (35)	7 (36)	9 (24)	12
Wilson's Storm-Petrel	WISP	6.5 (65)	7.5 (75)	11.9 (77)	12	4.5 (34)	5.5 (52)	9.5 (61)	27	5 (23)	6 (40)	8 (39)	17
Fork-tailed Storm-Petrel	FTSP	8 (50)	11 (55)	13.9 (60)	10	3.5 (50)	5.5 (52)	11 (42)	10	4 (35)	6 (40)	8 (39)	5
Leach's Storm-Petrel	LESP	7 (60)	12 (47)	15.4 (50)	13	4.5 (34)	5.5 (52)	7.9 (76)	42	5 (23)	6 (40)	6.4 (73)	50
Ashy Storm-Petrel	ASSP	20.6 (1)	27 (1)	29 (1)	0	3.5 (50)	5.5 (52)	11 (42)	10	4 (35)	7 (36)	9 (24)	12
Black Storm-Petrel	BLSP	9.5 (38)	13.5 (37)	16.6 (42)	5	3.5 (50)	5.5 (52)	11 (42)	10	4 (35)	6 (40)	8 (39)	5
Least Storm-Petrel	LSTP	7.5 (56)	12.5 (43)	19 (28)	28	4.5 (34)	5.5 (52)	10.5 (56)	22	4 (35)	6 (40)	8 (39)	5
Brandt's Cormorant	BRAC	19 (2)	21 (3)	23 (7)	5	4 (40)	8 (29)	13 (14)	26	2.6 (62)	5 (58)	7.4 (66)	8
Double-crested Cormorant	DCCO	11.8 (18)	15 (27)	18.2 (31)	13	4.8 (33)	9 (22)	13.2 (13)	20	2.6 (62)	5 (58)	7.4 (66)	8
Pelagic Cormorant	PECO	9.8 (34)	15 (27)	20.2 (19)	15	4 (40)	8 (29)	13 (14)	26	2.6 (62)	5 (58)	7.4 (66)	8
American White Pelican	AWPE	11.6 (21)	18 (11)	24.4 (6)	15	7 (12)	12 (4)	14 (1)	11	3 (58)	5 (58)	8 (39)	19
Brown Pelican	BRPE	18 (3)	22.5 (2)	25.5 (2)	1	7.5 (7)	12 (4)	13 (14)	10	3 (58)	5 (58)	8 (39)	19
Red-necked Phalarope	RNPH	7.5 (56)	9 (65)	12.9 (72)	16	3 (56)	6.5 (43)	12.5 (32)	24	2 (67)	5 (58)	8 (39)	28
Red Phalarope	REPH	9.6 (35)	12 (47)	16.4 (44)	12	3 (56)	7 (36)	13 (14)	42	2 (67)	5 (58)	8 (39)	28
South Polar Skua	SPSK	11.7 (20)	14 (32)	17 (39)	19	7.5 (7)	12.5 (3)	14 (1)	6	2 (67)	3 (78)	7 (70)	11
Pomarine Jaeger	POJA	4.5 (79)	9 (65)	14.5 (55)	24	9 (3)	12 (4)	13.5 (5)	2	2 (67)	3 (78)	6 (79)	12
Parasitic Jaeger	PAJA	5.5 (75)	7.5 (75)	13.5 (64)	11	10 (2)	13 (1)	14 (1)	1	2.6 (62)	3 (78)	4.4 (81)	19
Long-tailed Jaeger	LTJA	5.5 (75)	7.5 (75)	13.5 (64)	11	10.5 (1)	13 (1)	13.5 (5)	4	2 (67)	3 (78)	6 (79)	12
Common Murre	COMU	13.2 (11)	16 (20)	19.2 (27)	16	3 (56)	3.5 (69)	7.9 (76)	20	7.2 (5)	8 (15)	8.4 (35)	30
Pigeon Guillemot	PIGU	11.8 (18)	17 (13)	20.2 (19)	6	3 (56)	3 (78)	8 (72)	22	6 (10)	8 (15)	9 (24)	14
Marbled Murrelet	MAMU	15 (6)	20 (5)	25 (4)	2	3 (56)	3.5 (69)	8.5 (65)	13	6 (10)	8 (15)	9 (24)	14
Scripps's Murrelet	SCMU	14.8 (7)	19 (7)	21.3 (14)	7	3 (56)	3.5 (69)	8.5 (65)	13	7 (6)	9 (1)	10 (1)	5
Craveri's murrelet	CRMU	11.6 (21)	15 (27)	18 (32)	11	3 (56)	3.5 (69)	8.5 (65)	13	6 (10)	9 (1)	10 (1)	9
Ancient Murrelet	ANMU	5.6 (73)	10 (59)	14.4 (57)	16	3 (56)	3.5 (69)	8.5 (65)	13	6 (10)	8 (15)	9 (24)	14
Cassin's Auklet	CAAU	8 (50)	14 (32)	21 (15)	35	3 (56)	3.5 (69)	8.5 (65)	13	6 (10)	8 (15)	9 (24)	14
Parakeet Auklet	PAAU	6.1 (70)	8.5 (71)	12.9 (72)	2	3 (56)	3 (78)	8 (72)	22	5 (23)	7 (36)	8 (39)	16

(continued on next page)

Table 3 (*continued*)

Species	Alpha code	Population Vulnerability				Collision Vulnerability				Displacement Vulnerability			
Common Name		Lower (rank)	BE (rank)	Upper (rank)	Rank Range	Lower (rank)	BE (rank)	Upper (rank)	Rank Range	Lower (rank)	BE (rank)	Upper (rank)	Rank Range
Rhinoceros Auklet	RHAU	12.6 (13)	17 (13)	21.4 (13)	0	3 (56)	3.5 (69)	9.5 (61)	13	5 (23)	8 (15)	9 (24)	9
Horned Puffin	HOPU	8.1 (47)	10.5 (58)	13.9 (60)	13	3 (56)	3 (78)	8 (72)	22	6 (10)	8 (15)	9 (24)	14
Tufted Puffin	TUPU	13.5 (10)	19 (7)	21.5 (11)	4	3 (56)	3 (78)	8 (72)	22	6 (10)	8 (15)	9 (24)	14
Black-legged Kittiwake	BLKI	6.4 (69)	9 (65)	11 (79)	14	7 (12)	9 (22)	12 (34)	22	2.6 (62)	5 (58)	7.4 (66)	8
Sabine's Gull	SAGU	7 (60)	10 (59)	13 (69)	10	6 (21)	9.5 (15)	13.5 (5)	16	2 (67)	5 (58)	8 (39)	28
Bonaparte's Gull	BOGU	9 (42)	16 (20)	21 (15)	27	6 (21)	9.5 (15)	13.5 (5)	16	2 (67)	5 (58)	8 (39)	28
Heermann's Gull	HEEG	7.6 (54)	14 (32)	20.4 (18)	36	6 (21)	9.5 (15)	13.5 (5)	16	2 (67)	4 (70)	8 (39)	31
Mew Gull	MEGU	4.5 (79)	7 (78)	13 (69)	10	6 (21)	9.5 (15)	13.5 (5)	16	2 (67)	4 (70)	8 (39)	31
Ring-billed Gull	RBGU	7.6 (54)	11.5 (53)	15.4 (50)	4	6 (21)	10 (13)	14 (1)	20	2 (67)	4 (70)	8 (39)	31
Western Gull	WEGU	10.6 (29)	19 (7)	25.4 (3)	26	6.6 (16)	9 (22)	13 (14)	8	2 (67)	4 (70)	6.4 (73)	6
California Gull	CAGU	9.1 (41)	14.5 (31)	19.9 (21)	20	6 (21)	9.5 (15)	13.5 (5)	16	2 (67)	4 (70)	8 (39)	31
Herring Gull	HERG	5 (77)	9 (65)	14 (59)	18	7.1 (11)	9.5 (15)	13 (14)	4	2 (67)	4 (70)	6.4 (73)	6
Thayer's Gull	THGU	8.6 (44)	13 (38)	19 (28)	16	6.6 (16)	9.5 (15)	13.5 (5)	11	2 (67)	4 (70)	8 (39)	31
Glaucous-winged Gull	GWGU	7.1 (59)	12.5 (43)	19.9 (21)	38	6.6 (16)	9 (22)	13 (14)	8	2 (67)	4 (70)	7 (70)	3
Least Tern	LETE	15.1 (5)	21 (3)	24.5 (5)	2	7 (12)	9 (22)	12 (34)	22	4 (35)	8 (15)	10 (1)	34
Gull-billed Tern	GBTE	9.5 (38)	12.5 (43)	16 (46)	8	8.6 (4)	11 (7)	13 (14)	10	4 (35)	7 (36)	9 (24)	12
Caspian Tern	CATE	10.6 (29)	16 (20)	19.9 (21)	9	8.6 (4)	11 (7)	13 (14)	10	4 (35)	8 (15)	10 (1)	34
Black Tern	BLTE	6 (72)	9 (65)	15 (52)	20	6.5 (19)	9 (22)	11.5 (40)	21	5 (23)	8 (15)	9 (24)	9
Common Tern	COTE	7.5 (56)	9.5 (64)	13 (69)	13	7.5 (7)	11 (7)	13 (14)	7	5.6 (20)	8 (15)	8.4 (35)	20
Arctic Tern	ARTE	6.1 (70)	10 (59)	12.9 (72)	13	7.5 (7)	11 (7)	13 (14)	7	5.6 (20)	8 (15)	8.4 (35)	20
Forster's Tern	FOTE	10.8 (28)	15 (27)	17.7 (37)	10	8 (6)	11 (7)	13 (14)	8	4 (35)	8 (15)	10 (1)	34
Royal Tern	ROYT	9.6 (35)	13 (38)	16.9 (41)	6	7 (12)	10 (13)	13 (14)	2	4 (35)	8 (15)	10 (1)	34
Elegant Tern	ELTE	11.1 (24)	17.5 (12)	22 (9)	15	6.5 (19)	10.5 (12)	13 (14)	7	5 (23)	9 (1)	10 (1)	22
Black Skimmer	BLSK	12.8 (12)	17 (13)	19.7 (25)	13	5 (28)	9 (22)	13 (14)	14	5 (23)	9 (1)	10 (1)	22

areas, along the mainland coast and surrounding the Channel Islands (Fig. 3).

6. Discussion and conclusions

Herein, we provided the first quantification of marine bird vulnerability (collision, displacement, and population) to potential OWEI for the POCS. As OWEI construction started to increase significantly in Europe, quantification of collision and displacement of marine wildlife to OWEI was identified as a conservation priority (Bailey et al., 2014). As the U.S. also increases offshore renewable energy production, it is important to understand potential wildlife interactions with OWEI in U.S. waters specifically. Species population, collision, and displacement vulnerabilities in the POCS were driven by different factors and relative vulnerabilities of species varied between the three vulnerability types. Some species, however, were consistently more vulnerable than others (Fig. 2), highlighting which species-specific traits contribute more to overall marine bird vulnerability to OWEI.

Species with greatest PV were taxonomically-diverse. High PV in species such as Ashy Storm-Petrel, Brandt's Cormorant, Least Tern, Marbled Murrelet, and California Brown Pelican resulted from POCS endemism, breeding and year-round presence in the POCS, elevated threat status, and/or small population sizes (Ainley, 1995; Appendix Table A2). Although California Brown Pelican recently was removed from the Endangered Species list by USFWS, the species' PV remains high (U.S. Fish and Wildlife Service, 2014a; Appendix Table A2). Short-tailed Albatross (*Phoebastria albatrus*) and Pink-footed Shearwater have elevated PV due to high threat statuses associated with cumulative risks at-sea (i.e., fisheries bycatch; Croxall et al., 2012; Guy et al., 2013). Species with the lowest PV were also of diverse taxa and included migrants that spend little time in the POCS, have large population sizes, and/or are not species of state, national, or international concern.

High CV in jaegers, skuas, pelicans, gulls, and terns was due to low macro-avoidance rates and thus elevated collision risk (Table 3, Fig. 3, Appendix Table A3). Post-construction studies at OWEI sites in the North Sea indicate that gulls and terns did not demonstrate avoidance behavior at OWEI and, in some cases, are attracted to OWEI thus increasing risk for collision (Krijgsveld et al., 2011; Leopold et al., 2011; Peterson et al., 2006; Vanermen et al., 2014). In addition, cormorants and pelicans commute to and from roosting sites each day and roost at sea on artificial structures which is an indication that they are likely to roost on OWEI, increasing their potential for collision. Such attraction behavior among cormorants occurred at OWEI sites in the North Sea (Krijgsveld et al., 2011; Peterson et al., 2006) and oil platforms in the POCS (Hamer et al., 2014). Species groups with the greatest CV also include those with high percent time spent in the rotor sweep zone (e.g., skuas, jaegers, gulls and terns; Appendix Table A3). South Polar Skua (*Stercorarius maccormicki*) and Pomarine Jaeger (*Stercorarius pomarinus*) co-occur with gulls and terns, often fly more than 10 m above the water, and, except when resting during very high winds, are unlikely to change flight height with changing wind speed or direction (Ainley et al., 2015). Skua species in the North Sea have been observed in increased numbers at OWEI during construction and during operation, flying between turbines and within the rotor-swept zone (Peterson et al., 2006). Species groups with the lowest CV were those that show high macro-avoidance rates and included alcids and loons.

Most species with high CV also had low DV and vice versa (Figs. 2 and 3). High DV in loons, grebes, sea ducks, and alcids was due to high macro-avoidance rates (Table 3, Fig. 2), which is supported by studies in the North Sea in which alcids and loons avoided, or were found in significantly lower abundance at, OWEI areas during construction and initial stages of operation (Krijgsveld et al., 2011; Mendel et al., 2014, Peterson et al., 2006, Fig. 3, Appendix Table A4). However, tern and, to a lesser extent, gull species show high CV and DV in some cases. Perrow et al. (2011) found that Little Terns (*Sternula albifrons*) were displaced during OWEI construction and Leopold et al. (2011) observed that Sandwich Terns (*Thalasseus sandvicensis*) were more commonly seen flying around Egmond aan Zee wind farm than through, supporting their high DV ranking. It is important to note that gull and tern vulnerability might vary depending on location and species (e.g., gulls and terns may show displacement behavior in some sites and be found at risk of collision at others). Therefore, we suggest that site-specific

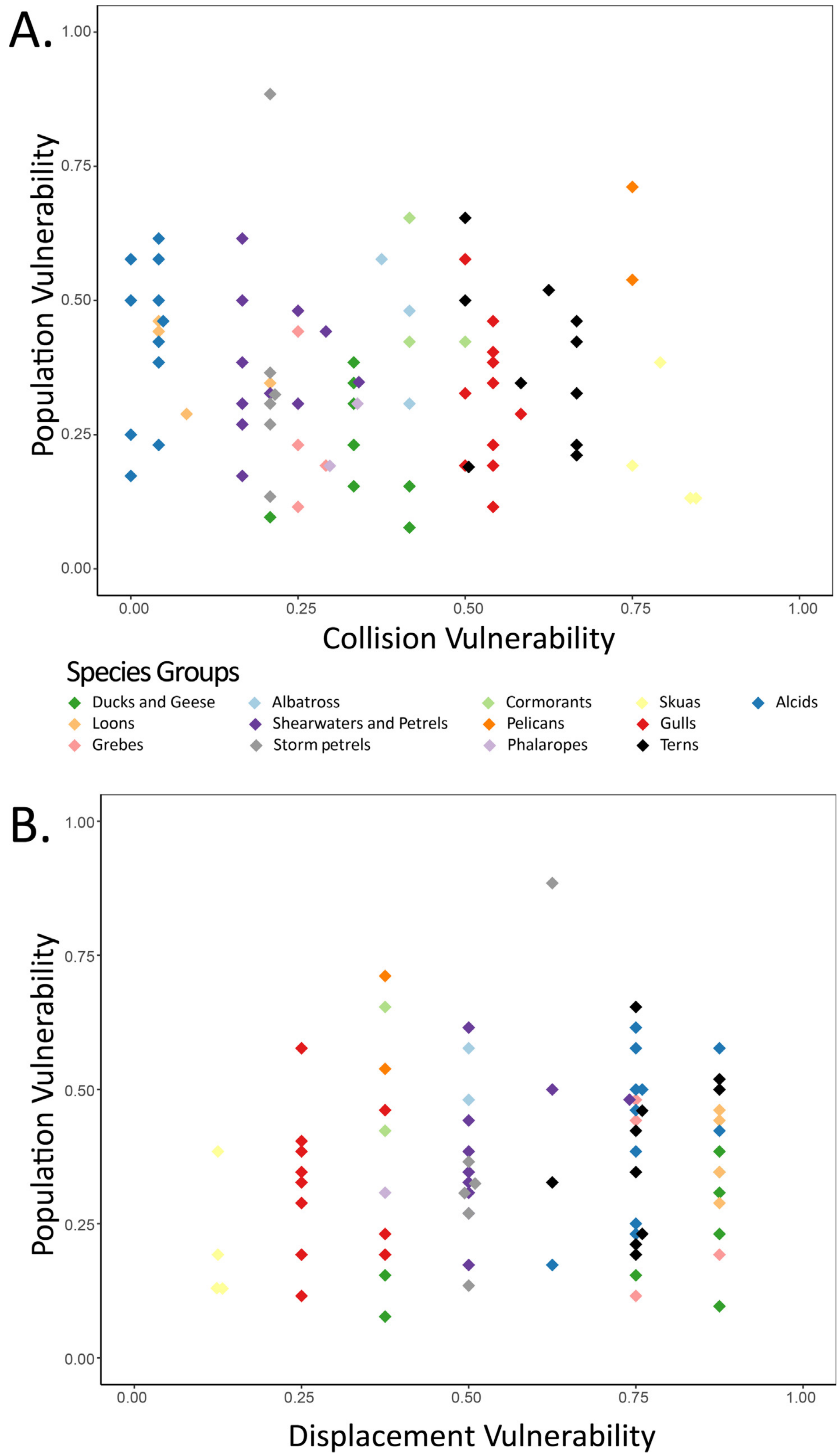

Fig. 2. Population Vulnerability vs. Collision Vulnerability percent rank values (A.) and Population Vulnerability vs. Displacement Vulnerability percent rank values (B.) for 81 marine bird species in the POCS; species taxonomic groups identified by color. Species with highest percent ranks are Ashy Storm-Petrel (*Oceanodroma homochroa*; gray) and Brown Pelican (*Pelecanus occidentalis*; orange). Overlapping values were adjusted slightly for clarity, refer to Table 3 for actual species values.

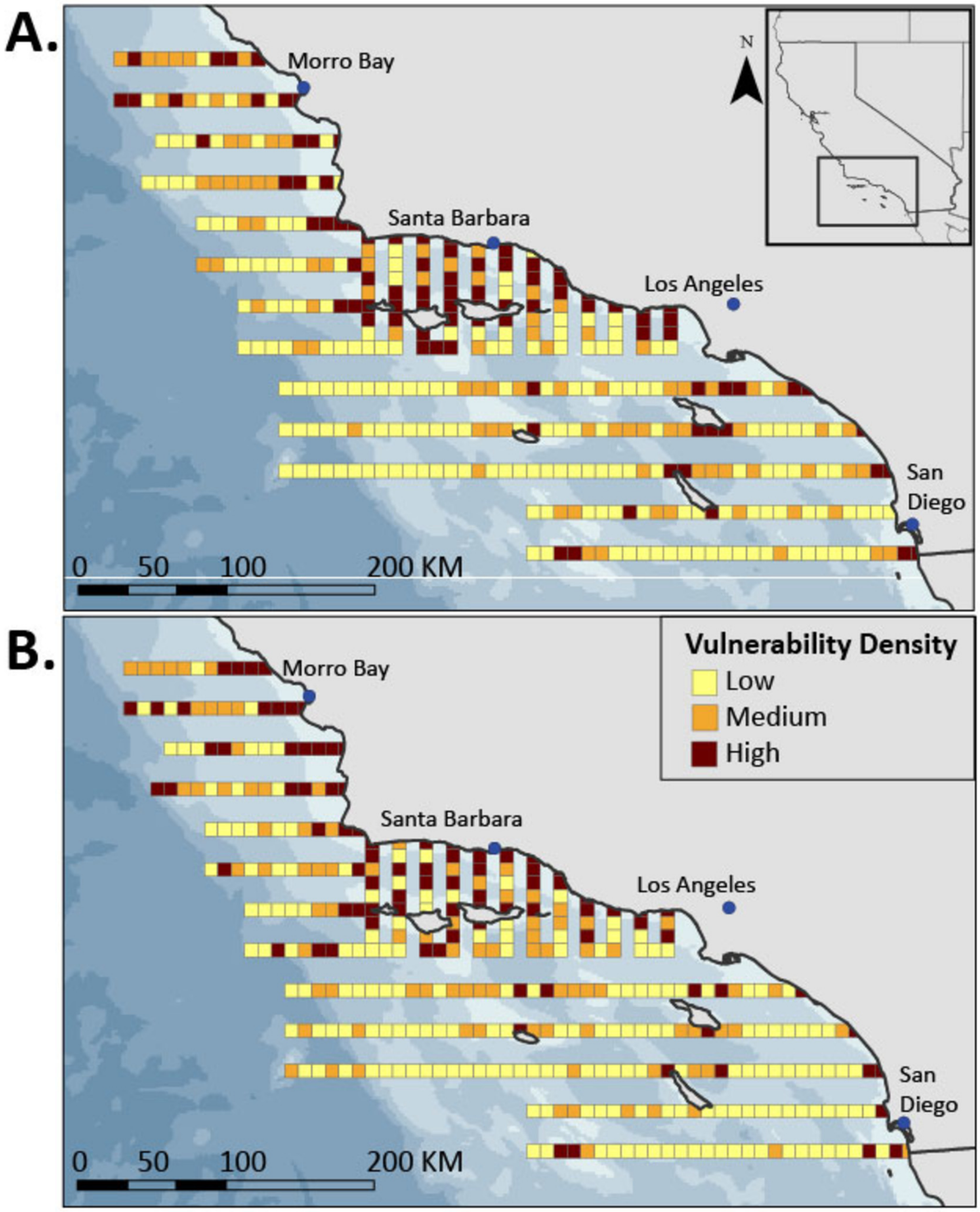

Fig. 3. Population Collision Vulnerability Density (A) and Population Displacement Vulnerability Density (B) off southern California. Vulnerability Densities are the sum of vulnerability density for all species and species groups detected in each cell during 1999–2002 aerial at-sea surveys (Mason et al., 2007). Vulnerability Densities displayed according to relative rank by color: yellow = low (lower 50% of score values), orange = medium (50–75%), and maroon = high (upper 25%).

vulnerability studies are necessary to assess gull and tern CV and DV (Corman and Garthe, 2014; Mendel et al., 2014; Vanermen et al., 2014).

Our calculations also were used to assess uncertainty associated with PV, CV and DV. Sensitivity to uncertainty was determined by the range in ranks of lower, best estimate, and upper values for each species. For each species, sensitivity to uncertainty can be used to identify knowledge gaps, help prioritize future studies, and guide interpretations of vulnerability assessments (Busch and Garthe, 2016; Masden et al., 2014; Wade et al., 2016). For example, species with relatively high vulnerabilities as well as high levels of uncertainty associated with those vulnerability values, such as Laysan Albatross, Red Phalarope, Manx Shearwater, Sooty Shearwater, Northern Fulmar, and Leach's Storm-Petrel, could be considered high priority for further research on OWEI impacts (Table 3).

By mapping vulnerability-densities off southern California, we evaluated the relative spatial vulnerability for the marine bird community in the southern region of the POCS (Fig. 3). PCV-densities and PDV-densities were greatest in near-shore environments where marine bird diversity and abundance were also greater (Fig. 3). Survey bins with contrasting vulnerability categories (e.g., high PCV-density but low PDV-density, or vice versa) were more commonly found offshore where a single, or few, species with different relative vulnerability scores were found in abundance (e.g., species with high collision vulnerability and low displacement vulnerability). Spatial variation in marine bird distribution at sea and the location of proposed OWEI will influence marine bird vulnerability (Brahman et al., 2015; Thaxter et al., 2015). Although informative, there are limitations to the vulnerability-densities provided by this dataset. For example, Short-tailed Albatrosses, which are known to associate with the shelf-break in this area, were not documented during aerial surveys due to low abundance. However, the species is globally threatened with a population size fewer than 5000 individuals (U.S. Fish and Wildlife Service, 2014b) and OWEI that negatively impacted few individuals could incur population-level consequences. Recognizing the limited capacity for broad-scale surveys to detect rare species is important when considering OWEI siting and spatial data used to assess vulnerabilities. Furthermore, it is important to note that the vulnerability-density values and categories applied here cannot be translated to actual risks or impacts to individual birds. For now, our map of spatial vulnerability-densities provides an example of how calculations of species vulnerability to OWEI can be applied.

The metrics, vulnerability values, and spatial vulnerability-density application presented here provide new information to assess marine bird vulnerability to OWEI in the POCS. In addition, our assessment can accommodate updates as new data and adjustments become available. Just as Wade et al. (2016) provided modifications to Furness et al. (2013) for Atlantic marine bird vulnerability, additional information pertaining to POCS species can be used to improve this assessment. For example, rapidly improving bird-borne data logger technology is now being employed to improve flight-height estimations (Cleasby et al., 2015; Ross-Smith et al., 2016) and such information can reduce uncertainty when estimating time spent in the rotor sweep zone (RSZt). Greater confidence in RSZt values for all species would also improve collision-risk-modeling and could influence regulations that set appropriate recommended rotor sweep zone height (e.g., greater than 30 m; Ross-Smith et al., 2016). We suggest that values for metrics in equations be modified as new information about the ranging behaviors and flight heights of marine birds at sea becomes available. Lastly, we acknowledge that the equations for calculating vulnerability herein are one example; others may find justifiable reasons to modify the equations or apply different weightings to metrics. Ultimately, we have provided a conceptual framework with which to address marine bird vulnerabilities to OWEI in the POCS. In conclusion, this assessment of marine bird vulnerabilities to OWEI is the first resource of its kind for the POCS to understand potential impacts and inform management decisions.

Authors' contributions

DP and JA conceived the study and methodology. JA and EK generated the species list and compiled literature sources. JA, EK, JF, and MC generated calculations and fine-tuned methods. EK generated the database and calculated the vulnerability values. JF and EK did the spatial analysis. JA and EK led the writing of the manuscript.

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Data accessibility

Adams, J., Kelsey, E.C., Felis, J.J., and Pereksta, D.M., 2017, Data for calculating population, collision and displacement vulnerability among marine birds of the California Current System associated with offshore wind energy infrastructure (ver. 2.0, June 2017): U.S. Geological Survey data release, http://doi.org/10.5066/F79C6VJ0.

Takekawa, J. Y., W. M. Perry, J. Adams, L. L. Williams, J. L. Yee, D. L. Orthmeyer, J. W. Mason, G. J. McChesney, W. R. McIver, H. R. Carter, and R. T. Golightly. 2008. Spatial database for the at-sea distribution and abundance of seabirds and marine mammals off southern California: 1999–2002. Western Ecological Research Center, Dixon and Vallejo, CA and Humboldt State University, Arcata, CA. U. S. Minerals Management Service Study Profile #2008-039. https://www.sciencebase.gov/catalog/item/57c75faae4b0f2f0cebed52e.

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Appendix

Appendix Table A1
Species and species groups within the POCS. Species are ordered by taxonomic classification number (Clements et al., 2015).

Taxon	Species name (English)	Species name (scientific)	Alpha code	Vulnerability density species group
Sea Ducks	Brant	*Branta bernicla*	BRAN	BRAN
	Common Merganser	*Mergus merganser*	COME	–
	Red-breasted Merganser	*Mergus serrator*	RBME	RBME
	Harlequin Duck	*Histrioicus histrionicus*	HADU	–
	Surf Scoter	*Melanitta perspicillata*	SUSC	SUSC
	White-winged Scoter	*Melanitta deglandi*	WWSC	WWSC
	Black Scoter	*Melanitta americana*	BLSC	–
	Long-tailed Duck	*Clangula hyemalis*	LTDU	–
	Unidentified scoter			USCR
Loons	Red-throated Loon	*Gavia stellata*	RTLO	RTLO
	Pacific Loon	*Gavia pacifica*	PALO	PALO
	Common Loon	*Gavia immer*	COLO	COLO
	Yellow-billed Loon	*Gavia adamsii*	YBLO	–
	Unidentified loon			UNLO

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Appendix Table A1 (*continued*)

Taxon	Species name (English)	Species name (scientific)	Alpha code	Vulnerability density species group
Grebes	Horned Grebe	*Podiceps auritus*	HOGR	HOGR
	Red-necked Grebe	*Podiceps grisegena*	RNGR	–
	Eared Grebe	*Podiceps nigricollis*	EAGR	–
	Western Grebe	*Aechmophorus occidentalis*	WEGR	WEGR
	Clark's Grebe	*Aechmophorus clarkii*	CLGR	WEGR
	Unidentified small grebe			USGR
Procellariids	Laysan Albatross	*Phoebastria immutabilis*	LAAL	LAAL
	Black-footed Albatross	*Phoebastria nigripes*	BFAL	–
	Short-tailed Albatross	*Phoebastria albatrus*	STAL	–
	Northern Fulmar	*Fulmarus glacialis rodgersii*	NOFU	NOFU
	Murphy's Petrel	*Pterodroma ultina*	MUPE	–
	Mottled Petrel	*Pterodroma inexpectata*	MOPE	–
	Hawaiian Petrel	*Pterodroma sandwichensis*	HAPE	–
	Cook's Petrel	*Pterodroma cookii*	COPE	–
	Pink-footed Shearwater	*Ardenna creatopus*	PFSH	PFSH
	Flesh-footed Shearwater	*Ardenna carneipes*	FFSH	–
	Buller's Shearwater	*Adrenna bulleri*	BULS	–
	Sooty Shearwater	*Adrenna grisea*	SOSH	SOSH
	Short-tailed Shearwater	*Ardenna tenuirostris*	SRTS	–
	Manx Shearwater	*Puffinus puffinus*	MASH	–
	Black-vented Shearwater	*Puffinus opisthomelas*	BVSH	BVSH
	Wilson's Storm-Petrel	*Oceanites oceanicus*	WISP	–
	Fork-tailed Storm-Petrel	*Hydrobates furcatus*	FTSP	–
	Leach's Storm-Petrel	*Hydrobates leucorhous*	LESP	–
	Ashy Storm-Petrel	*Hydrobates homochroa*	ASSP	ASSP
	Black Storm-Petrel	*Hydrobates melania*	BLSP	BLSP
	Least Storm-Petrel	*Hydrobates microsoma*	LSTP	–
	Unidentified shearwater			UNSH
	Unidentified storm-petrel			UNSP
Cormorants	Brandt's Cormorant	*Phalacrocorax penicillatus*	BRAC	BRAC
	Double-crested Cormorant	*Phalacrocorax auritus*	DCCO	DCCO
	Pelagic Cormorant	*Phalacrocorax pelagicus*	PECO	PECO
	Unidentified cormorant			UNCO
Pelicans	American White Pelican	*Pelecanus erythrorhynchos*	AWPE	–
	Brown Pelican	*Pelecanus occidentalis*	BRPE	BRPE
Phalaropes	Red-necked Phalarope	*Phalaropus lobatus*	RNPH	RNPH
	Red Phalarope	*Phalaropus fulicarius*	REPH	REPH
	Unidentified phalarope			UNPH
Jaegers and Skuas	South Polar Skua	*Stercorarius maccormicki*	SPSK	SPSK
	Pomarine Jaeger	*Stercorarius pomarinus*	POJA	POJA
	Parasitic Jaeger	*Stercorarius parasiticus*	PAJA	PAJA
	Long-tailed Jaeger	*Stercorarius longicaudus*	LTJA	LTJA
	Unidentified jaeger			UNJA
Alcids	Common Murre	*Uria aalge*	COMU	COMU
	Pigeon Guillemot	*Cepphus columba*	PIGU	PIGU
	Marbled Murrelet	*Brachyramphus marmoratus*	MAMU	–
	Scripps's Murrelet[a]	*Synthliboramphus hypoleucus*	SCMU	XAMU
	Craveri's Murrelet	*Synthliboramphus craveri*	CRMU	–
	Ancient Murrelet	*Synthliboramphus antiquus*	ANMU	–
	Cassin's Auklet	*Ptychoramphus aleuticus*	CAAU	CAAU
	Parakeet Auklet	*Aethia psittacula*	PAAU	–
	Rhinoceros Auklet	*Cerorhinca monocerata*	RHAU	RHAU
	Horned Puffin	*Fratercula corniculata*	HOPU	–
	Tufted Puffin	*Fratercula cirrhata*	TUPU	–
	Unidentified alcid			UNAL
	Unidentified small alcid			UNSA
	Unidentified murrelet			UNMU

(*continued on next page*)

Appendix Table A1 (*continued*)

Taxon	Species name (English)	Species name (scientific)	Alpha code	Vulnerability density species group
Gulls	Black-legged Kittiwake	*Rissa tridactyla*	BLKI	BLKI
	Sabine's Gull	*Xema sabini*	SAGU	SAGU
	Bonaparte's Gull	*Chroicocephalus philadelphia*	BOGU	BOGU
	Heermann's Gull	*Larus heermanni*	HEEG	HEEG
	Mew Gull	*Larus brachyrhynchus*	MEGU	MEGU
	Ring-billed Gull	*Larus delawarensis*	RBGU	RBGU
	Western Gull	*Larus occidentalis*	WEGU	WEGU
	California Gull	*Larus californicus*	CAGU	CAGU
	Herring Gull	*Larus smithsonianus*	HERG	HERG
	Thayer's Gull	*Larus thayeri*	THGU	–
	Glaucous-winged Gull	*Larus glaucescens*	GWGU	GWGU
	Unidentified gull			UNGU
	Unidentified small gull			UNSG
	Unidentified medium gull			UNMG
	Unidentified large gull			UNLG
Terns	Least Tern	*Sternula antillarum*	LETE	LETE
	Gull-billed Tern	*Sterna nilotica*	GBTE	–
	Caspian Tern	*Hydroprogne caspia*	CATE	CATE
	Black Tern	*Chlidonias niger*	BLTE	–
	Common Tern	*Sterna hirundo*	COTE	CMTE
	Arctic Tern	*Sterna paradisaea*	ARTE	CMTE
	Forster's Tern	*Sterna forsteri*	FOTE	FOTE
	Royal Tern	*Thalasseus maximus*	ROYT	ROYT
	Elegant Tern	*Thalasseus elegans*	ELTE	ELTE
	Black Skimmer	*Rynchops niger*	BLSK	BLSK
	Elegant or Royal Tern			ERTE
	Unidentified small tern			UNST
	Unidentified medium tern			UNMT
	Unidentified large tern			UNLT
	Unidentified tern			UNTE

"Vulnerability density species group", species and species groups used for spatial vulnerability analysis ("— " indicates species not represented in survey data; Mason et al., 2007).

[a] Xantus's Murrelet (*Synthliboramphus hypoleucus*) is now recognized as two distinct species: Scripps's and Guadalupe Murrelet (*S. scrippsi* and *S. hypoleucus*; Birt et al., 2012; Chesser et al., 2012). Because it is unclear to what extent Guadalupe Murrelet inhabits the greater POCS, all data for Xantus's Murrelet was applied to Scripps's Murrelet.

Appendix Table A2

Best estimate values and uncertainties for each metric in the Population Vulnerability calculation and final Population Vulnerability (Best, Upper, Lower values, and Percent Rank of Best value [used in Fig. 2]) for all species.

Species name (English)	POP	*u*	AO	POCS pop	*u*	TS	BR	AS	*u*	Population Vulnerability			
										Lower	Best	Upper	Percent
Brant	3.0	1.0	2.0	2.0	1.0	3.0	1.0	3.0	1.0	9.0	13.0	17.0	0.35
Common Merganser	2.0	0.4	1.5	1.0	2.0	1.0	1.5	1.0	2.0	5.6	6.0	12.4	0.08
Red-breasted Merganser	3.0	0.4	2.0	1.0	1.0	1.0	1.0	2.0	2.0	6.6	8.0	12.4	0.15
Harlequin Duck	4.0	0.4	1.5	2.0	2.0	3.0	1.0	4.0	2.0	10.1	14.0	18.4	0.38
Surf Scoter	3.0	2.0	2.0	3.0	1.0	1.0	1.0	2.0	2.0	7.0	12.0	18.0	0.31
White-winged Scoter	2.0	2.0	1.5	2.0	1.0	1.0	1.0	2.0	2.0	4.5	8.0	13.5	0.15
Black Scoter	3.0	1.0	1.5	2.0	1.0	2.0	1.0	2.0	2.0	6.5	10.0	14.5	0.23
Long-tailed Duck	1.0	0.4	1.5	1.0	2.0	3.0	1.0	1.0	1.0	6.5	6.5	10.9	0.10
Red-throated Loon	4.0	1.0	1.5	2.0	1.0	2.0	1.0	4.0	1.0	9.5	13.0	16.5	0.35
Pacific Loon	2.0	1.0	1.5	3.0	1.0	1.0	1.0	4.0	1.0	8.0	11.5	15.0	0.29
Common Loon	3.0	0.4	1.5	3.0	1.0	3.0	1.0	5.0	1.0	12.6	15.5	17.4	0.44
Yellow-billed Loon	5.0	0.4	2.0	2.0	1.0	2.0	1.0	5.0	1.0	12.6	16.0	18.0	0.46
Horned Grebe	3.0	2.0	2.0	1.0	1.0	3.0	1.0	1.0	2.0	7.0	9.0	15.0	0.19
Red-necked Grebe	4.0	0.4	1.5	2.0	1.0	2.0	1.0	1.0	2.0	8.1	10.0	13.9	0.23
Eared Grebe	1.0	0.4	2.0	2.0	1.0	1.0	1.0	1.0	2.0	5.0	7.0	11.4	0.12
Western Grebe	4.0	0.4	2.0	4.0	2.0	3.0	1.5	1.0	2.0	12.1	16.5	21.9	0.48

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Appendix Table A2 (*continued*)

Species name (English)	POP	*u*	AO	POCS pop	*u*	TS	BR	AS	*u*	Population Vulnerability			
										Lower	Best	Upper	Percent
Clark's Grebe	5.0	0.4	2.0	3.0	2.0	3.0	1.5	1.0	2.0	11.1	15.5	22.5	0.44
Laysan Albatross	2.0	0.4	2.0	1.0	0.4	3.0	1.0	5.0	0.4	11.2	12.0	13.2	0.31
Black-footed Albatross	4.0	0.4	1.5	3.0	2.0	3.0	1.0	5.0	2.0	11.1	16.5	19.9	0.48
Short-tailed Albatross	5.0	0.4	2.0	2.0	1.0	5.0	1.0	5.0	2.0	14.6	19.0	21.0	0.58
Northern Fulmar	1.0	0.4	2.0	2.0	1.0	1.0	1.0	5.0	0.4	8.6	11.0	13.4	0.27
Murphy's Petrel	4.0	2.0	1.0	2.0	2.0	2.0	1.0	5.0	2.0	8.0	13.0	16.0	0.35
Mottled Petrel	2.0	0.4	1.5	2.0	1.0	2.0	1.0	5.0	2.0	8.1	12.0	13.9	0.31
Hawaiian Petrel	5.0	0.4	1.5	1.0	1.0	5.0	1.0	5.0	2.0	14.1	16.5	18.0	0.48
Cook's Petrel	3.0	1.0	1.5	3.0	1.0	3.0	1.0	5.0	2.0	11.0	15.5	18.0	0.44
Pink-footed Shearwater	5.0	0.4	1.5	4.0	1.0	4.0	1.0	5.0	2.0	16.1	20.0	21.5	0.62
Flesh-footed Shearwater	3.0	0.4	1.5	1.0	2.0	3.0	1.0	5.0	2.0	10.1	12.5	15.9	0.33
Buller's Shearwater	2.0	0.4	1.0	2.0	2.0	3.0	1.0	5.0	2.0	8.6	12.0	14.4	0.31
Sooty Shearwater	1.0	0.4	2.0	3.0	1.0	2.0	1.0	5.0	2.0	10.0	14.0	16.4	0.38
Short-tailed Shearwater	1.0	0.4	1.5	1.0	1.0	1.0	1.0	5.0	2.0	6.5	8.5	10.4	0.17
Manx Shearwater	3.0	1.0	2.0	1.0	2.0	1.0	1.0	5.0	0.4	9.6	11.0	16.0	0.27
Black-vented Shearwater	4.0	0.4	2.0	2.0	1.0	4.0	1.0	5.0	2.0	12.6	17.0	19.4	0.50
Wilson's Storm-Petrel	1.0	0.4	1.5	1.0	2.0	1.0	1.0	4.0	1.0	6.5	7.5	11.9	0.13
Fork-tailed Storm-Petrel	1.0	1.0	1.0	1.0	0.4	3.0	1.5	4.0	2.0	8.0	11.0	13.9	0.27
Leach's Storm-Petrel	1.0	0.4	1.0	2.0	1.0	1.0	2.0	4.0	2.0	7.0	12.0	15.4	0.31
Ashy Storm-Petrel	5.0	0.4	2.0	5.0	1.0	4.0	2.0	4.0	2.0	20.6	27.0	29.0	0.88
Black Storm-Petrel	3.0	1.0	1.5	1.0	0.4	3.0	1.5	4.0	2.0	9.5	13.5	16.6	0.37
Least Storm-Petrel	3.0	2.0	1.5	1.0	2.0	2.0	1.5	4.0	2.0	7.5	12.5	19.0	0.33
Brandt's Cormorant	4.0	0.4	2.0	4.0	0.4	3.0	2.0	3.0	0.4	19.0	21.0	23.0	0.65
Double-crested Cormorant	2.0	0.4	2.0	2.0	0.4	1.0	2.0	4.0	1.0	11.8	15.0	18.2	0.42
Pelagic Cormorant	4.0	0.4	2.0	2.0	0.4	1.0	2.0	3.0	2.0	9.8	15.0	20.2	0.42
American White Pelican	4.0	0.4	2.0	3.0	2.0	5.0	1.0	3.0	2.0	11.6	18.0	24.4	0.54
Brown Pelican	4.0	1.0	2.0	3.0	1.0	5.0	1.5	5.0	1.0	18.0	22.5	25.5	0.71
Red-necked Phalarope	1.0	0.4	1.5	4.0	1.0	1.0	1.0	1.0	2.0	7.5	9.0	12.9	0.19
Red Phalarope	2.0	0.4	2.0	4.0	1.0	1.0	1.0	1.0	2.0	9.6	12.0	16.4	0.31
South Polar Skua	5.0	0.4	1.5	2.0	2.0	1.0	1.0	5.0	0.4	11.7	14.0	17.0	0.38
Pomarine Jaeger	2.0	2.0	1.5	2.0	1.0	1.0	1.0	3.0	2.0	4.5	9.0	14.5	0.19
Parasitic Jaeger	1.0	2.0	1.5	1.0	2.0	1.0	1.0	4.0	2.0	5.5	7.5	13.5	0.13
Long-tailed Jaeger	1.0	2.0	1.5	1.0	2.0	1.0	1.0	4.0	2.0	5.5	7.5	13.5	0.13
Common Murre	1.0	0.4	2.0	2.0	0.4	3.0	2.0	4.0	1.0	13.2	16.0	19.2	0.46
Pigeon Guillemot	4.0	0.4	2.0	2.0	0.4	1.0	2.0	4.0	2.0	11.8	17.0	20.2	0.50
Marbled Murrelet	3.0	1.0	2.0	2.0	1.0	5.0	2.0	4.0	1.0	15.0	20.0	25.0	0.62
Scripps's Murrelet	5.0	0.4	2.0	2.0	0.4	4.0	1.5	4.0	2.0	14.8	19.0	21.3	0.58
Craveri's Murrelet	5.0	0.4	1.0	2.0	2.0	4.0	1.0	4.0	2.0	11.6	15.0	18.0	0.42
Ancient Murrelet	2.0	0.4	1.0	3.0	2.0	1.0	2.0	2.0	1.0	5.6	10.0	14.4	0.23
Cassin's Auklet	1.0	1.0	2.0	2.0	1.0	3.0	2.0	3.0	2.0	8.0	14.0	21.0	0.38
Parakeet Auklet	2.0	0.4	1.5	1.0	2.0	1.0	1.0	4.0	2.0	6.1	8.5	12.9	0.17
Rhinoceros Auklet	2.0	0.4	2.0	2.0	1.0	3.0	2.0	4.0	1.0	12.6	17.0	21.4	0.50
Horned Puffin	2.0	0.4	1.5	1.0	2.0	2.0	1.0	5.0	2.0	8.1	10.5	13.9	0.25
Tufted Puffin	1.0	1.0	1.5	2.0	1.0	5.0	2.0	5.0	2.0	13.5	19.0	21.5	0.58
Black-legged Kittiwake	1.0	0.4	1.5	2.0	0.4	1.0	1.0	4.0	2.0	6.4	9.0	11.0	0.19
Sabine's Gull	3.0	0.4	1.5	2.0	0.4	1.0	1.0	3.0	2.0	7.0	10.0	13.0	0.23
Bonaparte's Gull	4.0	1.0	2.0	4.0	2.0	1.0	1.0	3.0	2.0	9.0	16.0	21.0	0.46
Heermann's Gull	3.0	0.4	2.0	3.0	2.0	2.0	1.0	3.0	2.0	7.6	14.0	20.4	0.38
Mew Gull	1.0	1.0	1.5	2.0	2.0	1.0	1.0	2.0	2.0	4.5	7.0	13.0	0.12
Ring-billed Gull	2.0	0.4	2.0	2.0	1.0	1.0	1.5	3.0	1.0	7.6	11.5	15.4	0.29
Western Gull	4.0	0.4	2.0	4.0	2.0	1.0	2.0	3.0	2.0	10.6	19.0	25.4	0.58
California Gull	3.0	0.4	2.0	3.0	1.0	1.0	1.5	3.0	2.0	9.1	14.5	19.9	0.40
Herring Gull	1.0	1.0	2.0	2.0	1.0	1.0	1.0	3.0	2.0	5.0	9.0	14.0	0.19
Thayer's Gull	5.0	0.4	2.0	2.0	2.0	1.0	1.0	3.0	2.0	8.6	13.0	19.0	0.35
Glaucous-winged Gull	3.0	0.4	2.0	2.0	2.0	1.0	1.5	3.0	2.0	7.1	12.5	19.9	0.33
Least Tern	5.0	0.4	1.5	2.0	1.0	5.0	2.0	4.0	2.0	15.1	21.0	24.5	0.65
Gull-billed Tern	4.0	1.0	1.5	1.0	1.0	3.0	1.0	4.0	2.0	9.5	12.5	16.0	0.33
Caspian Tern	4.0	0.4	2.0	2.0	1.0	2.0	1.5	4.0	2.0	10.6	16.0	19.9	0.46
Black Tern	2.0	2.0	1.0	1.0	2.0	3.0	1.0	3.0	2.0	6.0	9.0	15.0	0.19

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Appendix Table A2 (*continued*)

Species name (English)	POP	*u*	AO	POCS pop	*u*	TS	BR	AS	*u*	Population Vulnerability			
										Lower	Best	Upper	Percent
Common Tern	2.0	1.0	1.5	1.0	1.0	2.0	1.0	4.0	1.0	7.5	9.5	13.0	0.21
Arctic Tern	2.0	0.4	1.5	2.0	1.0	1.0	1.0	4.0	2.0	6.1	10.0	12.9	0.23
Forster's Tern	4.0	0.4	2.0	2.0	0.4	1.0	1.5	4.0	2.0	10.8	15.0	17.7	0.42
Royal Tern	4.0	0.4	2.0	1.0	1.0	1.0	1.5	4.0	2.0	9.6	13.0	16.9	0.35
Elegant Tern	5.0	0.4	1.5	3.0	2.0	2.0	1.5	4.0	2.0	11.1	17.5	22.0	0.52
Black Skimmer	4.0	0.4	2.0	2.0	0.4	3.0	1.5	4.0	2.0	12.8	17.0	19.7	0.50

POP, global population.
AO, Annual Occurrence in the POCS (no uncertainty).
POCSpop, percent of population in the Pacific Outer Continental Shelf.
TS, threat status (no uncertainty).
BR, Breeding Score (no uncertainty).
AS, adult survival.
u, uncertainty value (±).

Appendix Table A3

Best estimate values and uncertainties for each metric in the Collision Vulnerability calculation and final Collision Vulnerability (Best, Upper, Lower values, and Percent Rank of Best Value [used in Fig. 2]) for all species.

Species name	Average Flight Activity			RSZt	*u*	MAc	*u*	Collision Vulnerability			
	Lower	Best	Upper					Lower	Best	Upper	Percent
Brant	1.0	1.0	3.0	2.0	1.0	1.0	3.0	6.0	7.0	10.0	0.33
Common Merganser	1.0	1.0	2.0	1.0	1.0	1.0	2.0	5.0	8.0	11.0	0.42
Red-breasted Merganser	1.0	1.0	1.4	0.4	1.0	1.0	1.4	5.0	8.0	10.4	0.42
Harlequin Duck	3.0	5.0	5.0	2.0	3.0	5.0	5.0	5.0	7.0	10.0	0.33
Surf Scoter	1.5	3.0	4.5	2.0	1.7	3.0	4.3	3.7	7.0	11.3	0.33
White-winged Scoter	2.0	3.0	4.0	1.0	2.0	3.0	4.0	4.0	7.0	11.0	0.33
Black Scoter	1.0	3.0	5.0	2.0	1.0	3.0	5.0	4.0	7.0	11.0	0.33
Long-tailed Duck	2.0	3.5	4.5	1.0	2.0	3.7	4.7	4.0	5.7	8.7	0.21
Red-throated Loon	1.0	1.5	2.5	1.0	1.0	1.3	2.3	3.0	5.3	8.7	0.21
Pacific Loon	1.0	2.0	4.0	2.0	1.0	1.7	3.7	3.0	3.7	8.1	0.08
Common Loon	1.0	1.5	3.5	2.0	1.0	1.3	3.3	3.0	3.3	7.7	0.04
Yellow-billed Loon	1.0	1.5	3.5	2.0	1.0	1.3	3.3	3.0	3.3	7.7	0.04
Horned Grebe	1.0	2.5	4.5	2.0	1.0	2.7	4.7	3.0	6.7	12.7	0.29
Red-necked Grebe	1.0	2.0	4.0	2.0	1.0	2.3	4.3	3.0	6.3	12.3	0.25
Eared Grebe	1.0	2.0	4.0	2.0	1.0	2.3	4.3	3.0	6.3	12.3	0.25
Western Grebe	1.0	2.0	4.0	2.0	1.0	2.3	4.3	3.0	6.3	12.3	0.25
Clark's Grebe	1.0	2.0	4.0	2.0	1.0	2.3	4.3	3.0	6.3	12.3	0.25
Laysan Albatross	2.5	4.0	5.0	2.0	2.7	4.0	5.0	4.7	8.0	13.0	0.42
Black-footed Albatross	2.5	4.0	5.0	2.0	2.7	4.0	5.0	4.7	8.0	13.0	0.42
Short-tailed Albatross	1.5	3.5	5.0	2.0	1.3	3.3	5.0	3.3	7.3	13.0	0.38
Northern Fulmar	2.0	3.0	4.0	1.0	2.3	3.3	4.3	4.3	5.3	7.7	0.17
Murphy's Petrel	3.0	5.0	5.0	2.0	3.0	5.0	5.0	5.0	7.0	10.0	0.33
Mottled Petrel	2.0	4.0	5.0	2.0	1.7	3.7	5.0	3.7	5.7	11.0	0.25
Hawaiian Petrel	2.0	4.0	5.0	2.0	1.7	3.7	5.0	3.7	5.7	11.0	0.25
Cook's Petrel	2.5	4.5	5.0	2.0	2.3	4.3	5.0	4.3	6.3	11.0	0.29
Pink-footed Shearwater	1.0	3.0	5.0	2.0	1.0	3.0	5.0	3.0	5.0	11.0	0.17
Flesh-footed Shearwater	1.5	3.5	5.0	2.0	1.3	3.3	5.0	3.3	5.3	11.0	0.21
Buller's Shearwater	1.0	3.0	5.0	2.0	1.0	3.0	5.0	3.0	5.0	11.0	0.17
Sooty Shearwater	2.0	3.0	4.0	1.0	2.0	3.0	4.0	4.0	5.0	7.4	0.17
Short-tailed Shearwater	1.0	3.0	5.0	2.0	1.0	3.0	5.0	3.0	5.0	11.0	0.17
Manx Shearwater	2.0	3.0	4.0	1.0	2.0	3.0	4.0	4.0	5.0	9.0	0.17
Black-vented Shearwater	1.0	3.0	5.0	2.0	1.0	3.0	5.0	3.0	5.0	11.0	0.17
Wilson's Storm-Petrel	2.5	3.5	4.5	1.0	2.7	3.7	4.7	4.7	5.7	9.7	0.21
Fork-tailed Storm-Petrel	1.5	3.5	5.0	2.0	1.7	3.7	5.0	3.7	5.7	11.0	0.21
Leach's Storm-Petrel	2.5	3.5	4.5	1.0	2.7	3.7	4.7	4.7	5.7	8.1	0.21
Ashy Storm-Petrel	1.5	3.5	5.0	2.0	1.7	3.7	5.0	3.7	5.7	11.0	0.21
Black Storm-Petrel	1.5	3.5	5.0	2.0	1.7	3.7	5.0	3.7	5.7	11.0	0.21

(*continued on next page*)

Appendix Table A3 (*continued*)

Species name	Average Flight Activity			RSZt	*u*	MAc	*u*	Collision Vulnerability			
	Lower	Best	Upper					Lower	Best	Upper	Percent
Least Storm-Petrel	2.5	3.5	4.5	1.0	2.7	3.7	4.7	4.7	5.7	10.7	0.21
Brandt's Cormorant	1.0	2.0	4.0	2.0	1.0	1.7	3.7	4.0	7.7	12.7	0.42
Double-crested Cormorant	2.8	3.0	3.2	0.4	2.2	2.3	2.6	4.2	8.3	12.6	0.50
Pelagic Cormorant	1.0	2.0	4.0	2.0	1.0	1.7	3.7	4.0	7.7	12.7	0.42
American White Pelican	1.0	2.0	4.0	2.0	1.0	1.7	3.7	7.0	11.7	13.7	0.75
Brown Pelican	1.5	2.0	3.0	1.0	1.3	1.7	2.7	7.3	11.7	12.7	0.75
Red-necked Phalarope	1.0	2.5	4.5	2.0	1.0	2.3	4.3	3.0	6.3	12.3	0.29
Red Phalarope	1.0	3.0	5.0	2.0	1.0	3.0	5.0	3.0	7.0	13.0	0.33
South Polar Skua	1.5	2.5	4.0	2.0	1.3	2.0	3.7	7.3	12.0	13.7	0.79
Pomarine Jaeger	1.0	2.0	3.5	2.0	1.0	1.7	3.0	9.0	11.7	13.0	0.75
Parasitic Jaeger	2.0	3.0	4.0	2.0	1.7	2.3	3.7	9.7	12.3	13.7	0.83
Long-tailed Jaeger	2.5	3.0	3.5	1.0	2.0	2.3	3.0	10.0	12.3	13.0	0.83
Common Murre	1.0	1.5	3.5	2.0	1.0	1.7	3.7	3.0	3.7	8.1	0.04
Pigeon Guillemot	1.0	1.0	3.0	2.0	1.0	1.0	3.0	3.0	3.0	8.0	0.00
Marbled Murrelet	1.0	1.5	3.5	2.0	1.0	1.7	3.7	3.0	3.7	8.7	0.04
Scripps's Murrelet	1.0	1.5	3.5	2.0	1.0	1.7	3.7	3.0	3.7	8.7	0.04
Craveri's Murrelet	1.0	1.5	3.5	2.0	1.0	1.7	3.7	3.0	3.7	8.7	0.04
Ancient Murrelet	1.0	1.5	3.5	2.0	1.0	1.7	3.7	3.0	3.7	8.7	0.04
Cassin's Auklet	1.0	1.5	3.5	2.0	1.0	1.7	3.7	3.0	3.7	8.7	0.04
Parakeet Auklet	1.0	1.0	3.0	2.0	1.0	1.0	3.0	3.0	3.0	8.0	0.00
Rhinoceros Auklet	1.0	1.5	3.5	2.0	1.0	1.7	3.7	3.0	3.7	9.7	0.04
Horned Puffin	1.0	1.0	3.0	2.0	1.0	1.0	3.0	3.0	3.0	8.0	0.00
Tufted Puffin	1.0	1.0	3.0	2.0	1.0	1.0	3.0	3.0	3.0	8.0	0.00
Black-legged Kittiwake	2.0	3.0	4.0	1.0	2.0	3.0	4.0	7.0	9.0	12.0	0.50
Sabine's Gull	1.0	2.5	4.5	2.0	1.0	2.3	4.3	6.0	9.3	13.3	0.54
Bonaparte's Gull	1.0	2.5	4.5	2.0	1.0	2.3	4.3	6.0	9.3	13.3	0.54
Heermann's Gull	1.0	2.5	4.5	2.0	1.0	2.3	4.3	6.0	9.3	13.3	0.54
Mew Gull	1.0	2.5	4.5	2.0	1.0	2.3	4.3	6.0	9.3	13.3	0.54
Ring-billed Gull	1.0	3.0	5.0	2.0	1.0	3.0	5.0	6.0	10.0	14.0	0.58
Western Gull	1.0	3.0	5.0	2.0	1.0	3.0	5.0	6.6	9.0	13.0	0.50
California Gull	1.0	2.5	4.5	2.0	1.0	2.3	4.3	6.0	9.3	13.3	0.54
Herring Gull	1.5	2.5	4.0	2.0	1.7	2.7	4.0	7.3	9.7	13.0	0.54
Thayer's Gull	1.0	2.5	4.5	2.0	1.0	2.3	4.3	6.6	9.3	13.3	0.54
Glaucous-winged Gull	1.0	3.0	5.0	2.0	1.0	3.0	5.0	6.6	9.0	13.0	0.50
Least Tern	2.0	3.0	4.0	2.0	1.7	2.3	3.7	6.7	8.3	11.7	0.50
Gull-billed Tern	4.6	5.0	5.0	0.4	4.6	5.0	5.0	8.6	11.0	13.0	0.67
Caspian Tern	4.6	5.0	5.0	0.4	4.6	5.0	5.0	8.6	11.0	13.0	0.67
Black Tern	2.5	3.0	3.5	1.0	2.0	1.0	2.0	6.0	8.3	11.0	0.50
Common Tern	3.5	5.0	5.0	1.0	2.0	1.0	2.0	7.3	11.0	13.0	0.67
Arctic Tern	3.5	5.0	5.0	1.0	2.0	1.0	2.0	7.3	11.0	13.0	0.67
Forster's Tern	4.0	5.0	5.0	1.0	2.0	1.0	2.0	8.0	11.0	13.0	0.67
Royal Tern	3.0	4.0	5.0	1.0	2.0	1.0	2.0	7.0	10.0	13.0	0.58
Elegant Tern	2.5	4.5	5.0	1.0	2.0	1.0	2.0	6.3	10.3	13.0	0.63
Black Skimmer	1.0	3.0	5.0	1.0	2.0	1.0	2.0	5.0	9.0	13.0	0.50

Average Flight Activity, average of nocturnal flight activity (NFA) and diurnal flight activity (DFA; see Methods for description).
RSZt, percent time spent in rotor sweep zone.
MA, macro-avoidance.
u = uncertainty value (±).

Appendix Table A4
Best estimate values and uncertainties for each metric in the Displacement Vulnerability calculation and final Displacement Vulnerability (Best, Upper, Lower values, and Percent Rank of Best Value [used in Fig. 2]) for all species.

Species name (English)	MAd	*u*	HF	*u*	Displacement Vulnerability			
					Lower	Best	Upper	Percent
Brant	5.0	1.0	4.0	2.0	6.0	9.0	10.0	0.88
Common Merganser	4.0	2.0	1.0	1.0	3.0	5.0	7.0	0.38
Red-breasted Merganser	4.0	2.0	1.0	2.0	3.0	5.0	8.0	0.38
Harlequin Duck	5.0	1.0	4.0	0.4	7.6	9.0	9.4	0.88
Surf Scoter	5.0	1.0	4.0	2.0	6.0	9.0	10.0	0.88
White-winged Scoter	5.0	1.0	3.0	2.0	5.0	8.0	10.0	0.75
Black Scoter	5.0	1.0	4.0	2.0	6.0	9.0	10.0	0.88
Long-tailed Duck	5.0	1.0	4.0	0.4	7.6	9.0	9.4	0.88
Red-throated Loon	5.0	0.4	4.0	0.4	8.2	9.0	9.4	0.88
Pacific Loon	5.0	0.4	4.0	2.0	6.6	9.0	10.0	0.88
Common Loon	5.0	0.4	4.0	0.4	8.2	9.0	9.4	0.88
Yellow-billed Loon	5.0	0.4	4.0	2.0	6.6	9.0	10.0	0.88
Horned Grebe	5.0	2.0	4.0	0.4	6.6	9.0	9.4	0.88
Red-necked Grebe	5.0	2.0	3.0	0.4	5.6	8.0	8.4	0.75
Eared Grebe	5.0	2.0	3.0	2.0	4.0	8.0	10.0	0.75
Western Grebe	5.0	2.0	3.0	2.0	4.0	8.0	10.0	0.75
Clark's Grebe	5.0	2.0	3.0	2.0	4.0	8.0	10.0	0.75
Laysan Albatross	5.0	2.0	1.0	2.0	4.0	6.0	8.0	0.50
Black-footed Albatross	5.0	2.0	1.0	2.0	4.0	6.0	8.0	0.50
Short-tailed Albatross	5.0	2.0	1.0	2.0	4.0	6.0	8.0	0.50
Northern Fulmar	5.0	1.0	1.0	0.4	5.0	6.0	6.4	0.50
Murphy's Petrel	5.0	1.0	1.0	2.0	5.0	6.0	8.0	0.50
Mottled Petrel	5.0	2.0	1.0	2.0	4.0	6.0	8.0	0.50
Hawaiian Petrel	5.0	2.0	3.0	2.0	4.0	8.0	10.0	0.75
Cook's Petrel	5.0	2.0	1.0	2.0	4.0	6.0	8.0	0.50
Pink-footed Shearwater	5.0	2.0	1.0	2.0	4.0	6.0	8.0	0.50
Flesh-footed Shearwater	5.0	2.0	1.0	2.0	4.0	6.0	8.0	0.50
Buller's Shearwater	5.0	2.0	1.0	2.0	4.0	6.0	8.0	0.50
Sooty Shearwater	5.0	1.0	1.0	0.4	5.0	6.0	6.4	0.50
Short-tailed Shearwater	5.0	2.0	1.0	2.0	4.0	6.0	8.0	0.50
Manx Shearwater	5.0	1.0	1.0	0.4	5.0	6.0	6.4	0.50
Black-vented Shearwater	5.0	2.0	2.0	2.0	4.0	7.0	9.0	0.63
Wilson's Storm-Petrel	5.0	1.0	1.0	2.0	5.0	6.0	8.0	0.50
Fork-tailed Storm-Petrel	5.0	2.0	1.0	2.0	4.0	6.0	8.0	0.50
Leach's Storm-Petrel	5.0	1.0	1.0	0.4	5.0	6.0	6.4	0.50
Ashy Storm-Petrel	5.0	2.0	2.0	2.0	4.0	7.0	9.0	0.63
Black Storm-Petrel	5.0	2.0	1.0	2.0	4.0	6.0	8.0	0.50
Least Storm-Petrel	5.0	2.0	1.0	2.0	4.0	6.0	8.0	0.50
Brandt's Cormorant	3.0	2.0	2.0	0.4	2.6	5.0	7.4	0.38
Double-crested Cormorant	3.0	2.0	2.0	0.4	2.6	5.0	7.4	0.38
Pelagic Cormorant	3.0	2.0	2.0	0.4	2.6	5.0	7.4	0.38
American White Pelican	1.0	2.0	4.0	2.0	3.0	5.0	8.0	0.38
Brown Pelican	1.0	2.0	4.0	2.0	3.0	5.0	8.0	0.38
Red-necked Phalarope	3.0	2.0	2.0	1.0	2.0	5.0	8.0	0.38
Red Phalarope	3.0	2.0	2.0	1.0	2.0	5.0	8.0	0.38
South Polar Skua	1.0	2.0	2.0	2.0	2.0	3.0	7.0	0.13
Pomarine Jaeger	1.0	1.0	2.0	2.0	2.0	3.0	6.0	0.13
Parasitic Jaeger	1.0	1.0	2.0	0.4	2.6	3.0	4.4	0.13
Long-tailed Jaeger	1.0	1.0	2.0	2.0	2.0	3.0	6.0	0.13
Common Murre	5.0	0.4	3.0	0.4	7.2	8.0	8.4	0.75
Pigeon Guillemot	5.0	1.0	3.0	1.0	6.0	8.0	9.0	0.75
Marbled Murrelet	5.0	1.0	3.0	1.0	6.0	8.0	9.0	0.75
Scripps's Murrelet	5.0	1.0	4.0	1.0	7.0	9.0	10.0	0.88
Craveri's Murrelet	5.0	1.0	4.0	2.0	6.0	9.0	10.0	0.88
Ancient Murrelet	5.0	1.0	3.0	1.0	6.0	8.0	9.0	0.75
Cassin's Auklet	5.0	1.0	3.0	1.0	6.0	8.0	9.0	0.75
Parakeet Auklet	5.0	1.0	2.0	1.0	5.0	7.0	8.0	0.63

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Appendix Table A4 (*continued*)

Species name (English)	MAd	*u*	HF	*u*	Displacement Vulnerability			
					Lower	Best	Upper	Percent
Rhinoceros Auklet	5.0	2.0	3.0	1.0	5.0	8.0	9.0	0.75
Horned Puffin	5.0	1.0	3.0	1.0	6.0	8.0	9.0	0.75
Tufted Puffin	5.0	1.0	3.0	1.0	6.0	8.0	9.0	0.75
Black-legged Kittiwake	3.0	2.0	2.0	0.4	2.6	5.0	7.4	0.38
Sabine's Gull	3.0	2.0	2.0	1.0	2.0	5.0	8.0	0.38
Bonaparte's Gull	3.0	2.0	2.0	1.0	2.0	5.0	8.0	0.38
Heermann's Gull	3.0	2.0	1.0	2.0	2.0	4.0	8.0	0.25
Mew Gull	3.0	2.0	1.0	2.0	2.0	4.0	8.0	0.25
Ring-billed Gull	3.0	2.0	1.0	2.0	2.0	4.0	8.0	0.25
Western Gull	3.0	2.0	1.0	0.4	2.0	4.0	6.4	0.25
California Gull	3.0	2.0	1.0	2.0	2.0	4.0	8.0	0.25
Herring Gull	3.0	2.0	1.0	0.4	2.0	4.0	6.4	0.25
Thayer's Gull	3.0	2.0	1.0	2.0	2.0	4.0	8.0	0.25
Glaucous-winged Gull	3.0	2.0	1.0	1.0	2.0	4.0	7.0	0.25
Least Tern	5.0	2.0	3.0	2.0	4.0	8.0	10.0	0.75
Gull-billed Tern	5.0	2.0	2.0	2.0	4.0	7.0	9.0	0.63
Caspian Tern	5.0	2.0	3.0	2.0	4.0	8.0	10.0	0.75
Black Tern	5.0	2.0	3.0	1.0	5.0	8.0	9.0	0.75
Common Tern	5.0	2.0	3.0	0.4	5.6	8.0	8.4	0.75
Arctic Tern	5.0	2.0	3.0	0.4	5.6	8.0	8.4	0.75
Forster's Tern	5.0	2.0	3.0	2.0	4.0	8.0	10.0	0.75
Royal Tern	5.0	2.0	3.0	2.0	4.0	8.0	10.0	0.75
Elegant Tern	5.0	2.0	4.0	2.0	5.0	9.0	10.0	0.88
Black Skimmer	5.0	2.0	4.0	2.0	5.0	9.0	10.0	0.88

MA, macro-avoidance.
HF, habitat flexibility.
u, uncertainty value (±).

References

ABC, 2012. American bird conservancy list of the birds of the United States with conservation rankings. http://shop.abcbirds.org/abcprograms/science/conservationchecklist/index.html, Accessed date: 17 December 2015.

Adams, J., Felis, J., Mason, J.W., Takekawa, J.Y., 2014. Pacific Continental Shelf Environmental Assessment (PaCSEA): aerial seabird and marine mammal surveys off norhter California, Oregon, and Washington, 2011-2012. U.S. Dept. of the Interior, Bureau of Ocean Energy Mangement, Pacific OCS Region, Camarillo, CA, pp. 266 OCS Study BOEM 2014-003.

Ainley, D.G., Boekelheide, R.J., Morrell, S.H., Strong, C.S., 1990. Cassin's auklet. In: Ainley, D.G., Boekelheide, R.J. (Eds.), Seabirds of the Farallon Islands. Ecology, Dynamics, and Structure of an Upwelling-System Community Stanford University Press, Stanford, CA, pp. 306–338.

Ainley, D.G., 1995. Ashy storm-petrel (oceanodroma homochroa). In: Poole, A. (Ed.), The Birds of North America, Cornell Lab of Ornithology, https://doi.org/10.2173/bna.185. Ithaca, New York. http://bna.birds.cornell.edu/bna/species/185, Accessed date: 17 December 2015.

Ainley, D., Porzig, E., Zajanc, D., Spear, L.B., 2015. Seabird flight behavior and height in response to altered wind strength and direction. Mar. Ornithol. 43, 25–36.

Baird, P.H., 1990. Concentrations of seabirds at oil-drilling rigs. Condor 92, 768–771. https://www.jstor.org/stable/1368697.

Band, B., 2012. Using a Collision Risk Model to Assess Bird Collision Risks for Offshore Wind Farms: Strategic Ornithological Support Services. The Crown Estate, London, United Kingdom. http://www.bto.org/sites/default/files/u28/downloads/Projects/Final_Report_SOSS02_Band1ModelGuidance.pdf, Accessed date: 17 December 2015.

Birdlife International, 2014. IUCN Red List for Birds. http://www.Birdlife.org, Accessed date: 9 March 2014.

Birt, T.P., Carter, H.R., Whitworth, D.L., McDonald, A., Newman, S.H., Gress, F., Palacios, E., Koepke, J.S., Friesen, V.L., 2012. range wide population genetic structure of Xantus's Murrelet (Synthliboramphus hypoleucus). Auk 129, 44–55.

Blew, J., Hoffmann, M., Nehls, G., Hennig, V., 2008. Part I: Birds. Investigations of the Bird Collision Risk and the Responses of Harbour Porpoises in the Offshore Wind Farms Horns Rev, North Sea, and Nysted, Baltic Sea, in Denmark. Universität Hamburg, Hamburg, Germany.

Bradbury, G., Trinder, M., Furness, B., Banks, A.N., Caldow, R.W.G., Hume, D., 2014. Mapping seabird sensitivity to offshore wind farms. PLoS One 9 (9), e106366. http://doi.org/10.1371/journal.pone.0106366.

Brahman, M., Miller, T., Duerr, A.E., Lanzone, M., Fesnock, A., LaPre, L., Driscoll, D., Katzner, T., 2015. Home in the heat: dramatic seasonal variation in home range of desert golden eagles informes management ofor renewable energy develoipent. Biol. Conserv. 186, 225–232.

Briggs, K.T., Chu, E.W., Tyler, W.B., Lewis, D.B., Pitman, R.L., Hunt Jr., G.L., 1981. Distribution, Numbers, and Seasonal Status of Seabirds of the Southern California Bight (1975–1978). Pacific OCS Region Minerals Management Service. U.S. Department of the Interior.

Briggs, K.T., Tyler, W.B., Lewis, D.B., Bettman, K.F., 1983. Seabirds of Central and Northern California 1980–1983: Status, Abundance, and Distribution. Pacific OCS Region Minerals Management Service. U.S. Department of the Interior.

Briggs, K.T., Tyler, W.B., Lewis, D.B., Carlson, D.R., 1987. Bird communities at sea off California: 1975 to 1983. Stud. Avian Biol. 11.

Briggs, K.T., Varoujean, D.H., Williams, W.W., Ford, R.G., Bonnell, M.L., Casey, J.L., 1992. Chapter 3: seabirds of the Oregon and Washington OCS, 1989–1990. In: Brueggeman, J.J. (Ed.), Oregon and Washington Marine Mammal and Seabird Surveys. Final Report, OCS MMS 91–0093. Pacific OCS Region, Minerals Management Service, U.S. Department of the Interior, Los Angeles, CA 164 pp.

Burke, C.M., Montevecchi, W.A., Wiese, F.K., 2012. Inadequate environmental monitoring around offshore oil and gas platforms on the Grand Bank of Eastern Canada: are risks to marine birds known? J. Environ. Manag. 104, 121–126. http://doi.org/10.1016/j.jenvman.2012.02.012.

Busch, M., Garthe, S., 2016. Approaching population thresholds in presence of uncertainty: assessing displacement of seabirds from offshore wind farms. Environ. Impact Assess. Rev. 56, 31–42.

California Department of Fish and Wildlife, 2015. Threatened and endangered birds. https://www.dfg.ca.gov/wildlife/nongame/t_e_spp/bird.html, Accessed date: 10 December 2015.

Checkley Jr., D.M., Barth, J.A., 2009. Patterns and processes in the California current System. Prog. Oceanogr. 28, 49–64. https://doi.org/10.1016/j.pocean.2009.07.028.

Chesser, R.T., Banks, R.C., Barker, F.K., Cicero, C., Dunn, J.L., Kratter, A.W., Lovette, I.J., Rasmussen, P.C., Remsen Jr., J.V., Rising, J.D., Stotz, D.F., Winker, K., 2012. Fifty-third supplement to the American ornithologists' union check-list of North American birds. The Auk 129 (3), 573–588.

Cleasby, I.R., Wakefield, E.D., Bearhop, S., Bodey, T.W., Votier, S.C., Hamer, K.C., 2015. Three-dimensional tracking of a wide-ranging marine predator: flight heights and vulnerability to offshore wind farms. J. Appl. Ecol. 52, 1474–1482. http://doi.org/10.1111/1365-2664.12529.

Clements, J.F., Schulenberg, T.S., Iliff, M.J., Roberson, D., Fredericks, T.A., Sullivan, B.L., Wood, C.L., 2015. The eBird/Clements checklist of birds of the world: v2015. Downloaded from http://www.birds.cornell.edu/clementschecklist/download/.

Cook, A.S.C.P., Humphreys, E.M., Masden, E.A., Burton, N.H.K., 2014. The Avoidance Rates of Collision between Birds and Offshore Turbines, vol. 5 Aberdeen, Scotland.

Corman, A.-M., Garthe, S., 2014. What flight heights tell us about foraging and potential conflicts with wind farms: a case study in Lesser Black-backed Gulls (Larus fuscus). J. Ornithol. 155 (4), 1037–1043.

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

del Hoyo, J., Elliott, A., Sargatal, J., 1992. Handbook of the Birds of the World, vol. 1 Ostrich to Ducks. Lynx Edicions, Barcelona.

del Hoyo, J., Elliott, A., Sargatal, J., 1996. Handbook of the Birds of the World, vol. 3 Hoatzin to Auks. Lynx Edicions, Barcelona.

Desholm, M., 2009. Avian sensitivity to mortality: prioritizing migratory bird species for assessment at proposed wind farms. J. Environ. Manag. 90 (8), 2672–2679. http://doi.org/10.1016/j.jenvman.2009.02.005.

Dierschke, V., Furness, R.W., Garthe, S., 2016. Seabirds and offshore wind farms in European waters: avoidance and attraction. Biol. Conserv. 202, 59–68. https://doi.org/10.1016/j.biocon.2016.08.016.

eBird, 2015. eBird: an Online Database of Bird Distribution and Abundance. eBird, Ithaca, New York. http://www.ebird.org, Accessed date: 2 February 2015.

Furness, B., Wade, H., 2012. Vulnerability of Scottish Seabirds to Offshore Wind Turbines. MacAuthor Green Ltd, Glasgow, Scotland.

Furness, R.W., Wade, H.M., Masden, E.A., 2013. Assessing vulnerability of marine bird populations to offshore wind farms. J. Environ. Manag. 119, 56–66.

Garthe, S., Hüppop, O., 2004. Scaling possible adverse effects of marine wind farms on seabirds: developing and applying a vulnerability index. J. Appl. Ecol. 41, 724–734. http://doi.org/10.1111/j.0021-8901.2004.00918.x.

Guy, T.J., Jennings, S.L., Suryan, R.M., Melvin, E.F., Bellman, M.A., Ballance, L.T., Blackie, B.A., Croll, D.A., Deguchi, T., Geernaert, T.O., Henry, R.W., 2013. Overlap of North Pacific albatrosses with the US west coast ground fish and shrimp fisheries. Fish. Res. 147, 222–234.

Hamer, T., Reed, M., Colclazier, E., Turner, K., Denis, N., 2014. Nocturnal Surveys for Ashy Storm-petrels (Oceanodroma Homochroa) and Scripps's Murrelets (Synthliboramphus Scrippsi) at Offshore Oil Production Platforms, Southern California. OCS Study BOEM 2014-013. US Dept. of the Interior, Bureau of Ocean Energy Management, Pacific OCS Region, Camarillo, CA, pp. 62.

Hüppop, O., Hüppop, K., Dierschke, J., Hill, R., 2016. Bird collisions at an offshore platform in the North Sea. Hous. Theor. Soc. 63, 73–82.

Hyrenbach, K.D., Forney, K.A., Dayton, P.K., 2000. Marine protected areas and ocean basin management. Aquat. Conserv. Mar. Freshw. Ecosyst. 10, 437–458.

International Union for Conservation of Nature, 2014. Red list of threatened species. http://www.iucnredlist.org/, Accessed date: 27 August 2014.

Johnston, A., Cook, A.S.C.P., Wright, L.J., Humphreys, E.M., Burton, N.H.K., 2014. Modelling flight heights of marine birds to more accurately assess collision risk with offshore wind turbines. J. Appl. Ecol. 51, 31–41. http://doi.org/10.1111/1365-2664.12191.

Krijgsveld, K.L., Akershoek, K., Schenk, F., Dijk, F., Dirksen, S., 2009. Collision risk of birds with modern large wind turbines. Ardea 97, 357–366.

Krijgsveld, K.L., Fijn, R.C., Japink, M., van Horssen, P.W., Heunks, C., Collier, M.P., Poot, M.J.M., Beuker, Dirksen, S., 2011. Effect Studies Offshore Wind Farm Egmond aan Zee: Final Report on Fluxes, Flight Altitudes and Behaviour of Flying Birds, vol. 5027 IJmuiden, Netherlands.

Leopold, M., Dijkman, E., Teal, L., 2011. Local Birds in and Around the Offshore Wind Farm Egmond aan Zee (OWEZ T-0 and T-1, 2002-2010). IMARES—Institute for Marine Resources and Ecosystem Studies No. C187/11. IMARES, 2011.

Manuwal, D.A., 1972. The Population Ecology of Cassin's Auklet on Southeast Farallon, California. Ph. D. Thesis. Univ. of California, Los Angeles.

Marques, A.T., Batalha, H., Rodrigues, S., Costa, H., Pereira, M.J.R., Fonseca, C., Mascarenhas, M., Bernardino, J., 2014. Understanding bird collisions at wind farms: an updated review on the causes and possible mitigation strategies. Biol. Conserv. 179, 40–52. http://doi.org/10.1016/j.biocon.2014.08.017.

Masden, E.A., Fox, A.D., Furness, R.W., Bullman, R., Haydon, D.T., 2010. Cumulative impact assessments and bird/wind farm interactions: developing a conceptual framework. Environ. Impact Assess. Rev. 30, 1–7. http://doi.org/10.1016/j.eiar.2009.05.002.

Masden, E.A., McCluskie, A., Owen, E., Langston, R.H.W., 2014. Renewable energy developments in an uncertain world: the case of offshore wind and birds in the UK. Mar. Pol. 51, 169–172. http://doi.org/10.1016/j.marpol.2014.08.006.

Masden, E.A., Cook, A.S.C.P., 2016. Avian collision risk models for wind energy impact assessments. Environ. Impact Assess. Rev. 56, 43–49. https://doi.org/10.1016/j.eiar.2015.09.001.

Mason, J.W., McChesney, G.J., McIver, W.R., Carter, H.R., Takekawa, J.Y., Golightly, R.T., Ackerman, J.T., Orthmeyer, D.L., Perry, W.M., Yee, J.L., Pierson, M.O., 2007. At-sea distribution and abundance of seabirds off southern California: a 20-Year comparison. Cooper Ornithologi. Soc. Stud. Avian Biol. 33.

Mendel, B., Kotzerka, J., Sommerfeld, J., Schwemmer, H., Sonntag, N., Garthe, S., 2014. Effects of the Alpha Ventus Offshore Test Site on Distribution Patterns, Behavior, and Flight Heights of Seabirds. Federal Ministry for the Environment, Nature Conservation and Nuclear Safetyhttps://doi.org/10.1007/978-3-658-02462-8_11.

Musial, W., Ram, B., 2010. Large-scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers. National Renewable Energy Laboratory (Golden, Colorado).

Nevins, H., Adams, J., Moller, H., Newman, J., Hester, M., Hyrenbach, K.D., 2009. International and cross-cultural management in conservation of migratory species. J. Roy. Soc. N. Z. 39, 183–185. http://doi.org/10.1080/03014220909510576.

Oregon Department of Fish and Wildlife, 2014. Threatened, Endangered, and Candidate Fish and Wildlife Species: OAR 635-100-0105. http://www.dfw.state.or.us/wildlife/diversity/species/docs/Threatened_and_Endangered_Species.pdf, Accessed date: 28 July 2014.

Perrow, M.R., Gilroy, J.J., Skeate, E.R., Tomlinson, M.L., 2011. Effects of the construction of Scorby Sands offshore wind farm on its prey base of little tern sternula albiforns at tis most imporatant UK colony. Mar. Pollut. Bull. 62, 1661–1670.

Peterson, I.K., Christensen, T.K., Kahlert, J., Desholm, M., Fox, A.D., 2006;al.,. Final Results of Bird Studies at the Offshore Wind Farms at Nysted and Horns Rev, Denmark. Ministry of the Environment Research Institute, Denmark.

Plonczkier, P., Simms, I.C., 2012. Radar monitoring of migrating pink-footed geese: behavioral responses to offshore wind farm development. J. Appl. Ecol. 49, 1187–1194. http://doi.org/10.1111/j.1365-2664.2012.02181.x.

Robinson Willmott, J.R., Forcey, G., Kent, A., 2013. The Relative Vulnerability of Migratory Bird Species to Offshore Wind Energy Projects on the Atlantic Outer Continental Shelf: an Assessment Method and Database. OCS Study BOEM 2013-207. Final Report to the U.S. Department of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs 275 pp.

Ronconi, R.A., Allard, K.A., Taylor, P.D., 2014. Bird interactions with offshore oil and gas platforms: review of impacts and monitoring techniques. J. Environ. Manag. 147C, 34–45. http://doi.org/10.1016/j.jenvman.2014.07.031.

Ross-Smith, V.H., Thaxter, C.B., Masden, E.A., Shamoun-Baranes, J., Burton, N.H.K., Wright, L.J., Rehfisch, M.M., Johnston, A., 2016. Modelling flight heights of lesser black-backed gulls and Great skuas from GPS: a bayesian approach. J. Appl. Ecol. https://doi.org/10.1111/1365-2664.12760.

Sæther, B., Ringsby, T.H., Røskaft, E., 1996. Life history variation, population processes and priorities in species conservation: towards a reunion of research paradigms. OIKOS 77, 217–226.

Shuford, W.D., Gardali, T., 2008. California Bird Species of Special Concern—a Ranked Assessment of Species, Subspecies, and Distinct Populations of Birds of Immediate Conservation Concern in California—Studies of Western Birds, 1st Edition. Western Field Ornithologists and California Department of Fish and Game.

Stienen, E.W.M., Waeyenberge, V., Kuijken, E., Seys, J., 2007. Chapter 3: trapped within the corridor of the southern North Sea. In: de Lucas, M., Janss, G.F.E., Ferrer, M. (Eds.), The Potential Impact of Offshore Wind Farms on Seabirds. Birds and Wind Farms, Belgium, pp. 71–80.

Takekawa, J.Y., Perry, W.M., Adams, J., Williams, L.L., Yee, J.L., Orthmeyer, D.L., Mason, J.W., McChesney, G.J., McIver, W.R., Carter, H.R., Golightly, R.T., 2008. Spatial Database for the At-sea Distribution and Abundance of Seabirds and Marine Mammals off Southern California: 1999–2002. Western Ecological Research Center, Dixon and Vallejo, CA and Humboldt State University, Arcata, CA. U. S Minerals Management Service Study Profile #2008-039. https://www.sciencebase.gov/catalog/item/57c75faae4b0f2f0cebed52e, Accessed date: 13 September 2015.

Thaxter, C.B., Ross-Smith, V.H., Bouten, W., Clark, N.A., Conway, G.J., Rehfisch, M.M., Burton, N.H.K., 2015. Seabird–wind farm interactions during the breeding season vary within and between years: a case study of lesser black-backed gull Larus fuscus in the UK. Biol. Conserv. 186, 347–358.

Trident Winds LLC, 2016. Unsolicited Application for an Outer Continental Shelf Renewable Energy Commercial Lease under 30 CFR 585.230: Morro Bay Offshore, a Trident Winds' Project. Company # 15055, Public Version. http://www.boem.gov/MBO-Unsolicited-OCS-Lease-Request/, Accessed date: 8 August 2016.

Tucker, V.A., 1996. A mathematical model of bird collisions with wind turbine rotors. J. Sol. Energy Eng. 118, 256–269.

U.S. Fish and Wildlife Service, 2012. Birds of Conservation Concern: U.S. Fish and Wildlife Migratory Bird Program. https://www.fws.gov/birds/management/managed-species/birds-of-conservation-concern.php, Accessed date: 14 October 2015.

U.S. Fish and Wildlife Service, 2014a. Endangered Species. Available online. http://www.fws.gov/endangered/index.html, Accessed date: 29 July 2014.

U.S. Fish and Wildlife Service, 2014b. Short-tailed Albatross (Phoebastria Albatrus) 5-Year Review: Summary and Evaluation. Anchorage, Alaska. 42 pp. Available online. https://www.st.nmfs.noaa.gov/Assets/nationalseabirdprogram/doc4445.pdf, Accessed date: 9 April 2018.

Vanermen, N., Onkelinx, T., Courtens, W., Van de walle, M., Verstraete, H., Stienen, E.W.M., 2014. Seabird avoidance and attraction at an offshore wind farm in the Belgian part of the North Sea. Hydrobiologia. http://doi.org/10.1007/s10750-014-2088-x.

Wade, H.M., Masden, E.A., Jackson, A.C., Furness, R.W., 2016. Incorporating data uncertainty when estimating potential vulnerability of Scottish seabirds to marine renewable energy developments. Mar. Pol. 70, 108–113. http://doi.org/10.1016/j.marpol.2016.04.045.

Washington Department of Fish and Wildlife, 2015. Species of concern. http://wdfw.wa.gov/conservation/endangered/birds.html, Accessed date: 8 January 2016.