NOAA Professional Paper NMFS 17

Potential overlap between cetaceans and commercial groundfish fleets that operate in the California Current Large Marine Ecosystem

Blake E. Feist
Marlene A. Bellman
Elizabeth A. Becker
Karin A. Forney
Michael J. Ford
Phillip S. Levin

March 2015

NOAA Professional Papers NMFS

The NOAA Professional Paper NMFS (ISSN 1931-4590) series is published by the Scientific Publications Office, National Marine Fisheries Service, NOAA, 7600 Sand Point Way NE, Seattle, WA 98115.
The Secretary of Commerce has determined that the publication of this series is necessary in the transaction of the public business required by law of this Department. Use of funds for printing of this series has been approved by the Director of the Office of Management and Budget.

The NOAA Professional Paper NMFS series carries peer-reviewed, lengthy original research reports, taxonomic keys, species synopses, flora and fauna studies, and data-intensive reports on investigations in fishery science, engineering, and economics. Copies of the NOAA Professional Paper NMFS series are available free in limited numbers to government agencies, both federal and state. They are also available in exchange for other scientific and technical publications in the marine sciences. Professional Papers are published online in PDF format at http://spo.nmfs.noaa.gov

NOTICE: This series was established in 2003 to replace the NOAA Technical Report NMFS series.

NOAA Professional Paper NMFS 17

Potential overlap between cetaceans and commercial groundfish fleets that operate in the California Current Large Marine Ecosystem

Blake E. Feist
Marlene A. Bellman
Elizabeth A. Becker
Karin A. Forney
Michael J. Ford
Phillip S. Levin

March 2015

U.S. Department of Commerce
Seattle, Washington

Suggested reference

Feist, Blake E., Marlene A. Bellman, Elizabeth A. Becker, Karin A. Forney, Michael J. Ford, and Phillip S. Levin. 2015. Potential overlap between cetaceans and commercial groundfish fleets that operate in the California Current Large Marine Ecosystem. NOAA Professional Paper NMFS 17, 27 p. doi:10.7755/PP.17

Online dissemination

This report is posted online in PDF format at http://spo.nmfs.noaa.gov (click on *Professional Papers* link).

Copyright law

Proprietary products

Disclaimer

CONTENTS

Potential overlap between cetaceans and commercial groundfish fleets that operate in the California Current Large Marine Ecosystem

Blake E. Feist (contact author)[1]
Marlene A. Bellman[2]
Elizabeth A. Becker[3]
Karin A. Forney[3]
Michael J. Ford[1]
Phillip S. Levin[1]

Email address for the contact author: blake.feist@noaa.gov

[1] Conservation Biology Division
Northwest Fisheries Science Center
National Marine Fisheries Service, NOAA
2725 Montlake Blvd E.
Seattle, Washington 98112

[2] Fishery Resource Analysis and Monitoring Division
Northwest Fisheries Science Center
National Marine Fisheries Service, NOAA
2725 Montlake Blvd E.
Seattle, Washington 98112

[3] Protected Resources Division
Southwest Fisheries Science Center
National Marine Fisheries Service, NOAA
110 Shaffer Road
Santa Cruz, California 95060

Abstract—Cetacean populations are confronted by many anthropogenic threats, including commercial whaling, noise, vessel collisions, gear entanglement, exploitative competition, habitat disturbance, and global climate change. Evidence indicates that commercial fishing activities can have both direct (e.g., gear entanglement and bycatch) and indirect (e.g., prey reduction and noise) effects on cetaceans. However, few studies have addressed the potential vulnerability of a given cetacean species to an entire fishing fleet that operates over a large marine ecosystem. In this study, we overlaid spatially explicit multiyear predicted mean densities of 11 cetacean species and 1 species guild within the California Current Large Marine Ecosystem with data for commercial fishing effort of the fixed-gear, at-sea hake mid-water trawl, and bottom trawl fleets of the west coast groundfish fishery. We quantified the exposure of each species to each fleet type by multiplying the predicted mean cetacean density by the measured fishing fleet effort. We found large interspecific and interfleet variability in the overlap between cetaceans and fishing fleets. Although many of the species had relatively low overlap rates, others had substantial exposure to some of the fishing fleets, particularly those species with more nearshore distributions. Direct mortality from these fleets has been documented to be low, but our results indicate that there is opportunity for fisheries interactions with some cetacean species, particularly in the fixed-gear fleet. Our analyses make up an important first step in generating formal risk assessments for quantification of the impacts of various fishing fleets on populations of cetacean species that occur in the California Current.

Introduction

Risk is a function of the likelihood that a subject will experience adverse consequences of exposure to a single or many threats (Burgman, 2005; Suter, 2007). In the context of endangered species management, risk assessment evaluates the degree to which human activities or natural processes interfere with the achievement of management objectives related to recovery of imperiled species (Levin et al., 2009). Therefore, a risk assessment for endangered species fundamentally requires an understanding of the distribution and intensity of potentially harmful activities.

Cetaceans confront a number of anthropogenic pressures. Commercial whaling was once the primary risk to the viability of many whale populations, but many populations have rebounded since the International Whaling Commission's ban on commercial whaling began in 1986 (Clapham et al., 1999; Reeves et al., 2003). During the past few decades, the expansion of global fisheries has increased concern about the direct and indirect risks to cetaceans from fishing activities. Commercial fishing can affect cetaceans directly (e.g., contact with fishing gear) (Beverton, 1985; Read et al., 2006) or indirectly (e.g., exploitative competition) (Bearzi et al., 1999; DeMaster et al., 2001; DeMaster et al., 2006). For example, incidental catch of vaquitas (*Phocoena sinus*) in gillnet fisheries that operate in the northern Gulf of California has resulted in significant mortality and currently threatens this species with extinction (Gerrodette and Rojas-Bracho, 2011). Larger cetacean species occupy broader geographic extents and can encounter entanglement risks throughout their range. The majority of North Atlantic right whales (*Eubalaena glacialis*) and humpback whales (*Megaptera novaeangliae*) (Johnson et al., 2005), for example, have scarring associated with entanglement with fishing gear in a variety of areas along the Eastern Seaboard. Although evidence of commercial fishing fleets competing with cetaceans for prey resources exists (Trites et al., 1997; Herr et al., 2009; Gomez-Campos et al., 2011), population-level consequences of these interactions have proven difficult to demonstrate (Matthiopoulos et al., 2008).

The California Current Large Marine Ecosystem (CCLME) (Fig. 1) is actively fished by a variety of commercial fleets, and those fleets that are known or suspected of causing harm to cetaceans are monitored with observer programs. Other fleets that are considered less of a threat to cetaceans, such as the ones that use midwater and bottom trawl gear (Jannot et al.[1]), still have nearly 100% observer coverage to monitor catches of fish species, therefore reducing the likelihood that these gear types pose undetected threats to cetaceans. However, even with 100% observer coverage, indirect threats, such as exploitative competition, may exist. Certain fleets, such as those fleets that use fixed gear, have low levels of observer coverage yet employ gear types that pose risks to cetaceans (e.g., pots or traps with long lines and floats) and often are left unattended during fishing activities. Consequently, quantification of the co-occurrence of the fixed-gear fleet and cetacean populations is needed to better understand the potential risk imposed by these fisheries.

In some studies, the intensity of commercial fishing has been inferred from landings data recorded at ports along a given coast. These data then are used to infer the spatial pattern of commercial fishing vessels (Kaschner, 2004; Kaschner et al.[2]; Kaschner and Pauly[3]). Such approaches are not ideal because the specific locations of fishing activities are unknown. Studies that use direct observations of fishing effort provide a basis for generating reliable estimates of the exposure of cetaceans to fishing activities (Carretta et al., 2004; Herr et al., 2009; Vanderlaan et al., 2011).

The CCLME is home to several cetacean species that are listed as endangered under the U.S. Endangered Species Act (NMFS[4]). The CCLME also is considered a hotspot of extinction risk (Davidson et al., 2012), because of the high diversity of species with life history traits that make them vulnerable. Therefore, a rigorous determination of the magnitude and frequency of exposure of cetaceans to fisheries is necessary, especially for fisheries with low levels of observer coverage. In this paper, we address: 1) the general patterns of overlap of 11 cetacean species and 1 species guild with 3 of the major fishing fleets operating in the CCLME, and 2) interspecific and interfleet differences in the overlap patterns. We also present quantification of the potential for overlap between each cetacean species and fishing fleet. This spatially explicit assessment provides a measure of the potential risk from 3 specific fishing fleets that operate in the CCLME; however, actual bycatch rates will depend on the gear types used and cetacean species involved.

Materials and methods

To quantify the co-occurrence of cetacean populations and specific fishing activities, we overlaid 2 types of geospatial data layers: modeled cetacean density and observed commercial fishing effort. We compared general patterns of effort by 3 commercial fleets by gear type (bottom trawl, mid-water trawl for Pacific hake [*Merluccius productus*], and fixed gear) with general density patterns of 11 cetacean species and 1 species guild that occur in the CCLME (Fig. 1). The CCLME is one of many large marine ecosystems throughout the world that are adjacent to continents in coastal waters and generally exhibit higher primary productivity compared with open ocean areas (for more about large marine ecosystems, see the website Large Marine Ecosystems of the World, http://lme.edc.uri.edu/, accessed December 2014).

Cetacean data

We used estimates of cetacean density from habitat models that were generated by the NOAA Southwest Fisheries Science Center for a study area of approximately 1,141,800 km^2 off the U.S. west coast (Barlow et al., 2009; Forney et al., 2012). They used data from 5 systematic ship-based cetacean and ecosystem assessment surveys conducted during the period from June through November in 1991, 1993, 1996, 2001, and 2005 to build habitat-based density models for 11 species and 1 species guild. Models were built for striped dolphin (*Stenella coeruleoalba*), short-beaked common dolphin (*Delphinus delphis*), Risso's dolphin (*Grampus griseus*), Pacific white-sided dolphin (*Lagenorhynchus obliquidens*),

[1] Jannot, J., E. Heery, M. A. Bellman, and J. Majewski. 2011. Estimated bycatch of marine mammals, seabirds, and sea turtles in the US west coast commercial groundfish fishery, 2002–2009, 104 p. [Available from West Coast Groundfish Observer Program, Northwest Fisheries Science Center, National Marine Fisheries Service, 2725 Montlake Blvd. E., Seattle, WA 98112.]

[2] Kaschner, K., R. Watson, V. Christensen, A. W. Trites, and D. Pauly. 2001. Modeling and mapping trophic overlap between marine mammals and commercial fisheries in the North Atlantic. *In* Fisheries impacts on North Atlantic ecosystems: catch, effort and national/regional data sets. (D. Zeller, R. Watson, and D. Pauly, eds.), p. 35–45. [Available from Fisheries Centre, Univ. British Columbia, 2204 Main Mall, Vancouver, BC, Canada V6T 1Z4.]

[3] Kaschner, K., and D. Pauly. 2004. Competition between marine mammals and fisheries: food for thought, 28 p. [Available from Humane Society, 2100 L St. NW, Washington, DC 20037.]

[4] NMFS (National Marine Fisheries Service). Endangered and threatened marine mammals. Office of Protected Resources, National Marine Fisheries Service, 1315 East-West Highway, Silver Spring, MD 20910. [Available from http://www.nmfs.noaa.gov/pr/species/esa/listed.htm#mammals, accessed 9 April 2013.]

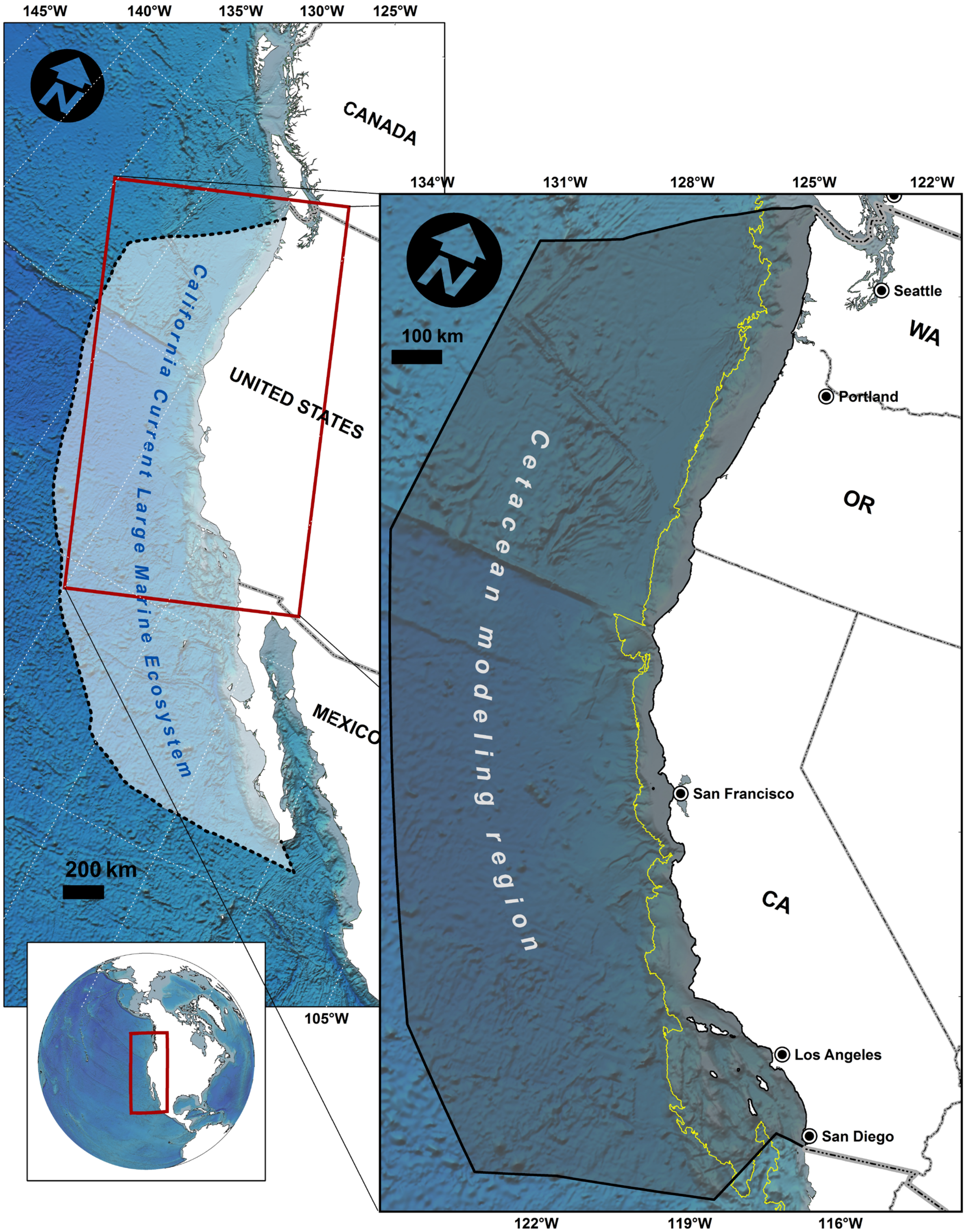

Figure 1

Maps of the boundary of the California Current Large Marine Ecosystem, which was the focus for this study of the overlap of cetaceans and fishing effort of commercial groundfish fleets, and its general location relative to the west coast of North America. The zoomed in map at right depicts the region for which density patterns of 11 species and 1 guild of cetaceans for the period between 1991 and 2005 were available from models generated by the NOAA Southwest Fisheries Science Center (Barlow et al., 2009; Forney et al., 2012). The yellow line indicates the 1600-m isobath, within which most groundfish fishery activity occurs.

Table 1

The 11 species and 1 guild of cetaceans represented in the geospatial data layer of predicted cetacean densities from habitat models that were generated by the NOAA Southwest Fisheries Science Center for a study area off the U.S. west coast (Barlow et al., 2009; Forney et al., 2012).

Cetacean	Suborder	Family	Endangered Species Act status
Baird's beaked whale (*Berardius bairdii*)	Odontoceti (toothed)	Ziphiidae (beaked whales)	–
Blue whale (*Balaenoptera musculus*)	Mysticeti (baleen)	Balaenopteridae	Endangered
Fin whale (*B. physalus*)	Mysticeti (baleen)	Balaenopteridae	Endangered
Short-beaked common dolphin (*Delphinus delphis*)	Odontoceti (toothed)	Delphinidae (dolphins)	–
Risso's dolphin (*Grampus griseus*)	Odontoceti (toothed)	Delphinidae (dolphins)	–
Northern right whale dolphin (*Lissodelphis borealis*)	Odontoceti (toothed)	Delphinidae (dolphins)	–
Pacific white-sided dolphin (*Lagenorhynchus obliquidens*)	Odontoceti (toothed)	Delphinidae (dolphins)	–
Humpback whale (*Megaptera novaeangliae*)	Mysticeti (baleen)	Balaenopteridae	Endangered
Dall's porpoise (*Phocoenoides dalli*)	Odontoceti (toothed)	Phocoenidae (porpoises)	–
Sperm whale (*Physeter macrocephalus*)	Odontoceti (toothed)	Physeteridae (sperm whales)	Endangered
Striped dolphin (*Stenella coeruleoalba*)	Odontoceti (toothed)	Delphinidae (dolphins)	–
Small beaked whales (*Ziphius* and *Mesoplodon*)	Odontoceti (toothed)	Ziphiidae (beaked whales)	–

northern right whale dolphin (*Lissodelphis borealis*), Dall's porpoise (*Phocoenoides dalli*), sperm whale (*Physeter macrocephalus*), fin whale (*Balaenoptera physalus*), blue whale (*B. musculus*), humpback whale (*Megaptera novaeangliae*), Baird's beaked whale (*Berardius bairdii*), and a guild of small beaked whales (including Cuvier's beaked whale [*Ziphius cavirostris*] and beaked whales of the genus *Mesoplodon*). Four of these species are listed as endangered under the U.S. Endangered Species Act (Table 1).

Generalized additive models (GAMs) were used by the Southwest Fisheries Science Center to predict cetacean densities from habitat variables that included remotely sensed measures of sea-surface temperature (SST) and the coefficient of variation of SST (to serve as a proxy for frontal regions); in situ measures of sea-surface salinity, water depth, mixed-layer depth (the depth at which temperature is 0.5°C less than surface temperature), and sea-surface concentration of chlorophyll-*a*; and geographic information system (GIS)-derived values of bathymetric slope and distance to the nearest 2000-m isobath (Barlow et al., 2009; Forney et al., 2012). Model validation was performed on a novel data set (2005), and selected models were then re-fit to the complete set of data (1991–2005). Predicted densities for each of the 5 individual years (1991, 1993, 1996, 2001, and 2005) were smoothed and then averaged to produce a composite grid that represents the best estimate of average cetacean density and distribution for the months from June through November. The grids were created at a resolution of approximately 25 km and covered most of the CCLME off the coasts of Washington, Oregon, and California. Further details of these models can be found in Barlow et al. (2009) and Forney et al. (2012). For the analyses in our study, we used predicted multiyear mean density (number of animals per square kilometer), which is the predicted density of each species or species guild in any given year between 1991 and 2005.

Commercial fishing effort

Fishing effort was represented on grids of 10 km for the bottom trawl fleet and Pacific hake mid-water trawl fleet and 20 km for the fixed-gear fleet. We used data that were provided by the At-sea Hake Observer Program (A-SHOP) and the West Coast Groundfish Observer Program (WCGOP) of the Fishery Resource Analysis and Monitoring Division, NOAA Northwest Fisheries Science Center (NWFSC). Results from analyses were adjusted for the differing grid-cell sizes of these data layers, which are described later in the "Materials and methods" section.

Data of commercial fishing effort are subject to restrictions that preserve confidentiality as required under the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2006. Because of these restrictions, data cannot be presented to the general public unless they represent information from 3 or more vessels. To comply with these confidentiality restrictions, grid cells in the final mapped overlap indices that contained data from 2 or fewer vessels are not displayed herein. However, we ran all of our analyses with the full set of grid cells, which included those grid cells representing 2 or fewer vessels.

Fishing effort of the fleet that uses mid-water trawls to fish for Pacific hake (hereafter called "hake fleet")

Table 2

Fixed-gear fishing effort, as represented in data from the West Coast Groundfish Observer Program, by sector observed for the period 2002–2009: the proportion of total observed effort (cumulative number of hours during which a gear was deployed), the observed sector coverage rate calculated as the observed retained catch weight of target species divided by the fleet-wide landed weight of target species, and the assumed proportion of total fleet-wide effort.

Sector	Total duration (%)	Coverage rate	Proportion of duration represented
Limited-entry sablefish primary	59.38%	26.12%	15.51%
Limited-entry non-tier-endorsed fixed gear	17.00%	7.41%	1.26%
Open access fixed gear	18.63%	3.00%	0.56%
Oregon nearshore fixed gear	3.83%	5.20%	0.20%
California nearshore fixed gear	1.16%	3.43%	0.04%
			Total proportion of duration represented=17.57%

was collected directly by the A-SHOP (NWFSC[5]). The A-SHOP collects information on total catch (fish discarded and retained) from all vessels that process Pacific hake at sea. All data were collected according to standard protocols and data quality control established by the A-SHOP (NWFSC[5]).

Fishing effort of the bottom trawl fleet (hereafter called "trawl fleet") (NWFSC[6]) was derived from fleet-wide logbook data submitted by state agencies to the Pacific Fisheries Information Network (PacFIN) regional database, maintained by the Pacific States Marine Fisheries Commission (PacFIN Coastwide Trawl Logbook Subsystem, http://pacfin.psmfc.org/pacfin_pub/data.php, accessed January 2011). A common-format logbook is used by Washington, Oregon, and California. Trawl logbook data are regularly used in analyses of the bottom trawl groundfish fishery observed by the WCGOP (Bellman et al.[7]).

For spatial data for both the trawl and hake fleets, a trawl towline model (straight line drawn from the start to end location of a trawl tow) was used to allocate data to grid cells that were 10 × 10 km. We did not use the trawl towline transect data directly because those data depict the exact locations of vessels and those locations are considered confidential.

[5] NWFSC (Northwest Fisheries Science Center). 2011. At-sea Hake Observer Program, observer sampling manual, 47 p. [Available from Fishery Resource Analysis and Monitoring Division, NWFSC, 2725 Montlake Blvd. E., Seattle, WA 98112.]

[6] NWFSC (Northwest Fisheries Science Center). 2010. West coast groundfish observer training manual, 665 p. [Available from West Coast Groundfish Observer Program, NWFSC, 2725 Montlake Blvd. E., Seattle, WA 98112.]

[7] Bellman, M. A., A. W. Al-Humaidhi, J. Jannot, and J. Majewski. 2011. Estimated discard and catch of groundfish species in the 2010 U.S. west coast fisheries. [Available from West Coast Groundfish Observer Program, Northwest Fisheries Science Center, National Marine Fisheries Service, 2725 Montlake Blvd. E., Seattle, WA 98112.]

Fixed gear is generally defined as fishing gear that is anchored to the bottom of the ocean, as opposed to gear that is towed through the water. The fishing effort of the fixed-gear fleet (hereafter called "fixed fleet") was collected directly by the WCGOP from the following commercial groundfish fixed-gear sectors: limited entry sablefish primary (target: sablefish), limited entry non-sablefish endorsed (target: sablefish and groundfish), open access fixed gear (target: groundfish), and Oregon and California state-permitted nearshore fixed gear (target: nearshore groundfish). We used the following gear types recorded by the WCGOP: historic longline, vertical hook and line, other hook and line, fish pot, fixed hook longline, and snap gear longline. We excluded troll and rod-and-reel gear from our analyses because those gear types represent a small fraction of the fishing effort and no cases of injury or mortality associated with these gear types have been documented for cetacean species off the U.S. west coast at the time that analyses were conducted (NMFS[8]). Gill nets were not included in our analysis because the groundfish fleets monitored by the WCGOP do not use them.

The observed portion of overall fishing effort in each sector of the fixed fleet varied by coverage level (Table 2). Coverage rates were calculated for each sector as the observed retained weight of target species divided by the sector-wide landed weight of target species for each sector. Because not all fishing operations were observed, neither the maps nor the data can be used to characterize the fishery completely. We did not correct our overlap indices to account for this underrepresentation because we did not have information about the spatial consistency of this deficiency. Both the observed fixed-gear set (start location of fishing) and haul (location of gear retrieval)

[8] NMFS. 2011. 2012 List of Fisheries (LOF). NMFS, NOAA, Silver Spring, MD. [Available from: http://www.nmfs.noaa.gov/pr/interactions/lof/final2012.htm, accessed 17 September 2012.]

were assigned to grid cells that were 20 × 20 km. In cases where a set and haul line crossed a given 20-km grid cell, fishing effort was divided proportionately using the length of the line that intersected any given grid cell as a weighting factor. Using a weighting factor accurately proportioned the duration of the contributions of a given set and haul line to multiple grid cells that had been intersected. As was the case with the data for the trawl and hake fleets, we did not use transect data for the set and haul locations directly because exact locations of vessels are confidential.

Fishing effort was expressed as the cumulative number of hours a given fishing fleet (trawl, hake, or fixed) had gear deployed in the water. All of the fishing effort data were reported as monthly sums for each type of fishing gear; therefore, for each year from 2002 through 2009, we calculated cumulative fishing effort (in hours) from June through November, the period that corresponded to the months over which the data were collected each year for building the habitat-based cetacean density models.

For the hake and trawl fleets, the data represent total fishing effort (100%). The National Marine Fisheries Service requires all hake vessels (catcher-processors and mother ships) longer than 38 m (125 ft) to carry 2 observers, and vessels under 38 m carry 1 observer (Bellman et al.[7]). PacFIN fleet-wide logbook data are assumed to represent the entire trawl fleet for our analysis. However, all fishing operations may not be recorded in logbooks, and logbook submission may not be complete. Because observer data did not capture 100% of the fishing effort for the fixed fleet, we calculated the proportion (C) of the fleet that was represented by the observer data:

$$C = \sum_{s=1}^{5} \left(\frac{t_s}{T} \times \frac{w_{s(\text{obs})}}{W_{s(\text{land})}} \right), \tag{1}$$

where s corresponds to each of the 5 sectors, t is the total time (in hours, 2002–2009) a given sector was observed with gear in the water, T is the total time (in hours, 2002–2009) during which all 5 of the sectors were observed with gear in the water, w is the total retained weight of target fish species caught on vessels with observers present (reported by sector, 2002–2009), and W is the total landed weight of target fish species by all vessels (reported by sector, from 2002–2009).

Cetacean and fishery overlap

We created maps of the index of overlap (for the period 2002–2009) for each of the 11 cetacean species and the 1 species guild, and we calculated the population overlap for each species with each of the 3 fleets as well as a cumulative overlap index.

We assumed that the various fishing fleets and cetacean species were randomly distributed in any given grid cell; therefore, we did not account for cetaceans avoiding commercial fishing activities (because of noise, general disturbance, or other disruption) or being attracted to these fishing activities (depredation by cetaceans in longline and other fisheries). The former would reduce the apparent influence of commercial fishing activity, whereas the latter would increase the potential effect.

We generated a simple index of predicted overlap (R_s) with this equation:

$$R_s = t \times \rho, \tag{2}$$

where t is fishing effort (total time, in hours, that a gear was in the water), and ρ is the predicted density of cetaceans (number of animals per square kilometer).

Maps We calculated the overlap indices for each of the combinations of species and fleet types (12×3=36) throughout the study area. Because the grid-cell size of the cetacean data (~25 km) was not the same as for the fishing effort data (10 or 20 km), we calculated an area-weighted mean cumulative fishing effort for each year that corresponded to each respective cetacean grid cell. Although all of the geospatial data layers were on regular grids, they were vector based, allowing us to explicitly account for varying sizes of grid cells. First, we combined each cetacean grid with the 3 fishing fleet grids through the use of the INTERSECT command in ArcGIS (vers. 9.3, Esri, Redlands, CA). Then, we used the information from this intersection to calculate an area-weighted mean (AWM) fishing effort for each cetacean grid cell with the following equation:

$$t_{\text{awm}} = \left[\sum_{1}^{n} t_{\text{n}}(a_{\text{n}}) \right] / A, \tag{3}$$

where t is the fishing effort in hours for a given portion of a given cetacean grid cell, a is the corresponding area for that effort, and A is the total area of the corresponding cetacean grid cell. This equation effectively weighted fishing effort for fragments of grid cells that fell within any given 25-km cetacean grid cell by multiplying the area of any given fragment by the corresponding value of the fishing effort in that grid cell.

Finally, we multiplied the AWM fishing effort (t) for each grid cell by the corresponding cetacean density (ρ) to yield the final map of predicted overlap index. We used ArcGIS to join the corresponding predicted overlap index for each combination of species and gear type to the original cetacean density grid to create 36 gridded maps, which we used to explore spatiotemporal patterns in the overlap of cetaceans and fishing fleets.

Population overlap index Given that species densities can vary by more than 3 orders of magnitude, standardizing mapped overlap indices by total abundance is important for evaluation of proportional overlap. To compare interspecific and fishery overlap relative to all of the modeled individuals in a given species, we used the following equation to calculate what fraction of the modeled population for each cetacean species overlapped with areas where commercial fishing occurred within the CCLME study area:

$$R_{\mathrm{p}} = \sum_{1}^{n} p_{\mathrm{n}}(a_{\mathrm{n}}) \,/ \sum_{1}^{n} P_{\mathrm{n}}(a_{\mathrm{n}}), \tag{4}$$

where ρ is the modeled cetacean density for a given grid cell that experienced commercial fishing by a given fleet, a is the area of the corresponding grid cell, and P is the modeled cetacean density for a given grid cell, regardless of whether or not that grid cell experienced commercial fishing by any of the fleets.

Cumulative overlap index We calculated with the following equation a cumulative overlap index over the area that each fleet operated for each combination of cetacean species and fishing fleet for all years from 2002 through 2009:

$$R_{\mathrm{c}} = \sum_{1}^{n} R(a_{\mathrm{n}}) \,/ A, \tag{5}$$

where R is the predicted overlap index for a given 25-km grid cell, a_{n} is the area of the corresponding grid cell, and A is the total area over which a given fleet operated. This approach allowed us to compare patterns of interspecific and fishery overlap that were standardized by the total area where the fleet operated.

Population-weighted cumulative overlap index We calculated a population-weighted cumulative overlap index by taking the product of population overlap and cumulative overlap indices over the entire study area for each combination of cetacean species and fishing fleets for all years from 2002 through 2009. This weighting adjusted the scores in the cumulative overlap index to better reflect the overall influence of each fleet on the modeled cetacean populations, as a function of fishing effort, cetacean density, and spatial distribution of cetacean populations.

Results

Commercial fishing effort

Overall, spatial and temporal patterns of fishing effort varied widely over the study area. The cumulative levels of effort during the months from June through November in 2002–2009 for the fixed, hake, and trawl fleets were 187,015; 24,132; and 287,886 hours, respectively.

For the fixed fleet, the fishing effort captured by observers varied across sectors (Table 2). In general, observers captured approximately 17.57% of the total fixed-gear effort (as a function of the cumulative hours during which a gear was deployed) that occurred over the entire study area, a finding based on the proportion of effort in 2002–2009 from each observed sector and the WCGOP coverage rate of fishery landings by sector for all years combined. Therefore, our indices for overlap of fixed-gear fishing with the various cetacean species likely underestimate the actual magnitude of this fleet's overlap by a factor of 5. However, this underrepresentation did not alter the proportion of each population that overlapped with the observed fixed fleet.

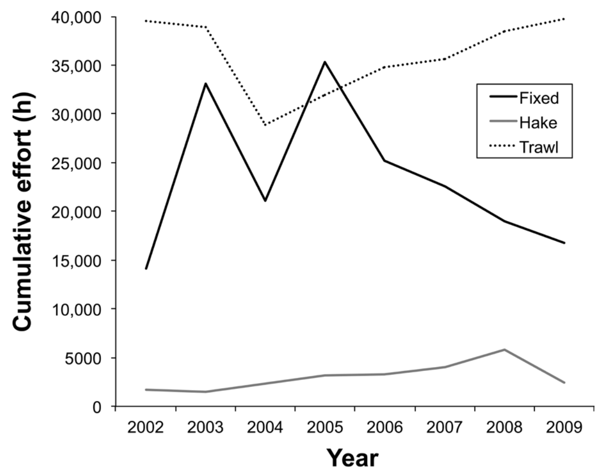

Figure 2

Interannual trends in fishing effort, expressed as the cumulative number of hours per year during which fishing gear was deployed in the water, for the period June through November in 2002–2009 for each of the 3 fleets in the commercial groundfish fishery that operate off the U.S. west coast (the fixed-gear, at-sea hake mid-water trawl, and bottom trawl fleets).

Interannual patterns Cumulative annual effort varied over time for each of the fleets (Fig. 2). Observed cumulative effort of the fixed fleet had peaks in 2003 and 2005, with a downward trend from 2005 to 2009 (Fig. 2). The hake fleet gradually increased in cumulative effort level until 2008 and decreased in 2009 (Fig. 2). The trawl fleet had a drop in cumulative annual fishing effort in 2004 but returned to 2002 levels of effort by 2009 (Fig. 2).

Monthly interannual and intraannual patterns There was considerable interannual, intra-annual, and inter-fishery variability in the cumulative effort, an observation based on the monthly data (Fig. 3). The fixed fleet had the greatest interannual and intraannual variability in observed effort. This fleet generally had peak efforts during the summer months (Fig. 3A). However, there was usually a second peak of effort in the fall (Fig. 3A). Effort was lowest during the months of January,

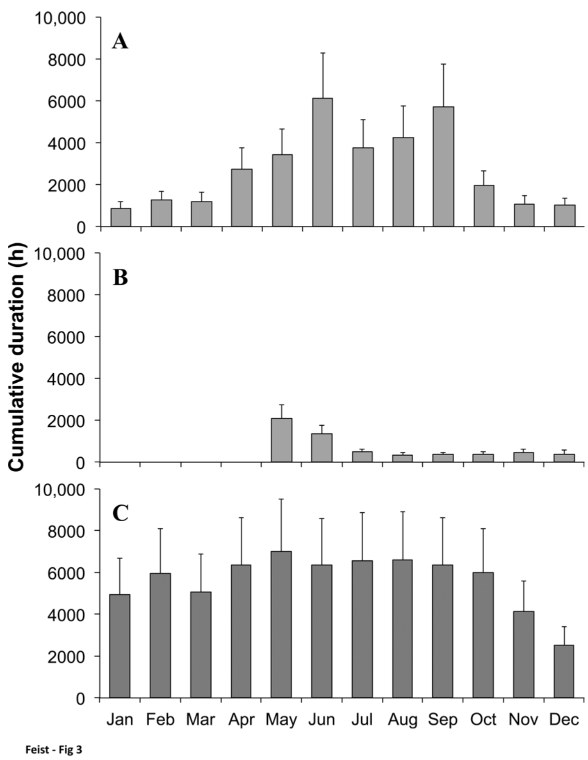

Figure 3

Monthly trends in commercial groundfish fishing effort, expressed as the cumulative number of hours per month during which fishing gear was deployed in the water, in 2002–2009 off the U.S. west coast for each of the 3 fleets: (**A**) observed fixed gear, (**B**) hake midwater trawl, and (**C**) bottom trawl. Error bars represent +1 standard error.

February, November, and December (Fig. 3A). The hake fleet had the least interannual but the greatest intraannual variability in effort. The hake fleet does not fish from January to April each year, but it clearly had its maximum effort in May and June, with a smaller peak often occurring in the late fall (Fig. 3B). The trawl fleet had higher interannual but moderate intraannual variability in effort. The trawl fleet generally has considerable and consistent effort year round, but it tends to taper off towards the end of the year (Fig. 3C). In 2002, however, there was a strong peak of effort from October through November by this fleet.

Spatial and temporal patterns There was substantial inter-fishery variability in the spatial extent of cumulative fishing effort (Fig. 4). For the period 2002–2009, various levels of observed effort of the fixed fleet occurred from the U.S.–Mexico border north to the U.S.–Canada border (Fig. 4). There were concentrations of effort off the California coastal areas of Los Angeles, San Diego, Caspar, and Eureka and off the northern half of the Oregon coast (Fig. 4). The patchy distribution of the observed effort of the fixed fleet is assumed to be representative of overall fishing patterns, but there is a lack of logbook or other data sources to corroborate fleet-wide spatial patterns of distribution. Fishing efforts of the hake fleet occurred over a much smaller region, spanning the coasts of Oregon and Washington (Fig. 4). The hake fleet effort was not as patchy compared with the observed effort of the fixed fleet, but there were areas of increased effort (Fig. 4). Trawl fleet efforts, occurring consistently from Point Conception, California, north to the U.S.–Canada border, were not quite as widespread as the observed efforts of the fixed fleet (Fig. 4). Effort of the trawl fleet was not as patchy compared with that of the observed effort of the fixed fleet, but there were areas where effort was higher (Fig. 4).

Interannual spatial variability was greatest and most patchy for the observed fixed fleet (figures are unavailable because of confidentiality restrictions). In some years (e.g., 2002), large expanses of hundreds of kilometers or more had no effort whatsoever. The effort of the hake fleet also became more patchy when examined on an annual basis, but there were few large areas that were unexploited in a given year. Of the 3 gear types, the trawl fleet had the most consistent effort over space and time. However, there was still considerable interannual variability among various 10-km grid cells in effort for this fleet.

Mapped overlap index: cetaceans and fishing efforts

Generally, there was low overlap spatially between the 11 cetacean species and 1 species guild and the 3 commercial fishing fleets (Figs. 5–16). Where there was overlap between the various cetacean species and the 3 commercial fishing fleets, there was considerable variation in the mapped overlap indices. Highly abundant species (short-beaked common dolphin and Dall's porpoise) and species with the greatest densities in shelf and slope waters, such as the Pacific white-sided dolphin, Risso's dolphin, and northern right whale dolphin, had the greatest predicted overlap with fisheries. Species with more offshore distributions, such as the sperm whale, beaked whales, and the striped dolphin, had very little overlap with these 3 fishing fleets. In the rest of this section, we describe species-specific spatial patterns of the predicted overlap index, in order of decreasing population-weighted overlap indices.

Overlap of the observed fixed fleet and the Dall's porpoise was concentrated from Astoria Canyon, Oregon, south to around Stonewall Bank, Oregon (R_S>630; Fig. 5). Maximum overlap of this species with the hake fleet was near Cape Flattery, Washington, and in the region off Oregon from Astoria Canyon south to around Heceta Valley (R_S>40; Fig. 5). The trawl fleet overlapped fairly

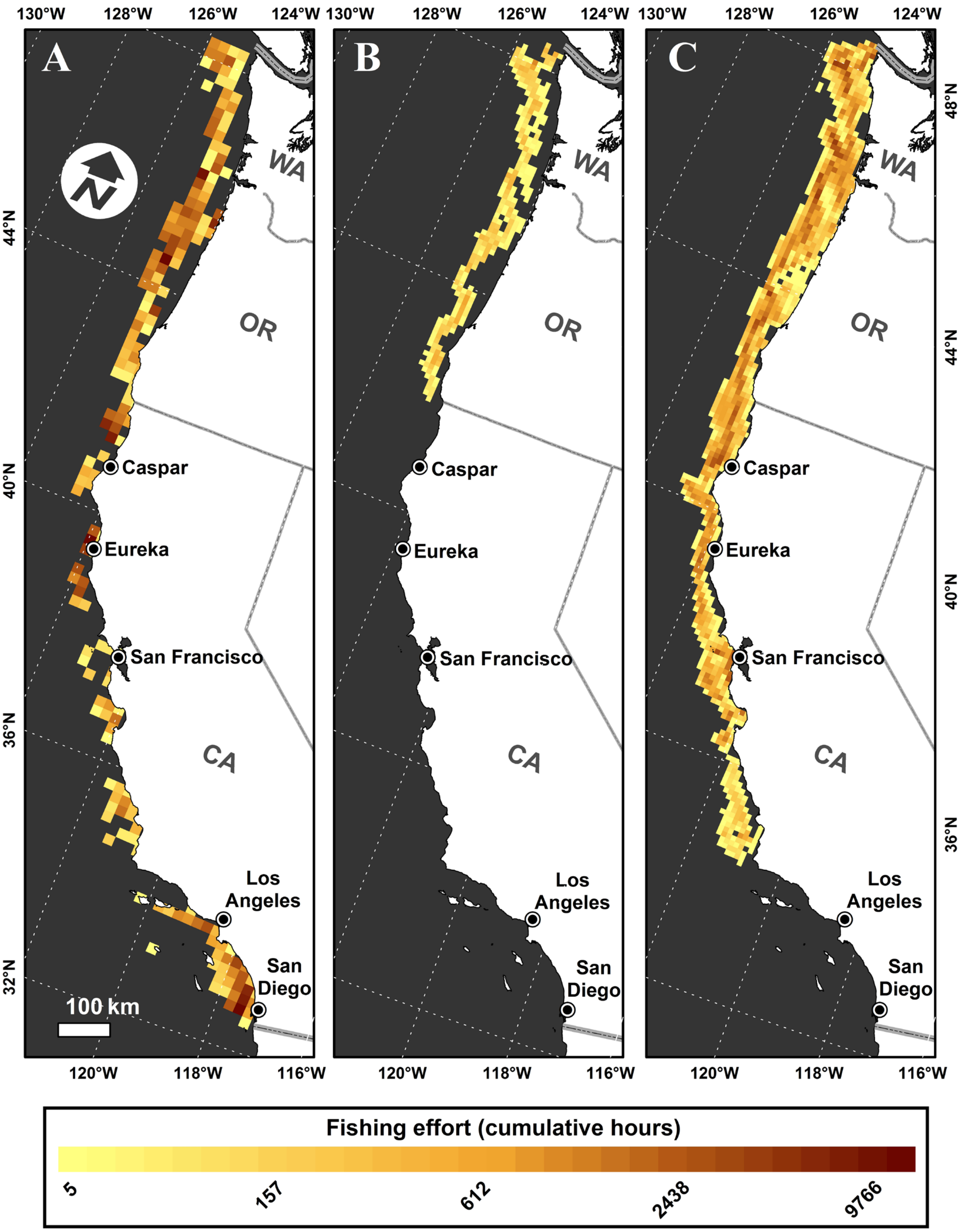

Figure 4

Patterns of commercial groundfish fishing effort along the U.S. west coast, expressed as the cumulative number of hours per grid cell during which fishing gear was deployed in the water, for all months in 2002–2009 for each of the following 3 fleets: (**A**) fixed-gear fleet, on a grid of 20 × 20 km, ~17% observer coverage; (**B**) hake mid-water trawl fleet, on a grid of 10 × 10 km, 100% observer coverage; and (**C**) bottom trawl fleet, on a grid of 10 × 10 km, 100% observer coverage.

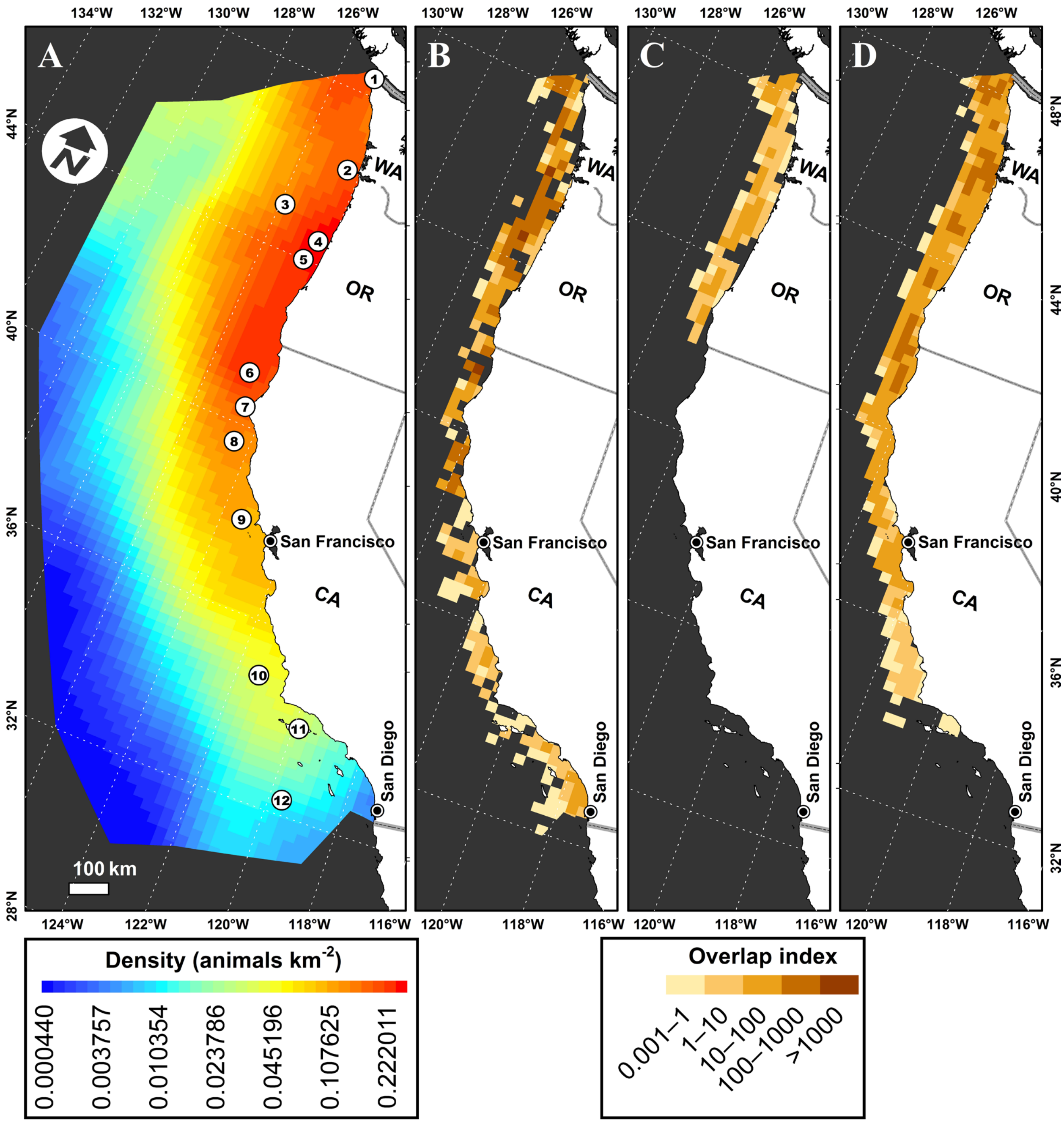

Figure 5

Maps of (**A**) modeled mean density of Dall's porpoise (*Phocoenoides dalli*), expressed as the number of individuals per square kilometer, off the U.S. west coast (on the basis of survey data collected during summer and fall in 1991–2005), and of overlap indices for this species and the (**B**) observed fixed-gear fleet, (**C**) hake mid-water trawl fleet, and (**D**) bottom trawl fleet. Numbers indicate geographic reference locations in the study area, which include 1) Cape Flattery, 2) Astoria Canyon, 3) Astoria Sea Channel, 4) Stonewall Bank, 5) Heceta Valley, 6) Trinidad Canyon, 7) Cape Mendocino, 8) Vizcaino Knoll, 9) Cordell Bank, 10) Santa Lucia Bank, 11) Channel Islands, and 12) Northeast Bank. Note that the density scales differ in Figures 5–16.

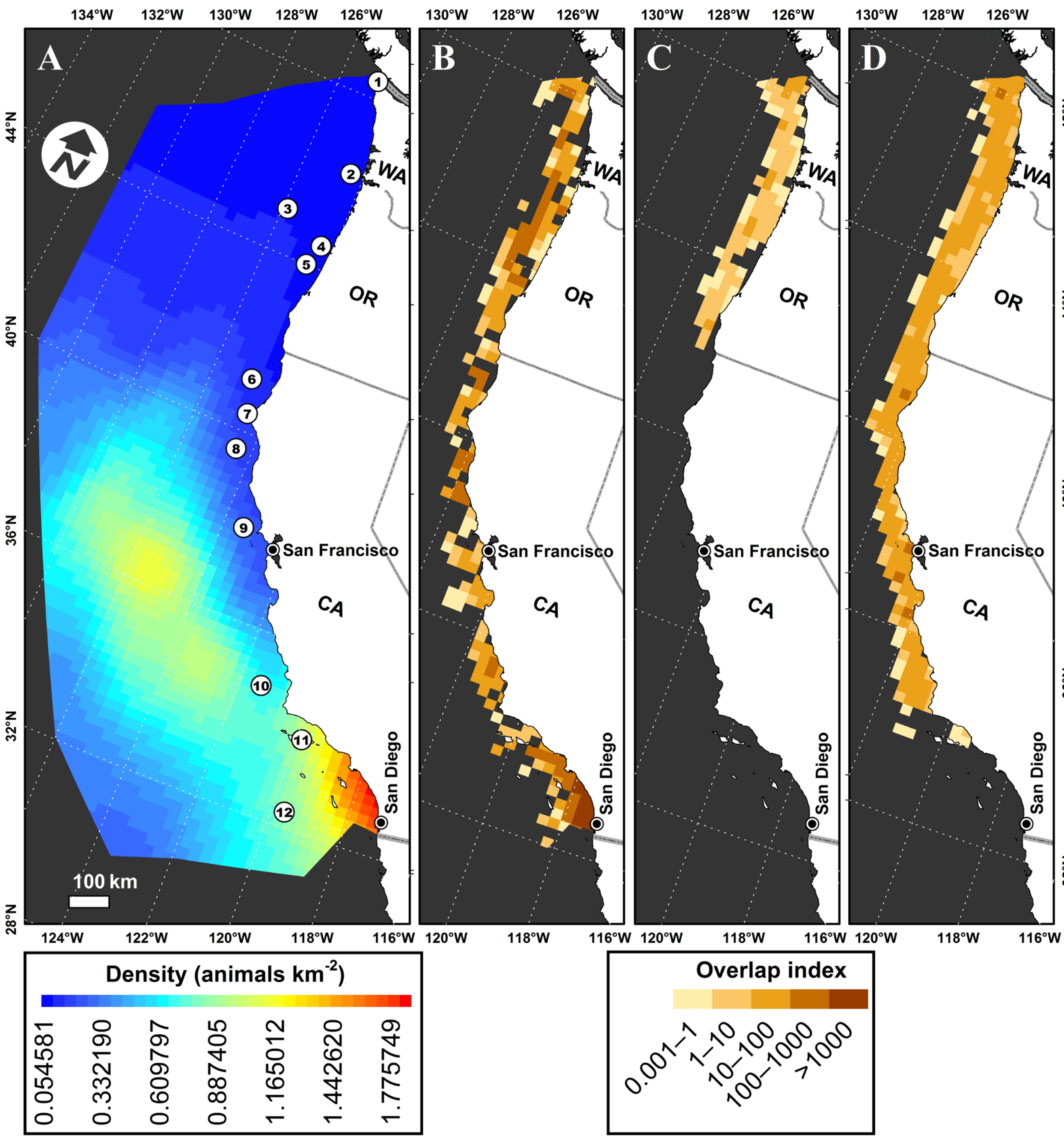

Figure 6

Maps of (**A**) modeled mean density of short-beaked common dolphins (*Delphinus delphis*), expressed as the number of individuals per square kilometer, off the U.S. west coast (on the basis of survey data collected during summer and fall in 1991–2005), and of overlap indices for this species and the (**B**) observed fixed-gear fleet, (**C**) hake mid-water trawl fleet, and (**D**) bottom trawl fleet. Numbers indicate geographic reference locations in the study area, which include 1) Cape Flattery, 2) Astoria Canyon, 3) Astoria Sea Channel, 4) Stonewall Bank, 5) Heceta Valley, 6) Trinidad Canyon, 7) Cape Mendocino, 8) Vizcaino Knoll, 9) Cordell Bank, 10) Santa Lucia Bank, 11) Channel Islands, and 12) Northeast Bank. Note that the density scales in Figures 5–16 differ.

consistently from Cape Flattery all the way south to Cape Mendocino, California (R_S>124; Fig. 5).

The short-beaked common dolphin overlapped the most with the fixed fleet from south of the Channel Islands, California, down to the U.S.–Mexico border (R_S>1076; Fig. 6). Overlap of this species with the hake fleet was greatest just southwest of Cape Flattery, Washington, near Astoria Canyon, Oregon, and east of the Astoria Sea Channel off Oregon (R_S>17; Fig. 6). Overlap indices with the trawl fleet were more evenly distributed over the entire fishing area than were the overlap indices for this dolphin with the fixed and hake fleets, with maximum overlap occurring just southwest of Cape Flattery, just north of Cape Mendocino, California, and off the coast of San Francisco (R_S>83; Fig. 6). Density predictions for this species ranged from very low to zero off the coasts of Oregon and Washington (Fig. 6A); therefore, overlap indices for this species with the hake and trawl fleets are very low overall.

Overlap of the Pacific white-sided dolphin with the observed fixed fleet occurred near Astoria Canyon and Stonewall Bank off Oregon and near Trinidad Canyon, California (R_S>289; Fig. 7). Overlap with the hake and trawl fleets was most pronounced for this species near Cape Flattery, Washington (R_S>28 and R_S>128, respectively; Fig. 7).

The overlap of the observed fixed fleet with Risso's dolphin was greatest near Astoria Canyon and Stonewall Bank off Oregon, just north of Cape Mendocino, California, and from the Northeast Bank, California, south to the U.S.–Mexico border (R_S>129; Fig. 8). Overlap with the hake fleet was greatest just southwest of Cape Flattery, Washington, and over the stretch from the Astoria Canyon south to Stonewall Bank (R_S>7; Fig. 8). Maximal overlap with the trawl fleet occurred over fairly large areas near Cape Flattery and in a fairly large area near Astoria Canyon (R_S>23; Fig. 8).

Maximum overlap between the northern right whale dolphin and the observed fixed fleet occurred near Astoria Canyon, Oregon, and Trinidad Canyon, California (R_S>115; Fig. 9). The hake fleet overlapped the most near Cape Flattery, Washington (R_S>9, Fig. 9), and trawl fleet efforts overlapped the most near Cape Flattery but had evenly distributed overlap all the way south to Cape Mendocino, California, and beyond (R_S>33; Fig. 9).

For the observed fixed fleet, peak areas of overlap with the humpback whale (R_S>17) occurred north of Cape Mendocino, California, off the central Oregon coast, and off Astoria Canyon, Oregon (Fig. 10). For the trawl fleet, the highest overlap indices with this species occurred along the northern portion of the coast from Cape Mendocino to Cape Flattery, Washington, with areas of overlap >3 (Fig. 10). The highest overlap indices for the hake fleet occurred near Cape Flattery and were <2 (Fig. 10).

The highest degree of spatial overlap for the blue whale with the fleets of the west coast groundfish fishery occurred with the observed fixed fleet, with some local overlap index values exceeding 20 near San Diego and just north of Cape Mendocino, California (Fig. 11). Overlap with the trawl fleet was much lower, with a few overlap indices that exceeded ~4 near Cape Mendocino and off of San Francisco Bay (Fig. 11). Overlap with the hake fleet was very limited, and it was <0.5 in all locations (Fig. 11).

The highest areas of spatial overlap for the fin whale with the fleets of the west coast groundfish fishery occurred from Astoria Canyon, Oregon, northward, with overlap indices for the observed fixed fleet >20 near Astoria Canyon and indices for the trawl fleet >3 along the Washington coast (Fig. 12). The highest overlap index with the hake fleet was <2, off the coast of northern Washington (Fig. 12).

Maximum overlap of the observed fixed fleet with the guild of small beaked whales occurred near Astoria Canyon and Stonewall Bank off Oregon, Trinidad Canyon and Vizcaino Knoll in California, and off the coast of San Diego (R_S>11; Fig. 13). Overlap indices were the highest for the fishing effort of the hake fleet that occurred near Cape Flattery off Washington, Astoria Canyon, and Stonewall Bank (R_S>0.6; Fig. 13). Finally, trawl fleet operations overlapped the most near Cape Flattery, Astoria Canyon, Stonewall Bank, Oregon's Heceta Valley, Trinidad Canyon, south of Cape Mendocino off California, and off the coast of San Francisco (R_S>2; Fig. 13). As was the case with the short-beaked common dolphin, density predictions for small beaked whales ranged from very low to zero off the coasts of Oregon and Washington (Fig. 13); therefore, overlap indices for this guild with the hake and trawl fleets were very low overall.

The observed fixed fleet overlapped the most (Fig. 14) with Baird's beaked whale (R_S>3.1) near Astoria Canyon and Stonewall Bank off Oregon and near Trinidad Canyon, California. Overlap with the hake fleet was considerably lower, with maxima occurring just southwest of Cape Flattery, Washington (R_S>0.239; Fig. 14). For the trawl fleet, overlap was generally higher in the northern two-thirds of the fishing grounds, with maxima occurring just southwest of Cape Flattery and north of Cape Mendocino, California (R_S>0.65; Fig. 14).

Overlap indices between the distribution of the sperm whale and the groundfish fisheries were generally lower compared with the overlap indices for other whales. For the observed fixed fleet, the maximum values were <6 and occurred in only a few places north of Cape Mendocino, California (Fig. 15). Overlap indices for the trawl fleet were fairly low and uniform from San Francisco to Cape Flattery, Washington, and generally <1 (Fig. 15). Overlap indices for the hake fleet were all <0.3 (Fig. 15).

The distribution of the striped dolphin overlapped most with the observed fixed fleet near Astoria Canyon and Stonewall Bank off Oregon and Trinidad Canyon, California, and over a fairly large area running south of Cape Mendocino down to just north of Cordell Bank off

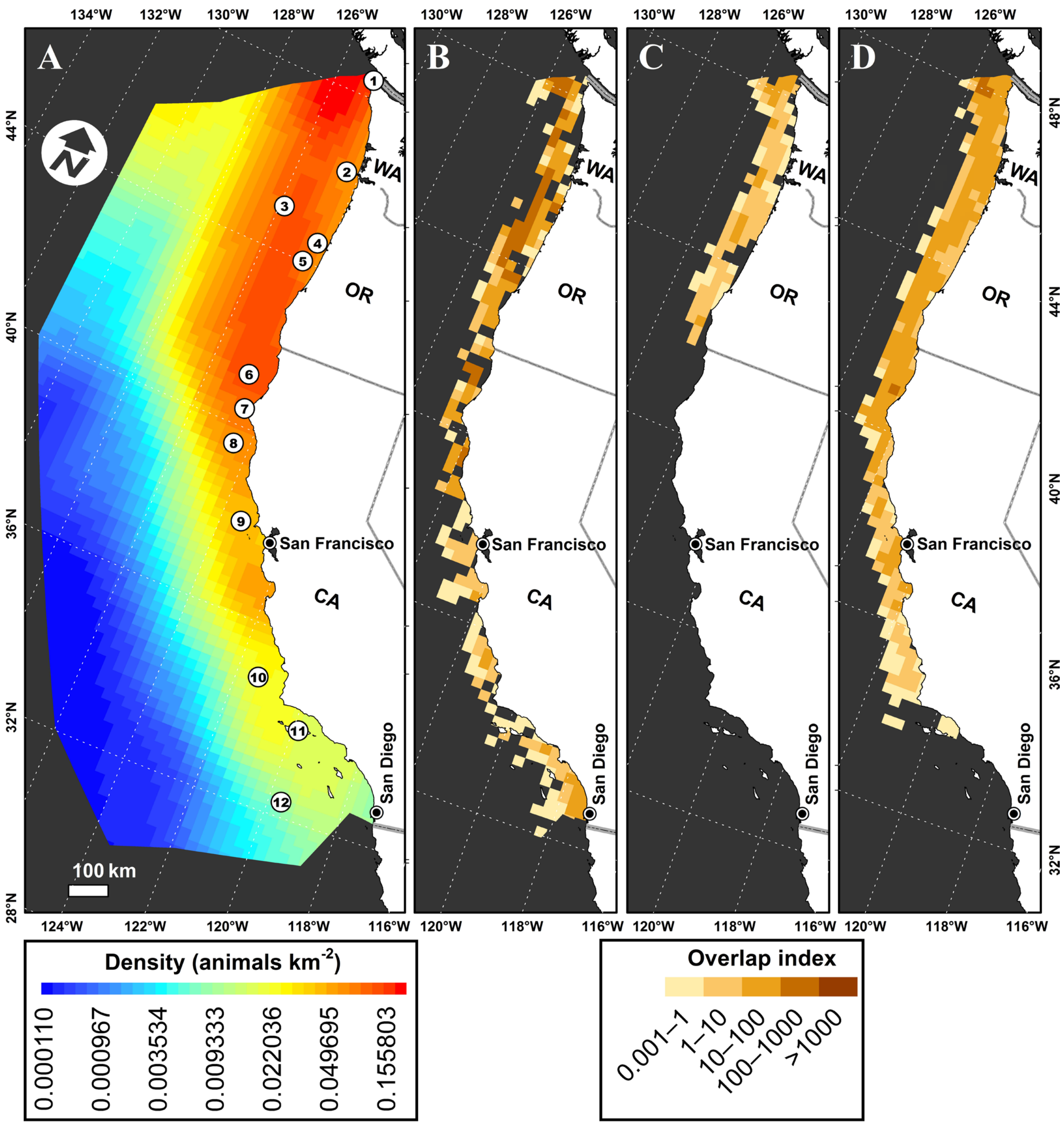

Figure 7

Maps of (**A**) modeled mean density of Pacific white sided dolphins (*Lagenorhynchus obliquidens*), expressed as the number of individuals per square kilometer, off the U.S. west coast (on the basis of survey data collected during summer and fall in 1991–2005), and of overlap indices for this species and the (**B**) observed fixed-gear fleet, (**C**) hake mid-water trawl fleet, and (**D**) bottom trawl fleet. Numbers indicate geographic reference locations in the study area, which include 1) Cape Flattery, 2) Astoria Canyon, 3) Astoria Sea Channel, 4) Stonewall Bank, 5) Heceta Valley, 6) Trinidad Canyon, 7) Cape Mendocino, 8) Vizcaino Knoll, 9) Cordell Bank, 10) Santa Lucia Bank, 11) Channel Islands, and 12) Northeast Bank. Note that the density scales in Figures 5–16 differ.

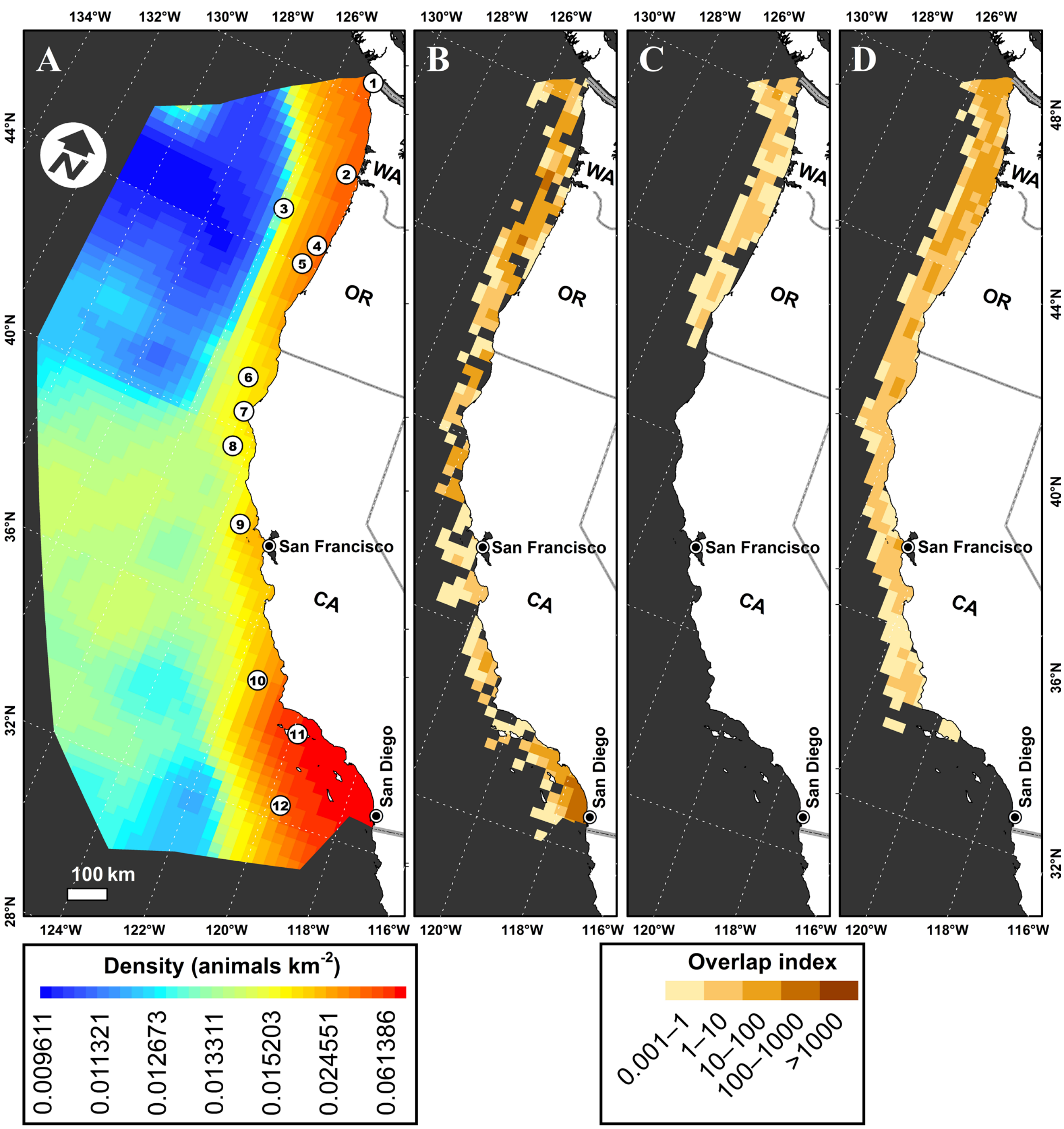

Figure 8

Maps of (**A**) modeled mean density of Risso's dolphins (*Grampus griseus*), expressed as the number of individuals per square kilometer, off the U.S. west coast (on the basis of survey data collected during summer and fall in 1991–2005), and of overlap indices for this species and the (**B**) observed fixed-gear fleet, (**C**) hake mid-water trawl fleet, and (**D**) bottom trawl fleet. Numbers indicate geographic reference locations in the study area, which include 1) Cape Flattery, 2) Astoria Canyon, 3) Astoria Sea Channel, 4) Stonewall Bank, 5) Heceta Valley, 6) Trinidad Canyon, 7) Cape Mendocino, 8) Vizcaino Knoll, 9) Cordell Bank, 10) Santa Lucia Bank, 11) Channel Islands, and 12) Northeast Bank. Note that the density scales in Figures 5–16 differ.

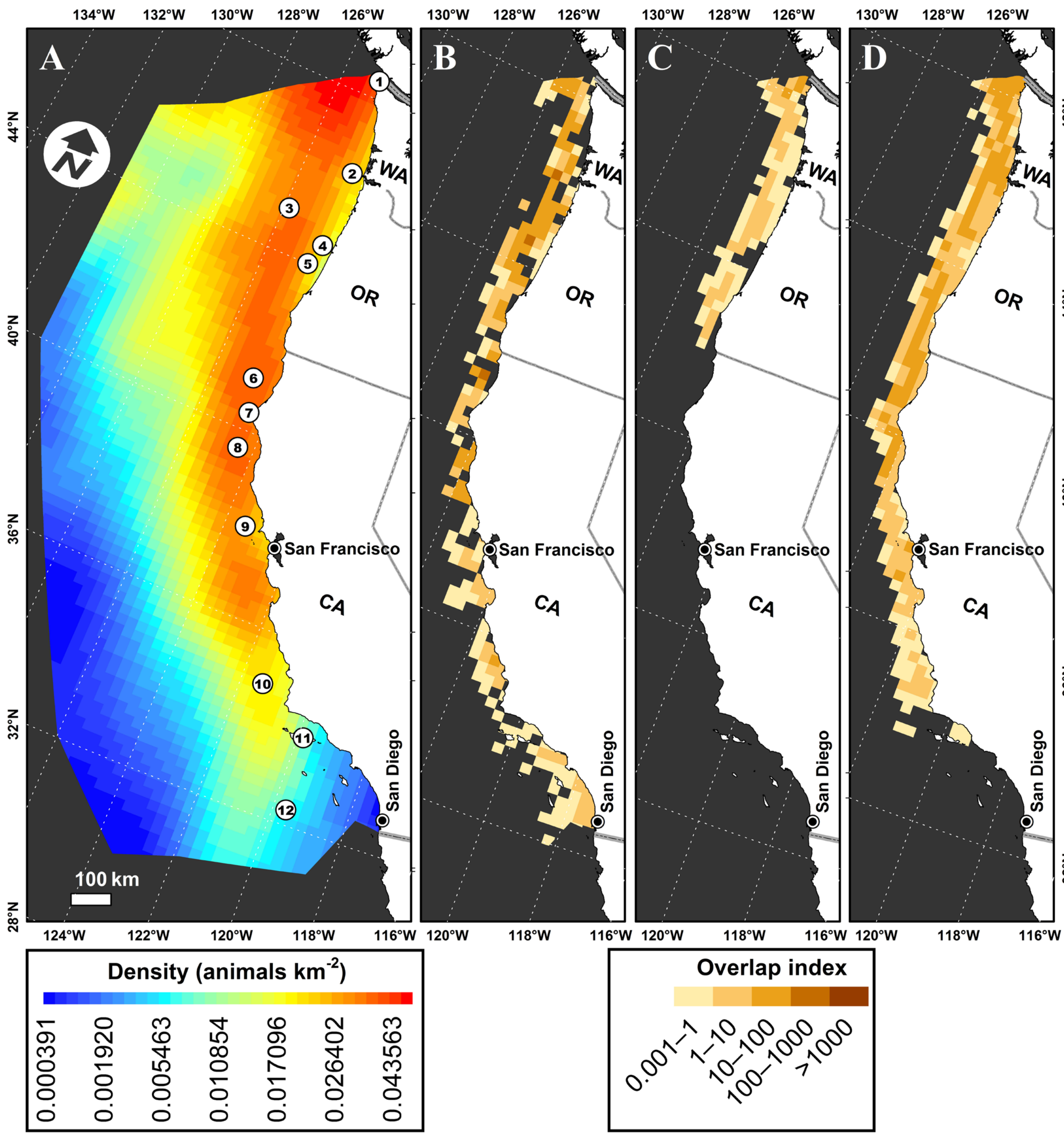

Figure 9

Maps of (**A**) modeled mean density of Northern right whale dolphins (*Lissodelphis borealis*), expressed as the number of individuals per square kilometer, off the U.S. west coast (on the basis of survey data collected during summer and fall in 1991–2005), and of overlap indices for this species and the (**B**) observed fixed-gear fleet, (**C**) hake mid-water trawl fleet, and (**D**) bottom trawl fleet. Numbers indicate geographic reference locations in the study area, which include 1) Cape Flattery, 2) Astoria Canyon, 3) Astoria Sea Channel, 4) Stonewall Bank, 5) Heceta Valley, 6) Trinidad Canyon, 7) Cape Mendocino, 8) Vizcaino Knoll, 9) Cordell Bank, 10) Santa Lucia Bank, 11) Channel Islands, and 12) Northeast Bank. Note that the density scales in Figures 5–16 differ.

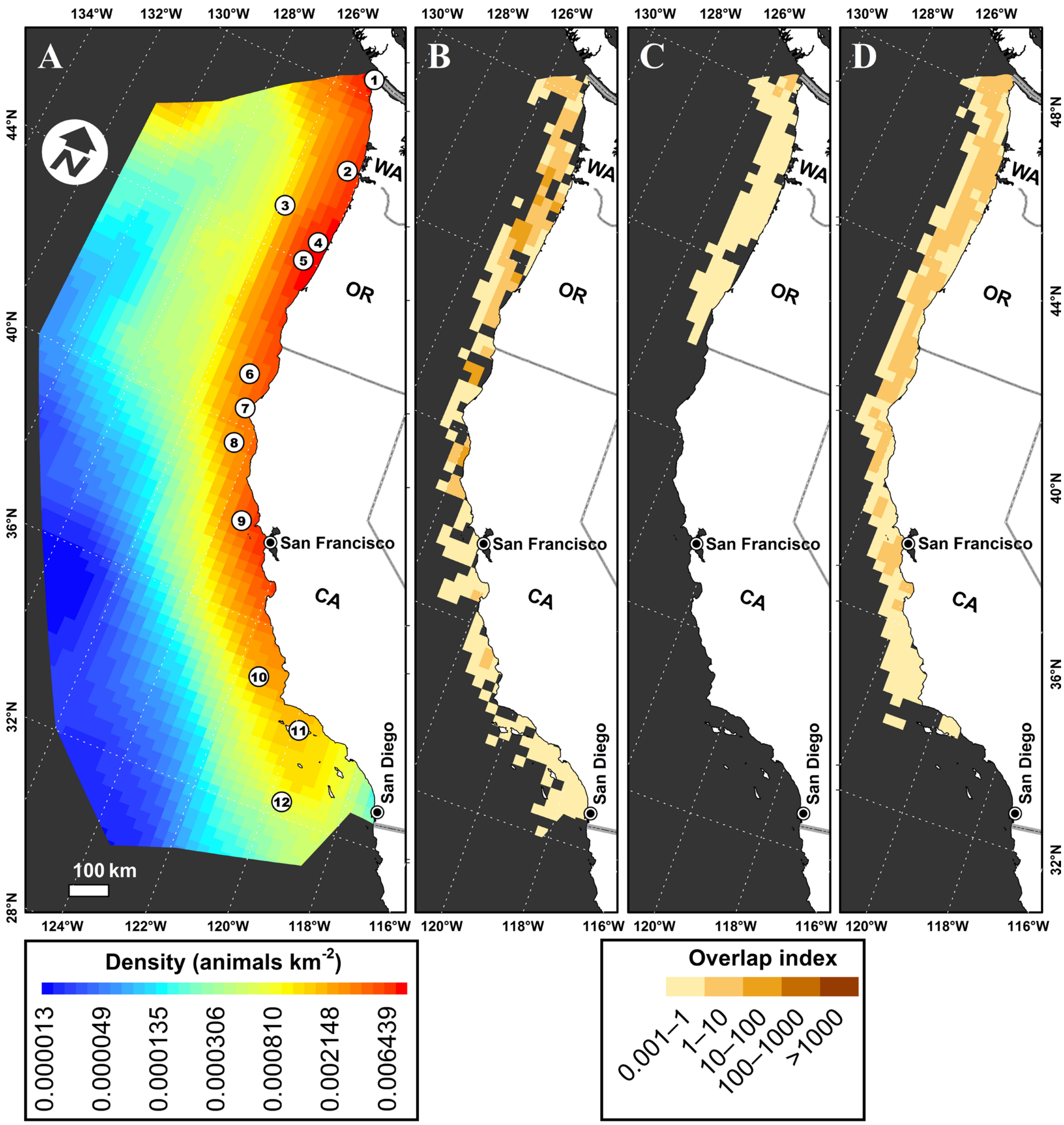

Figure 10

Maps of (**A**) modeled mean density of humpback whales (*Megaptera novaeangliae*), expressed as the number of individuals per square kilometer, off the U.S. west coast (on the basis of survey data collected during summer and fall in 1991–2005), and of overlap indices for this species and the (**B**) observed fixed-gear fleet, (**C**) hake mid-water trawl fleet, and (**D**) bottom trawl fleet. Numbers indicate geographic reference locations in the study area, which include 1) Cape Flattery, 2) Astoria Canyon, 3) Astoria Sea Channel, 4) Stonewall Bank, 5) Heceta Valley, 6) Trinidad Canyon, 7) Cape Mendocino, 8) Vizcaino Knoll, 9) Cordell Bank, 10) Santa Lucia Bank, 11) Channel Islands, and 12) Northeast Bank. Note that the density scales in Figures 5–16 differ.

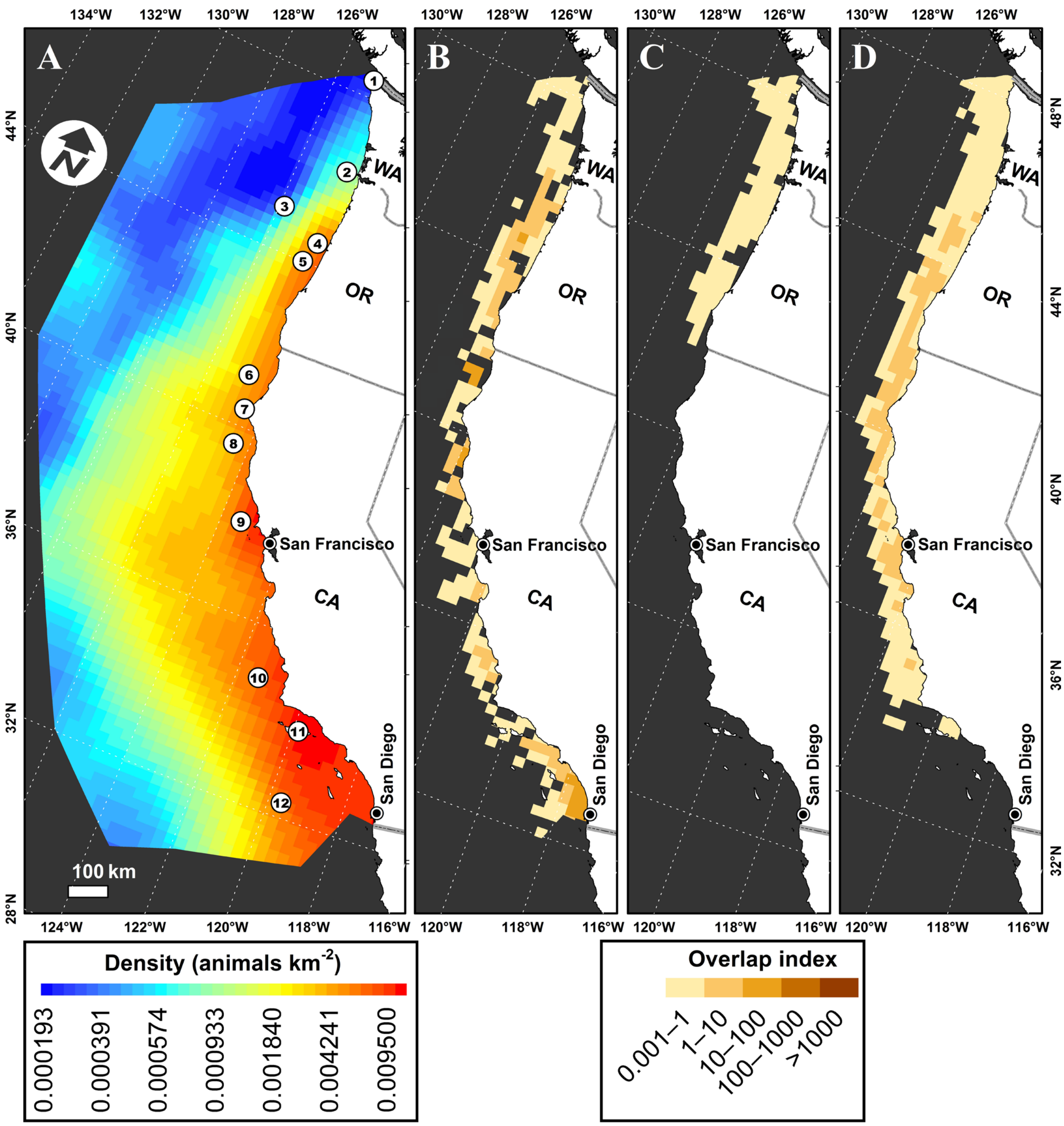

Figure 11

Maps of (**A**) modeled mean density of blue whales (*Balaenoptera musculus*), expressed as the number of individuals per square kilometer, off the U.S. west coast (on the basis of survey data collected during summer and fall in 1991–2005), and of overlap indices for this species and the (**B**) observed fixed-gear fleet, (**C**) hake mid-water trawl fleet, and (**D**) bottom trawl fleet. Numbers indicate geographic reference locations in the study area, which include 1) Cape Flattery, 2) Astoria Canyon, 3) Astoria Sea Channel, 4) Stonewall Bank, 5) Heceta Valley, 6) Trinidad Canyon, 7) Cape Mendocino, 8) Vizcaino Knoll, 9) Cordell Bank, 10) Santa Lucia Bank, 11) Channel Islands, and 12) Northeast Bank. Note that the density scales in Figures 5–16 differ.

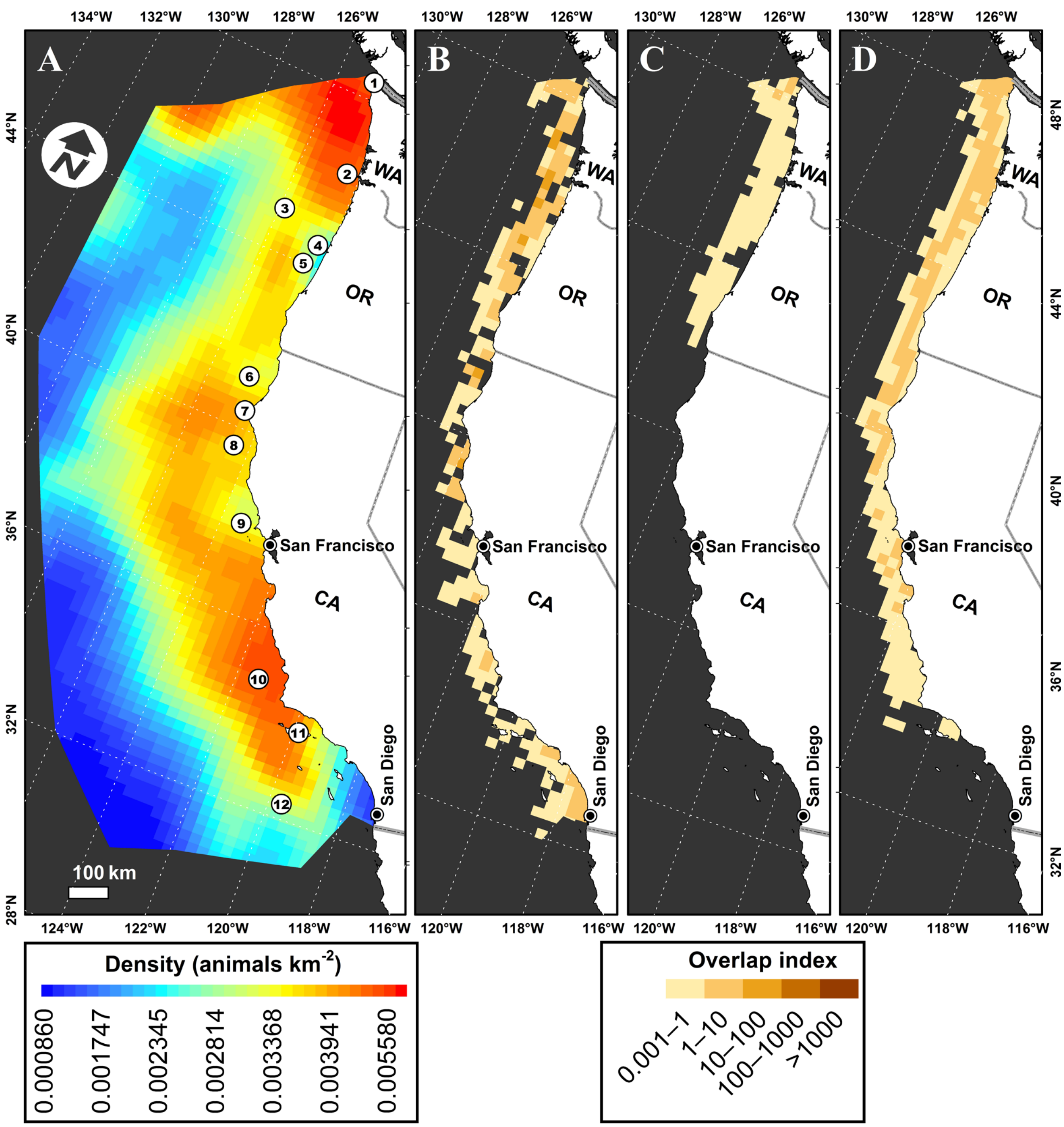

Figure 12

Maps of (**A**) modeled mean density of fin whales (*Balaenoptera physalus*), expressed as the number of individuals per square kilometer, off the U.S. west coast (on the basis of survey data collected during summer and fall in 1991–2005), and of overlap indices for this species and the (**B**) observed fixed-gear fleet, (**C**) hake mid-water trawl fleet, and (**D**) bottom trawl fleet. Numbers indicate geographic reference locations in the study area, which include 1) Cape Flattery, 2) Astoria Canyon, 3) Astoria Sea Channel, 4) Stonewall Bank, 5) Heceta Valley, 6) Trinidad Canyon, 7) Cape Mendocino, 8) Vizcaino Knoll, 9) Cordell Bank, 10) Santa Lucia Bank, 11) Channel Islands, and 12) Northeast Bank. Note that the density scales in Figures 5–16 differ.

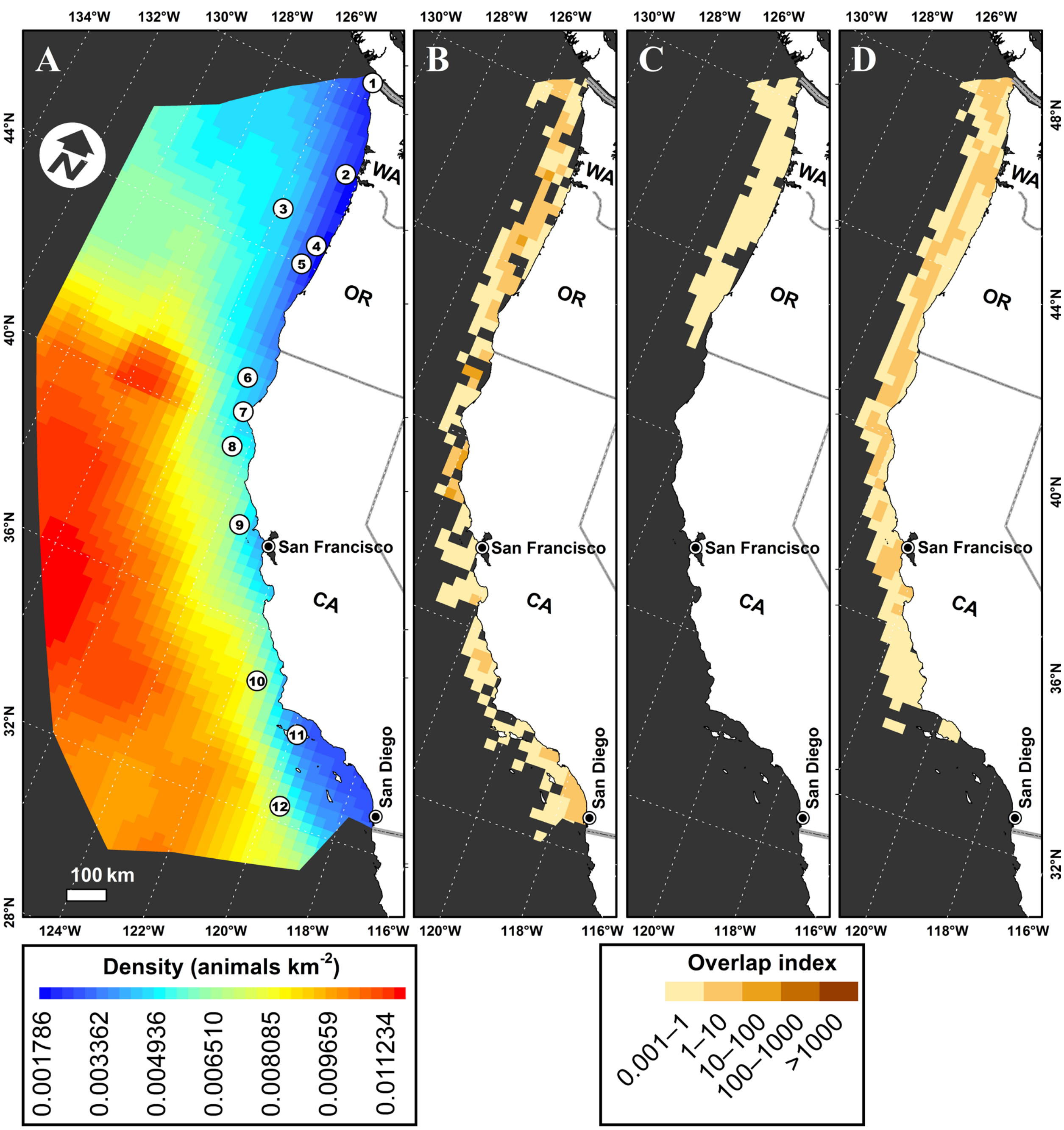

Figure 13

Maps of (**A**) modeled mean density of small beaked whales (*Ziphius* and *Mesoplodon*), expressed as the number of individuals per square kilometer, off the U.S. west coast (on the basis of survey data collected during summer and fall in 1991–2005), and of overlap indices for this species and the (**B**) observed fixed-gear fleet, (**C**) hake mid-water trawl fleet, and (**D**) bottom trawl fleet. Numbers indicate geographic reference locations in the study area, which include 1) Cape Flattery, 2) Astoria Canyon, 3) Astoria Sea Channel, 4) Stonewall Bank, 5) Heceta Valley, 6) Trinidad Canyon, 7) Cape Mendocino, 8) Vizcaino Knoll, 9) Cordell Bank, 10) Santa Lucia Bank, 11) Channel Islands, and 12) Northeast Bank. Note that the density scales in Figures 5–16 differ.

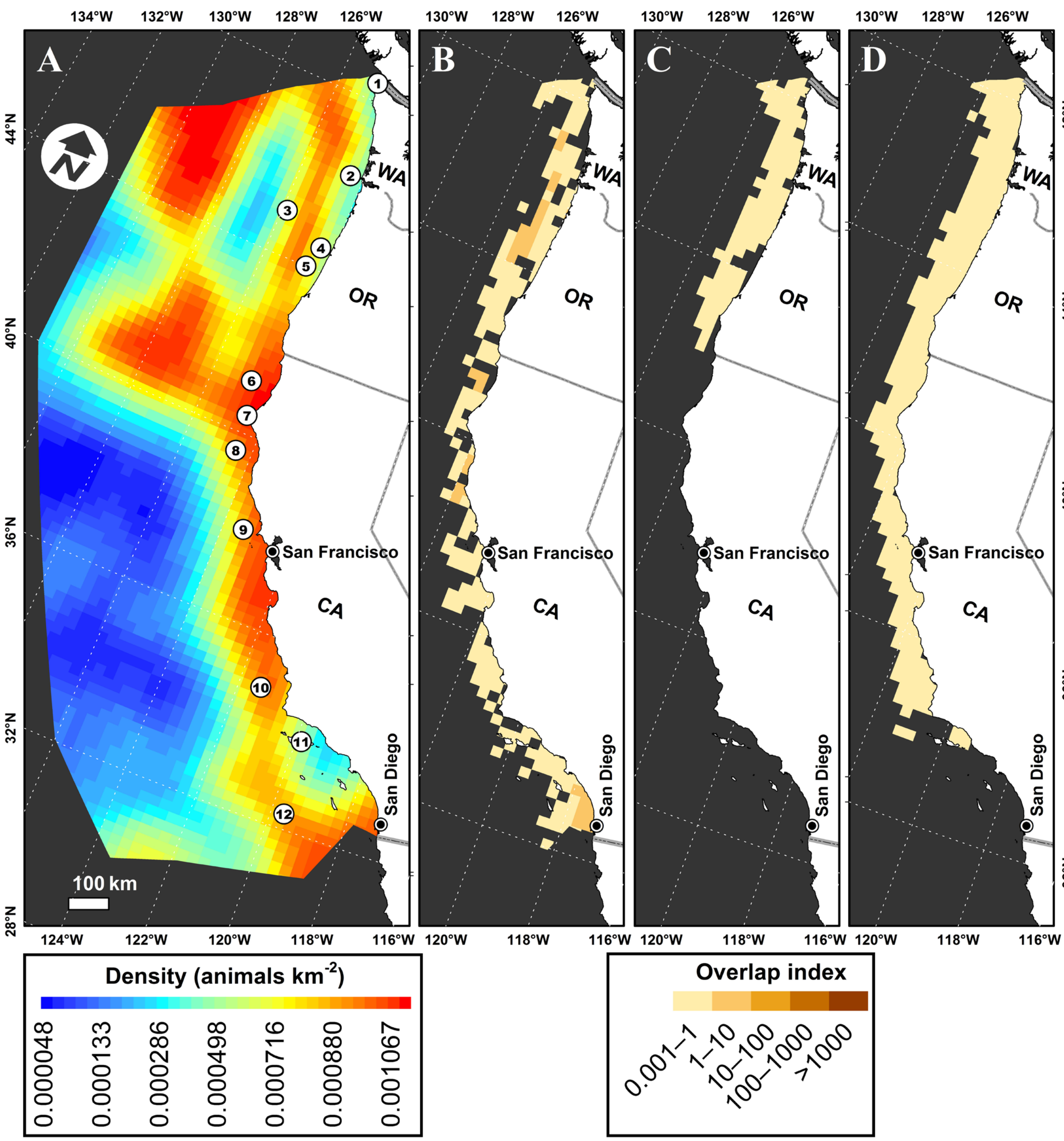

Figure 14

Maps of (**A**) modeled mean density of Baird's beaked whales (*Berardius bairdii*), expressed as the number of individuals per square kilometer, off the U.S. west coast (on the basis of survey data collected during summer and fall in 1991–2005), and of overlap indices for this species and the (**B**) observed fixed-gear fleet, (**C**) hake mid-water trawl fleet, and (**D**) bottom trawl fleet. Numbers indicate geographic reference locations in the study area, which include 1) Cape Flattery, 2) Astoria Canyon, 3) Astoria Sea Channel, 4) Stonewall Bank, 5) Heceta Valley, 6) Trinidad Canyon, 7) Cape Mendocino, 8) Vizcaino Knoll, 9) Cordell Bank, 10) Santa Lucia Bank, 11) Channel Islands, and 12) Northeast Bank. Note that the density scales in Figures 5–16 differ.

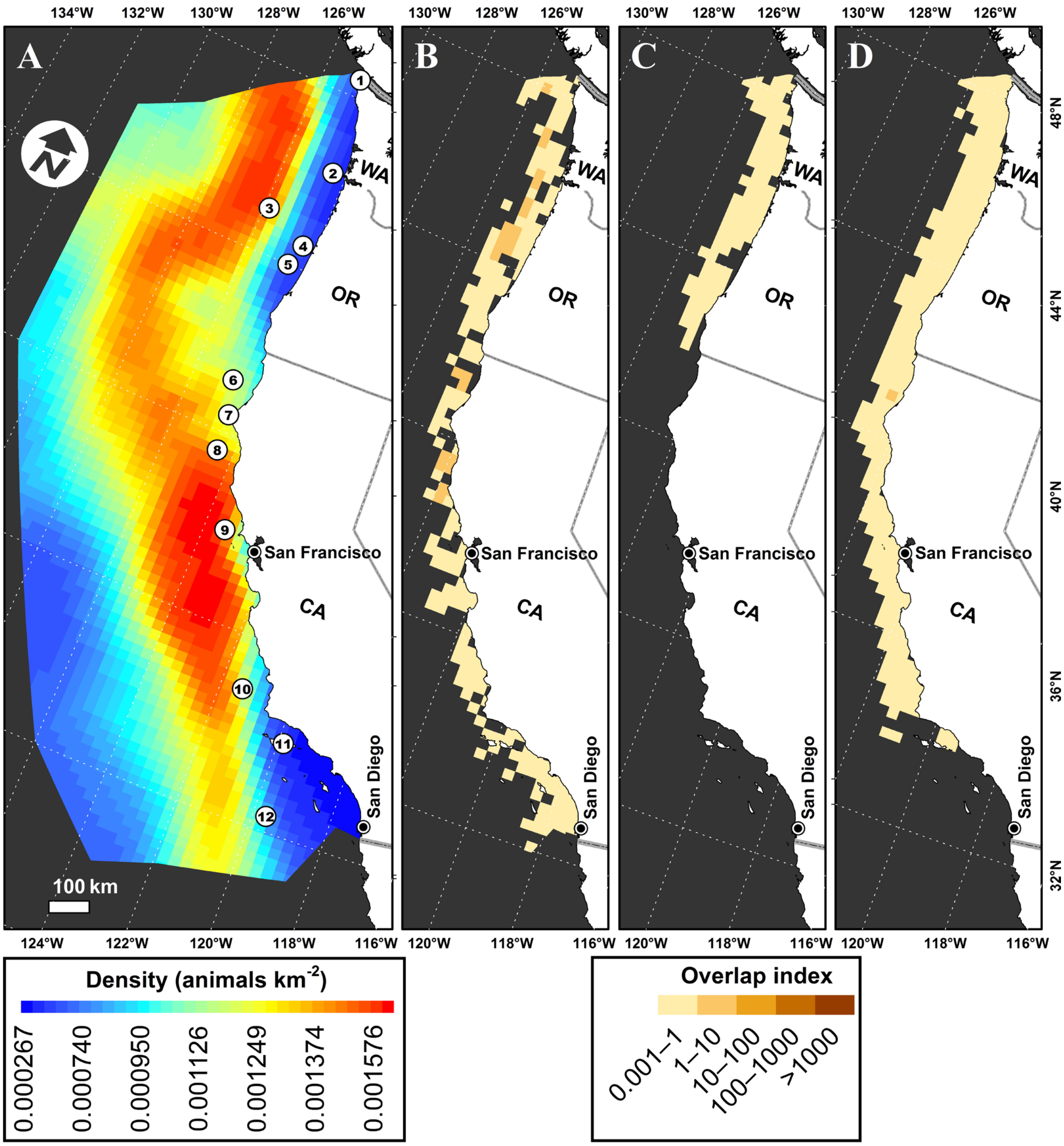

Figure 15

Maps of (**A**) modeled mean density of sperm whales (*Physeter macrocephalus*), expressed as the number of individuals per square kilometer, off the U.S. west coast (on the basis of survey data collected during summer and fall in 1991–2005), and of overlap indices for this species and the (**B**) observed fixed-gear fleet, (**C**) hake mid-water trawl fleet, and (**D**) bottom trawl fleet. Numbers indicate geographic reference locations in the study area, which include 1) Cape Flattery, 2) Astoria Canyon, 3) Astoria Sea Channel, 4) Stonewall Bank, 5) Heceta Valley, 6) Trinidad Canyon, 7) Cape Mendocino, 8) Vizcaino Knoll, 9) Cordell Bank, 10) Santa Lucia Bank, 11) Channel Islands, and 12) Northeast Bank. Note that the density scales in Figures 5–16 differ.

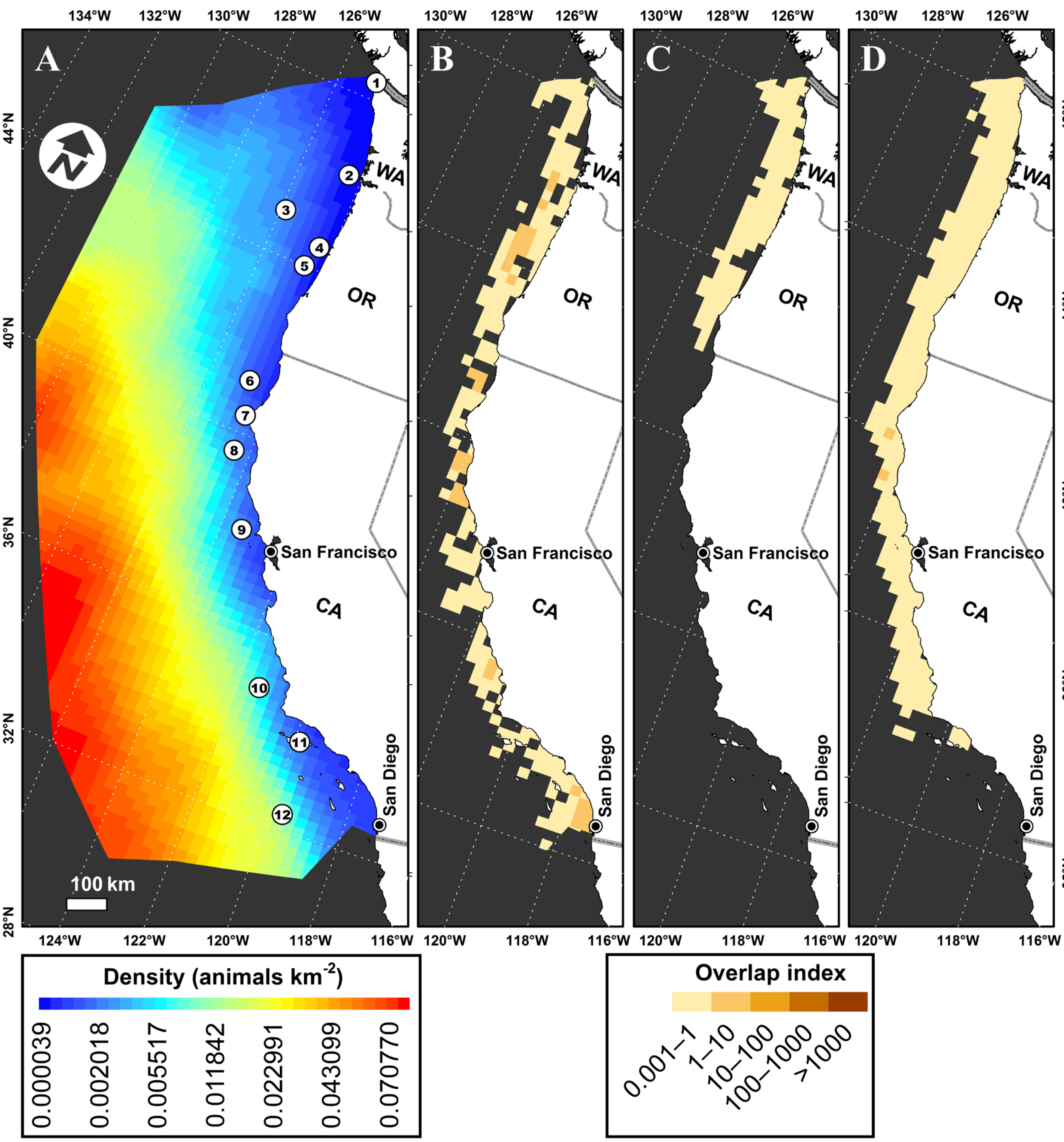

Figure 16

Maps of (**A**) modeled mean density of striped dolphins (*Stenella coeruleoalba*), expressed as the number of individuals per square kilometer, off the U.S. west coast (on the basis of survey data collected during summer and fall in 1991–2005), and of overlap indices for this species and the (**B**) observed fixed-gear fleet, (**C**) hake mid-water trawl fleet, and (**D**) bottom trawl fleet. Numbers indicate geographic reference locations in the study area, which include 1) Cape Flattery, 2) Astoria Canyon, 3) Astoria Sea Channel, 4) Stonewall Bank, 5) Heceta Valley, 6) Trinidad Canyon, 7) Cape Mendocino, 8) Vizcaino Knoll, 9) Cordell Bank, 10) Santa Lucia Bank, 11) Channel Islands, and 12) Northeast Bank. Note that the density scales in Figures 5-16 differ.

the coast of California (R_S>3; Fig. 16). In contrast, overlap with the hake fleet was concentrated over a fairly large area from Astoria Canyon, south to the border of Oregon and California (R_S>0.06; Fig. 16). Overlap with the trawl fleet was also fairly homogeneous and was consistently high from latitude 45° N south to Santa Lucia Bank, California (R_S>0.7, Fig. 16). Because density predictions for this species ranged from very low to zero off the coasts of Oregon and Washington (Fig. 16A), overlap indices with the hake and trawl fleets were very low, overall.

Population overlap index

Variability was considerable in the proportion of each modeled cetacean population that overlapped with the 3 fleet types for the period 2002–2009 (Fig. 17A). Overall, the humpback whale, Dall's porpoise, and Pacific white-sided dolphin had the greatest proportions of their populations that overlapped with each of the 3 fleets. The population overlap index generally was highest for the observed trawl fleet but not always (e.g., short-beaked common and Risso's dolphin; Fig. 17A).

Cumulative overlap index

The patterns of the cumulative overlap index were different from the population overlap index (Fig. 17B). The cumulative overlap index provides a measure of overlap between a population of a given species relative to the total fishing effort of each fleet. Overall, the short-beaked common dolphin, Dall's porpoise, and Pacific white-sided dolphin had the greatest cumulative overlap indices with each of the 3 fleets. The largest cumulative overlap indices occurred in the observed fixed fleet, and these indices were about 40 times and 2.5 times the cumulative overlap indices of the hake and trawl fleets, respectively. The striped dolphin, Baird's beaked whale, and sperm whale had the lowest cumulative overlap index (Fig. 17B). Within each of the 3 fleets, there was considerable variability in the cumulative overlap indices, with dolphins and porpoises experiencing the highest cumulative overlap indices, although large whales had the lowest cumulative overlap indices (Fig. 17B).

Population-weighted cumulative overlap index

Weighting the population overlap index with the cumulative overlap index accounted for the wide range of total modeled population size, cetacean density, and fishing effort. Although the weightings reduced the magnitude of interspecific differences of exposure, they did not appreciably alter the overall ranking of overlap (Fig. 17C). There were marked differences in the population-weighted cumulative overlap indices of the different cetacean species, but the magnitude in the differences changed (Fig. 17C). For example, the population-weighted cumulative overlap index for the short-beaked common dolphin with the fixed fleet was 115 times that with the hake fleet and more than 6 times that with the trawl fleet. The population-weighted cumulative overlap index for the fixed fleet was 3 orders of magnitude greater than the index for the hake fleet and more than 12 times the index of the trawl fleet.

Discussion

Overall, it is clear that in the California Current commercial fishing overlaps with the 11 cetacean species and 1 species guild included in our analyses. There were pronounced inter-fleet and interspecific differences in overlap, but the distribution of fishing effort varied over time. Our results indicate that some cetaceans have significantly more exposure to fishing gear than do others.

Although most of the cetacean populations in this study are increasing (Carretta et al., 2011) and direct population impacts that result from bycatch and vessel collisions are minimal (Jannot et al.[1]), indirect impacts, such as physical disturbance to benthic habitats and exploitative competition, may nonetheless pose threats to the various cetacean populations in the CCLME. Spatially explicit overlap analyses facilitate quantitative measures of population-level risk once the magnitude of those risks has been quantified and are useful to resource managers who need to know when and where potential risks to cetaceans occur. The methods we have employed could easily be used in other systems where risks from commercial fishing are a concern.

Impacts from commercial fisheries on cetaceans can be direct (or "operational," as described by Beverton [1985]) or indirect from trophic effects. In our study, we focused on direct effects. The greatest source of direct impacts is bycatch (Lien, 1994; Read et al., 2006; Reeves et al., 2003; Young and Ludicello, 2007), although impacts can also occur through vessel collisions (Panigada et al., 2006), stress (Curry, 1999; Fair and Becker, 2000), noise (National Research Council, 2003; Nowacek et al., 2007; Romano et al., 2004), and toxins, such as hydrocarbons and exhaust (Jarman et al., 1996; Marsili et al., 2001).

Although bycatch is often the single greatest deleterious direct impact of commercial fishing on cetaceans, the severity of this impact varies among geographic regions. In the California Current, in 2002–2009, observers documented 5 cases of cetacean bycatch across the 3 fleets examined in our study (Jannot et al.[1]). Each of these cases involved a single individual, and each individual was a different species of cetacean. Three were species included in our analyses: Pacific white-sided dolphin, Risso's dolphin, and sperm whale. The other 2 bycatch events were of a single bottlenose dolphin (*Tursiops truncatus*) and a single harbor porpoise (*Phocoena phocoena*). The cetacean modeling data we used did not include density

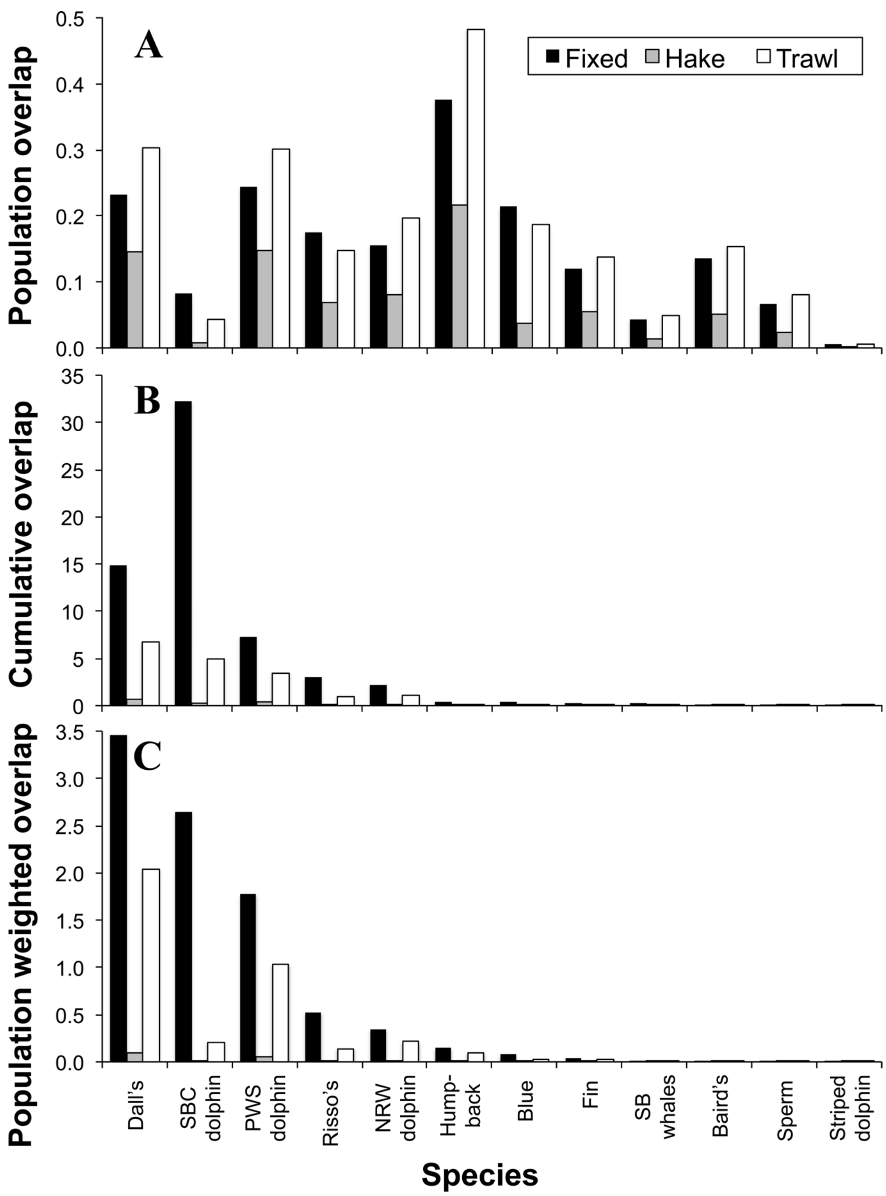

Figure 17

For each of 11 cetacean species and 1 species guild, (**A**) population overlap index, (**B**) cumulative overlap index, and (**C**) population-weighted overlap index of each population within the entire modeled area that overlapped with each of the fishing effort of 3 commercial fishing fleets, the fixed-gear, at-sea hake mid-water trawl, and bottom trawl fleets, off the U.S. west coast in 2002–2009. Overlap indexes were produced for the Dall's porpoise (*Phocoenoides dalli*), short-beaked common (SBC) dolphin (*Delphinus delphis*), Pacific white-sided (PWS) dolphin (*Lagenorhynchus obliquidens*), Risso's dolphin (*Grampus griseus*), northern right whale (NRW) dolphin (*Lissodelphis borealis*), humpback whale (*Megaptera novaeangliae*), blue whale (*Balaenoptera musculus*), fin whale (*B. physalus*), Baird's beaked whale (*Berardius bairdii*), sperm whale (*Physeter macrocephalus*), striped dolphin (*Stenella coeruleoalba*), and a guild of small beaked (SB) whales. Note that the proportions displayed by the bars in panel A could not be summed because there was overlap between the different fleet types.

predictions for these latter 2 species; therefore, we were unable to run spatial overlays accordingly. On the basis of the high levels of observer coverage, the 3 fishing fleets considered in our analyses do not appear to pose a significant bycatch threat to the cetaceans with which they overlap.

Vessel collisions can pose a serious threat to some cetaceans, especially larger whales (Laist et al., 2001). Overall, fishing vessels account for approximately 3% of all cetacean collisions (Jensen and Silber, 2003), with vessel speed and size as major factors in vessel collisions; vessels traveling in excess of 14 kn or more than 80 m in length are most likely to cause serious injury or mortality (Jensen and Silber, 2003; Laist et al., 2001). Consequently, because of the relatively small size (average ~19 m in length [Jannot et al.[1]]) and slow speeds (typical fishing speeds of 2–5 kn) of fishing vessels in the CCLME, it is unlikely that collisions with fishing vessels are a significant threat to cetaceans in this region. Indeed, collisions with vessels in the commercial groundfish fishery of the U.S. west coast are rarely observed—between 2002 and 2009 there was only one reported collision, between a sperm whale and a non-nearshore fixed-gear vessel (targeting sablefish) (Jannot et al.[1]). Although reported collisions with large cetaceans are rare, it is important to note that most components of the open access fixed fleets have very low observer coverage (Table 2), and if collisions occur when observers are not present, they may not be reported.

Entanglement with a variety of fishing gear can be fatal for many cetaceans, but it may also leave animals in a compromised condition where feeding, mating, or abilities for predator avoidance are diminished (Moore et al., 2007). Pot and gillnet gear account for the vast majority of fishing-gear entanglements of North Atlantic right and humpback whales in the western North Atlantic, although many other types of gear have been implicated (Johnson et al., 2005). Larger cetacean species are less likely to be captured as bycatch but are more likely to become entangled in actively fished or derelict gear (Laist, 1997; Read et al., 2006; Read, 2008). For example, among U.S. Pacific cetaceans that are monitored, the humpback whale has the highest rate of entanglement-related incidents, predicted at approximately 3.2 animals per year (Carretta et al., 2011), that are associated with trap and pot fishery gear in the CCLME. This rate is well below the predicted potential biological removal rate of 11.3 animals per year. The potential biological removal rate is defined in the Marine Mammal Protection Act as "the maximum number of animals, not including natural mortalities, that may be removed from a marine mammal stock while allowing that stock to reach or maintain its optimum sustainable population."

These entanglement data, however, are opportunistic and not based on observer data; therefore, they likely underestimate entanglements. Further, reports of dead or stranded cetaceans in the western North Atlantic with trailing fishing gear or scarring associated with fishing gear (Johnson et al., 2005) lend caution to the conclusion that unobserved mortality equates to no mortality. Nevertheless, the estimated annual population growth rate between 1991 and 2009 for the North Pacific stock of the humpback whale was between 7% and 8% (Carretta et al., 2011), a finding that indicates that the impacts of commercial fishing fleets are not large enough to prevent recovery of this species.

During the years for which we analyzed data, fishing fleets operated under a bimonthly system for landings limit management, in which any given vessel was given a landings limit every 2 months. However, in 2011 management of the trawl and hake fleets moved to a catch share system. The move to catch shares may have substantial effects on the level of exposure of cetaceans to groundfish vessels and gears because there are incentives to move from trawls to fixed gear (to reduce bycatch associated with trawling [Kaplan et al., 2010]). An increasing concentration of fixed gear in regions of high whale density could have unintended negative effects. Because bycatch of depleted species has constrained fishing on more abundant species (Hilborn et al., 2004), the reduction of bycatch associated with catch shares may increase the time and area that is currently fished (Kaplan et al., 2010), potentially having negative effects on whales. Finally, under catch shares, fishers can choose when to catch their quota, thereby allowing individuals to distribute their effort over longer time periods. Again, this potential expansion of the temporal window of fishing effort may change the exposure of cetaceans to fisheries activities. Regardless of exactly how fisheries effort changes, it is clear that it is a time of flux for the west coast groundfish fishery, and these changes have implications for the risks to cetaceans posed by these fleets.

An important caveat of our analysis is that we did not consider the impacts of gillnet fleets, because we focused solely on groundfish fleets which did not include gillnetters. Gill nets can present a significant risk to cetaceans (Read et al., 2006); however, the primary type of gill net used along the U.S. west coast that can catch cetaceans must now be deployed with pingers that alert cetacean species to the presence of the net, reducing mortality associated with gillnet gear (Barlow and Cameron, 2003).

Importantly, exposure to fishing gear alone cannot be used as an estimate of the direct risk experienced by cetaceans from fisheries (Samhouri and Levin, 2012). Rather, this risk is a product of both their exposure to gear and the consequence of coming into contact with the gear. In this study, for the first time, we quantified the relative level of exposure of whales to gear deployed by 3 fishing fleets in the CCLME; however, we did not quantify the potential consequences of this exposure. Nonetheless, these analyses that quantify exposure compose an important first step in characterization of the potential risk to cetaceans from commercial fishing fleets in the CCLME.

Given our incomplete understanding of the risks imposed by the groundfish fleets, especially indirect ones, running more comprehensive risk assessments for cetaceans in the CCLME becomes problematic. However, adopting the methodologies developed by Samhouri and Levin (2012) would facilitate a more quantitative and comprehensive risk assessment. Their approach calculates relative risk as a function of various "drivers and pressures" or stressors, accounts for data quality, and can incorporate disparate types of quantitative data. Applying this robust approach would be a next step for cetacean risk assessments in the CCLME and could incorporate risk from other threats that are not from the groundfish fishery. Finally, studies directed at quantifying the risks of threats not considered in our assessment would be beneficial to improve our ability to thoroughly assess the risks to cetaceans posed by various anthropogenic stressors found in the CCLME.

Acknowledgments

We thank J. Samhouri for significantly improving the quality of this manuscript. M. Sheer assisted with database manipulations of the groundfish fishery data. We also wish to thank the Fishery Resource Analysis and Monitoring Division at the NWFSC for collecting and processing the data on commercial fishing effort that we used. We dedicate this paper to the memory of West Coast Groundfish Observer Program observer Christopher Langel, who perished aboard the *Lady Cecelia*, which was lost at sea on 10 March 2012.

Literature cited

Barlow, J., and G. A. Cameron.
2003. Field experiments show that acoustic pingers reduce marine mammal bycatch in the California drift gill net fishery. Mar. Mamm. Sci. 19:265–283. doi: 10.1111/j.1748-7692.2003.tb01108.x.

Barlow, J., M. C. Ferguson, E. A. Becker, J. V. Redfern, K. A. Forney, I. L. Vilchis, P. C. Fiedler, T. Gerrodette, and L. T. Ballance.
2009. Predictive modeling of cetacean densities in the eastern Pacific Ocean. NOAA Tech. Memo. NMFS-SWFSC-444, 206 p.

Bearzi, G., E. Politi, and G. Notarbartolo di Sciara.
1999. Diurnal behavior of free-ranging bottlenose dolphins in the Kvarnerić (Northern Adriatic Sea). Mar. Mamm. Sci. 15:1065–1097. doi: 10.1111/j.1748-7692.1999.tb00878.x.

Beverton, R. J. H.
1985. Analysis of marine mammal–fisheries interactions. *In* Marine mammals and fisheries (J. R. Beddington, R. J. H. Beverton, and D. M. Lavigne, eds.), p. 3–33. George Allen & Unwin, London, UK.

Burgman, M.
2005. Risks and decisions for conservation and environmental management, 488 p. Cambridge Univ. Press, Cambridge, UK.

Carretta, J. V., T. Price, D. Petersen, and R. Read.
2004. Estimates of marine mammal, sea turtle, and seabird mortality in the California drift gillnet fishery for swordfish and thresher shark, 1996–2002. Mar. Fish. Rev. 66(2):21–30.

Carretta, J. V., K. A. Forney, E. Oleson, K. Martien, M. M. Muto, M. S. Lowry, J. Barlow, J. Baker, B. Hanson, D. Lynch, L. Carswell, R. L. Brownell, Jr., J. Robbins, D. K. Mattila, K. Ralls, and M. C. Hill.
2011. U.S. Pacific marine mammal stock assessments: 2010. NOAA Tech. Memo. NMFS-SWFSC-476, 352 p.

Clapham, P. J., S. B. Young, and R. L. Brownell, Jr.
1999. Baleen whales: conservation issues and the status of the most endangered populations. Mamm. Rev. 29:35–60. doi: 10.1046/j.1365-2907.1999.00035.x.

Curry, B. E.
1999. Stress in mammals: the potential influence of fishery-induced stress on dolphins in the eastern tropical Pacific Ocean. NOAA Tech. Memo. NMFS-SWFSC-260, 121 p.

Davidson, A. D., A. G. Boyer, H. Kim, S. Pompa-Mansilla, M. J. Hamilton, D. P. Costa, G. Ceballos, and J. H. Brown.
2012. Drivers and hotspots of extinction risk in marine mammals. Proc. Natl. Acad. Sci. USA 109:3395–3400. doi: 10.1073/pnas.1121469109.

DeMaster, D. P., C. W. Fowler, S. L. Perry, and M. F. Richlen.
2001. Predation and competition: the impact of fisheries on marine-mammal populations over the next one hundred years. J. Mammal. 82:641–651.

DeMaster, D. P., A. W. Trites, P. Clapham, S. Mizroch, P. Wade, R. J. Small, and J. Ver Hoef.
2006. The sequential megafaunal collapse hypothesis: testing with existing data. Prog. Oceanogr. 68:329–342. doi: 10.1016/j.pocean.2006.02.007.

Fair, P. A., and P. R. Becker.
2000. Review of stress in marine mammals. J. Aquat. Ecosyst. Stress Recovery 7:335–354. doi: 10.1023/A:1009968113079.

Forney, K. A., M. C. Ferguson, E. A. Becker, P. C. Fiedler, J. V. Redfern, J. Barlow, I. L. Vilchis, and L. T. Ballance.
2012. Habitat-based spatial models of cetacean density in the eastern Pacific Ocean. Endang. Species Res. 16:113–133. doi: 10.3354/esr00393.

Gerrodette, T., and L. Rojas-Bracho.
2011. Estimating the success of protected areas for the vaquita, *Phocoena sinus*. Mar. Mamm. Sci. 27:E101–E125. doi: 10.1111/j.1748-7692.2010.00449.x.

Gómez-Campos, E., A. Borrell, L. Cardona, J. Forcada, and A. Aguilar.
2011. Overfishing of small pelagic fishes increases trophic overlap between immature and mature striped dolphins in the Mediterranean Sea. PLoS ONE 6(9):e24554. doi:10.1371/journal.pone.0024554.

Herr, H., H. O. Fock, and U. Siebert.
2009. Spatio-temporal associations between harbour porpoise *Phocoena phocoena* and specific fisheries in the German Bight. Biol. Conserv. 142:2962–2972. doi: 10.1016/j.biocon.2009.07.025.

Hilborn, R., A. E. Punt, and J. Orensanz.
2004. Beyond Band-Aids in fisheries management: fixing world fisheries. Bull. Mar. Sci. 74:493–507.

Jarman, W. M., R. J. Norstrom, D. C. G. Muir, B. Rosenberg, M. Simon, and R. W. Baird.
1996. Levels of organochlorine compounds, including PCDDS and PCDFS, in the blubber of cetaceans from the west coast of North America. Mar. Pollut. Bull. 32:426–436. doi: 10.1016/0025-326X(96)83973-7.

Jensen, A. S., and G. K. Silber.
2003. Large whale ship strike database. NOAA Tech. Memo. NMFS-OPR-25, 37 p.

Johnson, A., G. Salvador, J. Kenney, J. Robbins, S. Kraus, S. Landry, and P. Clapham.
2005. Fishing gear involved in entanglements of right and humpback whales. Mar. Mamm. Sci. 21:635–645. doi: 10.1111/j.1748-7692.2005.tb01256.x.

Kaplan, I. C., P. S. Levin, M. Burden, and E. A. Fulton.
2010. Fishing catch shares in the face of global change: a framework for integrating cumulative impacts and single species management. Can. J. Fish. Aquat. Sci. 67:1968–1982. doi: 10.1139/F10-118.

Kaschner, K.
2004. Modelling and mapping resource overlap between marine mammals and fisheries on a global scale. Ph.D. diss., 240 p. Univ. British Columbia, Vancouver, Canada.

Laist, D. W.
1997. Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. *In* Marine debris: sources, impacts, and solutions (J. M. Coe and D. B. Rogers, eds.), p. 99–139. Springer-Verlag, New York.

Laist, D. W., A. R. Knowlton, J. G. Mead, A. S. Collet, and M. Podesta.
2001. Collisions between ships and whales. Mar. Mamm. Sci. 17:35–75. doi: 10.1111/j.1748-7692.2001.tb00980.x.

Levin, P. S., M. J. Fogarty, S. A. Murawski, and D. Fluharty.
2009. Integrated ecosystem assessments: Developing the scientific basis for ecosystem-based management of the ocean. PLoS Biol. 7(1): e1000014. doi: 10.1371/journal.pbio.1000014.

Lien, J.
1994. Entanglement of large cetaceans in passive inshore gear in Newfoundland and Labrador (1979–90). Spec. Issue Rep. Int. Whaling Comm. 15:149–157.

Marsili, L., A. Caruso, M. C. Fossi, M. Zanardelli, E. Politi, and S. Focardi.
2001. Polycyclic aromatic hydrocarbons (PAHs) in subcutaneous biopsies of Mediterranean cetaceans. Chemosphere 44:147–154. doi: 10.1016/S0045-6535(00)00206-X.

Matthiopoulos, J., S. Smout, A. J. Winship, D. Thompson, I. L. Boyd, and J. Harwood.
2008. Getting beneath the surface of marine mammal–fisheries competition. Mamm. Rev. 38:167–188. doi: 10.1111/j.1365-2907.2008.00123.x.

Moore, M. J., W. A. McLellan, P.-Y. Daoust, R. K. Bonde, and A. R. Knowlton.
2007. Right whale mortality: a message from the dead to the living. *In* The urban whale: North Atlantic right whales at the crossroads (S. D. Kraus and R. M. Rolland, eds.), p. 358–379. Harvard Univ. Press, Cambridge, MA.

National Research Council.
2003. Ocean noise and marine mammals, 204 p. National Academies Press, Washington, DC.

Nowacek, D. P., L. H. Thorne, D. W. Johnston, and P. L. Tyack.
2007. Responses of cetaceans to anthropogenic noise. Mamm. Rev. 37:81–115. doi: 10.1111/j.1365-2907.2007.00104.x.

Panigada, S., G. Pesante, M. Zanardelli, F. Capoulade, A. Gannier, and M. T. Weinrich.
2006. Mediterranean fin whales at risk from fatal ship strikes. Mar. Pollut. Bull. 52:1287–1298. doi: 10.1016/j.marpolbul.2006.03.014.

Read, A. J.
2008. The looming crisis: interactions between marine mammals and fisheries. J. Mammal. 89:541–548. doi: 10.1644/07-MAMM-S-315R1.1.

Read, A. J., P. Drinker, and S. Northridge.
2006. Bycatch of marine mammals in U.S. and global fisheries. Conserv. Biol. 20:163–169. doi: 10.1111/j.1523-1739.2006.00338.x.

Reeves, R. R., B. D. Smith, E. A. Crespo, and G. N. di Sciara.
2003. Dolphins, whales and porpoises: 2002–2010 conservation action plan for the world's cetaceans, 139 p. International Union for Conservation of Nature (IUCN)/Species Survival Commission (SSC) Cetacean Specialist Group, Gland, Switzerland, and Cambridge, UK.

Romano, T. A., M. J. Keogh, C. Kelly, P. Feng, L. Berk, C. E. Schlundt, D. A. Carder, and J. J. Finneran.
2004. Anthropogenic sound and marine mammal health: measures of the nervous and immune systems before and after intense sound exposure. Can. J. Fish. Aquat. Sci. 61:1124–1134. doi: 10.1139/f04-055.

Samhouri, J. F., and P. S. Levin.
2012. Linking land- and sea-based activities to risk in coastal ecosystems. Biol. Conserv. 145:118–129. doi: 10.1016/j.biocon.2011.10.021.

Suter, G. W., II.
2007. Ecological risk assessment, 2nd ed., 643 p. CRC Press, Boca Raton, FL.

Trites, A. W., V. Christensen, and D. Pauly.
1997. Competition between fisheries and marine mammals for prey and primary production in the Pacific Ocean. J. Northwest Atl. Fish. Sci. 22:173–187.

Vanderlaan, A. S. M., R. K. Smedbol, and C. T. Taggart.
2011. Fishing-gear threat to right whales (*Eubalaena glacialis*) in Canadian waters and the risk of lethal entanglement. Can. J. Fish. Aquat. Sci. 68:2174–2193. doi: 10.1139/f2011-124.

Young, N. M., and S. Ludicello.
2007. Worldwide bycatch of cetaceans. NOAA Tech. Memo. NMFS-OPR-36, 276 p.