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Identifying marine Important Bird Areas using at-sea survey data

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ABSTRACT

Effective marine bird conservation requires identification of at-sea locations used by populations for foraging, staging, and migration. Using an extensive database of at-sea survey data spanning over 30 years, we developed a standardized and data-driven spatial method for identifying globally significant marine Important Bird Areas in Alaska. To delineate these areas we developed a six-step process: binning data and accounting for unequal survey effort, filtering input data for persistence of species use, using a moving window analysis to produce maps representing a gradient from low to high abundance, drawing core area boundaries around major concentrations based on abundance thresholds, validating the results, and combining overlapping boundaries into important areas for multiple species. We identified 126 bird core areas which were merged into 59 pelagic sites important to 45 out of 57 species assessed. The final areas included approximately 34–38% of all marine birds in Alaska waters, within just 6% of the total area. We identified globally significant Important Bird Areas spanning 20 degrees of latitude and 56 degrees of longitude, in two different oceans, with climates ranging from temperate to polar. Although our maps did suffer from some data gaps, these gaps did not preclude us from identifying sites that incorporated 13% of the assessed continental waterbird population and 9% of the assessed global seabird population. The application of this technique over a large and productive region worked well for a wide range of birds, exhibiting a variety of foraging strategies and occupying a variety of ecosystem types.

1. Introduction

Effective marine bird conservation requires identification and appropriate management of locations at sea that serve necessary life cycle functions, such as foraging, staging, and migration. Ever-increasing anthropogenic demands on natural resources have amplified the need to identify and conserve important ecosystem functions and habitat for birds at sea. Compared with the other nations of the world, the USA supports the highest number of marine bird species, the second highest number of endemic breeding marine birds, and the third highest number of marine bird species of conservation concern, making it the highest priority among nations for marine bird conservation (Croxall et al., 2012). Alaska, the largest state in the USA, arguably offers some of the greatest opportunities for marine bird conservation worldwide. Alaska hosts more than 70 (~20%) of the world's seabird species and about 87% of the USA's nesting seabirds (US Fish and Wildlife Service, 2008).

Identification of important areas for marine birds has been attempted in a variety of ways, through different programs. Several recent seabird studies have focused on the theme of important areas for seabirds (Amorim et al., 2009; Louzao et al., 2009; BirdLife International, 2010; Arcos et al., 2012; Lascelles et al., 2012; Oppel et al., 2012). Important areas can be designated under a number of different terms, each with particular meaning. Important Bird Areas (IBAs) are based on an established program that uses standardized criteria to identify essential habitats for birds (BirdLife International, 2012; National Audubon Society, 2012b). IBAs are defined as places that hold a significant proportion of the population of one or more bird species, as evidenced by documented, repeated observation of significant congregations in an area. Areas important to marine birds constitute valuable

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information toward marine conservation efforts, as they can be indicative of productivity hotspots for a diversity of life, including primary producers, invertebrates, fish, and/or marine mammals (Piatt and Springer, 2003; Piatt et al., 2007; Parsons et al., 2008; Suryan et al., 2012).

There are no explicit restrictions on human use or development attached to IBA designations. Marine protected areas (MPAs), Ecologically and Biologically Significant Areas (EBSAs), or Particularly Sensitive Sea Areas (PSSAs), in contast, often incorporate binding restrictions on commercial and/or recreational activities, including fishing, boating, and oil and gas development. IBAs can provide a starting point for establishing legal protections, such as MPAs, EBSAs, or PSSAs because they are established using observational data and use standardized global criteria (Nur et al., 2011; Lascelles et al., 2012; Montevecchi et al., 2012; Ronconi et al., 2012). Likewise, IBA information can be utilized in regional to global applications, such as environmental assessment, designing best management practices, or broad-scale integrative marine spatial planning.

Currently, IBA criteria require a certain abundance of a species to trigger nomination of a site (e.g. 1% or more of the global population), but there are no specific rules on how the IBA boundaries should be spatially defined. The criteria do not prescribe what concentration of a species over an area is considered important, how to draw core area boundaries, or how to rectify overlapping important areas for multiple species in multiple seasons. Establishing spatial criteria for delineating important areas for Alaska's seabirds is an important step toward the conservation of populations of global concern. Our objective was to develop widely applicable spatial methods that delineate important areas for marine birds using at-sea survey data.

1.1. Identifying important areas for seabirds

There has been much effort applied to identifying important areas at sea for birds. The types of efforts can be broadly classified as (1) expert-drawn boundaries, (2) a buffer of some distance around known colonies based on foraging ranges, (3) predictive models of where birds are likely to congregate, and (4) abundance mapping estimated from direct observations on at-sea surveys.

Before the proliferation and accessibility of spatial analysis tools, expert consultation was the primary method used to draw boundaries around core areas. Although these expert-derived boundaries were based on areas of known species persistence, in some applications this method has yielded only moderately accurate overlap with the most biologically important areas (Cowling et al., 2003; Brown et al., 2004; O'Dea et al., 2006). Furthermore, the results were not strictly repeatable by different experts.

More rigorous spatial approaches use band resighting, satellite transmitters, and geolocators to derive information on the foraging ranges of colonial birds. Lascelles (2008) summarized the available information for marine bird species into a foraging distance database. This information has been used to broadly define the seaward extension of specific bird colonies into the marine environment by buffering those colonies based on mean or maximum foraging distances of the species present (Yorio, 2009; Thaxter et al., 2012). The colony buffer approach has been useful as a starting point for defining core areas (especially when other survey data are not available), and can be further refined by additional data on marine habitat use (BirdLife International, 2010). However, even where foraging distance data for a given species are extensive, the foraging distances are often highly variable from colony to colony, making it difficult to employ this method in areas not directly represented by foraging studies. In other instances, colonies and the primary foraging areas may be disjunct. Furthermore, colony-based methods do not account for long-distance foragers, migrants, or non-breeding members of populations.

A popular trend is to spatially relate seabird–environment interactions to produce predictive models of seabird use (Tremblay et al., 2009). These techniques use seabird survey or tracking data to relate locational information to associated environmental covariates, then identify known and predicted hotspots on a species by species basis (Yen et al., 2005; Piatt et al., 2006; Yen et al., 2006; Louzao et al., 2009; Louzao et al., 2011; Nur et al., 2011). Another closely related approach is to identify ecological hotspots based on one or more physical and/or biological attributes of the seascape, such as sea surface temperature (Etnoyer et al., 2004; O'Hara et al., 2006), salinity, prey distribution, bathymetry, or chlorophyll, then test those areas for significance to individual species or species groups using survey data (O'Hara et al., 2006; Palacios et al., 2006; Tremblay et al., 2009; Suryan et al., 2012). These data-intensive approaches work well when studying a limited number of species, in areas with extensive marine habitat data. Predictive models are a valuable tool, but are time intensive, species-specific, and/or landscape-specific, making them difficult to implement across multiple species guilds and marine ecoregions, such as the case in Alaska.

Our approach to IBA delineation focuses on at-sea surveys. At-sea surveys provide a measure of density across pelagic zones which is necessary for locating offshore concentration areas for non-colonial species, non-breeding birds during the breeding season, and wintering birds. Standard IBA criteria favor estimating IBAs based on estimates derived from observational data rather than predicted data. Analyzing at-sea survey data offers advantages over the alternative methods in that it does not require knowledge of specific use patterns by individual birds at individual colonies, or of the underlying functional relationships that cause birds to forage when and where they do. Often at-sea survey data are analyzed to produce maps indicating the relative importance of locations for a species or guild represented by a gradient map. Gradient mapping facilitates interpretation of hotspot distribution which can be visualized in multiple ways (e.g. natural breaks, isopleths, quantiles). To create gradient maps, kernel density estimation can be used to smooth survey data, or spatial interpolation (e.g. kriging) can be used to both smooth data and predict density across unsurveyed areas between transects (Skov et al., 2007; Kober et al., 2010). Here we suggest the use of a moving window to summarize and smooth survey data into "neighborhood" abundance gradient maps which can be translated into IBA thresholds.

1.2. Delineating important area boundaries

Although there are specific criteria describing the number of birds required to establish an IBA (National Audubon Society, 2012a), the area over which those birds might occur is undefined. Currently, IBAs reflect geopolitical boundaries, physiographic boundaries, study area boundaries, or habitat-type boundaries. In contrast, boundaries for terrestrial IBAs are typically recognizable by physical features (e.g. mountain ridges, river bottoms) and relatively static.

We know that marine waters are not uniformly valuable to birds; however, defining specific areas that are important for conservation has been challenging. The marine environment has greater ecological connectivity with fewer distinguishing surface features relative to the terrestrial landscape (Carr et al., 2003) which can make identifying boundaries more difficult. Food resources exploitable by marine birds are patchy and ephemeral, shifting between years, seasons, months, and even days (Hyrenbach et al., 2000; Gaston, 2004; Palacios et al., 2006; Weimerskirch, 2007). The lack of physical barriers in marine systems means that the spatial scales describing them may be much larger than terrestrial areas in order to encompass globally significant numbers of birds and their required habitat resources (Hyrenbach et al., 2000; Yorio, 2009; Rice and Houston, 2011). At present, there are no marine or terrestrial IBA guidelines for how intensive the sampling must be, or over what size area the sample density can be applied, to qualify an area as important.

Due to the complexities and error associated with ecological modeling and prediction for species conservation, especially for a large group of species with very different ranges and abundances (Guisan and Zimmermann, 2000; Rocchini et al., 2011), the optimal situation would be a complete census of species locations and abundances over the time period of interest. Given logistical and financial constraints, this is impossible. Even if the perfect dataset were available, drawing important-area boundaries would remain a challenge and a ruleset would be needed. A suitable method should be robust enough to accommodate multiple species, different foraging guilds with different habitat requirements, and concentrated or dispersed populations. Finally, the method should be as parsimonious as possible to meet these goals.

1.3. Study area

Our study area was the USA Exclusive Economic Zone (EEZ) surrounding the State of Alaska, or about 3.71 million km^2. The study area includes both the Pacific and Arctic oceans, from 47.9° to 74.7° north latitude, and from 130.5° west longitude, across the international dateline to 167.6° east longitude. The study area includes five large marine ecosystems: Gulf of Alaska, East Bering Sea, West Bering Sea, Chukchi Sea, and Beaufort Sea (Sherman et al., 2009). This includes temperate areas from the narrow fjords of Southeast Alaska's Inside Passage to the vast Gulf of Alaska; sub-Arctic areas from the very deep open ocean south of the Aleutian Islands north across the continental shelf and shelf edge waters of the Bering Sea; and into seasonally ice-covered Arctic waters north of the Bering Strait in the Chukchi and Beaufort seas.

2. Methods

Development of these methods involved exploring and testing a variety of spatial analysis approaches to identify the most effective workflow for delineating important areas for birds at sea with commonly used software: ArcGIS 10, Spatial Analyst, and ModelBuilder (ESRI, 2011). Issues involved rectifying survey effort; delineating persistent, high-use areas; smoothing data to avoid overfitting or overgeneralization; identifying areas that will be meaningful in a conservation context; and making our methods regionally to globally applicable. We analyzed IBAs for marine birds in two categories: waterbirds and seabirds. Waterbirds included loons (Gaviidae), grebes (Podicipedidae), cormorants (Phalacrocoracidae), sea ducks/geese/eiders/mergansers (Anatidae), phalaropes (Scolopacidae), and jaegers/gulls/terns (Laridae). Seabirds included albatrosses (Diomedeidae), fulmars/shearwaters (Procellariidae), storm-petrels (Hydrobatidae), and auks/murres/puffins (Alcidae).

Several criteria define the abundance of birds that can trigger IBA status. We applied the A4 criteria to marine birds: places that regularly hold more than 1% of the continental population of a congregatory waterbird species (A4i), or more than 1% of the global population of a congregatory seabird species (A4ii) (National Audubon Society, 2012a). Throughout this process we tended to favor decisions that made it more difficult to achieve IBA status; we felt that a stricter approach would best serve future management and conservation efforts. We focused on the A4 IBA criteria because, with Alaska's very high marine bird abundances, these criteria are the most stringent and therefore likely to result in the identification of IBAs of greatest importance.

We used at-sea survey data from the North Pacific Pelagic Seabird Database, version 2 (NPPSD) (Drew and Piatt, 2013). The NPPSD is a compilation of bird surveys covering the northern Pacific Ocean, including data from Japan, Russia, the USA, and Canada, with survey emphasis on the United States EEZ. The database included 301,406 transect locations that reported bird density data derived from at-sea surveys. The NPPSD is comprised of surveys conducted by dozens of organizations and hundreds of different observers using a wide variety of observation platforms over a 40 year period. While census protocols were generally similar among studies—mostly employing strip survey methods from large vessels—there were some protocol differences that contributed variability to the results (e.g. transect length, strip width, whether flying birds were counted continuously or in snapshots, etc.), as well as changing environmental conditions such as sea state and visibility that affect species-specific detection rates (Ronconi and Burger, 2009). These factors contribute unknown measurement error, for which we did not correct.

Our analysis focused on 57 marine bird species in Alaska sufficiently represented in the spatial data to generate IBAs (Table 1). For the identification of IBAs, we only used data for birds identified to species, which left out a large portion of data for some birds identified only to genus; this lowered our abundance estimates considerably for some species, particularly murres and shearwaters (for which 61% and 43% of all observations, respectively, were not identified to species).

To delineate important areas for marine birds, we followed a six-step process: (1) accounting for survey effort, (2) filtering input data for persistence, (3) producing abundance gradient maps, (4) drawing core area boundaries around major concentrations, (5) validating the results, and (6) combining overlapping boundaries into important areas for multiple species.

2.1. Step 1: Survey effort and bin size

To account for variability in survey effort, we used only on-transect surveys covering an area greater than 0.2 km^2, resulting in 125,683 survey transects within the study area collected between 1974 and 2009. We split observations into summer (May through September) and winter (October through April) seasons.

We required a bin size large enough to capture multiple survey samples in order to average density values, but not so large as to oversimplify the data or excessively inflate abundance estimates, which are derived by applying the mean density across the whole of the bin. We tested a range of bin sizes from 1×1 km to 100×100 km and selected 10×10 km bins, hereafter referred to as 100-km^2 bins, as the smallest bin size that would regularly include multiple overlapping surveys for summarizing densities. Additionally, Burger et al. (2008) found that alcids tend to aggregate in 1- to 11-km radius patches, and the 10×10 km bin size was found by Renner et al. (2012) to minimize spatial autocorrelation between measurements of oceanic variables.

We summarized data for all regularly occurring Alaskan species during each season in 100-km^2 bins. For each bin we calculated the number of surveys, number of different years a species was detected, and the mean density for each species. We included zero counts (absences) when computing the mean density. Fig. A1 showing survey effort across the study area can be found in the online supplemental material, Appendix A.

2.2. Step 2: filtering input data for persistence

We defined marine bird hotspots as areas in which significant aggregations of a species occur repeatedly. We translated this hotspot definition into spatial analysis parameters to identify areas of persistence (repeated presence in an area in multiple years) and

Table 1

Species code, common name, scientific name, and global Important Bird Area (IBA) threshold for 57 Alaskan marine bird species assessed.

Species code	Common name	Scientific name	Criteria[a]	IBA threshold[a]	Season analyzed[b]
ALTE	Aleutian Tern	*Onychoprion aleuticus*	A4i	160	Su
ANMU	Ancient Murrelet	*Synthliboramphus antiquus*	A4ii	10,000	Su
ARTE	Arctic Tern	*Sterna paradisaea*	A4i	10,000	Su
BAGO	Barrow's Goldeneye	*Bucephala islandica*	A4i	2300	Wi
BFAL	Black-footed Albatross	*Phoebastria nigripes*	A4ii	1100	Su
BLKI	Black-legged Kittiwake	*Rissa tridactyla*	A4i	21,500	Su, Wi
BLSC	Black Scoter	*Melanitta americana*	A4i	3300	Wi
BOGU	Bonaparte's Gull	*Chroicocephalus Philadelphia*	A4i	3900	Su
BRAN	Brant	*Branta bernicla*	A4i	3500	Su
CAAU	Cassin's Auklet	*Ptychoramphus aleuticus*	A4ii	37,500	Su
COEI	Common Eider	*Somateria mollissima*	A4i	13,000	Su
COGO	Common Goldeneye	*Bucephala clangula*	A4i	10,000	Wi
COME	Common Merganser	*Mergus merganser*	A4i	16,500	Su, Wi
COMU	Common Murre	*Uria aalge*	A4ii	180,000	Su, Wi
CRAU	Crested Auklet	*Aethia cristatella*	A4ii	82,000	Su, Wi
FTSP	Fork-tailed Storm-petrel	*Oceanodroma furcata*	A4ii	60,000	Su, Wi
GLGU	Glaucous Gull	*Larus hyperboreus*	A4i	5700	Su, Wi
GWGU	Glaucous-winged Gull	*Larus glaucescens*	A4i	5700	Su, Wi
HADU	Harlequin Duck	*Histrionicus histrionicus*	A4i	2100	Su, Wi
HEGU	Herring Gull	*Larus argentatus*	A4i	3700	Su, Wi
HOGR	Horned Grebe	*Podiceps auritus*	A4i	5000	Wi
HOPU	Horned Puffin	*Fratercula corniculata*	A4ii	8000	Su, Wi
KIEI	King Eider	*Somateria spectabilis*	A4i	4600	Su, Wi
KIMU	Kittlitz's Murrelet	*Brachyramphus brevirostris*	A4ii	240	Su, Wi
LAAL	Laysan Albatross	*Phoebastria immutabilis*	A4ii	8700	Su, Wi
LEAU	Least Auklet	*Aethia pusilla*	A4ii	240,000	Su
LESP	Leach's Storm-petrel	*Oceanodroma leucorhoa*	A4ii	80,000	Su
LTDU	Long-tailed Duck	*Clangula hyemalis*	A4i	10,000	Su, Wi
LTJA	Long-tailed Jaeger	*Stercorarius longicaudus*	A4ii	3000	Su
MAMU	Marbled Murrelet	*Brachyramphus marmoratus*	A4ii	6200	Su, Wi
MEGU	Mew Gull	*Larus canus*	A4i	3000	Su, Wi
MOPE	Mottled Petrel	*Pterodroma inexpectata*	A4ii	15,000	Su
NOFU	Northern Fulmar	*Fulmarus glacialis*	A4ii	200,000	Su, Wi
PAAU	Parakeet Auklet	*Aethia psittacula*	A4ii	8000	Su, Wi
PAJA	Parasitic Jaeger	*Stercorarius parasiticus*	A4ii	7500	Su
PALO	Pacific Loon	*Gavia pacifica*	A4i	12,000	Su
PECO	Pelagic Cormorant	*Phalacrocorax pelagicus*	A4i	1000	Su, Wi
PIGU	Pigeon Guillemot	*Cepphus columba*	A4ii	4700	Su, Wi
POJA	Pomerine Jaeger	*Stercorarius pomarinus*	A4ii	750	Su
RBME	Red-breasted Merganser	*Mergus serrator*	A4i	2500	Su, Wi
REPH	Red Phalarope	*Phalaropus fulicarius*	A4i	12,500	Su
RFCO	Red-faced Cormorant	*Phalacrocorax urile*	A4i	750	Su, Wi
RHAU	Rhinoceros Auklet	*Cerorhinca monocerata*	A4ii	8000	Su
RLKI	Red-legged Kittiwake	*Rissa brevirostris*	A4i	2600	Su, Wi
RNGR	Red-necked Grebe	*Podiceps grisegena*	A4i	450	Su, Wi
RNPH	Red-necked Phalarope	*Phalaropus lobatus*	A4i	25,000	Su
RTLO	Red-throated Loon	*Gavia stellata*	A4i	400	Su
SAGU	Sabine's Gull	*Xema sabini*	A4i	5100	Su
SOSH	Sooty Shearwater	*Puffinus griseus*	A4ii	200,000	Su
SPEI	Spectacled Eider	*Somateria fischeri*	A4i	1800	Su
STEI	Steller's Eider	*Polysticta stelleri*	A4i	930	Wi
STSH	Short-tailed Shearwater	*Puffinus tenuirostris*	A4ii	300,000	Su
SUSC	Surf Scoter	*Melanitta perspicillata*	A4i	7000	Su, Wi
TBMU	Thick-billed Murre	*Uria lomvia*	A4ii	220,000	Su, Wi
TUPU	Tufted Puffin	*Fratercula cirrhata*	A4ii	24,000	Su, Wi
WHAU	Whiskered Auklet	*Aethia pygmaea*	A4ii	1000	Su, Wi
WWSC	White-winged Scoter	*Melanitta fusca*	A4i	5000	Su, Wi

[a] A4i = IBA status triggered by 1% or more of the North American waterbird population; A4ii = IBA status triggered by 1% or more of the global seabird population.

[b] Su = assessed for summer-season IBAs (May–September), Wi = assessed for winter-season IBAs (October–April).

major concentration areas for marine birds (present in significant numbers).

To ensure that IBAs would not result from a single high count of birds, our persistence filter first identified survey bins with non-zero counts in two or more years for each species. Because a large proportion of the 100-km^2 bins were surveyed in only one year (51% during the summer season and 69% during the winter season), the persistence filter was leaving out a large pool of useful data, which hampered our ability to identify IBAs across much of the study area. Oceanic hotspots tend to be ephemeral, but predictable; therefore, patterns of use shift within the local area or region (Gaston, 2004; Reese and Brodeur, 2006). Accordingly, we added an adjacency step to retain data within three survey bins of the areas of persistent use. This step enabled us to utilize some single-year survey data, and to better account for spatial variation in hotspots.

2.3. Step 3: Mapping species abundance

Within each bin, the mean density was calculated from the density estimates for all transects. Although the IBA criteria can, technically, be based on a maximum count that exceeds thresholds, we chose to use the mean of multiple observations in a location. As a measure for identifying hotspots, the mean is sensitive to high counts of birds often lost when using a median, but provides a more conservative, stable measure of abundance across the season than a maximum. In later steps, we tested results for persistence to ensure that high density estimates were not simply outliers, but were repeated events. The mean density value was applied to the total area of the bin (i.e. birds/km^2 multiplied by 100 km^2) to estimate the species abundance (total number of birds) within each 100-km^2 area. Nearshore bins often included significant areas of land, inflating abundance estimates for nearshore species. To correct for this, we resampled our 100-km^2 bins to 1-km^2 bins, each representing the abundance of birds to the nearest integer. We then removed cells from the resampled 1-km^2 raster map that fell onto land, correcting a potential overestimate of the marine populations. The resulting 1-km^2 raster map for each species was our final input layer for creating abundance gradient maps.

Estimating abundances is a necessary step for IBA identification, nomination, and recognition. Global population sizes vary in their reliability as absolute estimates of abundance. These estimates can have poor precision due to the difficulty of obtaining accurate colony census counts, non-random survey design for observations collected at sea, and gaps in knowledge (Clarke et al., 2003). Abundances estimated during this project are prone to similar issues which include uneven sampling effort, non-random survey design, gaps in survey coverage, and observational bias. Therefore, these values were not computed as absolute numbers to revise current population estimates. For our purposes, abundances estimated here are used as indicies of abundance relative to global estimates for assessing areas of concentration (Gould et al., 1982; Tasker et al., 1984; Gould and Forsell, 1989) rather than an exact estimate of population size.

We used a moving window analysis (Dale et al., 2002) to draw smoothed abundance gradient maps from 100-km^2 binned data. An example of this process for a single species, the crested auklet (*Aethia cristatella*), is presented in Figs. A2–A4 in Appendix A. The resulting raster map for each species represents the sum of all birds within the specified local neighborhood (i.e. search radius). We experimented with several search radii (15, 25, 35, and 50 km). Shorter search distances fit the data more closely and longer search distances increasingly smoothed the data. We preferred a shorter search radius to more closely approximate the survey data and to avoid inflating the core areas. Having chosen an input bin size of 10 km on each side, a search radius of 25 km was the shortest distance we could use for a minimal (and fairly standard) three-bin moving window. The 25-km neighborhood fit our best estimate of the appropriate scale (size and connectivity) of the resulting core areas; it provided a balance between not overfitting the boundaries to the survey transects (generality), and not losing important local-scale information (precision) (i.e. Guisan and Zimmermann, 2000).

2.4. Step 4: Core area boundaries

Core area polygons were drawn around all major concentrations using the abundance gradient maps. For each raster map cell, results of the moving window analysis report the surrounding sum of birds within the local neighborhood. Major concentrations selected were cells with values that met or exceeded the threshold for each species based on the A4 IBA criteria. We used the term core area to indicate a boundary drawn around areas of major concentrations for each marine bird species. We treated core areas as synonymous with potential IBAs (one step prior to completing final validation steps).

2.5. Step 5: IBA validation steps

We qualified the core areas for IBA status based on three criteria. First, we checked for adequate abundance by summing the estimated abundance within bins (resampled to 1-km^2) falling within each core area to see if the enclosed population met the 1% abundance criteria. Small polygons that enclosed <1% of the population were removed from further analysis. Earlier in the process we checked for sufficient survey effort within individual 100-km^2 bins using persistence and adjacency filters on the input data. Because we used some bins containing only single-year input data, we needed to test the final results to ensure adequate data within the resulting IBA polygons. In this step we checked for repeated use by retaining only those polygons where surveys recorded a high density of the species five or more times (counted separately for summer and winter seasons). Then, we checked for persistent use by retaining polygons with high densities of the species recorded in two or more years. A high density was defined as any survey density that when multiplied by the area of the IBA exceeded the A4 threshold for the species.

Throughout the process, we evaluated the parameters of our spatial analysis under multiple scenarios for each step, and examined draft results in areas where our research team had substantial local knowledge to judge the IBA location and trigger species (i.e. species exceeding the abundance threshold for IBA status) for important areas identified. This adaptive approach helped us parameterize the spatial tools. A conceptual diagram of the geospatial processing steps for identifying IBAs can be found in Fig. A5 in the online supplemental material.

2.6. Step 6: Combining overlapping boundaries

Because IBAs are species specific, in many situations the IBAs for two or more species overlapped. If the overlapping IBAs were within the same marine ecoregion, we dissolved the boundaries to form a single larger, multi-species IBA. If the overlapping IBAs bridged a boundary between marine ecoregions, we created two IBAs—one in each ecoregion. The ecoregions we recognized came from two sources: (1) Marine Ecoregions of the World (Spalding et al., 2007), which separated large geographic areas: the Beaufort, Chukchi, and Bering seas, and the Gulf of Alaska and (2) Marine Ecoregions of Alaska (Piatt and Springer, 2007) which offered finer scale information based on physical and biological characteristics of Alaskan waters. After dissolving boundaries for IBAs assigned to the same ecoregion, polygons were smoothed using a tolerance limit of 50-km.

This step resulted in a smaller number of larger, multiple-species IBAs. Combining overlapping IBAs grouped important areas into larger management units. This step also resulted in areas where the edges of IBAs overlapped from one marine ecoregion to the next indicating a marine ecotone. We summed total abundance for all species present in the larger combined polygons. Recalculating total abundances for a larger IBA area increased the reported abundance for the original trigger species, and in some cases added additional qualifying trigger species to the IBA. Because the final boundaries were adjusted through smoothing, four areas that initially qualified as just over the 1% threshold fell just under the 1% threshold and we chose not to nominate them for IBA status.

3. Results

Hotspots were located near the Bering Sea and Gulf of Alaska shelf breaks, along the Aleutian chain, in lower Cook Inlet, Prince William Sound, and near Barrow Canyon. Summarized by geographic location, 8% of the summer season birds represented by the data were located in the Arctic Ocean, 64% in the Bering Sea, and 28% in the Gulf of Alaska.

3.1. Core areas

Initially, we identified 162 summer-season core areas for 37 of the 52 assessed marine bird species. Of these, 95 core areas qualified after the IBA validation steps. An initial 60 pelagic winter-season core areas were identified for 18 of the 34 assessed marine bird species. Of these, 31 core areas qualified after validation. Combined, a total 126 core areas for 41 out of 57 marine bird species qualified for IBA status before being merged into the final IBAs, as shown in Supplemental Figs. A6–A9, along with data showing number of surveys and multi-year and adjacent bins used in the analysis.

3.2. Final boundaries

Dissolving overlapping boundaries into multi-species IBAs reduced 126 qualifying core areas to 59 IBAs for single or multiple species (Fig. 1). The final set of IBAs, grouped by marine ecoregions, covered 229,017 km^2 with an average IBA area of 3990 km^2 and a range from 652 km^2 (Marmot Bay) to 19,365 km^2 (Buldir & Near Islands Marine).

After recalculating trigger species abundances based on the larger combined IBA boundaries, we identified IBAs for 39 of the 52 assessed species during the summer season and for 22 of the 34 assessed species during the winter season, or a total 45 out of 57 marine bird species between the two seasons (Table 2). Density of surveys within bins overlapping IBAs ranged from 0 to 465 with a median/mean of 7/11. Total number of surveys in the resulting IBAs ranged from 24 to 4723 with a median/mean of 188/646. Number of years an IBA was surveyed ranged from 3 to 30, with a median/mean of 10/11. The density of birds within IBAs (based on trigger populations only) ranged from 10 birds/km^2 to 595 birds/km^2, with a median/mean of 61/96 birds/km^2.

The Prince William Sound had the highest number of species triggering IBA status (18) and the highest number of survey transects (4723). The Unimak & Akutan Passes IBA had the greatest bird density (622/km^2) and species richness (58) based on all (trigger and non-trigger) species in the database, and the highest estimated summer season population for all species at approximately 7 million. Five other IBAs were estimated to encompass over 1 million total birds in the summer season: Bering Sea Shelf Edge 166W55 N (4.3 million), Kiska Island Marine (1.4 million), St. George Island Marine (1.3 million), Buldir & Near Islands Marine (1.1 million), and Fenimore Pass & Atka Island (1.1 million). Glaucous-winged gulls (*Larus glaucescens*) triggered the most pelagic IBAs (21 of them), followed by black-legged kittiwake (*Rissa tridactyla*) (11 IBAs). The Unimak & Akutan Passes IBA had the highest calculated abundance of a single species, with 3.4 million short-tailed shearwaters (*Puffinus tenuirostris*) estimated.

In total, we estimated 13.5 million summer and 2 million winter birds in globally significant trigger populations within pelagic IBAs. Including birds not identified to species, there were an estimated 24.6 million individuals in these IBAs during the summer season, and 5.9 million during the winter season. In summer birds were most abundant in the Bering Sea (73.3%), followed by the Gulf of Alaska (18.4%), and the Arctic Ocean (8.3%). This estimate represents about 34% of Alaska's summer-season marine birds, and 38% of the winter-season birds, covering 6% of the project area.

Population percentages are sensitive to the quality of the global population estimates, of which some are classified as poor by BirdLife International. Based on the best available estimates at the time of our analysis, compared with the abundances estimated for Alaska during this project, the IBAs included approximately 100% of the whiskered auklet (*Aethia pygmaea*) and red-faced cormorant (*Phalacrocorax urile*) populations, followed by glaucous-winged gull (55%), long-tailed duck (*Clangula hyemalis*; 54%), and Kittlitz's murrelet (*Brachyramphus brevirostris*; 52%). The final IBAs, trigger species, and population estimates are listed in the online supplemental material in Table A1. The final IBAs grouped by marine ecoregion are in Fig. A10.

4. Discussion

Our work spatially defined IBA criteria to standardize how important areas are located and boundaries drawn using at-sea survey data, adding to already established abundance criteria. These methods identified globally significant IBAs for the majority of species assessed. We identified IBAs throughout the Alaska EEZ, spanning 20 degrees of latitude and 56 degrees of longitude, in two different oceans, with climates ranging from temperate to polar. Our results suggest these methods are broadly applicable across

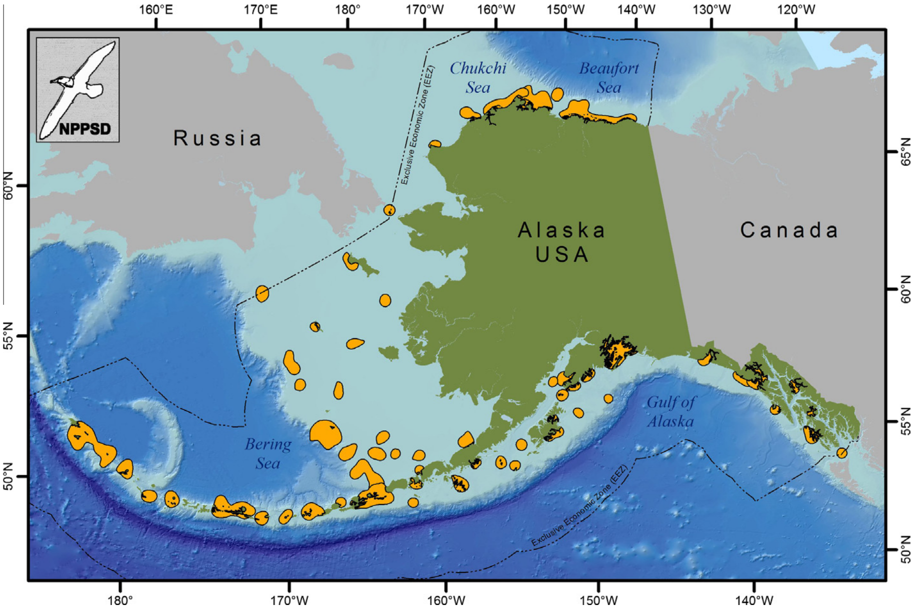

Fig. 1. Final multi-species Important Bird Areas (IBAs). IBAs were identified for 45 of the 57 species assessed (IBAs = 59; estimated abundance in trigger populations = 13.5 million birds; estimated abundance of all birds in IBAs = 24.6 million in summer and 5.9 million in winter; total area = 229,017 km^2).

Table 2

Summary of Important Bird Areas (IBAs) for 57 assessed species after combining qualifying areas into multi-species IBAs, then recalculating species abundances and species triggering IBA status. Values presented are most useful as indicies of abundance relative to global estimates for assessing areas of concentration, rather than an exact estimate of population size. Based on analysis of the North Pacific Pelagic Seabird Database, v2 (Drew and Piatt 2013).

Trigger species[a]	# Summer-season IBAs[b]	Est. abundance in trigger populations (summer)[c]	# Winter-season IBAs[b]	Est. abundance in trigger populations (winter)[c]	% Abundance in trigger populations[d] (%)
ALTE	1	299	NA	NA	2
ANMU	5	193,473	NA	NA	19
ARTE	4	90,323	NA	NA	9
BAGO	NA	NA	2	94,725	41
BFAL	1	1516	NA	NA	1
BLKI	11	576,984	2	57,997	27
BLSC	NA	NA	4	26,417	8
BOGU	1	4159	NA	NA	1
BRAN	1	5530	NA	NA	2
CAAU	2	147,173	NA	NA	4
COEI	0	0	NA	NA	0
COGO	NA	NA	1	12,753	1
COME	0	0	0	0	0
COMU	0	0	0	0	0
CRAU	5	727,082	1	396,896	9
FTSP	4	602,357	0	0	10
GLGU	5	176,005	2	110,760	31
GWGU	10	191,894	15	311,580	55
HADU	2	38,069	3	60,400	29
HEGU	0	0	0	0	0
HOGR	NA	NA	1	5600	1
HOPU	8	299,073	0	0	37
KIEI	2	106,604	1	4896	23
KIMU	7	12,389	1	633	52
LAAL	1	13,900	0	0	2
LEAU	2	1,492,602	NA	NA	6
LESP	0	0	NA	NA	0
LTDU	3	536,369	0	0	54
LTJA	0	0	NA	NA	0
MAMU	7	135,609	1	13,850	22
MEGU	1	6497	1	7130	2
MOPE	0	0	NA	NA	0
NOFU	6	1,866,169	2	743,411	9
PAAU	8	136,429	0	0	17
PAJA	0	0	NA	NA	0
PALO	0	0	NA	NA	0
PECO	8	19,129	4	16,735	19
PIGU	4	38,290	1	5406	8
POJA	7	12,730	NA	NA	17
RBME	0	0	1	5213	2
REPH	4	155,104	NA	NA	12
RFCO	2	83,513	0	0	111
RHAU	1	151,940	NA	NA	19
RLKI	2	58,196	1	13,287	22
RNGR	0	0	2	4339	10
RNPH	0	0	NA	NA	0
RTLO	2	1098	NA	NA	3
SAGU	2	22,802	NA	NA	4
SOSH	2	1,121,135	NA	NA	6
SPEI	1	11,434	NA	NA	6
STEI	NA	NA	0	0	0
STSH	2	3,463,326	NA	NA	12
SUSC	1	19,465	2	27,961	4
TBMU	0	0	0	0	0
TUPU	7	638,316	0	0	27
WHAU	9	308,858	1	12,118	309
WWSC	2	21,968	5	77,937	16

[a] See Table 1 for species codes and thresholds.

[b] NA = not assessed; 0 = assessed but no trigger populations.

[c] Estimated abundance values are the sum of trigger populations, i.e. total abundance in IBAs where that species triggered IBA status.

[d] Represents percent of the North American waterbird population or global seabird population for each species, relating to A4i and A4ii IBA criteria respectively. Refer to Table 1. Percent shown is the maximum of summer or winter trigger population estimate.

oceanic ecosystem types and marine species guilds, including both short- and long-range foragers, and locally aggregated to widely distributed species.

Both the global estimates and our localized estimates suffer from similar types of uncertainties; however, we accepted these uncertainties in favor of informing conservation with the best data available. This analysis can be revised as global population estimates are improved and new spatial survey data becomes available. In applying these methods elsewhere, we suggest applying the parameter values used here, then testing scenarios and adjusting values based on local conditions and data.

IBAs are but one approach to identifying areas of significance for marine birds. The A4 criteria used in our analysis focus on areas of congregation, which by definition are not well suited to identifying areas for rare, solitary, or abundant-but-dispersed species. Furthermore, the analysis is biased toward locating foraging destinations more than stop-over sites, because we averaged observations across several months (split into both summer and winter seasons). This should be addressed in future analyses. Averaging survey densities over the entire season tends to produce IBAs of two types: sustained high use over the period, or extremely high abundance for a shorter period of time that when averaged with low counts in other months still qualifies as an IBA. Had we not included zero counts, used maximum density values, or used multiple shorter time periods, our results may have better approximated migration stop-over or staging sites, but would not have done as well at estimating seasonal population abundances.

These methods were successful in several ways that we preferred over other available analytical options. In a multiple-variable spatial analysis, such as the one developed here, there is no single value that can be used to measure confidence in results, but validation by several metrics is a good indicator of overall success. Given the size of our study area (one third of the United States EEZ), we needed an approach that could address the range and variety of marine birds present in an efficient manner. The method did not require the development of predictive models. Such models could be used to suggest core area boundaries if empirical data were available to validate the areas, similar to IBAs identified in Spain by Arcos et al. (2012); however, employing such methods over 3.7 million km^2 for 57 species would not have been practical. By choosing not to use techniques such as interpolation or resource-selection modeling, our results are directly tied to observed data. This increases our confidence in the resultant IBAs. However, the obvious limiting feature of this method is it that it cannot be applied in areas with little or no survey coverage.

Throughout this process we took a conservative approach choosing to minimize Type I errors (false positives, or identifying an area as important that truly is not) while acknowleging the potential increase in Type II error (false negatives, or failure to identify an area that is truly important). This approach, along with survey coverage gaps, means that important areas exist in places not identified; failure to identify an IBA did not necessarily mean that a particular area was unimportant (Rocchini et al., 2011). We found several examples of areas known to be important to birds, but not identified in our analysis because the survey data was not yet incorporated in the NPPSD database. For example, surveys of spectacled eiders in Ledyard Bay, Norton Sound, and the St. Lawrence Island polynya (Petersen et al., 1999), surveys for Kittlitz's murrelet in selected areas of southeastern Alaska (Kissling et al., 2011), and surveys for marbled murrelet in Port Snettisham, Southeast Alaska (Kirchhoff, 2005).

Other areas of high abundance did not result in IBAs because the species present are very abundant globally and/or are dispersed on the water, making the 1% threshold value difficult to attain. This included Chirikov Basin south of the Bering Strait, where over 12 million birds, mostly alcids such as crested and least auklets, nest in region (World Seabird Union, 2011). Others areas of high abundance for northern fulmars, fork-tailed storm-petrels, crested auklets, and thick-billed murres occur in the Bering Sea and Aleutian Islands, but were not identified as IBAs for the same reason. Supplemental Fig. A11 illustrates this with a three-dimensional rendering of total bird abundance compared to IBA boundaries. The NPPSD is a pelagic-focused database, and accordingly, habitats for coastal/nearshore species were marginally surveyed in some areas of Alaska. Estimates are likely more accurate for seabirds under the A4ii IBA criterion than they are for waterbirds under the A4i criterion due to better survey coverage. Although our maps did suffer from some data gaps (64% of the EEZ was not surveyed in summer and 82% was not surveyed in winter), these gaps did not preclude us from identifying IBAs that incorporated 79% of the species assessed, as well as an estimated 13% of the assessed continental waterbird population and 9% of the assessed global seabird population.

The majority of IBAs are associated with physical features that influence productivity and/or cause upwelling and mixing. Among the most prolific seabird areas in the world, some 11 million birds nest in colonies along the the Aleutian Island chain where 10 IBAs surround islands and cross marine passes that rise steeply from the 7800-m deep Aleutian Trench. The importance of the Bering Sea shelf break for seabird foraging is long-recognized (Schneider, 1982; Springer et al., 1996), and was previously identified as an IBA using expert assessment. This analysis revealed six IBAs just east of the break on the shallow shelf, in waters presumably influenced by that feature, but not directly straddling the feature as previously drawn. Seven IBAs in the nearshore Chukchi and Beaufort seas overlay a productive system of sea ice leads and polynyas which attract seabirds (Stirling, 1997). IBAs in Southeast Alaska's fjords, such as Glacier Bay, are influenced by glacial runoff and strong tidal currents that increase productivity (Etherington et al., 2007).

The final IBAs cover 26% of Alaska's coastline and 6% of the Alaska EEZ. The success of this project depended on access to at-sea survey data, which are essential for the identification of pelagic IBAs beyond simply the seaward extension of nesting colonies (e.g. along the Bering Sea shelf break). In addition to the important-area boundaries generated, the resulting multi-layered spatial databases provide information on species abundance and richness for all species assessed, as well as information on ownership, land use, and threats. The information enables further inquiry, such as spatial relationships among breeding colonies and associated foraging areas, or recognition of core areas that did not qualify as global IBAs but are important for other reasons, such as total abundance of common species, or potential state or continental IBA status. Currently there are no national-level MPAs in offshore waters (i.e. areas not associated with land-based parks or refuges), nor any exclusive restriction MPAs in any area of Alaska. Marine birds may be threatened by a variety of industrial uses, including pelagic and demersal fisheries, shipping accidents, and offshore energy development, which MPAs could help mitigate. This information will be useful in exploring whether and where MPAs should be established and what restrictions should be in place to protect important resources.

We suggest that standardized methods can, and should, be articulated for other situations, including local knowledge-based boundaries (Brown et al., 2004), colony buffers (BirdLife International, 2010; Thaxter et al., 2012), tracking data (BirdLife International, 2009; Montevecchi et al., 2012), and predictive modeling to draw boundaries which are validated with empirical data (Amorim et al., 2009; Nur et al., 2011; Arcos et al., 2012). Ultimately, the global marine IBA network will be a blend of techniques. Global integration of regional IBA projects calls for transparency, repeatability, and objectivity, and these standardized methods contribute to that effort.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2014.02.039.

References

Amorim, P., Figueiredo, M., Machete, M., Morato, T., Martins, A., Santos, R.S., 2009. Spatial variability of seabird distribution associated with environmental factors: a case study of marine Important Bird Areas in the Azores. ICES J. Mar. Sci. 66, 29–40.

Arcos, J.M., Becares, J., Villero, D., Brotons, L., Rodriguez, B., Ruiz, A., 2012. Assessing the location and stability of foraging hotspots for pelagic seabirds: an approach to identify marine Important Bird Areas (IBAs) in Spain. Biol. Conserv. 156, 30–42.

BirdLife International, 2009. Using Seabird Satellite Tracking Data to Identify Marine IBAs: A Workshop to Determine How to Achieve This Goal. CNRS, Chize, France.

BirdLife International, 2010. Marine Important Bird Areas Toolkit: Standardised Techniques for Identifying Priority Sites for the Conservation of Seabirds at Sea. BirdLife International, Cambridge, UK.

BirdLife International, 2012. Important Bird Areas (IBAs). BirdLife International, Cambridge, UK. <http://www.birdlife.org/action/science/sites>. (Accessed online 28.08.12).

Brown, G., Smith, C., Alessa, L., Kliskey, A., 2004. A comparison of perceptions of biological value with scientific assessment of biological importance. Appl. Geogr. 24, 161–180.

Burger, A.E., Hitchcock, C.L., Stewart, E.A., Davoren, G.K., 2008. Coexistence and spatial distributions of marbled murrelets (*Brachyramphus marmoratus*) and other alcids off southwest Vancouver Island, British Columbia. Auk 125, 192–204.

Carr, M.H., Neigel, J.E., Estes, J.A., Andelman, S., Warner, R.R., Largier, J.L., 2003. Comparing marine and terrestrial ecosystems: implications for the design of coastal and marine reserves. Ecol. Appl. 13, 90–107.

Clarke, E.D., Spear, L.B., McCracken, M.L., Marques, F.F.C., Borchers, D.L., Buckland, S.T., Ainley, D.G., 2003. Validating the use of generalized additive models and at-sea surveys to estimate size and temporal trends of seabird populations. J. Appl. Ecol. 40, 278–292.

Cowling, R.M., Pressey, R.L., Sims-Castley, R., Le Roux, A., Baard, E., Burgers, C.J., Palmer, G., 2003. The expert or the algorithm? Comparison of priority conservation areas in the Cape Floristic Region identified by park managers and reserve selection software. Biol. Conserv. 112, 147–167.

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.

Dale, M.R.T., Dixon, P., Fortin, M.-J., Legendre, P., Myers, D.E., Rosenberg, M.S., 2002. Conceptual and mathematical relationships among methods for spatial analysis. Ecography 25, 558–577.

Drew, G.F., Piatt, J., 2013. North Pacific Pelagic Seabird Database, v 2.0. US Geological Survey Alaska Science Center & US Fish and Wildlife Service, Anchorage, AK. Accessed online at <http://alaska.usgs.gov/science/biology/nppsd/index.php>.

ESRI, 2011. ArcGIS Desktop, v 10.0. Environmental Systems Research Institute, Redlands, CA.

Etherington, L.L., Hooge, P.N., Hooge, E.R., Hill, D.F., 2007. Oceanography of Glacier Bay, Alaska: implications for biological patterns in a glacial fjord estuary. Estuaries Coasts 30, 927–944.

Etnoyer, P., Canny, D., Mate, B., Morgan, L., 2004. Persistent pelagic habitats in the Baja California to Bering Sea ecoregion. Oceanography 17, 90–101.

Gaston, A.J., 2004. Seabirds: A Natural History. Yale University Press, New Haven, CT.

Gould, P.J., Forsell, D.J., 1989. Techniques for Shipboard Surveys of Marine Birds. Fish and Wildlife Technical Report 25. U.S Fish and Wildlife Service, Washington, D.C.

Gould, P.J., Forsell, D.J., Lensink, C.J., 1982. Pelagic Distribution and Abundance of Seabirds in the Gulf of Alaska and Eastern Bering Sea. U.S. Fish and Wildlife Service, Biological Services Program.

Guisan, A., Zimmermann, N.E., 2000. Predictive habitat distribution models in ecology. Ecol. Model. 135, 147–186.

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.

Kirchhoff, M.D., 2005. Monitoring Marbled Murrelet Population Trends with Flyway and Radar Counts. Federal Aid in Wildlife Restoration Report. Alaska Department of Fish and Game, Juneau, AK.

Kissling, M.L., Lukacs, P.M., Lewis, S.B., Gende, S.M., Kuletz, K.J., Hatch, N.R., Schoen, S.K., Oehlers, S., 2011. Distribution and abundance of the Kittlitz's Murrelet *Brachyramphus brevirostris* in selected areas of southeastern Alaska. Mar. Ornithol. 39, 3–11.

Kober, K., Webb, A., Win, I., Lewis, M., O'Brien, S., Wilson, L.J., Reid, J.B., 2010. An analysis of the numbers and distribution of seabirds within the British Fishery Limit aimed at identifying areas that qualify as possible marine SPAs. Joint Nature Conservation Committee.

Lascelles, B., 2008. The BirdLife Seabird Foraging Database: Guidelines and Examples of its Use. BirdLife International, Cambridge, UK.

Lascelles, B.G., Langham, G.M., Ronconi, R.A., Reid, J.B., 2012. From hotspots to site protection: identifying Marine Protected Areas for seabirds around the globe. Biol. Conserv. 156, 5–14.

Louzao, M., Becares, J., Rodriguez, B., Hyrenbach, K.D., Ruiz, A., Arcos, J.M., 2009. Combining vessel-based surveys and tracking data to identify key marine areas for seabirds. Mar. Ecol. Prog. Ser. 391, 183–197.

Louzao, M., Pinaud, D., Péron, C., Delord, K., Wiegand, T., Weimerskirch, H., 2011. Conserving pelagic habitats: seascape modelling of an oceanic top predator. J. Appl. Ecol. 48, 121–132.

Montevecchi, W.A., Hedd, A., McFarlane Tranquilla, L., Fifield, D.A., Burke, C.M., Regular, P.M., Davoren, G.K., Garthe, S., Robertson, G.J., Phillips, R.A., 2012. Tracking seabirds to identify ecologically important and high risk marine areas in the western North Atlantic. Biol. Conserv. 156, 62–71.

National Audubon Society, 2012a. Criteria Overview. National Audubon Society, New York, NY. <http://web4.audubon.org/bird/iba/criteria.html>. (Accessed online January 2012).

National Audubon Society, 2012b. Important Bird Areas Program: A Global Currency for Bird Conservation. National Audubon Society, New York, NY. <http://web4.audubon.org/bird/iba/index.html>. (Accessed online January 2012).

Nur, N., Jahncke, J., Herzog, M.P., Howar, J., Hyrenbach, K.D., Zamon, J.E., Ainley, D.G., Wiens, J.A., Morgan, K., Ballance, L.T., Stralberg, D., 2011. Where the wild things are: predicting hotspots of seabird aggregations in the California Current System. Ecol. Appl. 21, 2241–2257.

O'Dea, N., Araújo, M.B., Whittaker, R.J., 2006. How well do Important Bird Areas represent species and minimize conservation conflict in the tropical Andes? Divers. Distrib. 12, 205–214.

O'Hara, P.D., Morgan, K.H., Sydeman, W.J., 2006. Primary producer and seabird associations with AVHRR-derived sea surface temperatures and gradients in the southeastern Gulf of Alaska. Deep Sea Res. Part II 53, 359–369.

Oppel, S., Meirinho, A., Ramírez, I., Gardner, B., O'Connell, A.F., Miller, P.I., Louzao, M., 2012. Comparison of five modelling techniques to predict the spatial distribution and abundance of seabirds. Biol. Conserv. 156, 94–104.

Palacios, D.M., Bograd, S.J., Foley, D.G., Schwing, F.B., 2006. Oceanographic characteristics of biological hot spots in the North Pacific: a remote sensing perspective. Deep Sea Res. Part II 53, 250–269.

Parsons, M., Mitchell, I., Butler, A., Ratcliffe, N., Frederiksen, M., Foster, S., Reid, J.B., 2008. Seabirds as indicators of the marine environment. ICES J. Mar. Sci. 65, 1520–1526.

Petersen, M.R., Larned, W.W., Douglas, D.C., 1999. At-sea distribution of spectacled eiders: a 120-year-old mystery resolved. Auk 116, 1009–1020.

Piatt, J.F., Springer, A.M., 2003. Advection, pelagic food webs, and the biogeography of seabirds in Beringia. Mar. Ornithol. 31, 141–154.

Piatt, J.F., Springer, A.M., 2007. Marine ecoregions of Alaska. In: Spies, R.B. (Ed.), Long-term Ecological Change in the Northern Gulf of Alaska. Elsevier, Amsterdam, pp. 522–526.

Piatt, J.F., Wetzel, J., Bell, K., DeGange, A.R., Balogh, G.R., Drew, G.S., Geernaert, T., Ladd, C., Byrd, G.V., 2006. Predictable hotspots and foraging habitat of the endangered short-tailed albatross (*Phoebastria albatrus*) in the North Pacific: implications for conservation. Deep Sea Res. Part II 53, 387–398.

Piatt, J.F., Sydeman, W.J., Wiese, F., 2007. Introduction: a modern role for seabirds as indicators. Mar. Ecol. Prog. Ser. 352, 199–204.

Reese, D.C., Brodeur, R.D., 2006. Identifying and characterizing biological hotspots in the northern California Current. Deep Sea Res. Part II 53, 291–314.

Renner, M., Arimitsu, M.L., Piatt, J.F., Rochet, M.J., 2012. Structure of marine predator and prey communities along environmental gradients in a glaciated fjord. Can. J. Fish. Aquat. Sci. 69, 2029–2045.

Rice, J., Houston, K., 2011. Representativity and networks of marine protected areas. Aquat. Conserv.: Mar. Freshw. Ecosyst. 21, 649–657.

Rocchini, D., Hortal, J., Lengyel, S., Lobo, J.M., Jiménez-Valverde, A., Ricotta, C., Bacaro, G., Chiarucci, A., 2011. Accounting for uncertainty when mapping species distributions: the need for maps of ignorance. Prog. Phys. Geogr. 35, 211–226.

Ronconi, R.A., Burger, A.E., 2009. Estimating seabird densities from vessel transects: distance sampling and implications for strip transects. Aquat. Biol. 4, 297–309.

Ronconi, R.A., Lascelles, B.G., Langham, G.M., Reid, J.B., Oro, D., 2012. The role of seabirds in marine protected area identification, delineation, and monitoring: introduction and synthesis. Biol. Conserv. 156, 1–4.

Schneider, D., 1982. Fronts and seabird aggregations in the southeastern Bering Sea. Mar. Ecol. Prog. Ser. Oldendorf 10, 101–103.

Sherman, K., Aquarone, M.C., Adams, S. (Eds.), 2009. Sustaining the World's Large Marine Ecosystems. IUCN, Gland, Switzerland.

Skov, H., Durinck, J., Leopold, M.F., Tasker, M.L., 2007. A quantitative method for evaluating the importance of marine areas for conservation of birds. Biol. Conserv. 136, 362–371.

Spalding, M.D., Fox, H.E., Allen, G.R., Davidson, N., Ferdaña, Z.A., Finlayson, M., Halpern, B.S., Jorge, M.A., Lombana, A., Lourie, S.A., Martin, K.D., McManus, E., Molnar, J., Recchia, C.A., Robertson, J., 2007. Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. Bioscience 57, 573–583.

Springer, A.M., McROY, C.P., Flint, M.V., 1996. The Bering Sea green belt: shelf-edge processes and ecosystem production. Fish. Oceanogr. 5, 205–223.

Stirling, I., 1997. The importance of polynyas, ice edges, and leads to marine mammals and birds. J. Mar. Syst. 10, 9–21.

Suryan, R.M., Santora, J.A., Sydeman, W.J., 2012. New approach for using remotely sensed chlorophyll a to identify seabird hotspots. Marine Ecology Progress Series 451 (2012), 213–225.

Tasker, M.L., Jones, P.H., Dixon, T., Blake, B.F., 1984. Counting seabirds at sea from ships: a review of methods employed and a suggestion for a standardized approach. Auk 101, 567–577.

Thaxter, C.B., Lascelles, B., Sugar, K., Cook, A.S.C.P., Roos, S., Bolton, M., Langston, R.H.W., Burton, N.H.K., 2012. Seabird foraging ranges as a preliminary tool for identifying candidate marine protected areas. Biol. Conserv. 156, 53–61.

Tremblay, Y., Bertrand, S., Henry, R.W., Kappes, M.A., Costa, D.P., Shaffer, S.A., 2009. Analytical approaches to investigating seabird-environment interactions: a review. Mar. Ecol. Prog. Ser. 391, 153–163.

US Fish and Wildlife Service, 2008. Seabirds Overview. USFWS, Anchorage, AK. <http://alaska.fws.gov/mbsp/mbm/seabirds/seabirds.htm>. (Accessed online 15.07.13).

Weimerskirch, H., 2007. Are seabirds foraging for unpredictable resources? Deep Sea Res. Part II 54, 211–223.

World Seabird Union, 2011. Seabird Information Network: North Pacific Seabird Data Portal. World Seabird Union, <www.seabirds.net>.

Yen, P.P.W., Sydeman, W.J., Morgan, K.H., Whitney, F.A., 2005. Top predator distribution and abundance across the eastern Gulf of Alaska: temporal variability and ocean habitat associations. Deep Sea Res. Part II 52, 799–822.

Yen, P.P.W., Sydeman, W.J., Bograd, S.J., Hyrenbach, K.D., 2006. Spring-time distributions of migratory marine birds in the southern California Current: oceanic eddy associations and coastal habitat hotspots over 17 years. Deep Sea Res. Part II 53, 399–418.

Yorio, P., 2009. Marine protected areas, spatial scales, and governance: implications for the conservation of breeding seabirds. Conserv. Lett. 2, 171–178.