PREDICTING NONRESIDENT SEABIRD FORAGING HABITAT TO INFORM CONSERVATION PLANNING

A Thesis submitted to the faculty of
San Francisco State University
In partial fulfillment of
the requirements for
the Degree

Master of Arts

In

Geography

by

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San Francisco, California

May 2016

CERTIFICATION OF APPROVAL

I certify that I have read Predicting Nonresident Seabird Foraging Habitat to Inform Conservation Planning by Anna Justine Studwell, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirement for the degree Master of Arts in Geography and Environment at San Francisco State University.

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2016

Seabirds are considered indicators of marine health and food web dynamics, making them sentinel organisms that can alert humans to changes in the marine environment. With increasing human access to the ocean, it is important to understand the risk of disturbance that maritime activities pose to seabirds to support decision-makers in prioritizing areas for elevated management. This research focuses on pelagic, non-locally breeding seabird species in the Greater Farallones National Marine Sanctuary and Cordell Bank National Marine Sanctuaries. A hypothesis was that high-use foraging areas for pelagic seabirds would be influenced by oceanographic and bathymetric factors and that spatial and temporal distributions are similar within planktivorous and piscivorous foraging guilds but differ between them. With data collected by the Applied California Current Ecosystem Studies (ACCESS) partnership, species distribution models were generated to identify high-use foraging areas of six pelagic seabird species. Model results highlighted the continental shelf break, particularly the vicinity of Cordell Bank, as highest use areas. With the exception of one species, there were no significant differences between distributions of individual seabird species within a foraging guild or between guilds. Risk of disturbance to seabirds was assessed using a habitat risk assessment (HRA) model from the inVEST suite of tools. To target seabird foraging that conflicted least with human activities, a conservation prioritization tool, Marxan, was used with seabird foraging area representing the conservation feature of interest and risk derived from the HRA model representing cost. If human activities were not considered in the prioritization, prioritized areas were parts of the continental shelf break and the vicinity of Cordell Bank. If human activities were considered, prioritized areas were to the west of the continental shelf break, in the vicinity and to the northeast of Cordell Bank, and in the vicinity of pre-existing marine protected areas. This research shows that the continental shelf break hosts critical areas for seabirds and provides methods that can be implemented elsewhere to prioritize critical habitat for elevated management as human development pressures continue to expand to the ocean.

I certify that the Abstract is a correct representation of the content of this thesis.

______________________________ 4/28/16
Chair, Thesis Committee Date

ACKNOWLEDGEMENTS

I would like to thank my family and friends who have listened appreciatively and embraced my fixation with seabirds; I am lucky to have you and am incredibly grateful for your thoughtful discussions and support. I would also like to thank my committee, Ellen Hines, Barbara Holzman, and Jaime Jahncke who have pushed me to look for creative solutions when a task was challenging. I would like to thank the many partners and contributors who have helped make this research a reality. This thesis was supported by the Applied California Current Ecosystem Studies (ACCESS) partnership, a continuing collaboration between Point Blue Conservation Science, the Greater Farallones National Marine Sanctuary, and Cordell Bank National Marine Sanctuary. I would like to acknowledge the Council on Ocean Affairs, Science, and Technology (COAST), San Francisco State University Robert Maxwell and University Scholarships, and the Romberg Tiburon Center Bay Scholarship and Student Association for their support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: PREDICTIVE MODELING AND PRIORITIZATION OF SEABIRD FORAGING HABITAT

Abstract

Seabirds are considered indicators of marine health and food web dynamics, making them sentinel organisms that can alert humans to changes in the marine environment. Previous research identified Central California as a highly used foraging area for seabirds, with locally breeding species predominantly foraging in close proximity to their island colonies. Herein, we focus on pelagic, non-locally breeding seabird species; we hypothesize that high-use foraging areas for these pelagic seabirds would be influenced by oceanographic and bathymetric factors and that spatial and temporal distributions are similar within planktivorous and piscivorous foraging guilds but differ between them. With data collected by the Applied California Current Ecosystem Studies (ACCESS) partnership, we developed generalized linear models (GLMs) to identify high-use foraging areas of each of six pelagic seabird species that visit the waters of two national marine sanctuaries between the months of April and October: *Phoebastria nigripes* (black-footed albatross), *Ardenna griseus* (sooty shearwater), *Ardenna creatopus* (pink-footed shearwater), *Fulmarus glacialis* (northern fulmar), *Phalaropus lobatus* (red-necked phalarope), and *Phalaropus fulicarius* (red phalarope). Negative binomial GLMs were the best fit for *P. nigripes*, *F. glacialis*, and *A. creatopus* distributions while zero-inflated negative binomial GLMs were the best fit for *A. griseus*, *P. fulicarius*, and *P. lobatus*. Model results of multi-use seabird foraging area highlighted the continental shelf break and particularly the vicinity of Cordell Bank. No single oceanographic variable was included in all models, sea surface temperature was significant for piscivorous species, and sea surface salinity was important to planktivorous species. Basin-scale climate indices influenced all models while regional upwelling index indices only influenced a single species. Distance to the continental shelf break was important to five of six seabird models; and for three models, distance to Cordell Bank and average depth were important. Distance variables had minimal influence, as distance to the nearest island was included in two models and distance to the mainland was included in only one model. We did not find significant differences between distributions of individual seabird species within a foraging guild or between guilds, with the exception of *A. griseus*. We used a conservation prioritization tool to select high-use pelagic foraging areas that met conservation targets for all species. We identified regions of the continental shelf break and the vicinity of Cordell Bank as priority areas for seabirds. Offshore energy development plans target locations up to 15 miles offshore from the California Coast extending toward the continental shelf break in some regions. Our research shows the continental shelf break hosts critical areas for seabirds and we provide methods that can be implemented elsewhere to identify critical habitat that needs protection as human development pressures continues to expand to the ocean.

Introduction

Seabirds have been portrayed as conspicuous, long-lived, and wide-ranging marine predators that forage at high trophic levels, making them indicators of marine health and food web dynamics [1–3]. Because of these characteristics, they have been regarded as sentinel organisms indicative of pollution or food supply changes in the marine environment [4,5]. Yet many seabird populations have been threatened where they forage and breed [6–8]. Pollution including plastics, heavy metals, and oil spills as well as incidental bycatch from commercial fisheries have been identified as principal threats [9–12]. While special regulations [13–15] have combatted these threats for the waters around breeding colonies, pelagic seabirds have remained at risk from threats to their offshore foraging area [16–18], which has been inadequately recognized world-wide [19]. Seabird management approaches generally have considered protection of breeding colonies or ocean areas directly surrounding those colonies [20], however, less attention has been paid to offshore areas where important feeding aggregations occur. For example, *A. griseus* breeds on islands offshore from Australia, New Zealand, and Chile but visits the California Current during its nonbreeding season to feed, yet their numbers declined by 90% between 1987 and 1994 [21] despite protections for their distant breeding areas. Compared to the more compact space around breeding colonies, it has been more challenging to effectively manage pelagic foraging sites because these areas can be large, have unclear boundaries, and can fluctuate with the dynamic nature of the marine environment [19,22–24]. Detailed understanding of spatial and temporal distribution patterns of pelagic seabird foraging area would assist the prioritization of critical foraging locations that require similar status as areas surrounding breeding colonies. Identifying important pelagic foraging sites will support ocean management and zoning with critical wildlife response planning.

Using predictive modeling to identify important habitat at a range of scales has empowered managers at state, national, and international levels to prioritize conservation of critical habitat. Species distribution modeling (SDM) has been shown as an important group of predictive modeling strategies [25–28]. Using SDM based on environmental conditions to identify pelagic seabird foraging areas would help generate a more complete picture of seabirds' spatial and temporal use of an area beyond sampled locations. Global scale research efforts have focused on mapping seabird at-sea foraging distributions and overlap with fisheries world-wide [29]. Species-specific habitat models of marine top predator habitat coupled with climate change projections have located the most threatened ecosystems at the scale of the North Pacific [30]. Critical seabird habitat research at the scale of the eastern North Pacific's California Current region highlighted the importance of the Greater Farallones region offshore from Central California [31].

We can predict where specific high-use foraging areas have persisted by working at a finer scale specific to this region. For example, SDM results for a study conducted in Cordell Bank National Marine Sanctuary and Greater Farallones National Marine Sanctuary (hereafter referred to as "the Sanctuaries") showed that the distributions of multiple central place foraging seabirds [32] (hereafter called 'breeding' species) were significantly associated with the distance from their island colonies [33]. In contrast, SDMs showed that distribution of a pelagic seabird visiting from its Hawaiian breeding grounds, *Phoebastria nigripes* (black-footed albatross), was significantly associated with the continental shelf break [34]. However, no research has taken a multispecies approach to assess critical foraging area for pelagic, non-locally breeding species (hereafter referred to as 'pelagic species') that visit the Sanctuaries. Foraging areas were likely to differ between breeding and pelagic species because pelagic seabirds are not constrained to local islands in the Sanctuaries as are breeding seabirds [35]. This research sought insight into the differences between foraging areas for breeding and pelagic seabird species.

Many pelagic seabirds forage in the California Current, a dynamic system with a varying regional and basin-scale climate that affects local conditions [36]. Major influences in the California Current system have included: the Pacific Decadal Oscillation (PDO), an interdecadal index, which is the first principal component of monthly sea surface temperature (SST) anomalies over the North Pacific and describes Pacific SST variation north of 20°N [37]; the North Pacific Gyre Oscillation (NPGO), also an interdecadal index described as the second principal component of sea surface height in the North Pacific, which is correlated with productive conditions in the California Current as indicated by variation in salinity, nutrients, and chlorophyll [38]; the Southern Oscillation Index (SOI), which is a measurement of the sea level pressure differences between Darwin and Tahiti that indicate interannual oceanic warming and cooling trends related to El Niño and La Niña in the Pacific Ocean [39]; and the Upwelling Index (UI), which is a regional metric of upwelling strength based on Ekman's theory of mass transport due to wind stress [40]. Variability within these climate indices has manifested in changes to the local oceanographic metrics that influence productivity [37–39] to which seabird prey species respond [41]. Interdecadal fluctuations (i.e. regime shifts) of basin-wide climate indices have been linked to population impacts for seabirds breeding on Pacific islands [42].

Prey species have been found to respond differently to environmental features and fluctuations, consequently influencing their predators' foraging behavior. Marine prey such as plankton and forage fish have exhibited patchiness over multiple scales [43,44]. Where seabirds forage has been indicative of where prey species occur consistently although not always in highest abundance [43,45]. Previous research showed that locations where prey was predictably available at an accessible near-surface depth were preferred by two seabird species over locations where prey was predictably abundant at variable depths [46]. Distinguishing spatial differences between distributions of pelagic seabird foraging guilds has been used to suggest where different clusters of prey types were available [43,47]. We have chosen to describe species patterns of 1) flexible piscivorous and 2) strictly planktivorous foraging guilds in the Sanctuaries. We have described flexible piscivorous species (hereafter referred to as 'piscivorous') as eating a mixed diet of fish, squid, krill, and offal. On the other hand, we have characterized strictly planktivorous species (hereafter referred to as 'planktivorous') as almost exclusively eating planktonic organisms such as krill and copepods. We chose to work with common pelagic piscivorous species not known to breed in the Sanctuaries including *Ardenna griseus* (sooty shearwater), *Ardenna creatopus* (pink-footed shearwater), *Fulmarus glacialis* (northern fulmar), and *Phoebastria nigripes* (black-footed albatross) as well as common pelagic planktivorous species including *Phalaropus fulicarius* (red phalarope) and *Phalaropus lobatus* (red-necked phalarope).

Our first hypothesis was that pelagic seabirds would be influenced by oceanographic and bathymetric features that enhance foraging opportunities and less so by their distance to islands and the mainland generally associated with breeding seabirds. Our second hypothesis was that flexible piscivorous and strictly planktivorous species would forage in different areas of the Sanctuaries. To address these hypotheses, our research asked the following questions: 1) what are the environmental factors that drive pelagic seabird aggregations, 2) where and when do pelagic foraging seabirds aggregate, and 3) how can we identify high-use foraging areas for conservation?

Methods

Study Area

The study region (Fig 1.1) was off the coast of Central California falling under the jurisdiction of the Sanctuaries. The Farallon Islands have been considered critical wildlife breeding and feeding grounds and the waters of Cordell Bank have been described as hosting a large diversity of marine life [20]. The California Current, a cold-water system spanning from southern British Columbia to Baja California has been shown to influence Sanctuary waters that host this variety and abundance of marine life ranging from lower trophic level species, such as krill, up to top-predators including seabirds and whales [31,48]. Between the months of April and June, strong seasonal upwelling has been shown to drive primary productivity attracting numerous marine fauna to the region [31].Our study area encompassed the southern portion of each sanctuary (Cordell Bank: 1370 km^2, Greater Farallones: 3320 km^2) ranging from north of Cordell Bank (38°8'N) to south of the Farallon Islands (37° 34'N) and extended from the upper continental slope to coastal waters within 15 km from shore. Many seabird species have flocked to this coastal region of central California specifically to forage in highly productive, upwelled waters [49], making it an ideal area to monitor for local scale conservation planning.

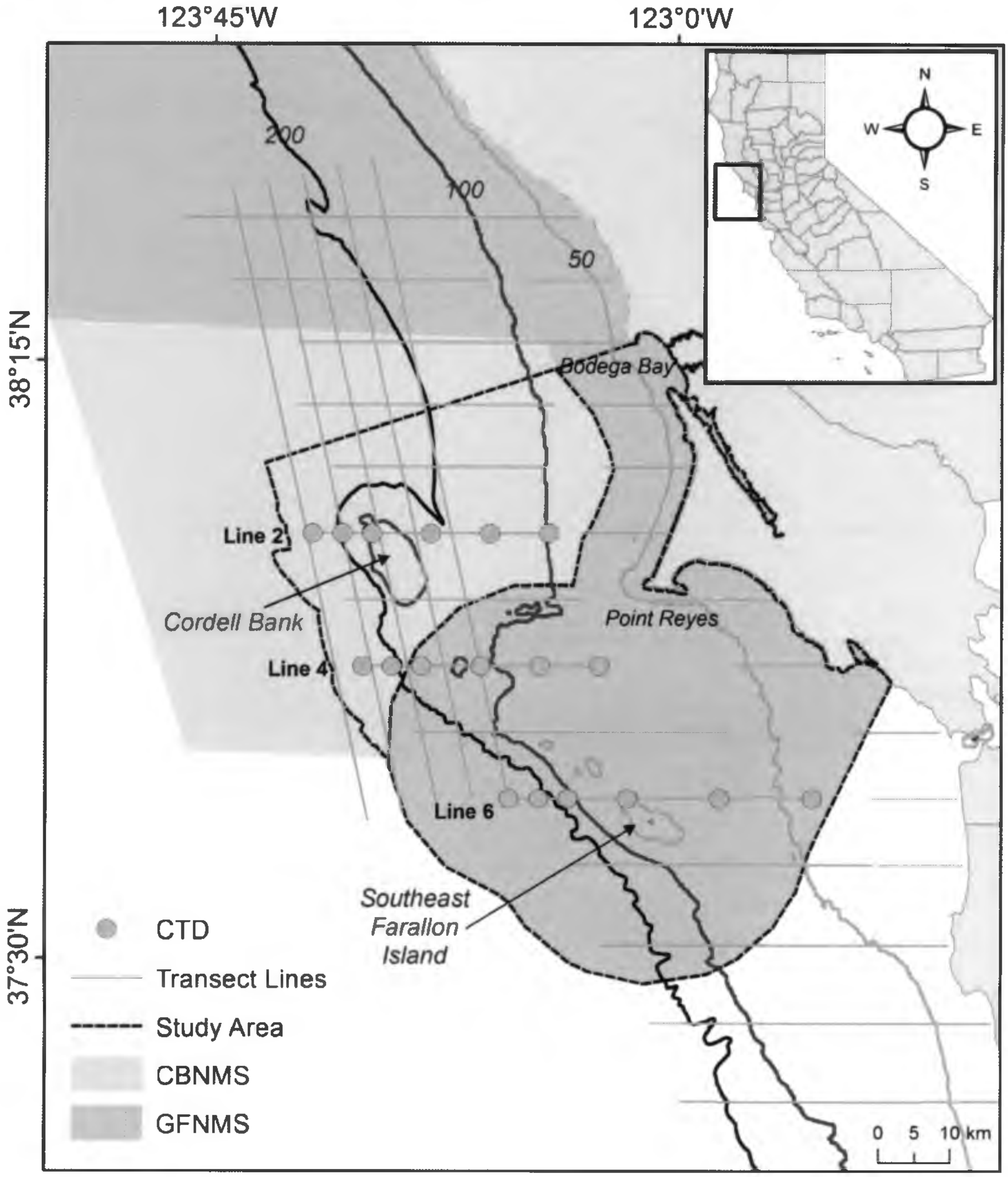

Figure 1.1. Study area. The study region encompassing ACCESS transect lines and target Conductivity, Temperature, and Depth (CTD) deployment stations on lines 2, 4, and 6 within the sanctuary boundaries of Cordell Bank (CBNMS) and Greater Farallones (GFNMS) National Marine Sanctuaries.

Data Collection and Processing

This study used ten years of field survey data collected by the Applied California Current Ecosystem Services (ACCESS) team, a partnership between GFNMS, CBNMS, and Point Blue Conservation Science (www.accessoceans.org). Between April and October from 2004-2013, a total of 37 cruises were completed. Surveys were conducted on one of three research vessels: the John H. Martin (Moss Landing Marine Laboratories, Moss Landing, California, USA), the McArthur II (National Oceanic and Atmospheric Administration (NOAA), Seattle, Washington, USA), and the Fulmar (Monterey Bay National Marine Sanctuary, Monterey, California, USA). Observers followed the ACCESS standardized strip-survey design and sampling methodology (see Jahncke et al. 2008 [49] for further details). Transect lines spanned nearshore and offshore areas along the continental margin (Fig 1.1). We used seabird counts, detection variables, and oceanographic information collected from ACCESS transects as well as bathymetric, distance, and climate data from the sources detailed in Table 1.1.

Table 1.1. Environmental variables. Variables used to analyze seabird distribution in GFNMS and CBNMS per 3-km bin for 37 ACCESS cruises from 2004-2013.

Variable	*Mean ± SD*	*Min−Max values*	*Description*	*Data Source*
Oceanography				
SSF	2.5 ± 6.7	−8.6−28.1	Ave. sea surface fluorescence (1-6 meters from surface) per bin (RFU)	ACCESS Survey Strip Transect
SSS	33.4 ± 0.36	29.7−34.1	Ave. sea surface salinity (1-6 meters from surface) per bin (mg/m^3)	ACCESS Survey Strip Transect
SST	12.3 ± 1.7	8.2−16.4	Ave. sea surface temperature (1-6 meters from surface) per bin (^oC)	ACCESS Survey Strip Transect
Bathymetric Features				
Distance to Cordell Bank	37.6 ± 24.9	0.8−115.5	Distance from bin midpoint to Cordell Bank midpoint (km)	See Source for Average Depth
Distance to 200-m isobath	11.6 ± 10.3	0.02−47.3	Distance from bin midpoint to 200-m isobath (km)	See Source for Average Depth
Depth	179.2 ± 240.0	7.6-2075.6	Average depth (m)	Department of Fish and Game. Available from: ftp://ftp.dfg.ca.gov/R7_MR/BATHYMETRY/ (Accessed March, 2014).
Contour Index	0.2 ± 0.2	0−1	(max depth - min depth)/max depth per bin	See Source for Average Depth
Terrestrial Features				
Distance to mainland	26.5 ± 10.5	1.2−50.5	Distance from bin midpoint to nearest mainland (km)	United States Census Bureau. Available from: http://www.census.gov/geo/maps-data/data/cbf/cbf_counties.html (Accessed March, 2014).
Distance to island	25.9 ± 16.4	0.1−89.4	Distance from bin midpoint to nearest island (km)	United States Census Bureau. Available from: http://www.census.gov/geo/maps-data/data/cbf/cbf_counties.html (Accessed March, 2014).

Variable	*Mean ± SD*	*Min−Max values*	*Description*	*Data Source*
Climate Indicecs				
UI	183.7 ± 71.3	46−339.5	Monthly Upwelling Index Value	Pacific Fisheries Environmental Laboratory. Available from: http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/NA/data_download.html (Accessed March, 2014).
NPGO	0.6 ± 0.9	−1.7−2.1	Monthly North Pacific Gyre Oscillation Value	Emanuele DiLorenzo. Available from: http://eros.eas.gatech.edu/npgo/ (Accessed March, 2014).
PDO	−0.4 ± 1.0	−2.2−1.9	Monthly Pacific Decadal Oscillation Value	Joint Institute for the Study of the Atmosphere and Ocean. Available from: http://jisao.washington.edu/pdo/PDO.latest (Accesssed March, 2014).
SOI	0.4 ± 1.6	−2.7−4.3	Monthly Southern Oscillation Index Value	CGD University Corporation for Atmospheric Research. Available from: http://www.cgd.ucar.edu/cas/catalog/climind/soi.html (Accessed March, 2014).
Detection Variables				
Sea State	2.8 ± 1.4	0−6	Observed Beaufort Scale conditions per bin (0-9 scale)	ACCESS Survey Strip Transect
Swell	1.8 ± 4.0	0−8	Observed swell height per bin (0-9 scale)	ACCESS Survey Strip Transect
Visibility	5.3 ± 2.0	0−9	Observed visibility per bin (0-9 scale)	ACCESS Survey Strip Transect
Cloud Cover	4.7 ± 3.4	0-9	Observed cloud cover per bin (0-9 scale)	ACCESS Survey Strip Transect
Time of Day	12:19:00 ± 03:00	06:08-20:05	Time of completion per bin (hh:mm)	ACCESS Survey Strip Transect

For our data collection, processing, and analysis, we followed the schematic in Figure 1.2. Prior to analysis, data were processed so that values were assigned to each midpoint of 3 kilometer (km) transect line segments, referred to as 'bins'[31,50] and to each centroid of a 1 km^2 prediction grid cell [51,52]. For each 3-km bin midpoint and each 1 km^2 prediction grid cell centroid (covering up to 5 km beyond the footprint of the Sanctuaries), we extracted data on a cruise-by-cruise basis. Binned data were used to generate detailed predictive models while the gridded data provided a matrix to which models were used to predict values for the unsampled space of the study area. We used *in situ* oceanographic data for temperature, salinity, fluorescence, and detection variables (sea surface swell, visibility, Beaufort scale); we extracted bathymetric data for depth; and we calculated distances to the 200-m isobath, California mainland, the edge of the Farallon Islands, and the midpoint of Cordell Bank. We assigned monthly values for all climate indices and upwelling index to each bin and grid centroid.

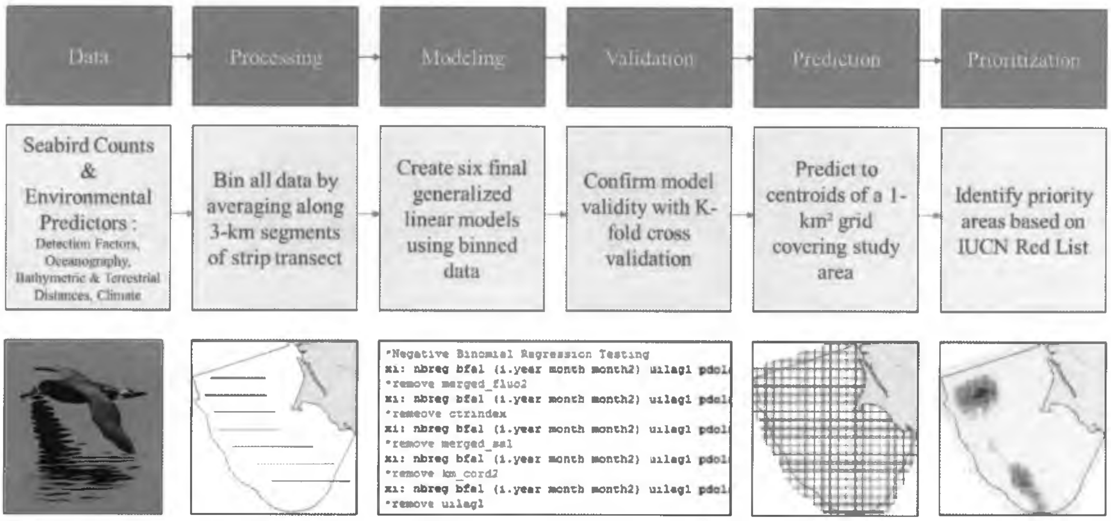

Figure 1.2. Schematic. Flow chart illustrating the methods for data collection, processing, and analysis.

Seabird observations and detection variable values were recorded from the flying bridge of the research vessel using standardized strip transect methods following transect lines in the study area [49]. While traveling at a speed of 10 knots aboard a research vessel, an expert observer stationed on the flying bridge recorded seabird presence and behavior within a 90^0 arc from the bow to the vessel's starboard side within 50-300 m. We only used records of seabirds foraging, feeding, or sitting on the sea surface to represent foraging behavior. We assumed all seabirds exhibiting these behaviors were either actively searching for food (foraging), had prey visible in the mouth (feeding), or had just finished feeding and were resting to digest (sitting on the sea surface). While underway, observers also recorded changes in the detection variables of sea state

(Beaufort scale), swell height, cloud cover, and visibility. These methods have been used previously to survey seabirds offshore of California [35].

A thermosalinograph (TSG) positioned in the sea chest of each ship recorded continuous underway measurements for sea surface temperature (SST), salinity (SSS), and fluorescence (SSF) at the sea surface directly below the hull of the ship. A Sea-Bird Electronics SBE 19Plus SEACAT Conductivity-Temperature-Depth (CTD) Profiler equipped with a WETStar fluorometer was deployed at designated sampling stations (Fig 1.1) to collect the same three oceanographic variables at the sea surface (1-6 m depth). To extend our observations to within and up to 5 km beyond the larger study area, we interpolated surface water maps on a cruise-by-cruise basis from binned oceanographic data using ordinary kriging (ESRI v. 10.2) [53]. Kriging has been characterized as an interpolation technique that fits a spatial-dependence model to a set of data and generates a surface by calculating values for unsampled locations within a specified radius of sampled locations using an advanced semivariogram [54]. We were interested in capturing general oceanographic trends (n = 107 total surfaces for SSF, SSS, and SST) in a patchy environment for which kriging has been shown to produce accurate estimates [55–57]. We identified outlying cruises based on plots of the mean square error for each variable's prediction surface, which were detrended as necessary to minimize errors across all cruises used in our analysis. We compared average standard errors across all surfaces of each variable to ensure all surfaces were within three standard deviations of the mean. One cruise (n = 3 surfaces) was excluded due to limited spatial coverage, and we only included extracted values to the region south of ACCESS transect line 3 for two others (n = 6 surfaces).

Additional processing was required for oceanographic data as thermosalinograph (TSG) malfunctioning led to missing sea surface values for some cruises. For seabird bins that didn't have corresponding TSG data, the closest CTD stations (within a 3 kilometer radius of missing record locations) were used to derive raster surfaces (n = 23 of the 107 total oceanographic surfaces) from which we extracted values to make local predictions. We used a simple linear regression incorporating TSG values and extracted CTD values while controlling for month and year. Our linear models predicted ($p < 0.05$) average fluorescence ($R^2 = 0.63$), salinity ($R^2 = 0.88$), and temperature ($R^2 = 0.94$) to fill in missing values.

In addition to our *in situ*-collected data, we also included bathymetric and distance-related factors. Based on observations, accessibility to the mainland, islands, Cordell Bank, and the 200-m isobath were thought to potentially influence pelagic seabird distributions. The shortest distance from the midpoint of each 3-km bin and from the centroid of each grid cell to the nearest part of each geographic feature and depths were calculated using a geographic information system (ArcGIS v. 10.2, Environmental

Systems Research Institute, 2014). Average depth was calculated from a bathymetric surface and contour index (a metric of ocean floor complexity) was derived using the following equation described in previous research: (maximum depth – minimum depth)/maximum depth [50].

To account for climatic influences on seabird distribution, we included four climate indices known to influence the California Current System: (1) North Pacific Gyre Oscillation (NPGO); (2) Pacific Decadal Oscillation (PDO); (3) Southern Oscillation Index (SOI); and (4) Upwelling Index (UI). Values for each variable were matched with cruises based on month. NPGO [38], PDO [37], and SOI [58] have been characterized as basin-wide indices while UI was calculated regionally (Table 1). To represent upwelling for this study region, we used an average monthly value for two locations along the California coastline (Big Sur, 36°N 122°W and Point Arena, 39°N 125°W) as no single value matched the Sanctuaries' region. To see if a delayed effect could influence seabird population distribution, lagged values of 1, 2, and 3 months were also calculated [59].

Species Distribution Modeling

We used generalized linear models (GLMs) to predict distributions based on binned observations for the six pelagic foraging species most frequently observed in GFNMS and CBNMS during ACCESS cruises from 2004-2013: *A. griseus, A. creatopus,* *F. glacialis, P, nigripes, P. fulicarius,* and *P. lobatus*. GLMs have been documented as parametric statistical modeling approaches often used for studies that depend on count data and are useful for detecting temporal interactions between variables in a model [60,61]. A strength of this study was using GLMs to examine how species distribution patterns differed among months and among years.

Field survey count data for ecological studies often follow a Poisson, negative binomial, or zero-inflated Poisson, or zero-inflated negative binomial distribution [60,62]. Negative binomial regression has been effective for modeling data that have greater variability than would be expected from Poisson-distributed data [60]. In some cases, however, a zero-inflated negative-binomial regression has been shown to be more appropriate for producing a best-fit model given data with a proportion of zeroes exceeding what is expected from a negative binomial [62]. Models of data containing an excess of zeroes, of which some may be "false zeroes," have been improved with zero-inflated modeling [62]. "False zeroes" could occur, for example, during a survey with unfavorable field conditions (e.g. phalaropes are small birds and may not be detected in weather conditions that bring about high swell height). All seabird species had a larger proportion of zero count bins than non-zero count bins (bird observations) in our field survey (Table 1.2), thus we only selected species with more than 100 non-zero bins to allow for model fitting.

Table 1.2. Description and counts of seabird species. Foraging type depicted by * (flexible piscivorous) and † (strictly planktivorous).

Seabird	*Mean ± SD*	*Min–Max values*	*Non-zero Binned Observations (of 4073)*
Phoebastria nigripes (black-footed albatross)*	2.1 ± 2.3	1–20	229
Fulmarus glacialis (northern fulmar)*	3.9 ± 10.7	1–109	210
Ardenna creatopus (pink-footed shearwater)*	4.0 ± 7.1	1–50	192
Phalaropus fulicarius (red phalarope)†	6.7 ± 11.8	1–70	100
Phalaropus lobatus (red-necked phalarope)†	7.8 ± 12.1	1–86	174
Ardenna griseus (sooty shearwater)*	35.9 ±104.3	1–1405	651

Covariate Selection

Using negative binomial regression (STATA 13, StataCorp.), we developed a systematic approach to selecting the most significant relationship of each variable to include as a covariate in a later multivariable model. For all models, we controlled for month and year as respective quadratic and categorical variables and used the log of the binned areas as an offset to account for seabird detection differences that result from bins with different areas [60,62]. We used the log-likelihood test of alpha (over-dispersion parameter) to determine whether negative binomial models were preferable to Poisson regression. Depending on the variable, we used one of several different strategies as follows.

For oceanographic (SSF, SSS, SST) and bathymetric variables (average depth and contour index), we compared linear or quadratic relationships tested in a univariate regression. Significant quadratic variables ($p < 0.05$) were always included, and if the quadratic term was not significant, the linear variation ($p < 0.20$) was included. For distance variables (distance to: 200-m isobath, mainland, nearest island, and Cordell Bank), we selected the most significant relationship of linear, quadratic, logarithmic, or inverse logarithmic relationships. Because environmental conditions prior to the time of observation may influence seabird foraging distributions [31], we compared the present conditions (no lag) as well as 1-, 2-, and 3-month lag periods for each climate index (NPGO, PDO, SOI, and UI) and chose from either linear or quadratic relationships, only including the lag and relationship that were most significant.

Multivariable Model Selection

All significant variables from the univariate models were included in a preliminary multivariable model. As in the univariate models, we controlled for month and year in multivariable models and included an offset of the log of the binned area. We used manual backwards stepwise removal until all variables in the multivariable model were significant ($p < 0.05$). We used the variance inflation factor (VIF) statistic to test for multicollinearity between all final model variables and ensured that all VIF values were below 10 [63,64].

To allow for the effect of covariates to vary among years [31], we examined the possible effect of interactions of local and regional predictors over time. We tested for interactions of significant local and regional covariates, specifically the interaction of depth, the 200-m isobath, SST, and UI each with year (as a categorical covariate). If more than one interaction was significant ($p < 0.05$), we included all interactions in the model.

We accounted for potential "false zeroes" or detection error that are common to field-collected data [35,62,65] by evaluating whether zero-inflated GLMs outperformed the negative binomial model version. Detection error has been shown to occur when a species is present at a survey site but goes undetected by the observer due to survey-specific factors (e.g. weather or time of day), species traits (e.g. life history or rarity), and individual traits (e.g. distance to the observer) [66]. We attempted to improve each of our negative binomial regression models by testing whether several potential sources of detection error (hereafter called 'detection variables') collected *in situ* contributed to zero-inflation of the data. We used the Vuong test statistic to determine if the zero-inflated negative binomial version was preferable to the standard negative binomial model [67]. If more than one detection variable was significant, all significant detection variables were included in the final model.

Model Validation and Interpretation

We validated model fit using k-fold cross validation, repeating cross validation ($k = 10$) 20 times to validate each model's fit. For k-fold validation, each 1/k subset, in this case 10%, of the binned data was predicted from the remaining 90% of the data to derive a goodness of fit to the original model [68,69], a process that was repeated multiple times. A median pseudo R^2 value was calculated for each of the 20 runs and a median of that median was compared against the final model pseudo R^2 value for validation ($p < 0.05$). We performed a log-likelihood ratio test for models with more than one climate index and identified the variable with the greatest log-likelihood value (of NPGO, PDO, or SOI) as the dominant climate index. We interpreted the influence of each quadratic covariate by graphing its relationship with predicted seabird values while controlling for the marginal effects of other covariates in the final models (margins, STATA 13).

Habitat Prioritization

We used a conservation prioritization software (Marxan v. 2.4.3, University of Queensland, Australia) to optimize potential pelagic seabird high-use foraging areas to target for potential changes in management. Marxan has provided decision support for reserve system design and is capable of solving the minimum set problem, for which the objective is to optimize for some minimum representation of biodiversity features, at a minimum cost [70]. Using Marxan, we generated scenarios reflecting 10%, 30%, and 50% conservation targets for seabird foraging area in the Sanctuaries. Using the perimeter of the 1 km^2 planning units previously derived for seabird predictions, we computed reserve boundary length. To minimize habitat fragmentation of the targeted reserve area, we calibrated for an appropriate boundary length modifier [71]. Reserve optimizations for n = 100 iterations were generated, each of which gave a count of the number of times each grid cell was included in the optimal reserve solution resulting from each run of the software [72]. The number of times each grid cell was selected for inclusion in reserve design was converted to a percent rank and the upper 50 percent were displayed for 10%, 30%, and 50% conservation scenarios.

Because global populations of seabirds encounter different levels of stress, we applied a higher species penalty factor to those seabirds whose populations were facing a greater threat of extinction according to the IUCN Red List [73–78]. Using a species penalty factor (spf) enabled the Marxan software to prioritize some species' habitat as greater importance for inclusion in the targeted conservation output. We assigned a spf of 1 to species listed as 'Least Concern' (*F. glacialis*, *P. fulicarius*, and *P. lobatus*), 2 to those listed as 'Near Threatened' (*P. nigripes* and *A. griseus*), and 3 to those listed as 'Vulnerable' (*A. creatopus*).

Seabird Distribution Visualization and Interpretation

Using final seabird models, we predicted abundance and distribution for each of the six seabird species to the 1-km² grid centroids covering our study area. In monthly maps for each species, we displayed predicted high to low seabird abundances for the months of May through October. Yearly maps for each species depicted high to low predicted seabird abundances incorporating only the top three months of peak predicted abundance (*P. nigripes*: May, June, July; *A. creatopus*, *A. griseus*, and *F. glacialis*: June, July, September; *P. lobatus*, and *P. fulicarius*: July, September, October). To generate a comprehensive map across all six species and across all months and years, we standardized seabird abundance with the following equation:

$$z_i = \left(\frac{x_i - \mu}{\sigma}\right)^{-1} \qquad \text{(Eq. 1)}$$

Where, z_i is the standardized seabird abundance for grid cell i, x_i is the log of each seabird species' abundance value (x) by grid cell (i), μ is the population mean for that species, and σ is the standard deviation, where μ and σ are log-transformed. Values were then converted to a percentile rank for map display. We generated maps by individual species, foraging guild, and for all species standardized and averaged. We visualized spatial differences in foraging guild by subtracting standardized piscivorous values from planktivorous values. Spatial differences were mapped relative to the mean of the difference distribution in terms of standard deviations, i.e. 0 (no difference): 1 (little to none), 2 (medium), and 3 (high) standard deviations.

Species distributions predicted from final models were compared for spatial difference. The Cramer-von Mises (CVM) test statistic (Ψ) is a modification of the Kolmogorov-Smirnov test that asks whether two populations come from the same distribution [79]. Adapted from Syrjala et al. (1996), seabird abundance values were log-normalized to remove the effect of different population sizes yielding Equation 2. A script was generated to calculate Ψ (Eq. 3; Python v. 2.7.5) for the normalized seabird distributions:

$$p_{ij} = \frac{x_{ij}}{\sum x_{ij}} \qquad \text{(Eq. 2)}$$

$$\Psi = \sum(\Gamma p_{i1} - \Gamma p_{i2})^2 \qquad \text{(Eq. 3)}$$

Where p_{ij} is the log-normalized seabird abundance for log seabird abundance value x, grid cell i, and species j. Ψ ranged from 0 (equivalent distributions) to 0.02 (no overlap of distributions), p_{i1} and p_{i2} are two compared log-normalized seabird species distributions (p) by grid cell (i) and Γ is the cumulative distribution function. Each of the six species was compared to one another and piscivorous were compared to planktivorous foraging guilds. To determine whether observed difference between two distributions was statistically significant ($p < 0.05$), we calculated Ψ for n = 1000 randomizations where log-normalized values were randomized for one of the species in the comparison. Before testing with our data, we verified that our CVM script could detect a significant difference ($p < 0.05$) between mock populations with less than 15 percent overlapping distributions. The p-value was the proportion of the 1000 random Ψ that were greater than or equal to the observed Ψ. For example, if 200 random Ψ were greater than the observed Ψ, then $p = 0.2$, indicating that the difference between distributions was not significant.

Results

All final models were significant ($p < 0.05$) and successfully validated (k = 10, n = 20, $p < 0.05$; Table 1.3). We found no multicollinearity between covariates in any of the final models (VIF < 10). *A. griseus*, *P. fulicarius*, and *P. lobatus* were modeled using a zero-inflated negative binomial regression while *P. nigripes*, *F. glacialis*, and *A. creatopus* were modeled using negative binomial regressions. Models produced different spatial and temporal patterns depending on species and foraging guild.

Table 1.3. Description of predictive models for six seabird species. Strongest relationship of predictor variable from univariate testing is depicted as linear 'L', quadratic 'Q', or logarithmic 'Lg'. Coefficient value for main effect of predictor variable (i.e. without interaction) in predictive model is depicted as positive (+) or negative (-). Dominant climate index is outlined with a box. Foraging type is depicted by * (flexible piscivorous) and † (strictly planktivorous). Variables exhibiting a significant interaction with year are in bold. Variables represented were significant ($p < 0.05$) in models of each associated seabird species.

Variable	*P. nigripes**	*F. glacialis**	*A. creatopus**	*A. griseus**	*P. fulicarius†*	*P. lobatus†*
Oceanography						
SSF		Q (-)			L (+)	Q (+)
SSS					L (+)	
SST	**L(+)**			**Q (-)**		
Bathymetric Features						
Distance to Cordell Bank	L (-)	L (-)		Q (+)		
Distance to 200m isobath	**L (-)**		L (-)	Lg (-)	L (-)	L (-)
Depth	L (-)	**Q (-)**	**Q (-)**			
Terrestrial Features						
Distance to mainland		L (+)				
Distance to island			Q (-)		Lg (+)	
Climate Indices						
UI 3-month lag		Q (-)				
NPGO 1-month lag			$\boxed{\text{L (-)}}$			
NPGO 2-month lag		L (+)			L (-)	
NPGO 3-month lag				$\boxed{\text{Q (+)}}$		
PDO 1-month lag		$\boxed{\text{Q (-)}}$				
PDO 3-month lag	Q (-)			Q (-)	$\boxed{\text{Q (-)}}$	$\boxed{\text{L (+)}}$
SOI current				Q (+)		
SOI 2-month lag	$\boxed{\text{Q (-)}}$					
Detection Variables						
Seastate				L (+)		L (+)
Swell					L (-)	
Visibility				L (-)		
Model χ^2 (df)	517.81 (37)	586.51 (31)	308.55 (26)	654.80 (40)	169.44 (18)	117.10 (15)
Model P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Model Pseudo-R^2	0.2251	0.2556	0.1315	0.0970	0.1800	0.0829
Vuong test for zero inflation P				0.0007	0.0324	0.0002
Model Validation						
k=10, n=20)	0.0900	0.1100	0.0128	0.0401	0.1444	0.0185
Validation P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Oceanographic Associations

At least one oceanographic variable was important for five seabird models, though no single oceanographic variable was important for the majority of models. High abundances of species visiting from Arctic waters were associated with high SSF: both *P. fulicarius* and *P. lobatus* increased without restriction (Table 1.3, Fig 1.3), and *F. glacialis* peaked in number at approximately 20 relative fluorescence units (rfu; Fig 1.4). Of all species, only *P. fulicarius* was associated with more saline sea surface waters (Table 1.3). High numbers of *A. griseus* showed an overall negative association with SST (more seabirds in colder waters); however, this effect differed by year (Table 1.3, Fig 1.5). Conversely, *P. nigripes* was positively associated with SST (more seabirds in warmer waters), which also differed by year (Table 1.3). SST was only significant for piscivorous species while SSS was only important to planktivorous species.

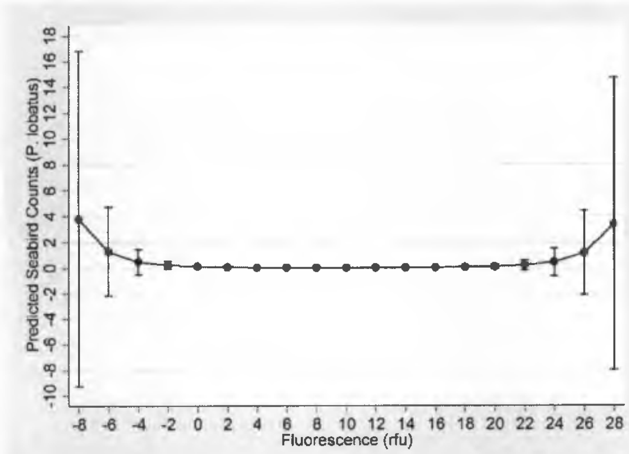

Figure 1.3: *P. lobatus* quadratic relationship with SSF. Graphs display estimated mean seabird count (y axis) at fluorescence measurement (x axis). Bars depict standard error.

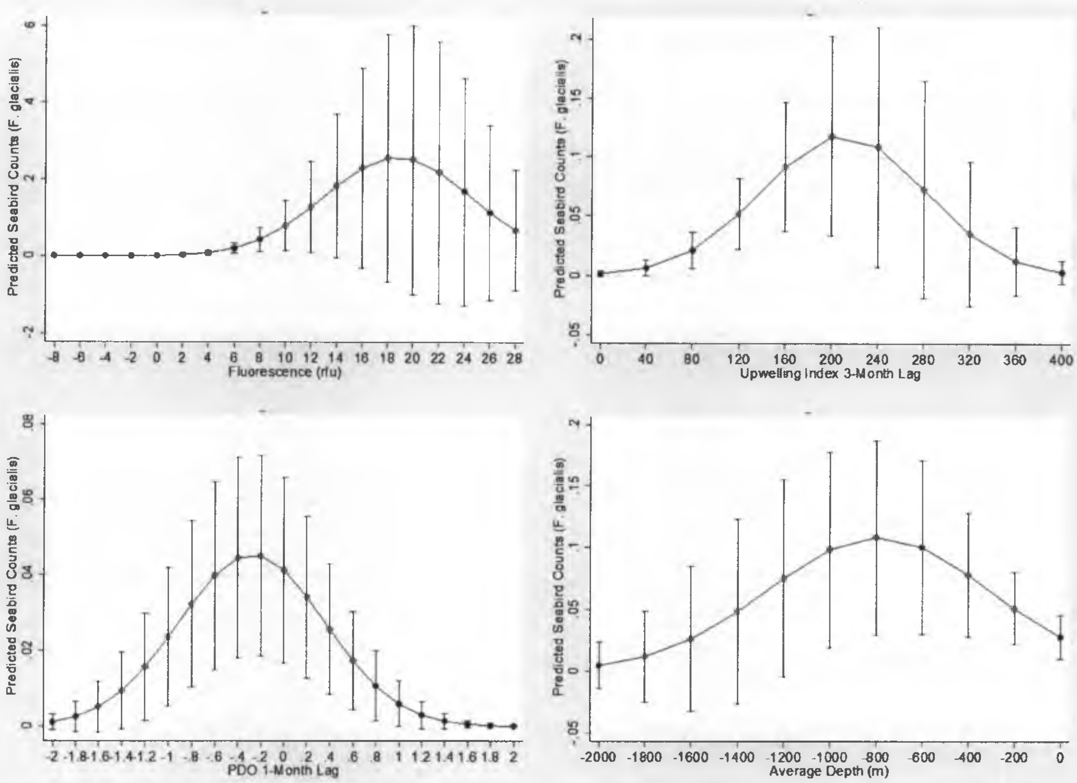

Figure 1.4: *F. glacialis* quadratic relationships with SSF, UI, PDO, and depth. Graphs display estimated mean seabird count (y axis) at UI, PDO, or depth measurements (x axis). Bars depict standard error.

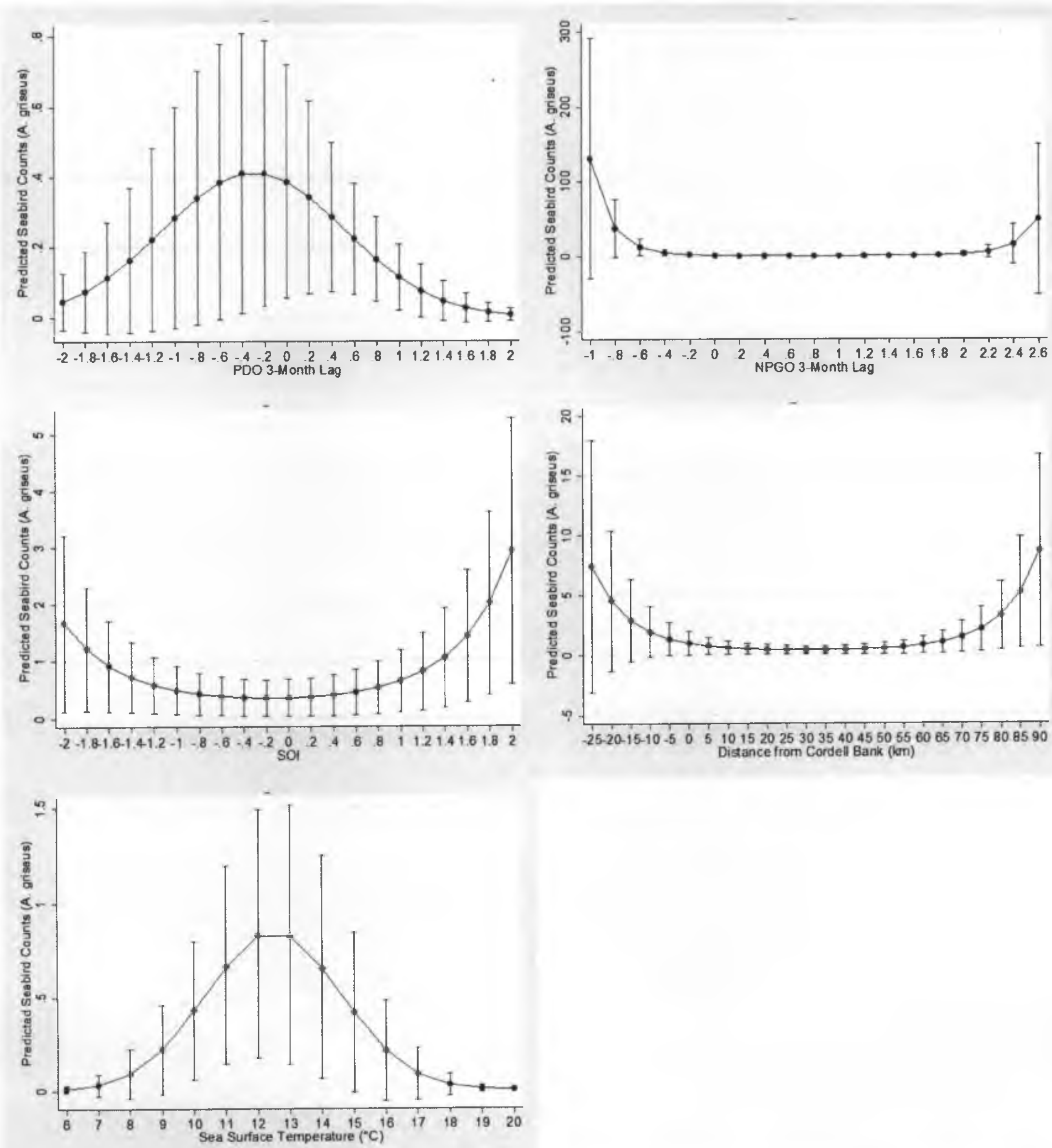

Figure 1.5. *A. griseus* quadratic relationships with PDO, NPGO, SOI, distance to Cordell Bank, and SST. Graphs display estimated mean seabird count (y axis) at PDO, NPGO, SOI, distance to Cordell Bank, or SST measurements (x axis). Bars depict standard error.

Bathymetric and Distance-Related Associations

Bathymetric features were significant to all seabird models and in four models, two or more bathymetric features were included. High seabird abundance for five models was associated with the 200-meter isobath (Table 1.3). Only *A. griseus* showed a logarithmic association with proximity to the shelf break (Table 1.3). The association of *P. nigripes* with the shelf break was significant but varied by year (Table 1.3). Proximity to Cordell Bank was associated with three species: *P. nigripes* and *F. glacialis* had a positive association with Cordell Bank (the closer in proximity, the more birds), and though *A. griseus* had a slightly positive association with waters directly above the bank, a greater proportion of this species' abundance was associated with distances far from the bank (e.g. approaching Monterey Bay National Marine Sanctuary; Table 1.3, Fig 1.5). Depth was negatively associated with *P. nigripes*, *F. glacialis*, and *A. creatopus* (Table 1.3). However, the effect of depth differed by year for *F. glacialis* and *A. creatopus,* which both peaked in abundance at a depth of approximately 800 meters (Figs 4 & 6). Seabirds were generally associated with greater distances from the terrestrial mainland and islands: *F. glacialis* and *P. fulicarius* abundances, respectively, increased linearly from shore and exponentially from Southeast Farallon Island, while *A. creatopus* abundance peaked at approximately 30 km from the island (Table 1.3, Fig 1.6). Depth and Cordell Bank were associated only with piscivorous species, but were not significant to planktivorous species.

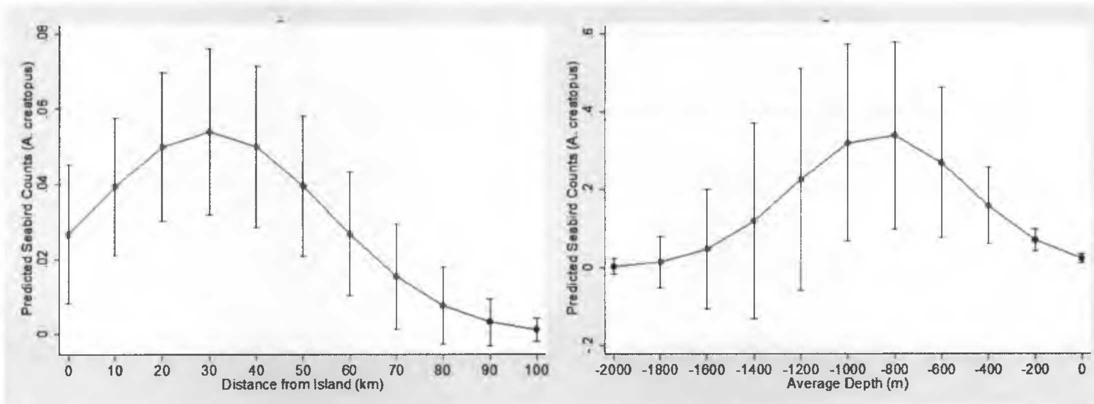

Figure 1.6. *A. creatopus* quadratic relationships with Southeast Farallon Island and depth. Graphs display estimated mean seabird count (y axis) at distance to Southeast Farallon Island or depth measurements (x axis). Bars depict standard error.

Climatic Index Associations

We found that seabirds were associated with a unique dominant climate index depending on their site of origin. PDO was the dominant driver of seabirds visiting from the Arctic (*F. glacialis*, *P. lobatus*, and *P. fulicarius*); NPGO was dominant for the shearwaters visiting from the South Pacific (*A. griseus* and *A. creatopus*); and SOI was dominant for *P. nigripes* traveling from the mid-Pacific Hawaiian Islands and a close secondary dominant driver for the shearwater *A. griseus* (Table 1.3). No single climate index was consistently dominant among all piscivores; however, PDO with a 3-month lag was the dominant climate index for all planktivores.

All seabirds were significantly associated with climate indices at multiple time lags. We found that high numbers of piscivores were associated with neutral or slightly negative PDO with either a 1- (*F. glacialis*) or 3- (*A. griseus* and *P. nigripes*) month lag (Figs 1.4, 1.5, & 1.7). Conversely, high numbers of both planktivores (*P. lobatus* and *P. fulicarius*) were associated with positive PDO with a 3-month lag (Table 1.3, Fig 1.8). Two species from the Arctic were associated with NPGO with a 2-month lag: high numbers of *P. fulicarius* were associated with a negative NPGO; while *F. glacialis* was associated with a positive NPGO (Table 1.3). In addition, high abundances of two piscivores visiting from the South Pacific were negatively associated with NPGO with a 3-month lag (*A. griseus*) or a 1-month lag (*A. creatopus*) (Table 1.3, Figs 5 & 6). High abundance of two piscivores were associated with positive SOI at the time of observation (*A. griseus*) and neutral SOI with a 2-month lag (*P. nigripes*) (Table 1.3, Figs 1.5 & 1.7). High abundance of *F. glacialis* was associated with a high upwelling index with a 3-month lag (Fig 1.4).

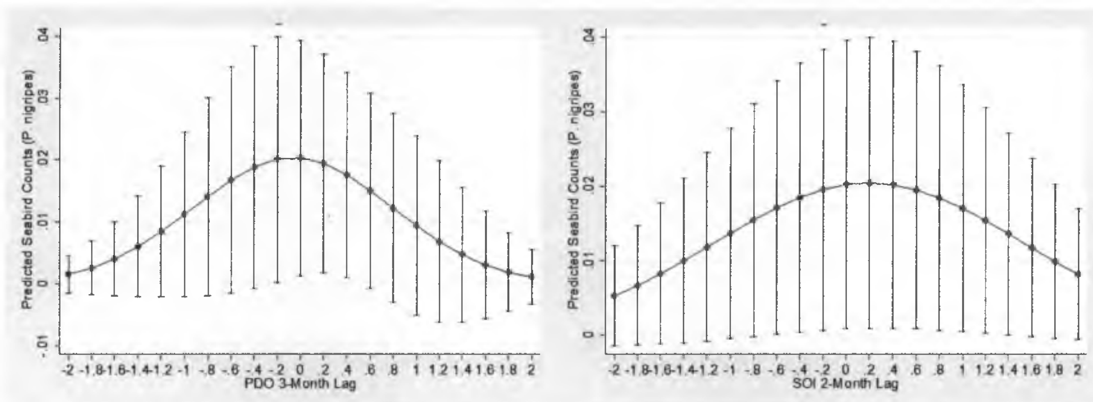

Figure 1.7. *P. nigripes* quadratic relationships with PDO and SOI. Graphs display estimated mean seabird count (y axis) at PDO or SOI measurements (x axis). Bars depict standard error.

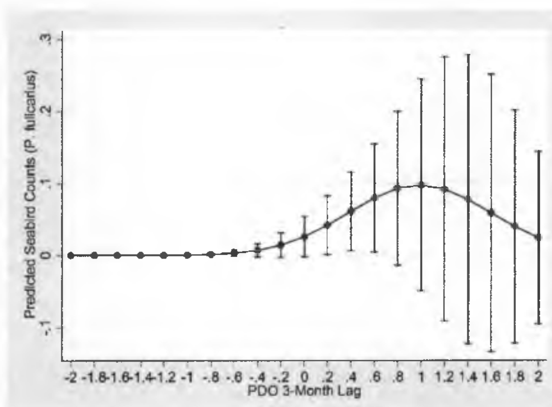

Figure 1.8. *P. fulicarius* quadratic relationship with PDO. Graphs display estimated mean seabird count (y axis) at PDO measurements (x axis). Bars depict standard error.

Species and Guild Distribution Differences

Maps of modeled seabird abundances ranged spatially and temporally by individual species and by foraging guild. The continental shelf break was the most visible high-use foraging spatial feature in all seabird maps depicting a composite of individual species predicted distributions standardized across all months and years of the survey (Fig 1.9). Highest predicted abundances of *P. nigripes* were in June; *F. glacialis*, *A. creatopus*, and *A. griseus* were in July with some variability; and *P. fulicarius* and *P. lobatus* peaked in September (Fig 1.10). Predicted piscivorous species abundance declined while predicted planktivorous species abundance dramatically increased in the year 2009 (Fig 1.11). The differences between distributions of all seabird species were not significant except *A. griseus*, which was significantly different ($p < 0.05$) from all others (Table 1.4). Piscivorous and planktivorous species abundances were associated with many of the same areas and the differences between their distributions were not considered significant (Table 1.4). However, categorizations between two and three standard deviations from the mean difference distribution suggest that some areas had a stronger association with one guild than the other (Fig 1.12). The area along the shelf break west of Cordell Bank in northwestern CBNMS, for instance, were more important to piscivorous species; on the other hand, the very northernmost and southern parts of the 200-m isobath and a region to the east of Cordell Bank were important to planktivorous species (Fig 1.12).

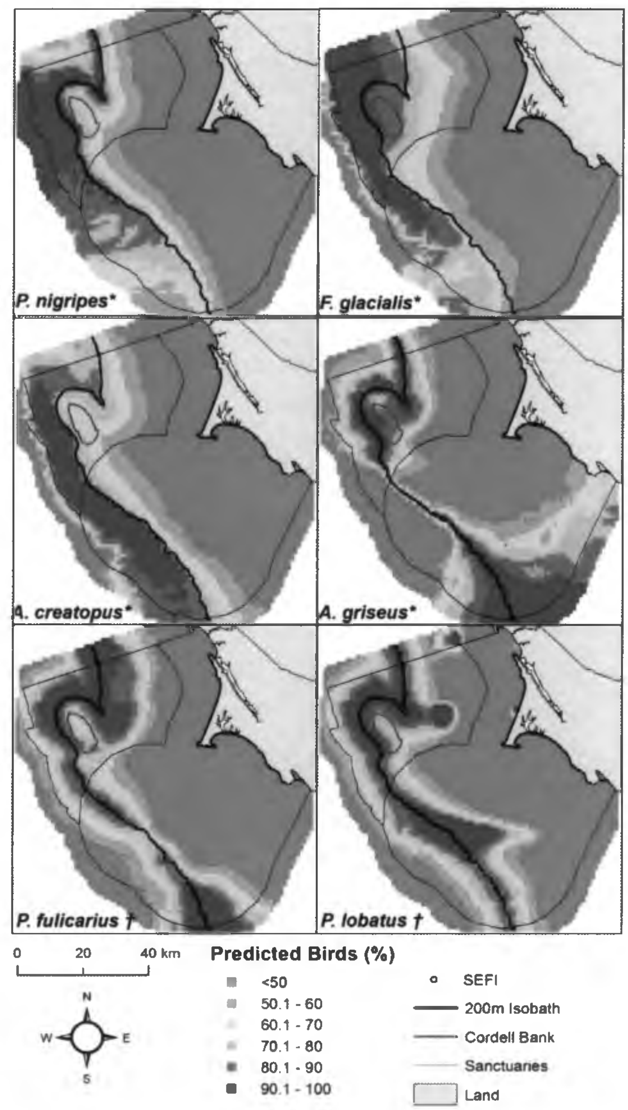

Figure 1.9. All seabirds standardized and averaged for each species across all years (2004-2013) using predicted values from the top three months of greatest abundance between May and October. Top months were: May, June, July (P. nigripes); June, July, Sept (F. glacialis, A. creatopus, A. griseus); July, September, October (P. fulicarius, P. lobatus). Map represents highest use foraging areas (upper 50 percent) for each species independent of other species. Foraging type depicted by * (flexible piscivorous) and † (strictly planktivorous).

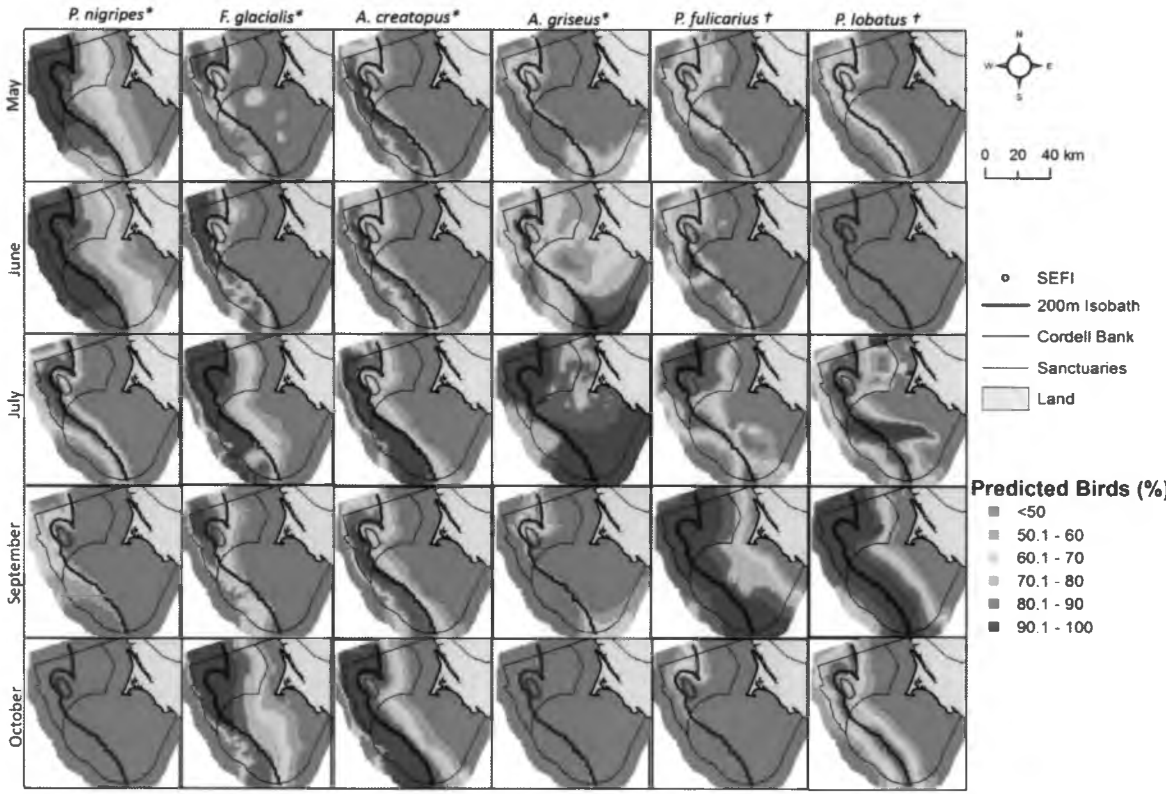

Figure 1.10. Monthly seabird distributions. Each species was standardized across months (May-October) using predicted values for all months in this range. Map represents highest use foraging areas (upper 50 percent) for each species relative to month but independent of other species. Foraging type depicted by * (flexible piscivorous) and † (strictly planktivorous).

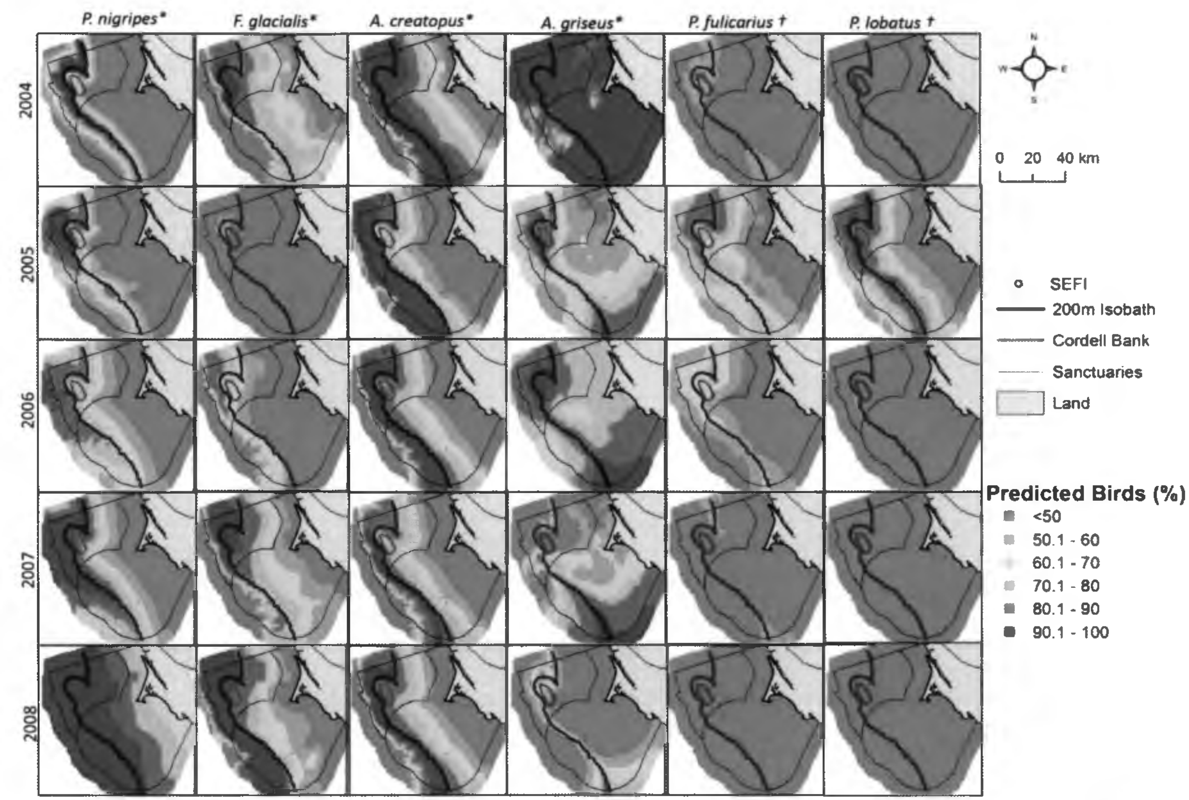

Figure 1.11a. Yearly seabird distributions. Each species was standardized across years (2004-2008) using predicted values from the top three months of greatest abundance between May and October. Top months were: May, June, July (*P. nigripes*); June, July, Sept (*F. glacialis, A. creatopus, A. griseus*); July, September, October (*P. fulicarius, P. lobatus*). Map represents highest use foraging areas (upper 50 percent) for each species relative to year but independent of other species. Foraging type depicted by * (flexible piscivorous) and † (strictly planktivorous).

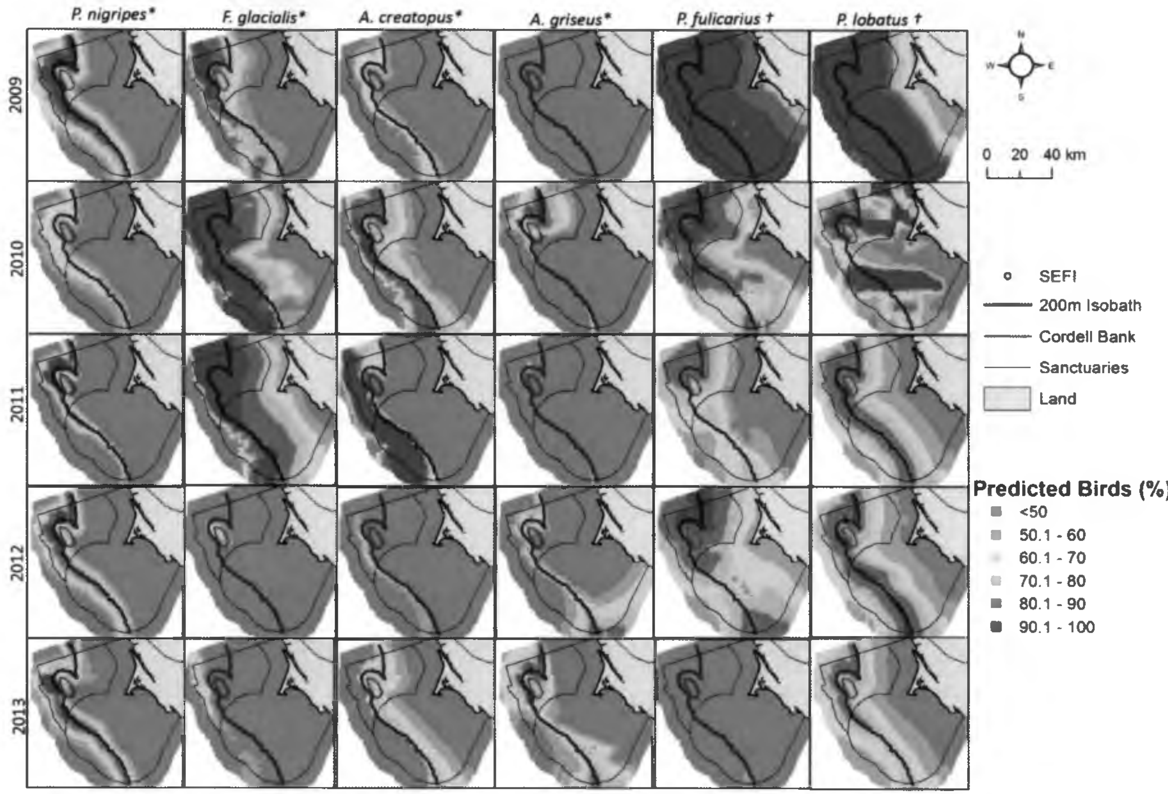

Figure 1.11b. Yearly seabird distributions. Each species was standardized across years (2009-2013) using predicted values from the top three months of greatest abundance between May and October. Top months were: May, June, July (*P. nigripes*); June, July, Sept (*F. glacialis, A. creatopus, A. griseus*); July, September, October (*P. fulicarius, P. lobatus*). Map represents highest use foraging areas (upper 50 percent) for each species relative to year but independent of other species. Foraging type depicted by * (flexible piscivorous) and † (strictly planktivorous).

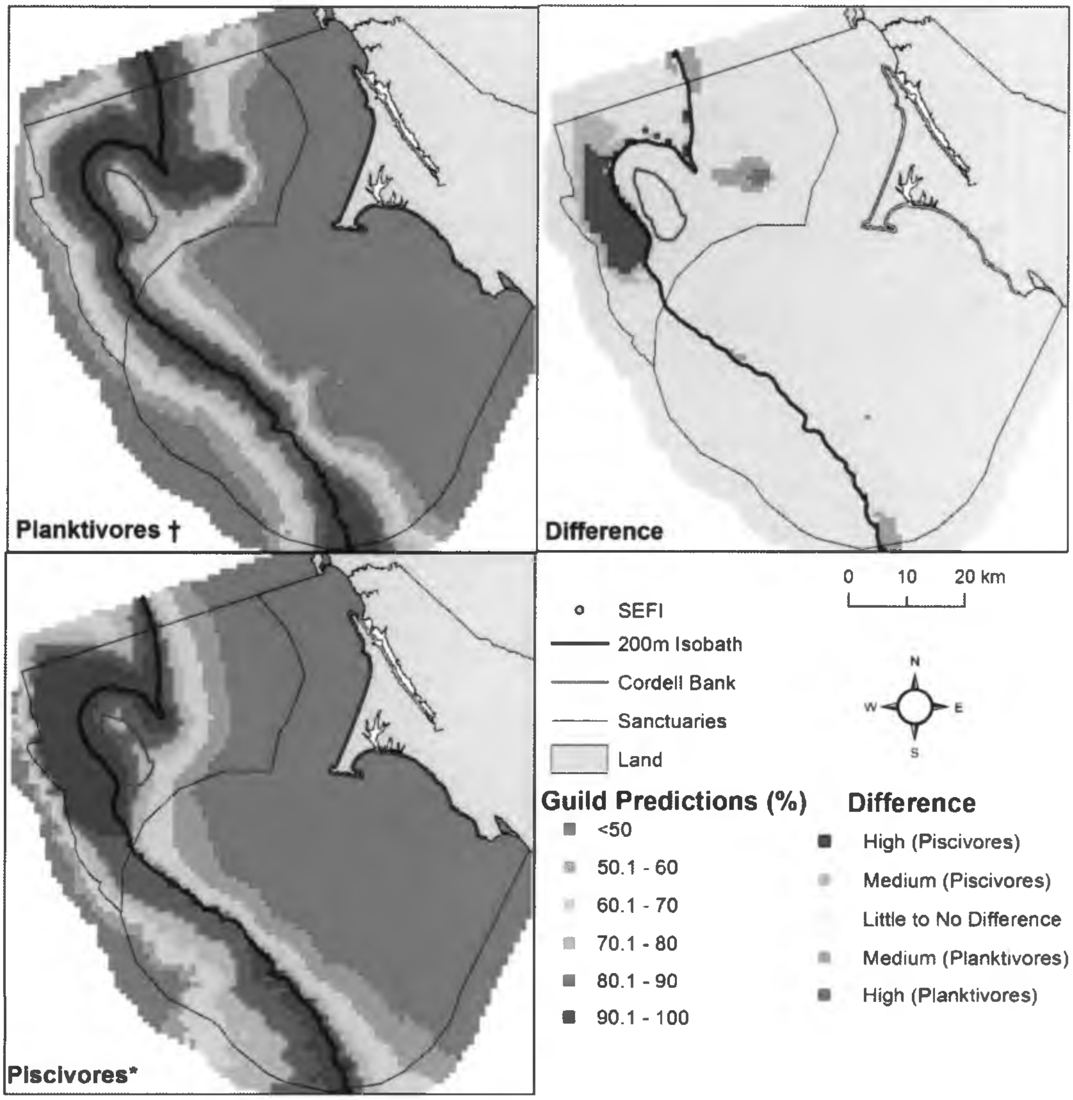

Figure 1.12. Spatial distributions by foraging guild. Flexible piscivores (*P. nigripes, F. glacialis, A. creatopus, and A. griseus*) and strict planktivores (*P. fulicarius and P. lobatus*) were standardized and averaged across species to generate two foraging guilds. 'Difference' shows where planktivore and piscivore distributions differ. Little to none, medium, and high difference are represented as 1, 2, and 3 standard deviations from the mean of the difference distribution histogram.

Table 1.4. Species distribution differences characterized by the Cramer-von Mises test statistic 'Ψ'. Ψ ranges from 0 (complete species distribution overlap) to 0.02 (distributions do not overlap at all). All species and two foraging guilds were compared. Foraging type depicted by * (flexible piscivorous) and † (strictly planktivorous). Significant distribution differences are in bold.

Species / Ψ	*P. nigripes**	*F. glacialis**	*A. creatopus**	*A. griseus*†	*P. fulicarius**	*P. lobatus* †
P. nigripes	–	–	–	–	–	–
F. glacialis	0.000044	–	–	–	–	–
A. creatopus	0.000053	0.000027	–	–	–	–
A. griseus	**0.000161**	**0.000152**	**0.000223**	–	–	–
P. fulicarius	0.000064	0.000058	0.000090	**0.000052**	–	–
P. lobatus	0.000052	0.000065	0.000057	**0.000208**	0.000075	–
Planktivores v. Piscivores	Ψ = 0.000403					

Detection Error

Our modeling approach accounted for errors in detecting birds that may have been obscured by non-ideal observation conditions. The three seabird species that fit zero-inflated models were significantly improved by including three of the tested detection variable factors (Vuong test statistic < 0.05). Sea state and visibility contributed to zero-inflation for *A. griseus* while swell height and sea state accounted for zero inflation for *P. fulicarius* and *P. lobatus,* respectively (Table 1.3). Sea state's influence on both *A. griseus* and *P. lobatus* indicated that rougher seas (i.e. a higher Beaufort classification) hindered detection of both species (i.e. zero inflation was more likely during a rougher sea state). Better visibility increased detection of *A. griseus* (i.e. false zeroes were more likely in poor visibility) and, counterintuitively, a higher swell height improved detection of *P. fulicarius* (i.e. false zeroes were more likely with lower swell height). Detection of *P. fulicarius* may have improved with high swell conditions because it is a small pelagic seabird that tends to fly in troughs of leeward wave crests during periods of high swell [80] and may be more likely to catch an observer's attention upon flushing from the sea surface by the joint effect of high swell and research vessel passage.

Habitat Prioritization

Our habitat prioritization exercise identified areas reflecting the most optimal 10%, 30%, and 50% of seabird foraging area, which encompassed the dominant space frequented among the species in this study. Calibration of all scenarios showed that habitat fragmentation and cost were optimally reduced using a boundary length modifier of 10. To differing degrees, all three scenarios satisfied our conservation targets, which were shown in seabird models to be in the Cordell Bank vicinity and along the 200-m isobath. The 10% conservation scenario highlighted only an area northwest of Cordell Bank and a southern portion of the 200-m isobath, while 30% and 50% scenarios more fully emphasized the targeting of the full 200-m isobath including an area radiating out from Cordell Bank (Fig 1.13).

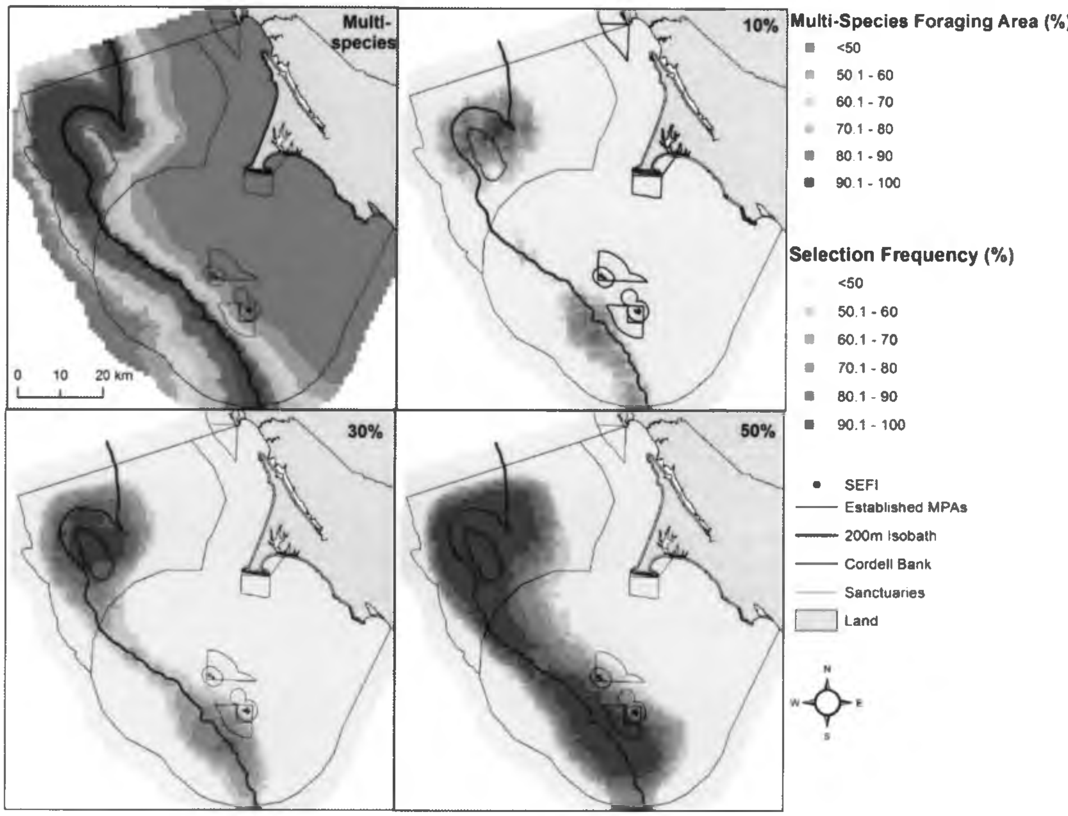

Figure 1.13. Conservation priority areas. Optimal locations to elevate management status when targeting either 10%, 30%, or 50% of multi-species seabird foraging area. Using IUCN Red List criteria, a higher level of priority was assigned to seabirds with an at-risk level greater than 'Least Concern:' *A. creatopus* (vulnerable), *P. nigripes* and *A. griseus* (near threatened).

Discussion

Pelagic seabird foraging area off the coast of Central California was more sensitive to oceanographic and bathymetric features and less influenced by distance to island and mainland likely because the species in our study do not breed locally. This finding contrasts to a previous study that found a strong association between locally breeding seabirds and distance to their colonies on the Farallon Islands and the mainland [33]. In comparison to previous modeling of seabird foraging areas in the larger California Current, which broadly characterized the Greater Farallones region as a foraging hotspot [31], our maps highlight the importance of the continental shelf break and the vicinity of Cordell Bank in this region, because of the different spatial scales used for modeling. Three habitat prioritization scenarios developed using our predictive models highlighted parts of the shelf break and particularly the vicinity of Cordell Bank as priority areas for the multiple species included in this study.

Model Interpretation

Though oceanographic variables were important for explaining spatial variability in most models, no single variable was important across all models and only one model was significantly influenced by two oceanographic variables. Our local scale findings in the Sanctuaries were similar to findings at the scale of the California Current [31], which suggested that no single oceanographic variable played a key role for all seabird models.

Bathymetric features influenced all pelagic seabird species. The influence of the continental shelf break was prominent as evidenced by the inclusion of the 200-m isobath in the majority of seabird models. Such a strong association has been found in studies of seabirds in deep waters around the shelf break at the scale of the California Current [48,81], above undersea canyons near the shelf break offshore from Vancouver Island, British Columbia [82], and along the Atlantic shelf break front of austral South America [83]. Our findings suggest that Cordell Bank was a bathymetric feature driving the distribution of several piscivorous, but not planktivorous, species. Banks in other regions of the world have been featured prominently as important bathymetric drivers of seabird aggregations, though, to our knowledge, no studies have explicitly isolated seabird foraging guild distributions in relation to banks [84–86]. While the continental shelf break and Cordell Bank were important bathymetric features, some of the seabird species in our study, particularly *P. nigripes* and *F. glacialis*, were influenced by depths far deeper than the 200-m isobath. As we focused on pelagic seabirds, many of which spend the majority of their life at sea, the importance of depth lends support to further investigate seabird high-use foraging areas in waters beyond Sanctuary boundaries.

Our results suggested that seabirds visiting from different regions of the Pacific were influenced by different climate indices. Fulmars and phalaropes visiting from the Arctic were influenced by the PDO; shearwaters visiting from the South Pacific were influenced by the NPGO; and albatrosses from the Hawaiian Islands were influenced by the SOI. No single climate index affected all piscivores, whereas both planktivores were influenced similarly by the PDO. Only one seabird, *F. glacialis,* was associated with peak upwelling strength, suggesting that the basin-wide climate indices influencing all other species captured most variability in local productivity due to upwelling. These findings support recent research suggesting that climate variability, anthropogenic or otherwise, may have increasing ecological significance for seabird foraging activity [41,87]. Foraging behavior plasticity in response to climate change has been expected to differ among species, making it important to identify which species are more sensitive to the current rate of climate change [88].

The abundance of pelagic seabirds was influenced by climate conditions 1-3 months prior to their presence in our study area. Associations with negative PDO suggested that productive conditions 1-3 months prior influenced the presence of piscivores, whereas the association to phalaropes, the planktivores in our study, was less clear. In our region of the California Current, a negative PDO has been associated with favorable upwelling conditions, strong winds, and typically high productivity [89]. High abundance of phalaropes in our region was influenced by positive PDO, which represents generally unfavorable upwelling conditions in the our region of the California Current, but also represents warmer, stratified upper well-mixed ocean layers [89] where fronts are more common [90] and can result in increased foraging opportunities for surface-feeding seabirds [91]. Thus, our results have shown that conditions associated with negative PDO were linked to pelagic piscivorous seabirds, which travel to Central

California to feed on prey drawn to productive waters, while conditions associated with positive PDO were more influential to planktivorous phalaropes, which pass through this area and likely stop off in the presence of plankton-aggregating fronts.

Associations with NPGO suggested that ocean conditions 1-3 months prior to their presence in this region influenced the Arctic species, *F. glacialis* and *P. fulicarius* and South Pacific shearwaters, *A. creatopus* and *A. griseus*. High abundance of the fulmar *F. glacialis* was associated with positive NPGO with a 2-month lag, a relationship that links this species to upwelling-favorable, productive ecosystem conditions in the Gulf of Alaska and the California Current. Conversely, high numbers of phalaropes and shearwaters were associated with negative NPGO 1-3 months prior to their presence in this region. A negative NPGO has been shown to represent unproductive conditions, characterized by weak upwelling, and stratified upper well-mixed ocean layers and the presence of fronts [89]. As indicated above, these conditions have been described as conducive to the formation of oceanographic features that are used by birds to find prey near the surface; this includes the phalaropes [92] and also shearwaters [93].

Associations with positive SOI suggested that productive ocean conditions 0-2 months prior influenced the presence of *A. griseus* and *P. nigripes*. A positive SOI has been associated with cold productive waters while a negative SOI has been representative of the more El Niño-like conditions of warm unproductive waters. At the scale of the

California Current, Nur et al. (2011) found no association between SOI and *A. griseus* or *P. nigripes* when investigating associations with this climate index at 0-5 month lags, suggesting that the influence of SOI on this species may have escaped detection at this coarser scale. At our more local scale, SOI influenced both *A. griseus* and *P. nigripes,* indicating that the inclusion of this index in our models improved their predictive capability for identifying important seabird foraging area.

Beyond the physical features of the shelf break and Cordell Bank that were significant for several seabirds in our analysis, fronts have been characterized as oceanographic phenomena that may further explain predicted seabird foraging distributions. The importance of fronts as areas of plankton accumulation has been well documented [94–96]. Associations have been found between predictable, persistent frontal areas and *P. fulicarius* near Cornwall in the United Kingdom [97], *Morus bassanus* in the Celtic Sea [98], and *A. griseus* and *Uria aalge* in the Columbia River plume region offshore from the U.S. states of Washington and Oregon [99]. Frequent occurrence of fronts were found in the vicinity of Cordell Bank and along parts of the shelf break in the Sanctuaries [100]. The locations of prograde (offshore, upwelling-related) fronts in Fontana et al. (2013) aligned with our predicted distributions of planktivorous *P. lobatus* and *P. fulicarius.* Thus, our results have indicated that the presence of fronts in the Sanctuaries directly contributed to occurrence of planktivorous species, which feed on accumulated plankton and indirectly contributed to piscivorous species distributions via their forage fish prey that also feed at fronts.

Conservation Prioritization

Our research has served as a demonstration of methods that may be adapted and implemented to identify critical marine habitats and inform ocean zoning efforts globally. Previous research showed that high-use foraging area of five locally breeding seabird species concentrated around and east of Southeast Farallon Island and northwest of Cordell Bank [33]. Our study has shown that priority pelagic seabird habitat concentrated over and around Cordell Bank and along the continental shelf break. Some of this optimal seabird foraging area fell within established marine protected areas, however, the majority did not.

We have shown that pelagic seabirds use different foraging regions than local breeders. The continental shelf break along other coastal areas of the western Pacific has been confirmed as high-use habitat for seabirds offshore from Canada [82] and South America [101]. Shelf breaks have been shown to be important because they are the bathymetric transition point where shelf turns to slope, providing a vertical gradient conducive to a diversity of undersea habitat types, and promoting the aggregation of a high diversity of species [102,103]. In the mid-Atlantic, the entire continental shelf break from the 100 to 400 meter isobath was recommended for elevated protection status for its harboring of marine species important to commercial fisheries [102].

In addition to Cordell Bank, other banks along western North America's coast (e.g. Oregon's Heceta Bank) have been recognized as Important Bird Areas (IBAs), areas holding a significant proportion of the population of one or more bird species, as identified by repeatedly documented observation of aggregations [104]. Though no explicit restrictions on human use or development have been attached to IBA designation, they can provide a starting point for establishing legal status because their establishment requires observational data assessed with standardized global criteria [104]. Recognizing banks as critical foraging areas or fueling stations along migratory routes by elevating their regulatory status would help expand the actively regulated conservation network, or "string of pearls" [105] accommodating seabird migratory paths along North America's western seaboard.

Recently the National Oceanic and Atmospheric Association expanded the boundaries of the Sanctuaries. Important seabird breeding colonies were protected within special wildlife protection zones; however, the expansion did not consider protections for critical foraging areas for seabirds or any other wildlife. In general, there is a lack of pelagic protected areas because of the difficulties in identifying the critical habitat areas used by highly mobile wildlife and the challenges of effectively managing these sites

[19,23,24]. Habitat prioritization scenarios like those we have provided are useful tools to identify critical seabird foraging areas and inform conservation efforts. For example, critical habitats should be prioritized during response activities in case of catastrophic events such as an oil spills or during ocean zoning efforts while considering appropriate location for coastal development for alternative energy. New offshore energy development plans to create wind farms along the California Coast are proposing locations at least 15 miles from shore [106] reaching the continental shelf break in some regions, which, in our study, was among the highest used foraging areas for pelagic seabirds. Anticipating potential conflicts between critical habitat and potential human development in the ocean will minimize negative consequences for marine wildlife.

Conclusion

In this paper we identified the environmental factors that drive pelagic seabird distributions in our study area in Central California. We found that pelagic seabirds aggregated along the continental shelf break and in the vicinity of Cordell Bank. Using habitat prioritization, we identified critical areas that should be targeted for conservation because they are highly-used and are not currently protected. To identify critical seabird foraging areas for conservation, we followed a conservation biology perspective [107] and considered habitat prioritization from the seabirds' perspective (i.e. no human activities were considered). Further research coupling social and natural systems would be an alternate way to locate areas for special status in global marine reserves and would benefit from assessment of where and when human activities occur in relation to wildlife. The global lack of pelagic protected areas has been called "the missing dimension in ocean conservation" [19]. Implementing an elevated management or protective status for the critical areas found in this study would be a strategic step forward to lead ocean zoning efforts in the Pacific.

CHAPTER 2: USING HABITAT RISK ASSESSMENT FOR HABITAT PRIORITIZATION: AN EVALUATION OF DISTURBANCE FROM MARITIME ACTIVITIES TO INFORM SEABIRD CONSERVATION

Abstract

Habitat prioritization is a powerful tool for identifying critical wildlife areas for conservation. We evaluated the risk of disturbance from maritime activities to seabird pelagic foraging area to prioritize critical foraging habitat for conservation. Predicted seabird distributions were derived from ten years of Applied California Current Ecosystem Studies (ACCESS) at-sea data. Maritime activity data were obtained from the California Ocean Use Atlas, and informed by expert consultation and primary literature. Activities included benthic fishing with fixed and mobile gear, military operations, oil spill, shipping, and wildlife viewing. Habitat risk (i.e. cost) calculations incorporated: management effectiveness, spatial and temporal overlap, change in area, severity, and connectivity. High-use pelagic seabird foraging area concentrated around Cordell Bank and the continental shelf-break. High risk areas concentrated to the north and northeast of Cordell Bank, along segments of the shelf break, and along parts of the shipping lanes. We then demonstrated the use of the inVEST Habitat Risk Assessment (HRA) tool to quantify costs for use in Marxan habitat prioritization software. Marxan identified waters around the Farallon Islands as well as in the vicinity of and northeast of Cordell Bank for conservation. Prioritized areas for pelagic seabird species occupied 2.1% or 117 km^2 of the study area at a 10% conservation target, 21.6% or 1,198 km^2 at a 30% target, and 34.1% or 1,892 km^2 at a 50% target. The HRA model provided a transparent and replicable cost metric and enabled classification of risk into exposure and consequence. This approach provided two options for meeting conservation goals: 1) protecting the low cost Marxan-prioritized area or 2) managing high risk maritime activities highlighted by the HRA model. Either approach could be scaled up to include a larger habitat area, multiple habitat types, and different maritime activities. Our methods can be applied globally to improve ocean zoning where critical wildlife areas are threatened by human activities.

Introduction

Habitat prioritization is a powerful tool to identify and conserve critical wildlife areas [108–110]. Habitat prioritization methods call for the application of rigorous science, transparent conservation planning principles, and the best knowledge available to enable practical solutions that can be understood by decision-makers [108]. Habitat is the geographical space and the collection of biotic and abiotic factors therein that supports reproduction and survival of a species or individuals of a given species [111]. However, effective prioritization of important habitats is a challenging task because standardized metrics to identify important characteristics of a habitat must be considered. Marxan [110] is a commonly used prioritization program that has been applied to help address this challenge to develop terrestrial and marine reserve networks. It is a tool designed to support, not make, decisions on the location of conservation areas providing the basis for discussions but not providing an answer that should be unequivocally accepted [112,113]. Marxan is capable of solving the minimum set problem [112,114,115],where the objective is to optimize at a minimum cost (e.g. area or management) for some minimum amount of conservation features (e.g. habitat or biodiversity) using specific conservation targets (e.g. biological thresholds, political mandates, or social considerations) [116]. Previous research has used Marxan to reach conservation targets for invertebrates [115], fishes [117], and marine mammals [118].

Using Marxan, different strategies have been employed to quantify costs, conservation features, and conservation targets. Cost is the metric used to evaluate potential impact to human activity of implementing a reserve. This may be determined by reserve area, acquisition or management expense, or costs of lost economic opportunity. Conservation features are spatial units under consideration for conservation planning and might include the distribution of species, habitats, or ecological processes. Conservation targets are definitions of a suitable level of conservation for particular conservation features and might be dictated by biological thresholds or political mandates [112]. Established methods have been applied to determine what constitutes conservation features and targets using Marxan [115]. However, it is challenging to generate a standardized and reliable cost metric because spatially explicit information is difficult to obtain [113,115,119].

While variations on reserve area, acquisition, management, and lost opportunity costs have been analyzed for decision support with Marxan, the strategy of evaluating cost as a measure of habitat risk has not been investigated. The inVEST Habitat Risk Assessment (HRA) model [120] has the capacity to incorporate multiple habitat stressors into a single risk value that can be used as a novel cost metric. Using habitat risk as cost in Marxan provides a framework to select areas with important conservation features and low risk of conflict with human activities, thereby prioritizing critical habitat areas while minimizing impact to human activity. The HRA model has previously been used to assist with ocean zoning [121–123], due to its flexibility in incorporating either peer-reviewed resources and/or expert opinion [120]. Previous research has used the HRA model to assist with national-level ocean zoning based on three critical habitats in Belize [122] and at the state-level for six marine indicator species in the state of Washington [123]. However, no research has yet used the HRA model for a local approach that parses out relative risk of multiple human activities for a single habitat type.

We present a case study that uses the HRA model to assess spatial distribution of risk for use as a cost metric in Marxan to identify critical pelagic seabird foraging area at the scale of two federally managed national marine sanctuaries. Seabirds are conspicuous, long-lived, and wide-ranging marine predators that forage at high trophic levels, making them indicators of marine health and food web dynamics [1–3]. Many seabird populations are threatened in areas where they forage and breed [6–8], and will benefit from analysis using the Habitat Risk Assessment (HRA) model. The primary way human activity has been shown to impact seabirds is by restricting access to critical resources comprising habitat such as foraging or nesting areas, or by diminishing the quality of either of these [124]. Seabirds within the Sanctuaries have protections for their nesting areas [31,125,126], but not for their critical offshore pelagic foraging areas.

Maritime human activities result in disturbance to seabirds, but some activities can cause more detrimental effects than others. High levels of disturbance can change seabird foraging behavior such that feeding time is reduced or foraging sites are abandoned for less productive areas [127,128]. Maritime activities can threaten seabirds at sea by directly disturbing their foraging activity through a range of interactions that increase from impeding foraging by eliciting a flight response to harming or killing via bycatch or oiling (covering with oil during a spill) [127,129–131]. For this study, we defined disturbance as avoidance behavior such as diving or flushing increasing up to harming or killing. We considered the potential disturbance to seabirds of six activities included in the California Ocean Use Atlas [132]: benthic fishing with fixed gear or mobile gear, military operations, commercial shipping, oil spill, and wildlife viewing.

The purpose of this study was to demonstrate the use of inVEST's Habitat Risk Assessment (HRA) to generate a transparent cost layer to inform habitat prioritization using Marxan. We demonstrate our methodology using a case study that focuses on common maritime activities in National Marine Sanctuaries in Central California, where seabirds forage extensively and high-use pelagic seabird foraging areas have been identified. In this study we address three main questions: 1) what is the risk of disturbance from maritime activities to seabirds, 2) where is disturbance from maritime activities affecting seabirds, and 3) how can we use these tools to identify critical seabird foraging areas that meet selected conservation targets?

Methods

Study Area

Many pelagic seabirds have been observed foraging in the California Current, a dynamic system with a varying regional and basin-scale climate that affects local conditions [36]. The study area (Fig 2.1) covers sections of the Sanctuaries off the coast of Central California. The site encompasses a portion of each sanctuary (Cordell Bank: 1370 km^2, Greater Farallones: 3320 km^2) ranging from north of Cordell Bank (38°8'N) to south of the Farallon Islands (37° 34'N) and extends from the upper continental slope to coastal waters within 15 km from shore. The study area is located outside of the metropolitan San Francisco Bay Area, which has some of the busiest port cities in the United States. Maritime activities are drawn not only by the region's proximity to the city but also by the diversity and abundance of marine life. The Port of Oakland, for example, is the fourth largest destination for container ships in the United States [133].

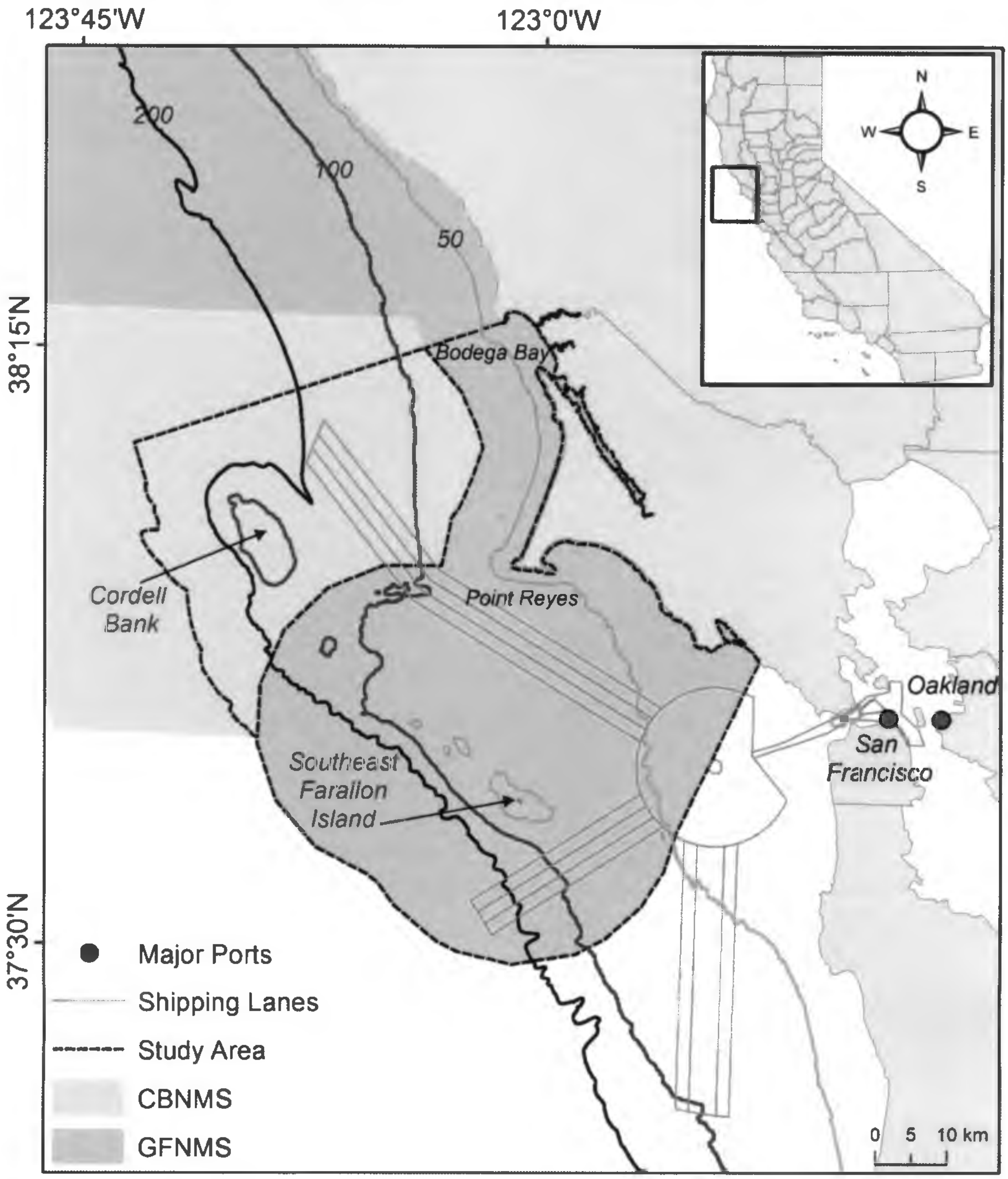

Figure 2.1. Study area. CBNMS: Cordell Bank National Marine Sanctuary, GFNMS: Greater Farallones National Marine Sanctuary.

Human Use Spatial Data

We used the dominant spatial footprints of maritime activities provided by the California Ocean Use Atlas (hereafter called the Atlas) [134]. The Atlas was generated from a series of participatory geographic information systems (GIS) workshops held by the Marine Life Protection Act Initiative between 2008-2009, which were structured to incorporate expert knowledge and experience from people familiar with the waters of the California Coast [134]. Workshop participants used a digital whiteboard to collectively refine the patterns of each activity's use through group discussion and deliberation [134]. Upon workshop completion, data were processed and mapped to a 1x1 nautical mile grid [134]. Using a GIS, we used the Atlas's dominant spatial footprints of maritime activities. We chose a collection of maritime activities with potential to disturb seabird foraging area based on prior seabird and human use research conducted in our study area [33]: 1) benthic fishing with fixed gear, 2) benthic fishing with mobile gear, 3) military operations, 4) oil spill, 5) shipping, and 6) wildlife viewing (Table 2.1).

Table 2.1. Description of human activities and primary disturbance events of locally active groups. *Primary disturbance event was evaluated for severity criteria only. **Oil spill as an activity used the spatial footprint of the commercial shipping lanes because the California Ocean Use Atlas did not provide a dominant spatial footprint for oil spills.

Human Activities in the Sanctuaries	California Ocean Use Atlas General Description	Primary Disturbance Event*	Locally Active Groups
Benthic Fishing (Fixed Gear)	Traps, pots, bottom longlines, bottom gillnets, vertical hook and line gear	Potential for bycatch	Vertical hook and line gear used in groundfish fishery and nearshore finfish fishery
Benthic Fishing (Mobile Gear)	Trawling, dredging, other mobile gear	Potential for bycatch	Trawling gear used in groundfish fishery and halibut fishery
Military Operations	Test ranges, war games, acoustic arrays, ship and submarine manouevers, munitions disposal	Ship transiting	Coast Guard
Oil Spill	**Based on commercial shipping	Oiling of seabirds	Commercial Shipping
Shipping	Ships, large commercial vessels, shipping routes and channels including maintenance, and ferries	Ship transiting	Commercial Shipping
Wildlife Viewing	Any commercial boat-based or aerial wildlife-viewing at sea	Ship transiting	Whalewatching

Disturbance Rank Data

Following the schematic in Figure 2.2, primary literature and expert opinion were systematically incorporated into our analysis to evaluate each maritime activity's risk of disturbance to pelagic seabirds in the Sanctuaries. Experts were five marine sanctuary officials from the Gulf of the Farallones National Marine Sanctuary (GFNMS) and Cordell Bank National Marine Sanctuary (CBNMS). We first asked experts to respond to an eight-question survey about criteria related to potential disturbance of pelagic seabird species posed by the six aforementioned maritime activities. The survey included a mixture of open- and closed-ended questions designed to open a discussion [135].

Several questions elicited discussion by encouraging participants' reasoning for their opinion (e.g. "Feel free to elaborate"). Responses to the survey were synthesized and presented during a ninety minute focus group designed to allow discussion among experts to reach a best approximation of disturbance risk. Expert opinion from this focus group guided our interpretation of peer-reviewed literature to define four criteria according to Table 2.2: management effectiveness, temporal overlap, change in area, and severity. Maritime activities were considered for their general activity in the Sanctuaries for all criteria except severity for which the primary event to cause disturbance to foraging seabirds was considered (Table 2.1).

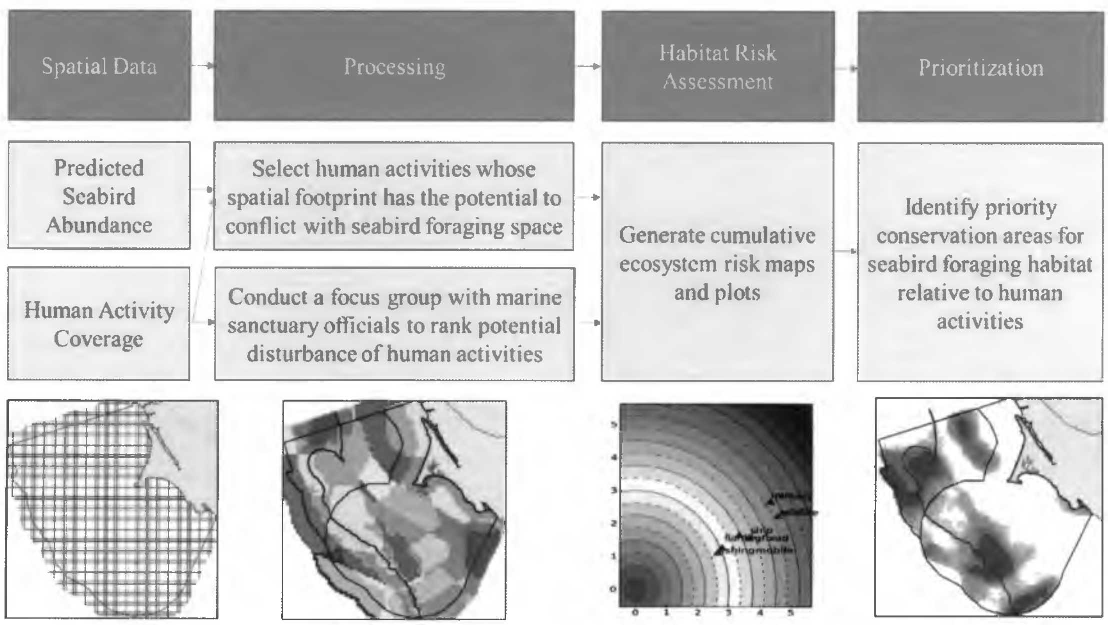

Figure 2.2. Schematic. Flow chart illustrating the methods for data collection, processing, and analysis.

Table 2.2. Criteria definitions, scale, and resources.

Criteria	Defintion	1	2	3	Resources
Management effectiveness	How effective are regulations at reducing disturbance?	Effective	Moderately effective	Ineffective	Expert panel, National Marine Sanctuaries Act [139], Airborne Hunting Act [140], Migratory Bird Treaty Act [141], Standardized Bycatch Reporting Methodology [158], Moore et al. (2009) [159], Vessel Spill Response Technologies [160], Be Whale Wise [161]
Temporal overlap	How often does the activity occur?	Yearly or less often	Monthly	Weekly or more often	Expert panel, Marine Traffic (2014) [144], Gulf of the Farallones National Marine Sanctuary Condition Report (2010) [145], Cordell Bank National Marine Sanctuary Condition Report (2009) [146], San Francisco Whale Tours (2016) [147]
Change in area	How much foraging area could be lost due to the activity?	<33% lost	33-66% lost	>66% lost	Expert panel, California Ocean Use Atlas [132], Schwemmer et al. (2011) [148]
Severity	How severe is the disturbance of the activity when it occurs?	Flushes birds	Kills few birds	Kills many birds	Expert panel, CBNMS (2008) [125], GFNMS (2008) [126], Bellefleur et al. (2009) [129], Carter (2003) [130], Schwemmer et al. (2011) [148], Bergin et al. (1997) [149], Lewison & Crowder (2003) [11], Guy et al. (2013) [10], Arata et al. (2009) [150], Weimerskirch et al. (2000) [151], Sullivan et al. (2006) [152], NMFS (2011) [153], Larkin et al. (1996) [154], Rojek (2007) [155], GFNMS (2002) [157]

Pelagic Seabird Data

We used modeled seabird distribution and abundance information derived from ten years of cruise data provided by the Applied California Current Ecosystem Studies (ACCESS) partnership between GFNMS, CBNMS, and Point Blue Conservation Science (www.accessoceans.org). Between April and October from 2004-2013, a total of 37 cruises were completed. Observers followed the ACCESS standardized strip-survey design and sampling methodology (see Jahncke et al. 2008 [49] for further details).

Seabird counts were modeled as a function of oceanographic and environmental variables collected *in situ* during ACCESS cruises, bathymetric and distance variables generated using a GIS, and widely available climate indices according to methods described in Studwell et al. (accepted) [136].

Marxan Parameters

Planning Unit

Using a GIS, we divided the Sanctuaries into whole 1-km² planning units to which values for costs and conservation features were assigned to provide the necessary information for meeting conservation targets. A planning unit is the geographical unit of analysis used to conduct Marxan analysis; essentially a grid covering the extent of our study area. The data analysis to determine the values for cost and conservation parameters is described below.

Risk of Disturbance

We used the InVEST Habitat Risk Assessment (HRA) model to develop a Marxan cost layer, defined as the risk of disturbance from maritime activities to pelagic seabirds. We used the HRA model to assign criteria relevant to maritime activities as either an exposure- or consequence-of-exposure-related risk [120]. Temporal overlap of shipping activity with seabird foraging area, for example, is an exposure criteria that can be evaluated as the frequency of ship transits. The potential for shipping activity to reduce seabird foraging area (i.e. change in area), on the other hand, would be an example of a consequence of exposure. Criteria rankings were incorporated into the following equations [120] to develop an additive risk value *R* for each activity in each sub-region (GFNMS or CBNMS) of seabird foraging area:

$$E = \frac{\sum_{i=1}^{N} \frac{e_i}{d_i * w_i}}{\sum_{i=1}^{N} \frac{1}{d_i * w_i}} \qquad \text{(Eq. 1)}$$

$$C = \frac{\sum_{i=1}^{N} \frac{c_i}{d_i * w_i}}{\sum_{i=1}^{N} \frac{1}{d_i * w_i}} \qquad \text{(Eq. 2)}$$

$$R_{ij} = \sqrt{(E-1)^2 + (C-1)^2} \qquad \text{(Eq. 3)}$$

where *E* is exposure score, *C* is consequence score, d_i is data quality for criterion i, w_i is the weight for criterion i, *N* is the total number of criteria assessed, and *R* is Euclidean Risk calculated using risk to habitat i caused by maritime activity j [122,123,137,138]. Using *R*, the HRA model generated cumulative risk values for each planning unit covering our study area, which were extracted for use as the cost input in Marxan.

We developed a ranking system for exposure criteria (management effectiveness and temporal overlap) and consequence criteria (change in area and severity). Spatial overlap was computed separately from other exposure criteria for each maritime activity according to parameters detailed below. To better assess the HRA model and usefulness of our chosen criteria (below), we used equivalent weight and data quality values (all values = 2).

Management effectiveness was determined based on the existence and enforcement of federal and state regulations that aim to reduce disturbance to pelagic seabird foraging area caused by a maritime activity (Table 2.2). The management effectiveness criteria helps identify activities that could potentially be regulated or managed differently to better reduce disturbance to seabirds. Regulations such as the National Marine Sanctuaries Act [139], the Airborne Hunting Act [140], and the Migratory Bird Treaty Act [141] seek to reduce take or killing of seabirds, the most severe form of disturbance. If we found that regulations existed to reduce the primary event causing disturbance and these regulations were well-enforced, management was considered effective. If these regulations existed but were partially enforced, management effectiveness was considered moderately effective. If regulations did not exist, management was considered ineffective.

Spatial Overlap. We delineated spatial overlap as the area of a maritime activity overlapping with the seabird foraging area. Because seabirds forage throughout the Sanctuaries and we wanted to determine how risk differs throughout the area, we used the footprint of the Sanctuaries to represent pelagic seabird foraging area. At the subregional scale of either of the two Sanctuaries, for areas where spatial overlap between the foraging area and maritime activity overlap, the HRA model calculated an exposure value using the following equation:

$$e_{spatial} = 3x_i + 1(1 - x_i) \qquad \text{(Eq. 4)}$$

where $e_{spatial}$ represents the spatial criteria computation, x_i represents the proportion of spatial overlap of a maritime activity with foraging area on a 0 to 1 scale, and 3 and 1 represent the maximum and minimum possible ranks of our scale.

With only a few exceptions, spatial overlap rankings were evaluated using the dominant spatial footprint determined by the California Ocean Use Atlas [134]. Local conservation areas have changed considerably since the creation of the Atlas so we updated both fishing spatial footprints to reflect spatial restrictions posed by Essential Fish Habitat [142] and Rockfish Conservation Areas [143] reflecting restrictions relevant to June of 2014. In addition, the footprint of the shipping lanes has changed since 2010, so we generated an alternate to the Atlas using the coordinates for the new boundaries buffered out by 9km with a 45 degree fan at the distal end of each lane to reflect the pattern caused by shipping traffic convergence and divergence from the lanes [144].

Temporal Overlap. We defined temporal overlap as the frequency that pelagic seabird foraging area and a maritime activity experience spatial overlap (Table 2.2). We asked experts to approximate the frequency of each human activity and verified by viewing the websites of local activities where the information was available: oil spills [145,146], shipping [144], and wildlife viewing [147]. An assumption of our model was that if a maritime activity overlaps with foraging area more frequently, seabirds would be more exposed to disturbance than if the activity overlaps less frequently.

Change in Area. Change in area for this research was the percent of foraging area that could be temporarily lost due to a maritime activity (Table 2.2). We asked experts to identify which of the six activities could lead to a loss of foraging area. For those activities that could reduce foraging area, we divided the area of the activity's dominant spatial footprint by the seabird foraging area in a GIS to estimate percent of lost pelagic seabird foraging area assuming maximum use of each activity's spatial footprint. The shipping lane area included a 804-m buffer to account for potential seabird flushing distances [148].

Severity. Severity in this context was based on how impactful the primary disturbance event (Table 2.1) of a maritime activity was as determined by consulting an expert panel comprised of five officials from GFNMS and CBNMS and review of primary literature (Table 2.2). Our scale sought to capture variability on a continuum of less severe (flushing) to more severe (mortality). We considered benthic fishing with fixed or mobile gear as a primary disturbance event of bycatch [10,11,149]. Fishing practices active in the Sanctuaries [125,126] that use longline and trawling gear have caused incidental bycatch via ensnarement with hooks [150] or entanglement with cables and nets [151,152], which has led to harm or death of pelagic seabirds [10,153]. Military, shipping, and wildlife viewing activities were considered as a primary disturbance event of ship transits in the Sanctuaries [129,148,154]. While helicopter overflight of Coast Guard military drills has been shown as a main disturbance to a seabird species, *Uria aalge* (the common murre) [155], we verified through a discussion with Coast Guard personnel that drills do not occur in the Sanctuaries, which is why military operations were evaluated based on transiting ships, not drills. Commercial shipping activities are common in the Sanctuaries [156] and have been shown to cause seabirds to flush at variable distances [148]. Small recreational boats have been shown to flush seabirds by eliciting a flight or dive response [129] indicating that boat disturbance from wildlife viewing can decrease the amount of time available for foraging or reduce the effectiveness of foraging due to increased vigilance and escape time. Oiling of seabirds has occurred in the Sanctuaries [130]. We considered this a primary disturbance as oiling degrades seabird insulation, waterproofing, and flight- and buoyancy-providing qualities of feathers and often leads to death of the oiled individual [157].

Conservation Feature Amounts

We used the multi-species predicted distribution of foraging pelagic seabirds as the conservation feature in this analysis. In Studwell et al. (accepted), we described the data collection, processing, and analysis used to characterize predicted habitat use of six pelagic seabird species: sooty shearwater (*Ardenna griseus*), pink-footed shearwater (*Ardenna creatopus*), northern fulmar (*Fulmarus glacialis*), black-footed albatross (*Phoebastria nigripes*), red phalarope (*Phalaropus fulicarius*), and red-necked phalarope (*Phalaropus lobatus*) that were most commonly sighted in the ACCESS survey. In this research, we predicted the multi-species pelagic seabird distribution for the Sanctuary area. For this research, we chose to use Sanctuary habitat use of these species for summer (July) because we most consistently had the greatest number of sightings during this season.

Conservation Targets

A conservation target is defined as the fraction of a conservation feature that must be represented in the conservation scenarios Marxan generates [110]. For example, a 2005 study set the conservation target to a fraction of 0.2 for six biophysical data layers used to develop a marine reserve in South Australia [115]. This target meant that each conservation feature would be represented at 20% of its total abundance or distribution. For this analysis, we sought to show three plausible conservation targets at 10%, 30%, and 50% for comparative purposes with Studwell et al. (accepted) and other previous research [33] that prioritized foraging area for locally breeding seabird species in our study area using these same conservation targets.

Additional Parameters

Our Marxan analysis required calibration of two additional parameters: reserve boundary length and a boundary length modifier. To calculate reserve boundary length, we used the perimeter of each of the planning units. To emphasize reserve compactness while minimizing reserve cost, we calibrated a boundary length modifier (BLM) [71]. Using a smaller BLM will get Marxan to focus on minimizing overall reserve cost and will only select planning units that improve compactness with little extra cost added to the final reserve design. Using a larger BLM will result in the opposite: a high emphasis will be placed on improving compactness (i.e. reducing boundary length) despite increasing the cost of the final reserve solution [71]. A boundary length modifier of 10 was optimal for reducing habitat fragmentation (increasing reserve compactness) and reducing reserve cost (Fig 2.3). We generated reserve optimizations for n = 100 iterations, each of which gave a count of the number of times each planning unit was included in the optimal reserve solution resulting from each run of the software [72]. The upper 50 percent of times each planning unit was selected for inclusion in reserve design was displayed for each scenario for clarity in visualization.

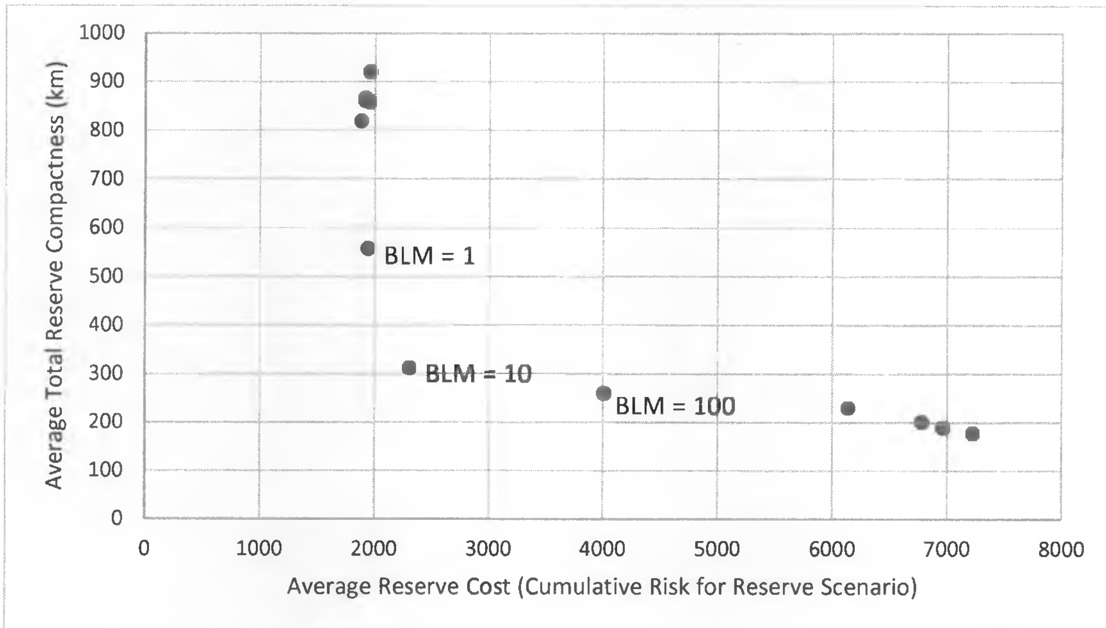

Figure 2.3. Representative Boundary Length Modifier (BLM) Calibration. X axis: average reserve cost as represented by cumulative risk for whole reserve design. Y axis: Average reserve compactness based on perimeter of planning units. This calibration example was calculated for summer with the 10% conservation scenario.

Results

Risk of Disturbance

We have divided our results for calculating disturbance risk (cost) into two parts. We first generated ranked values of disturbance risk based on criteria characterizing maritime activity (see Table 2.2). We then used these ranked values as inputs to the HRA model to produce risk plots and a cumulative spatial risk surface from which values were extracted for use as our Marxan cost layer. Values for the conservation feature layer in Marxan were extracted from the seabird foraging area (Fig 2.4) predicted in Studwell et al. (accepted).

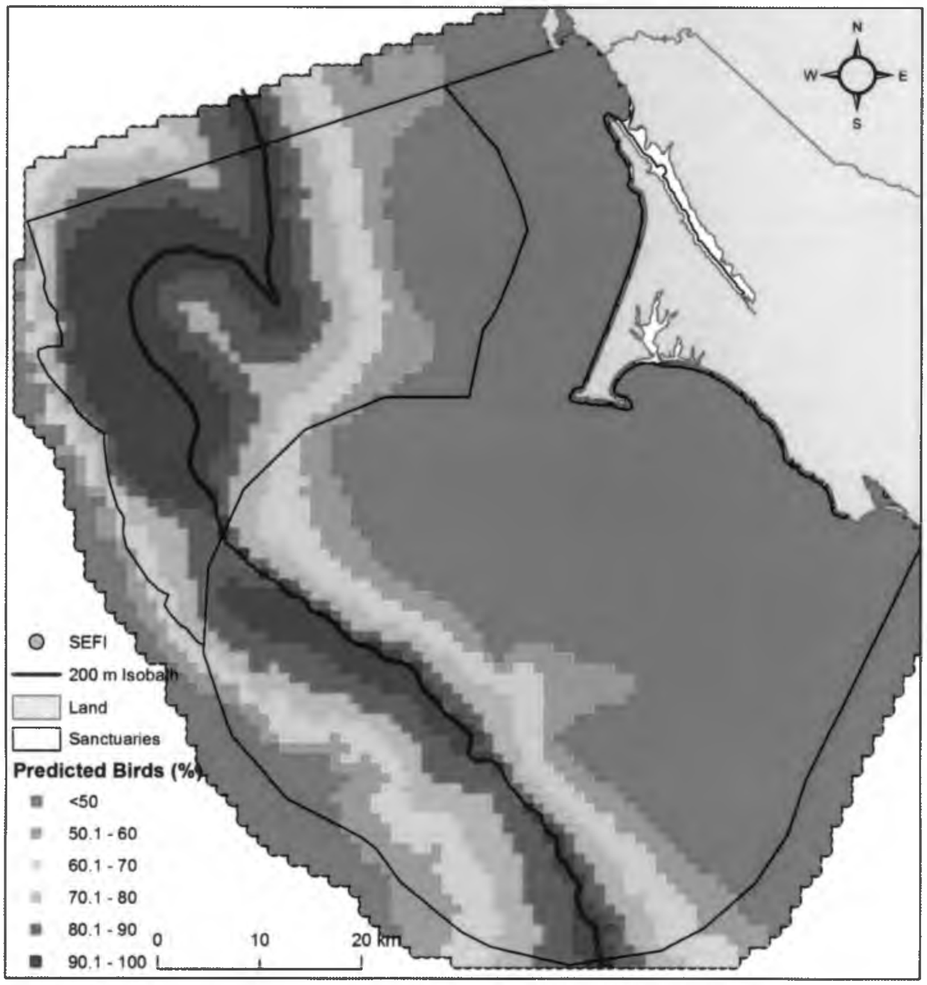

Figure 2.4. Multi-species seabird distribution. Each species was standardized across years and averaged across species using predicted values for July. Map represents highest use foraging areas (upper 50 percent) for multiple species from Studwell et al. (accepted).

Disturbance Rankings

Management Effectiveness. All seabird disturbance rankings can be found in Table 2.3 where a 1 represents low and a 3 represents high risk of disturbance due to management effectiveness. Expert panelists referred us to fisheries observer programs for benthic fishing with fixed and mobile gear which are in the process of national standardization and monitor for take in the form of bycatch [158]. We found that while a goal of fisheries observer programs is to minimize bycatch, observers do not directly prevent killing of seabirds and primary literature has shown that management agencies have never enforced important laws (e.g. the Migratory Bird Treaty Act) in cases of incidental seabird mortality in marine fisheries operations [159]. In contrast to an oil spill, which initiates a response plan, there is not currently an explicit management plan for remediation of seabirds caught as bycatch, so both fishing activities received a ranking of 2. Expert panelists did not reference any seabird disturbance-minimizing observer programs or explicit promotion of disturbance-minimizing policies specific to military operations or shipping, so these activities received a rank of 3. Panelists referred us to a vessel spill response plan [160] that aims to reduce disturbance and is specifically enforced in the Sanctuaries, so we considered the activity of oil spill to be effectively managed and assigned a ranking of 1. In contrast to military operations and shipping activities, experts referred us to disturbance-minimizing guidelines implemented by wildlife viewing activities (e.g. "Be Whale Wise") [161] , however, there are no observer programs specific to wildlife viewing, so these activities received a ranking of 2.

Table 2.3. Disturbance rankings. Ranked values for each criteria range from 1 (low) to 3 (high) risk according to interpretation of primary literature and focus group discussion. Management effectiveness, spatial overlap, and temporal overlap are exposure criteria. Change in area and severity are consequence of exposure criteria.

	Exposure Criteria			Consequence of Exposure Criteria	
Human Activities/Criteria	Management Effectiveness	Spatial Overlap CBNMS/GFNMS	Temporal Overlap	Change in Area	Severity
Benthic Fishing (Fixed Gear)	2	1.2 / 1.7	3	1	2
Benthic Fishing (Mobile Gear)	2	1.1 / 1.9	3	1	2
Military Operations	3	2.4 / 1.4	3	2	1
Oil Spill	1	1.5 / 1.5	1	3	3
Shipping	3	1.5 / 1.5	3	1	1
Wildlife Viewing	2	2.5 / 2.8	3	1	1

Spatial Overlap. All seabird disturbance rankings can be found in Table 2.3 where a 1 represents low and a 3 represents high risk of disturbance due to spatial overlap. Based on a GIS-generated overlap with pelagic seabird foraging area (i.e. the spatial footprint of the Sanctuaries), the HRA model calculated a disturbance risk rank for each maritime activity for each Sanctuary. Using Equation 4, benthic fishing with fixed gear received a rank of 1.2 for Cordell Bank (CBNMS) and a rank of 1.7 for Greater Farallones (GFNMS). Benthic fishing with mobile gear received a rank of 1.1 for CBNMS and a rank of 1.9 for GFNMS. Military operations received a rank of 2.4 for CBNMS and a rank of 1.4 for GFNMS. Oil spill received a rank of 1.5 for CBNMS and a rank of 1.5 for GFNMS. Shipping received a rank of 1.5 for CBNMS and a rank of 1.5 for GFNMS. Wildlife viewing received a rank of 2.5 for CBNMS and a rank of 2.8 for GFNMS.

Temporal Overlap. All seabird disturbance rankings can be found in Table 2.3 where a 1 represents low and a 3 represents high risk of disturbance due to temporal overlap. Verification with experts revealed that the activities of benthic fishing with fixed and mobile gear, military operations, shipping, and wildlife viewing occurred on a weekly or more frequent basis in our study area so all were assigned a ranking of 3 (Table 2.3). Oil spills occurred least frequently of all activities, occurring yearly or less often and were assigned a ranking of 1.

Change in Area. All seabird disturbance rankings can be found in Table 2.3 where a 1 represents low and 3 represents high risk of disturbance due to change in area. Expert panelists suggested that benthic fishing with fixed and mobile gear and wildlife viewing do not reduce the area available for pelagic seabird foraging so these activities each received the lowest ranking of 1 (Table 2.3). They identified three major threats that could reduce seabird foraging area: military operations, oil spills, and shipping. Based on their assessment, using the dominant spatial footprints from the California Use Atlas, we calculated the percentages of potential foraging area reduction. Panelists proposed that military operations could potentially reduce pelagic seabird foraging area, which our computation showed would reduce foraging area by 35%, giving this activity a rank of 2. An oil spill could potentially spread across the full extent of the Sanctuaries, so we calculated 100% reduction, giving this activity a rank of 3. These expert respondents also proposed that shipping could potentially reduce pelagic seabird foraging area, which our computation showed would reduce foraging area by 26%, giving this activity a rank of 1 (Table 2.3).

Severity. As mentioned earlier, benthic fishing activities have decreased as a result of Rockfish Conservation Areas and Essential Fish Habitat. However, because we found previously documented bycatch incidents for both benthic fishing with fixed and mobile gear occurring offshore from Central California in the past decade, we assigned the severity of these activities' primary disturbance event a ranking of 2 (Table 2.3). Consultation with experts suggested that the primary disturbance event of transiting ships from military operations, shipping, and wildlife viewing activities each can flush birds, but are not typically known to harm or kill so these activities were assigned a ranking of 1 (Table 2.3). An oil spill can oil and subsequently kill multiple seabirds, so this activity received a ranking of 3 (Table 2.3).

Risk

The HRA model generated risk plots showing a classification of risk by exposure and consequence of exposure for each Sanctuary. Risk from each maritime activity differed between Sanctuaries (Table 2.4, Fig 2.5). The top two highest exposure activities for CBNMS were military operations and wildlife viewing followed by shipping, benthic fishing with fixed gear, benthic fishing with mobile gear, and oil spill (Table 2.4, Fig 2.5). In contrast, the top two highest consequence activities for CBNMS were oil spill and military operations followed by benthic fishing with fixed gear, benthic fishing with mobile gear, shipping, and wildlife viewing (Table 2.4, Fig 2.5). The top two highest exposure activities for GFNMS were wildlife viewing and shipping followed by benthic fishing with mobile gear, military operations, benthic fishing with fixed gear, and oil spill (Table 2.4, Fig 2.5). The top two highest consequence activities for GFNMS were oil spill and benthic fishing with mobile gear followed by benthic fishing with fixed gear, military operations, shipping, and wildlife viewing (Table 2.4, Fig 2.5). The HRA model calculated risk scores (*R*) according to Equation 3. Table 2.4 shows Risk (*R*) for each activity in CBNMS and GFNMS.

Table 2.4. Exposure, consequence, and total risk scores developed from the HRA model.

	Cordell Bank			Greater Farallones		
Maritime Activity	Exposure	Consequence	Risk	Exposure	Consequence	Risk
Benthic fishing with fixed gear	1.9	1.1	0.9	2.2	1.2	1.2
Benthic fishing with mobile gear	1.8	1.0	0.8	2.3	1.2	1.3
Military operations	2.7	1.3	1.7	2.2	1.1	1.2
Oil spill	1.3	1.5	0.6	1.3	1.4	0.5
Shipping	2.3	1.0	1.3	2.3	1.0	1.3
Wildlife viewing	2.5	1.0	1.5	2.6	1.0	1.6

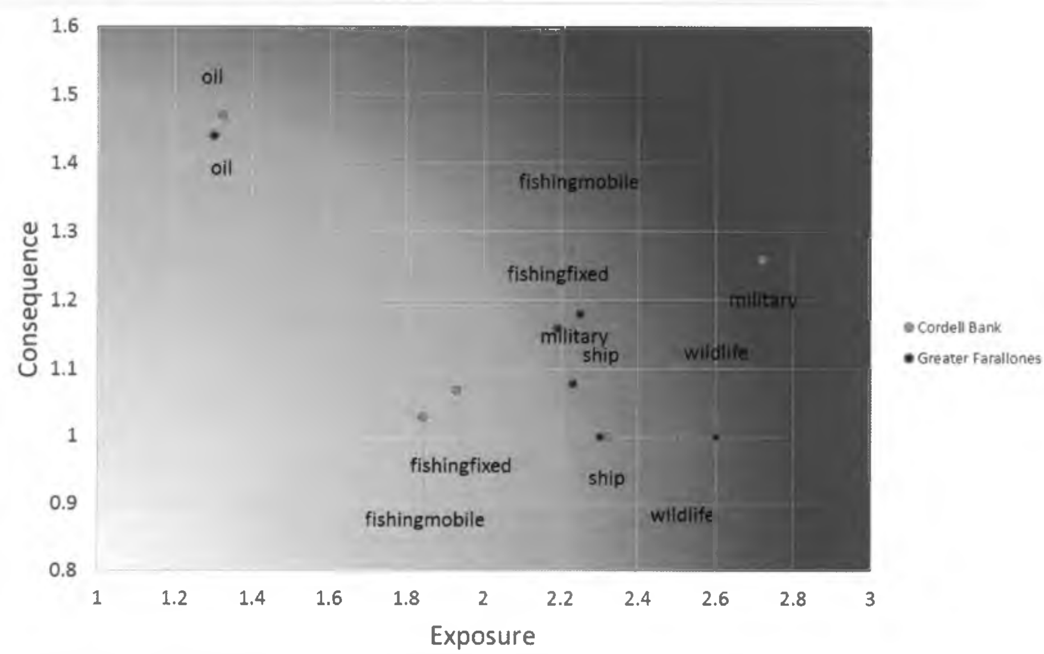

Figure 2.5. Risk plots displayed by exposure and consequence of exposure to human activity evaluated in relation to pelagic seabird foraging area.

Out of a possible risk score of 18, which would be a case where all activities overlapped and $R = 3$ for a single unit, the highest cumulative risk score for a planning unit was 9.9 while the lowest was 0. This cumulative risk score indicates that no single planning unit of seabird foraging area was in the upper third of possible disturbance risk. Higher risk areas generally occurred where multiple activities overlapped and lower risk areas occurred where few activities overlapped (Fig 2.6). Model results showed that higher risk areas concentrated to the north and northeast of Cordell Bank and along segments of the shelf break as well as in a nearshore region south of Point Reyes (Fig 2.6).

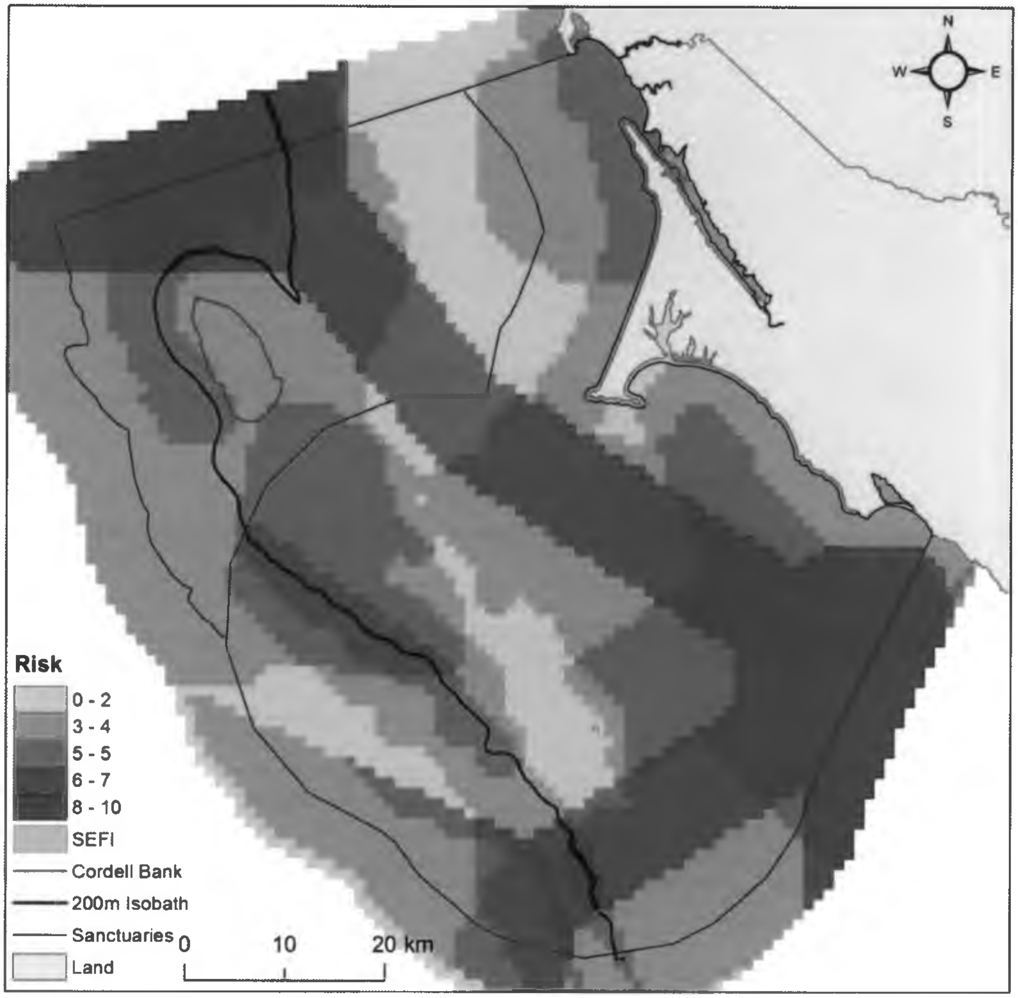

Figure 2.6. Cumulative risk map derived from the inVEST habitat risk assessment model.

Habitat Prioritization

We generated scenarios that met the three conservation targets of 10%, 30%, and 50% of seabird foraging area. For each scenario, we displayed the top 50 percent of pelagic seabird foraging area prioritized by Marxan. In all scenarios, Sanctuary waters to the west of the shelf break were targeted (Fig 2.7). Maps show the waters directly near the Farallon Islands as frequently selected areas in all scenarios (Figs. 2.7). If allowing for more conservation (30% and 50% scenarios), waters in the vicinity of Cordell Bank and in the northeastern part of CBNMS were also targeted frequently (Fig 2.7). The upper 50% area of the final reserve network consisted of conservation focal areas for pelagic seabird species that occupied 2.1% of the study area or approximately 117 km² at the 10% scenario, 21.6% or approximately 1198 km² at the 30% scenario, and 34.1% or approximately 1892 km² at the 50% scenario (Fig 2.7).

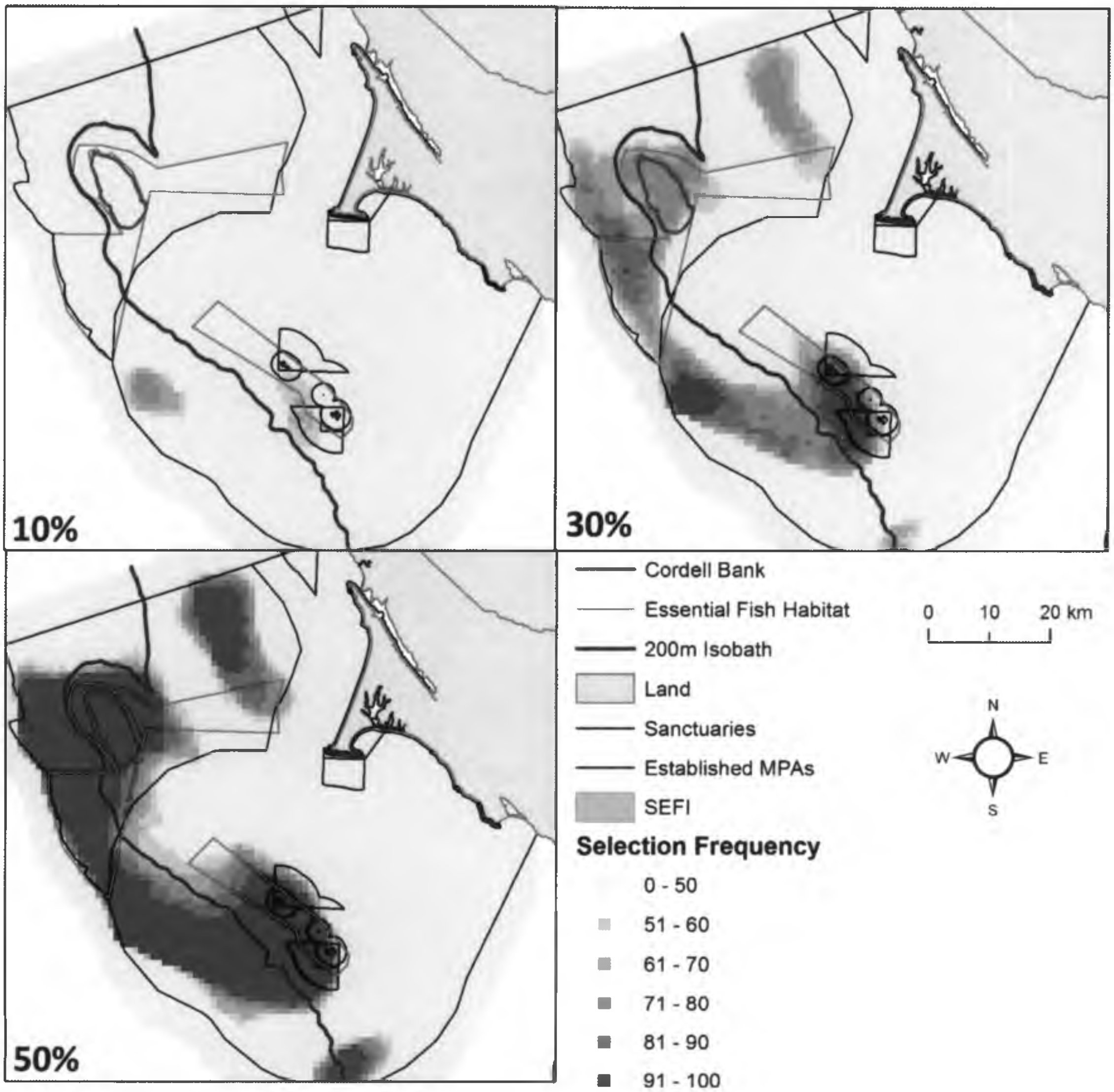

Figure 2.7 Marxan conservation prioritization exercise displaying where to prioritize 10%, 30%, and 50% when considering both pelagic seabird foraging area and disturbance rankings as applied to the dominant spatial footprint of human activities in the Sanctuaries.

Discussion

In this research, we used inVEST's Habitat Risk Assessment (HRA) model to develop a Marxan cost layer based on seabird disturbance from maritime activities to inform habitat prioritization. We assumed that Marxan planning units with high risk of seabird disturbance from maritime activities were less suitable for conservation and should carry a high cost. We demonstrated our methodology by selecting critical pelagic seabird foraging areas for inclusion in a reserve network. We found that areas at high risk of disturbance occurred north and northeast of Cordell Bank, along segments of the shelf break, and along most parts of the shipping lanes. Habitat prioritized by Marxan occurred west of the shelf break, around the Farallon Island archipelago, and in the vicinity of Cordell Bank. Our methodology identified critical seabird foraging areas that met conservation targets demonstrating the use of risk as a transparent, replicable cost metric to evaluate reserve networks.

Using the HRA model to develop a cost metric for Marxan had benefits and limitations. The ability to explain how each maritime activity contributed to risk was a benefit, whereas limitations included the lack of incorporation of past activities' influence on risk and the dilution of risk through spatially averaging exposure and consequence criteria. Risk plots allowed ease of identifying management priorities based on classification of exposure and consequence criteria. For instance, the high exposure risk of wildlife viewing suggested that disturbance could be reduced by making changes to the geographic range used for wildlife viewing operations, by constraining the season wildlife viewing is open to the public, or by improving management policies to minimize disturbance to seabirds. Conversely, the high consequence of oil spill suggested that once seabirds were oiled, high disturbance was inevitable, indicating that an oil spill plan or further research that minimizes the negative consequences of oil to seabirds would be a course of action to reduce disturbance.

A limitation of the HRA model was that equations 1 and 2 diluted risk by averaging criteria scores to compute consequence (C) and exposure (E) used to generate the risk score (R). For example, while both consequence criteria for oil spill were ranked highest for severity and change in area, a low risk value for habitat connectivity, led to an overall mid-level consequence risk. An additional limitation was that the HRA model's risk computation did not allow trends in activities to influence the outcome (i.e. a temporal accumulation or decrease of risk). For example, while the model assumed that each criteria contributed equally to the final cumulative risk [122,123,137,138], an option that allows for synergistic or antagonistic interactions could have improved the final risk assessment. The criteria, severity and temporal overlap, for instance, may have exhibited an interactive relationship [162] simultaneously increasing or decreasing the effects of each maritime activity on our habitat.

No others studies have used inVEST's HRA model to develop a Marxan cost layer. Other studies using the HRA model to inform marine spatial planning faced similar benefits and limitations in quantifying risk. One study found that classifying risk into exposure and consequence helped in prioritizing strategies for risk reduction [122]. Primarily, the authors suggested that management approaches are likely to accommodate shifts in risk exposure and not as likely to reduce the consequence components of risk because consequence is based on habitat- or species-specific life history attributes that do not respond quickly to change in a maritime pressure [122]. Another study found a primary benefit of the HRA model was its use as a rigorous method in its use of best available science while maintaining simplicity, efficiency, and ease of implementation for analysts and stakeholders [123]. Similar to our findings, other researchers found that a limitation of the HRA model was its inability to accommodate prior risk to a study area (i.e. trends in activities) [122]. Furthermore, other researchers found it challenging to apply the HRA model framework at subregional scales because there was the potential to mismatch the scale of analysis with the scale that was most relevant ecologically [123]. Our research focused on evaluating disturbance risk for two Sanctuaries comprising our entire study area, a strategy we would recommend for reducing this potential mismatch in scale.

In contrast to our research using inVEST's HRA model to inform Marxan, a few studies have used the Environmental Risk Surface (ERS) module in ArcGIS to conduct habitat risk evaluations also as a cost metric for use with Marxan [117,163]. These studies, similar to our own, focused habitat prioritization by directing habitat selection away from high risk areas where the reduction of pressures on conservation features seemed less likely. One study developed a means to develop spatial accumulation of risk using an ERS [117]. They used the ERS to investigate the downstream influence of human activities (i.e. spatial accumulation of risk) in a river system by developing risk magnitudes in a directionally appropriate way [117]. Like the HRA model, however, this ERS surface was also developed using primary literature and the authors' judgement of risk for each human activity considered, so it is likely that the quality of risk information was similar.

Our strategy to inform habitat prioritization using the HRA model and Marxan was effective in several ways. First, we were able to work with spatially explicit, fine-scale conservation feature data—pelagic seabird foraging area. This high resolution data enabled Marxan to prioritize high-use foraging planning units. Second, we were able to improve upon the spatial data provided by the California Ocean Use Atlas data by using expert opinion and peer-reviewed literature to inform our risk layer. While risk was limited to non-spatially-explicit human data, we gained an understanding of how the dominant spatial footprints of maritime activities overlapped and posed disturbance risk to seabird high-use foraging areas. Third, with this information, Marxan was a powerful tool for prioritizing areas of value to seabirds that faced less pressure from maritime pressures, making these areas more likely to be adapted and implemented for conservation purposes. Alternately, if our method were to be applied to an endangered seabird species, decision-makers could use our habitat risk assessment approach to prioritize the shifting or reduction of high risk areas.

Acquiring additional spatially explicit data for maritime activities in our analysis would improve the HRA model risk surface. First, we found that though we incorporated spatial information, the usefulness of the HRA model diminished without identifying sufficient spatially explicit detail [120] because a single risk value (*R*) derived from our criteria must be applied to the full extent of each maritime activity's dominant spatial footprint. Our analysis suggests this is true particularly for an activity like wildlife viewing that has localized negative impacts, but a large spatial footprint. Without specifying high- and low-use areas for wildlife viewing, this activity's dominant spatial footprint covers a vast area of the Sanctuaries, offering the most broad-brush suggestion of what areas are most at risk of disturbance. A large spatial footprint of a maritime activity therefore strongly influenced the additive risk scores used to represent cost in Marxan. Without finer spatially explicit information of maritime use in the Sanctuaries, our method for determining cost based on risk was limited to the imperfect assumption that the full extent of each activity's spatial footprint was under constant use. As more spatially and temporally explicit data becomes available, both the HRA model's risk surface and Marxan's subsequent habitat prioritization will improve. Second, our analysis required the use of primary literature and expert opinion, which is accompanied by the uncertainty associated with heuristic modeling strategies [164].

Our approach provides two contrasting options for meeting our conservation goals. Decision-makers could choose to protect the low cost (i.e. low risk) habitat prioritized using Marxan, or to manage the maritime activities to decrease their impact to wildlife. Here we offer specific recommendations to reduce the risk of disturbance from maritime activities to pelagic seabirds in our study. For example, both types of fishing ranked higher for exposure than consequence, suggesting that regulating fishing seasonality and spatial coverage would help reduce disturbance. Military operations ranked higher for exposure than consequence, indicating that transit to and from drill areas should avoid critical foraging areas to minimize disturbance. While shipping ranked high for exposure and low for consequence, the threat of oil spills ranked higher for consequence than exposure. Actions have been implemented to reduce the footprint of shipping, and additional speed reductions have been requested to minimize risk of ship strikes. Reducing the consequence of oil spills is challenging and will require rapid and effective response plans. Wildlife viewing ranked higher for exposure than consequence, suggesting the need for targeted areas for this recreational set of activities.

Conclusion

In this study, we demonstrated a novel method using inVEST's Habitat Risk Assessment (HRA) model to develop a Marxan cost layer to inform habitat prioritization. Our model had benefits such as the transparent nature of the HRA analysis that enabled classification of risk into exposure and consequence. The main limitations of the model were the dilution of risk by averaging criteria scores for exposure and consequence and the static nature of the model that doesn't allow trends in the activities. Our approach provided two options for meeting conservation goals by protecting the Marxan-prioritized area or by managing the maritime activities to decrease their impact to wildlife. Either approach could be scaled up to include a larger habitat area, multiple habitat types, and different maritime activities. Our method can be applied to help improve ocean zoning anywhere where critical wildlife areas coincide with locations marked for development.

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