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Evaluating stakeholder-derived strategies to reduce the risk of ships striking whales

Jessica V. Redfern[1] | Thomas J. Moore[1] | Elizabeth A. Becker[2] | John Calambokidis[3] | Sean P. Hastings[4] | Ladd M. Irvine[5] | Bruce R. Mate[5] | Daniel M. Palacios[5]

[1]Marine Mammal and Turtle Division, Southwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, La Jolla, California

[2]Marine Mammal and Turtle Division, Southwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration contracted by ManTech International Corporation, Solana Beach, California

[3]Cascadia Research Collective, Olympia, Washington

[4]Channel Islands National Marine Sanctuary, Office of National Marine Sanctuaries, National Oceanic and Atmospheric Administration, Santa Barbara, California

[5]Marine Mammal Institute and Department of Fisheries and Wildlife, Hatfield Marine Science Center, Oregon State University, Newport, Oregon

Correspondence
Jessica V. Redfern, Marine Mammal and Turtle Division, Southwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 8901 La Jolla Shores Drive, La Jolla, CA.
Email: Jessica.Redfern@noaa.gov

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Abstract

Aim: Ship strikes are one of the largest sources of human-caused mortality for baleen whales on the West Coast of the United States. Reducing ship-strike risk in this region is complicated by changes in ship traffic that resulted from air pollution regulations and economic factors. A diverse group of stakeholders was convened to develop strategies to reduce ship-strike risk in the Southern California Bight. Strategies proposed by some stakeholders included: (a) adding a shipping route; (b) expanding the existing area to be avoided (ATBA); and (c) reducing ship speeds.

Location: Southern California Bight, off the coast of California, United States.

Methods: We developed methods to estimate ship traffic in the stakeholder-derived strategies using 8 years of ship traffic data. To assess ship-strike risk for fin, humpback, and blue whales, we used habitat models developed from 7 years of survey data and home ranges derived from 53 blue whale tags. We defined collision risk as the co-occurrence between whales and ships. The risk of a lethal collision was calculated by multiplying collision risk by the probability that a collision is lethal, which is estimated using ship speed.

Results: Speed reductions resulted in a large decrease in the risk of a lethal ship strike. Creating a shipping route or expanding the ATBA reduced the risk of a strike by removing traffic from a whale feeding area. Creating a shipping route was opposed by the United States Navy and the shipping industry, but expanding the ATBA was broadly supported.

Main conclusions: Our analyses suggest that speed reductions and expanding the ATBA may provide an optimal solution for addressing stakeholder needs and reducing ship strikes in the Southern California Bight. The methods we developed can be used to address the global issue of balancing human use of the marine environment with the protection of whale populations.

KEYWORDS
area to be avoided, commercial shipping, fin whales, humpback whales, blue whales, ship speed reductions, shipping route, ship-strike risk, spatially explicit risk assessment, species distribution modelling, variability in ocean use

1 | INTRODUCTION

Ship strikes are one of the largest sources of human-caused mortality for fin (*Balaenoptera physalus*), humpback (*Megaptera novaeangliae*), and blue (*Balaenoptera musculus*) whales on the West Coast of the United States (Berman-Kowalewski et al., 2010; Carretta et al., 2017). Increases in fin and humpback whale abundance have been documented at broad scales in the North Pacific (Barlow et al., 2011; Moore & Barlow, 2011), suggesting that current levels of ship strikes do not preclude population growth at these broad scales. However, ship strikes may be an issue at regional scales. In particular, populations of humpback whales that breed off Mexico and Central America remain listed as Threatened and Endangered, respectively, under the United States Endangered Species Act. Both of these populations feed in the Southern California Bight (Figure 1; hereafter Bight) and it is possible that ship strikes could have negative population-level consequences (for example, reduced population growth rates). It is also possible that a unique population of resident fin whales remains year-round in the Bight (Calambokidis et al., 2015; Forney & Barlow, 1998; Scales et al., 2017) and that ship strikes may impact this population. There is no evidence that the abundance of blue whales in the North Pacific is increasing and it

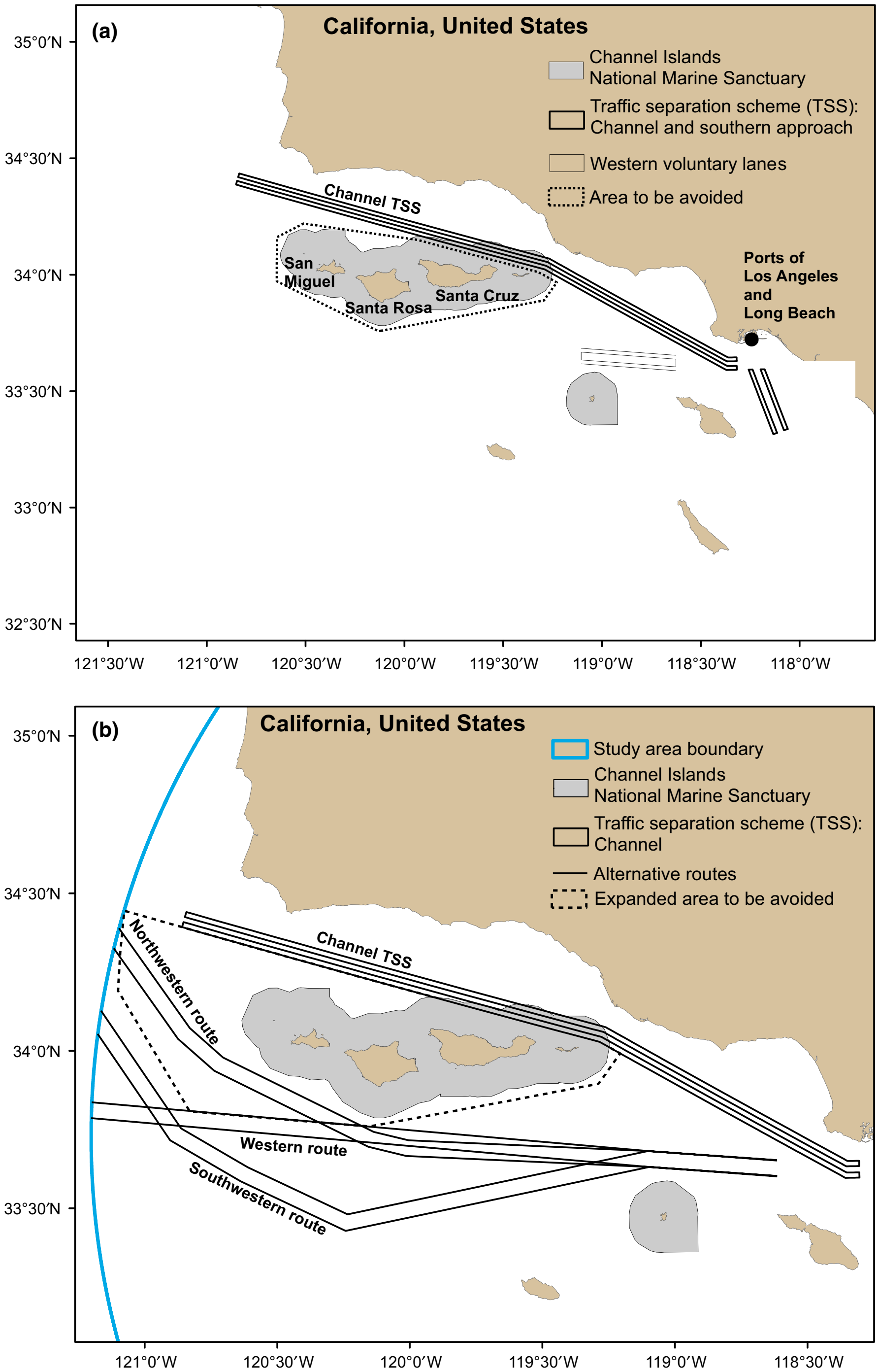


FIGURE 1 (a) Existing ship traffic management in the Southern California Bight. The Channel Traffic Separation Scheme (TSS) shown in this map represents the width reduction implemented by the International Maritime Organization in 2013 to decrease overlap between ship traffic and a whale feeding area. (b) Management strategies considered by the stakeholder group: the western route and expanding the area to be avoided. The northwestern and southwestern routes capture the primary ship traffic patterns between 2009 and 2011 and between 2012 and 2014, respectively

has been suggested that this population may have reached carrying capacity (Monnahan, Branch, & Punt, 2015).

Reducing ship-strike risk in the Bight is complicated by changes in ship traffic that occurred from 2008 to 2015 as a result of air pollution regulations and economic factors (Moore et al., 2018). In 2008, a majority of ship traffic travelled in the Traffic Separation Scheme (TSS) in the Santa Barbara Channel (hereafter, Channel), which is one of the primary entry and exit points for the Ports of Los Angeles and Long Beach (two of the busiest ports in the United States). Ship traffic shifted from the Channel TSS to a western approach (travel in an east-west direction south of the Channel) between 2009 and 2011 (Figure 2a). Traffic in the western approach shifted farther offshore and some traffic began to return to the Channel between 2012 and 2014 (Figure 2a). In 2015, a majority of ships had returned to the Channel TSS, although the proportion was not as high as it was in 2008 (Figure 2a). Over the entire time period (i.e., 2008–2015), very few ships travelled in the area to be avoided (ATBA) that surrounds the Channel Islands National Marine Sanctuary. This ATBA was created by the International Maritime Organization (IMO) in 1991 to reduce groundings and oil pollution risks. Travel in an ATBA is not prohibited, but would be a major factor when determining liability in the event of an accident.

Ship speeds also became progressively slower in the Bight from 2008 to 2015 (Moore et al., 2018). Although speeds were slower in 2015, the speed of ships travelling on east-west routes to the Ports would still result in a >70% probability that a ship strike would be lethal in many areas (Figure 2b). To reduce this risk, voluntary and incentivized speed reductions have been implemented in the Channel (Freedman et al., 2017). To address the increased traffic using the western approach, the Los Angeles and Long Beach Harbor Safety Committee established western voluntary lanes in October 2009 (Figure 1a). To reduce overlap between ship traffic and a whale feeding area in the Channel, the IMO reduced the width of the Channel TSS in 2013. The Channel Islands National Marine Sanctuary Advisory Council also convened a diverse group of stakeholders and scientists to develop strategies to reduce ship-strike risk, decrease air pollution, promote safe and efficient ship travel, and reduce conflicts with other ocean users (NOAA, 2016).

Stakeholders represented the shipping industry, tourism industry, conservation organizations, air pollution control districts, and the United States Navy, Coast Guard, National Park Service, and National Oceanic and Atmospheric Administration. Some members of this group (primarily conservation organizations and air pollution control districts) put forward a spatial management approach that recommended: (a) adding a western shipping route; (b) expanding the ATBA; and (c) reducing ship speeds (Figure 1b). We designed an optimal route for the western approach and assessed ship-strike risk in all of the proposed strategies. In particular, we compare risk in the western route, assuming an expanded ATBA, and in routes drawn to capture the primary traffic patterns observed in 2009-2011 and 2012-2014. We also assess whether each strategy reduces risk relative to existing traffic patterns. Redfern et al. (2013) assessed ship-strike risk for fin, humpback, and blue whales in alternative shipping routes in the Bight. We update the Redfern et al. (2013) risk assessment using new sources of whale distributions, explore an expanded suite of management strategies, and develop methods to compare risk from the management strategies to risk from existing traffic.

2 | METHODS

2.1 | Ship traffic

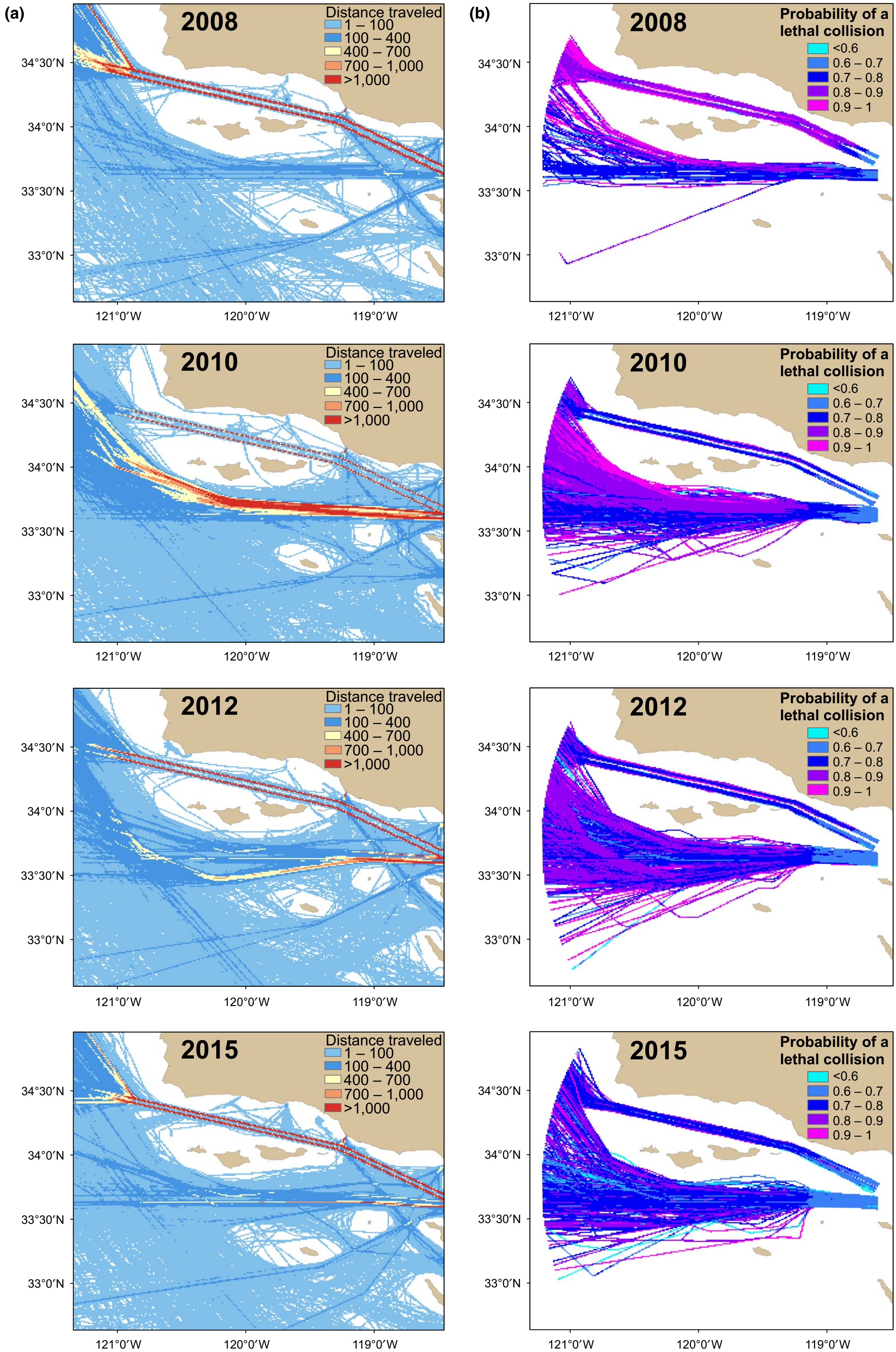
The automatic identification system (AIS) is a maritime tracking system that was adopted in 2000 by the IMO (2014). Requirements for using AIS are determined at both international (i.e., the IMO) and national levels (for example, the United States Coast Guard). Data include dynamic information, such as ship position, speed, and course, and static information, such as ship identifier, type, and dimensions. Moore et al. (2018) used an eight-year time series of AIS data (2008–2015) collected off California to construct transits for ships ≥80 m in length.

Management strategies in the Bight are likely to primarily affect ships travelling to and from the Ports of Los Angeles and Long Beach. To ensure our analyses included only the subset of affected transits, we defined our study area as occurring within a 150 nmi radius from the Ports. Within this area, we extracted transits from the Moore et al. (2018) data set that use the TSS between the Ports and Santa Cruz Island or that enter and exit the Bight in the west and pass through the western voluntary lanes (Figure 2b). We used transits occurring between July and December each year to match the time period of whale survey data (see the next section).

We excluded atypical transits (for example, transits that contain a loop or have missing segments) to ensure estimates of existing traffic are not biased relative to the management strategies, which assume direct travel to and from the Ports. To account for these atypical transits, we adjusted all estimates of risk by the ratio of all transits versus typical transits: (all transits)/(all transits − atypical transits). We used the methodology of Moore et al. (2018) to summarize the distance travelled and distance-weighted mean ship speeds in a 1 km × 1 km grid. To account for data gaps in 2008 and 2010, we divided the distance travelled in each grid cell by the number of days of data collection.

2.2 | Whale distributions

Becker et al. (2016) developed habitat models for fin, humpback, and blue whales using 7 years of research vessel line-transect survey data collected by NOAA Fisheries' Southwest Fisheries Science Center from July to December (i.e., 1991, 1993, 1996, 2001, 2005, 2008 and 2009). Specifically, Becker et al. (2016) used generalized additive models (GAMs) (Wood, 2006) to relate habitat variables to the number of whales in transect segments that were approximately 5 km long. They fit GAMs in the R (version 3.1.1; R Core Team, 2014) package "mgcv" (version 1.8-3; Wood, 2011). The Becker et al. (2016) models predict the number of whales in a 10 km × 10 km grid for distinct 8-day composites covering the entire survey period. The predictions from these models have been extensively validated



(a)
(b)
2008
2010
2012
2015
Distance traveled
1 – 100
100 – 400
400 – 700
700 – 1,000
>1,000
Probability of a lethal collision
<0.6
0.6 – 0.7
0.7 – 0.8
0.8 – 0.9
0.9 – 1
34°30′N
34°0′N
33°30′N
33°0′N
121°0′W
120°0′W
119°0′W

FIGURE 2 (a) A 1 km × 1 km gridded representation of the distance travelled (m/day) by ships from July to December was derived from the transits created by Moore et al. (2018). We show 4 years that represent the primary traffic patterns. Specifically, a majority of traffic travelled in the Traffic Separation Scheme in the Santa Barbara Channel (hereafter, Channel) in 2008. From 2009 to 2011 (represented by 2010), ships travelled south of the Channel. Traffic south of the Channel shifted farther offshore and some traffic began to return to the Channel between 2012 and 2014 (represented by 2012). In 2015, a majority of ships had returned to the Channel, although the proportion was not as high as it was in 2008. (b) A distance-weighted mean of the probability that a collision is lethal was calculated in each grid cell using the speed (higher speeds are associated with an increased probability that a collision is lethal) on transits made by ships most likely to be affected by the management strategies (i.e., ships travelling to and from the Ports of Los Angeles and Long Beach)

(Becker et al., 2016) using cross-validation, predictions on novel data sets, expert opinion, and comparisons to standard line-transect estimates. We used the average of all composites in our analyses to represent expected long-term patterns in whale distributions (Figure 3) and to match the long-term, static management strategies considered by the stakeholder group. We extracted the average predicted number of whales at the centre of each grid cell in the 1 km × 1 km ship traffic grid to explore the management strategies. The management strategies were designed to account for the coarser spatial resolution of the predicted whale distributions (for example, the spacing between the routes used in the analyses).

The Becker et al. (2016) models suggest that high blue whale densities occur in the Channel and western approach (Figure 3c). However, blue whale home ranges derived from tagging data (Figure 3d) suggest higher blue whale use of the Channel (Irvine et al., 2014). In particular, Irvine et al. (2014) created kernel home ranges from 53 blue whale tags lasting ≥30 days using the least-squares cross-validation bandwidth selection method. All tags were deployed along the California coast and 31 tags were deployed at the western end of the Channel. The blue whale home ranges assume the movement of tagged individuals is representative of the population while foraging on coastal resources, although the number of tagged animals is a small percentage of the whole population. The

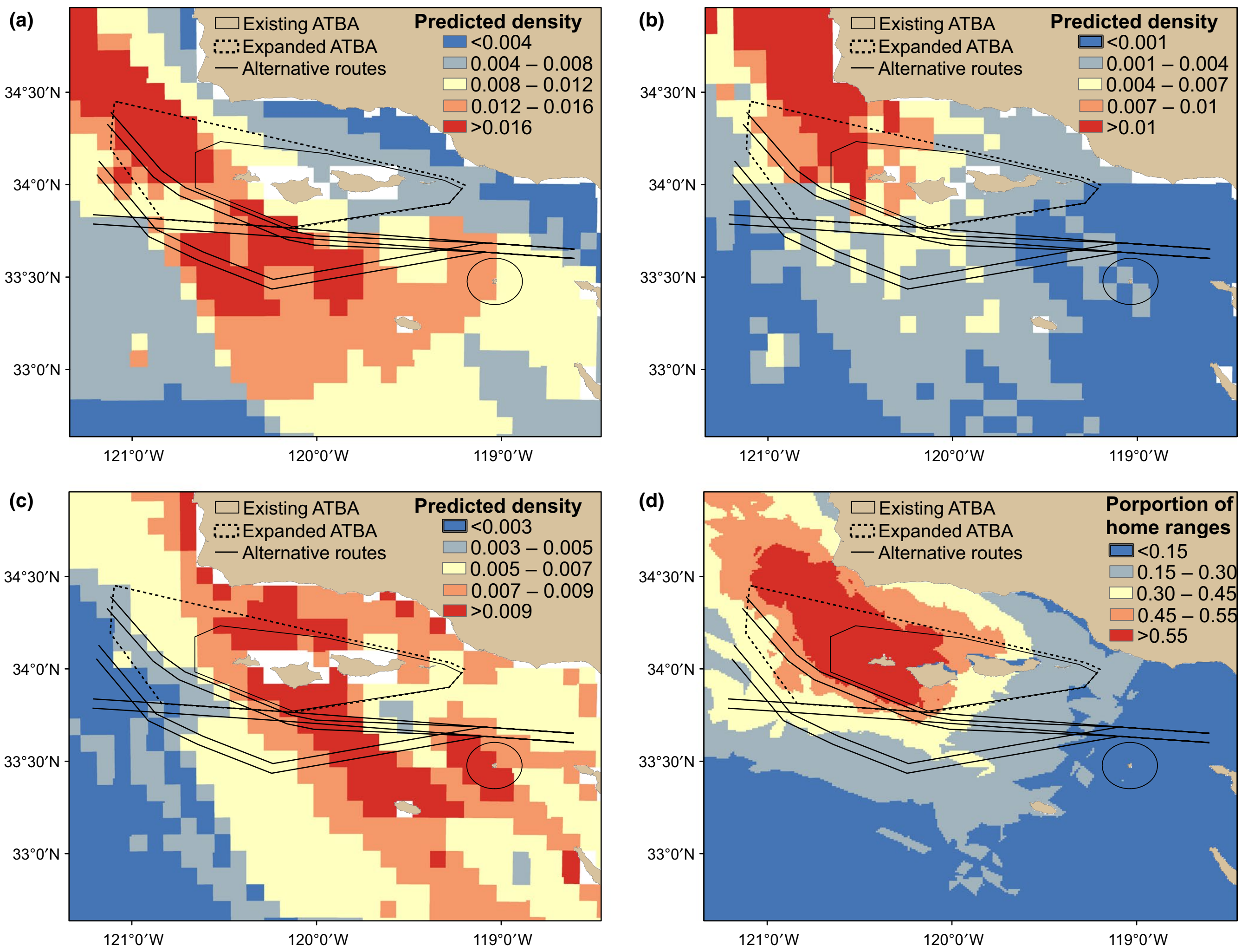


FIGURE 3 Predicted (a) fin, (b) humpback, and (c) blue whale distributions from models produced by Becker et al. (2016) using line-transect survey data. (d) Density of blue whale home ranges derived by Irvine et al. (2014). Ship traffic management strategies (i.e., expanding the area to be avoided (ATBA) and alternative routes) are overlaid on each map

sample of tagged animals provides additional information to the Becker et al. (2016) blue whale models, which represent data collected from the coast to 300 nmi offshore and only contain a small percentage of effort close to the coast. To incorporate coastal blue whale distributions in our analyses, we used the number of overlapping home ranges (Irvine, Mate, & Palacios, 2019), defined by the 90% isopleth, calculated by Irvine et al. (2014). Specifically, we extracted the proportion of the total 53 home ranges in each cell of the 1 km × 1 km ship traffic grid.

2.3 | Risk

Encounter rate theory has been used to predict the relative mortality resulting from ship strikes by estimating (a) the encounter rate; (b) the number of encounters that result in a collision; and (c) the probability that a collision is lethal (Crum, Gowan, Krzystan, & Martin, 2019; Martin et al., 2016; Rockwood, Calambokidis, & Jahncke, 2017). Several components of encounter rate models are typically treated as fixed across a study area, including whale size and swim speed, the probability that ships or whales avoid collisions, and the probability that a whale occurs within the upper part of the water column where it is susceptible to a collision. However, the ship parameters used in encounter models vary across space.

We estimated the risk of a collision by multiplying the predicted number of whales by the m/day of ship traffic within each grid cell. This estimate of risk does not include spatial differences in ship parameters. Consequently, we defined collision risk as the co-occurrence between whales and ships, as has been done for multiple species (for example, Nichol, Wright, O'Hara, & Ford, 2017; Redfern et al., 2013; Vanderlaan et al., 2009; Williams & O'Hara, 2010). Conn and Silber (2013) estimated the relationship between ship speed and the probability that a collision is lethal. We calculated the probability that a collision is lethal in each grid cell using a distance-weighted mean of the probability that a collision is lethal estimated for each ship transit using the Conn and Silber (2013) relationship. The risk of a lethal collision was calculated by multiplying collision risk by the probability that a collision is lethal.

We calculated collision risk and the risk of a lethal collision in existing traffic as the sum of the risk in the Channel and the western approach. We assessed the percent change in collision risk and the risk of a lethal collision relative to 2008 values for the time series of ship traffic data to understand how changes in traffic initiated by the shipping industry affected risk. We also assessed the percent change between collision risk from existing traffic and four management strategies: three alternative routes and expanding the ATBA. In particular, we assessed the effect of concentrating all transits in the western approach in two routes derived from the primary traffic patterns observed between 2009 and 2011 and between 2012 and 2014 (termed the northwestern and southwestern routes, respectively; Figure 1b). We also assessed the effect of concentrating all transits in the western approach in a route similar to the optimal route in Redfern et al. (2013) and the route derived by the stakeholders, but shifted this route (termed the western route) to align with the western voluntary lanes (Figure 1b). Concentrated traffic was partitioned into inbound and outbound lanes according to the number of ship transits through the western voluntary lanes. Specifically, transits were redrawn in each route assuming that traffic was normally distributed within the inbound and outbound lanes (~68% of transits were expected to occur within 0.25 nmi of either side of the centreline).

To assess the effects of expanding the ATBA, we had to adjust traffic in the Channel and the western approach. We assumed all traffic in the Channel travelled in a straight approach from the western edge of the expanded ATBA to the TSS. The TSS adjustment made by the IMO in 2013 was used for the 2013–2015 ship traffic. Transits from ships using the western approach (i.e., ships travelling in an east-west direction south of the Channel) that intersected the expanded ATBA were removed. Risk from the remaining transits was increased by the proportion of transits removed, which assumes that expanding the ATBA does not alter traffic patterns outside the ATBA. To ensure our comparisons between collision risk from existing traffic and the management strategies were not biased by changes in traffic magnitude, the risk estimate for each year was divided by the number of transits corrected by the days of AIS data collection.

The effects of speed reductions were assessed using the percent change between the risk of a lethal collision from speeds in existing traffic and assuming vessel speeds were reduced to 14, 12, and 10 knots. Risk for the speed reductions was calculated by replacing speeds above the threshold with the threshold value. We assessed risk when speeds were reduced throughout the Bight and when speeds were reduced only in the Channel.

We cannot combine analyses of the routes and expanded ATBA with speed reductions because the speeds associated with these management strategies are unknown and making assumptions about the speeds may be misleading. For example, we could assume speeds on the western route are an average of speeds on transits in radial bands around the route. However, this assumption makes the speeds on the western route higher than the speeds observed in the route in 2010 because the faster traffic to the west of San Miguel Island is included in the average (i.e., the higher probabilities of a lethal collision in Figure 2b). It is unknown whether the ships travelling at these faster speeds would also travel faster in the route or follow the speeds observed in the route. Consequently, we used percent change in collision risk to assess the routes and expanded ATBA and the percent change in the risk of a lethal collision to asses speed reductions. The uncertainty in the effects of the management strategies is represented in our analyses by the range of the percent change in risk across the 8 years of ship traffic.

3 | RESULTS

Collision risk was lowest for fin whales in 2008 (Figure 4a) when a majority of ship traffic occurred in the Channel (Figure 2a) because predicted fin whale densities are generally low in the Channel. Collision risk increased by up to 45%, compared to 2008, for fin whales between 2009 and 2011 when a majority of ships used the western approach. Collision risk decreased as ships began to return to the Channel between 2012 and 2014 and in 2015 was 9% higher than in 2008. The opposite pattern was seen for humpback whales and tagged blue whales (Figure 4a), which had higher predicted densities in the Channel. In particular, collision risk decreased by up to 28% for humpback whales and 17% for tagged blue whales in 2010 and 2011 when a majority of ships used the western approach and in 2015 was 8%–9% lower than the 2008 risk for both species. Collision risk for the blue whale distributions derived from line-transect data decreased, but showed much less variation (range: −1 to −6%) because predicted densities were high both within and south of the Channel. The risk of a lethal collision followed similar patterns (Figure 4b). However, the

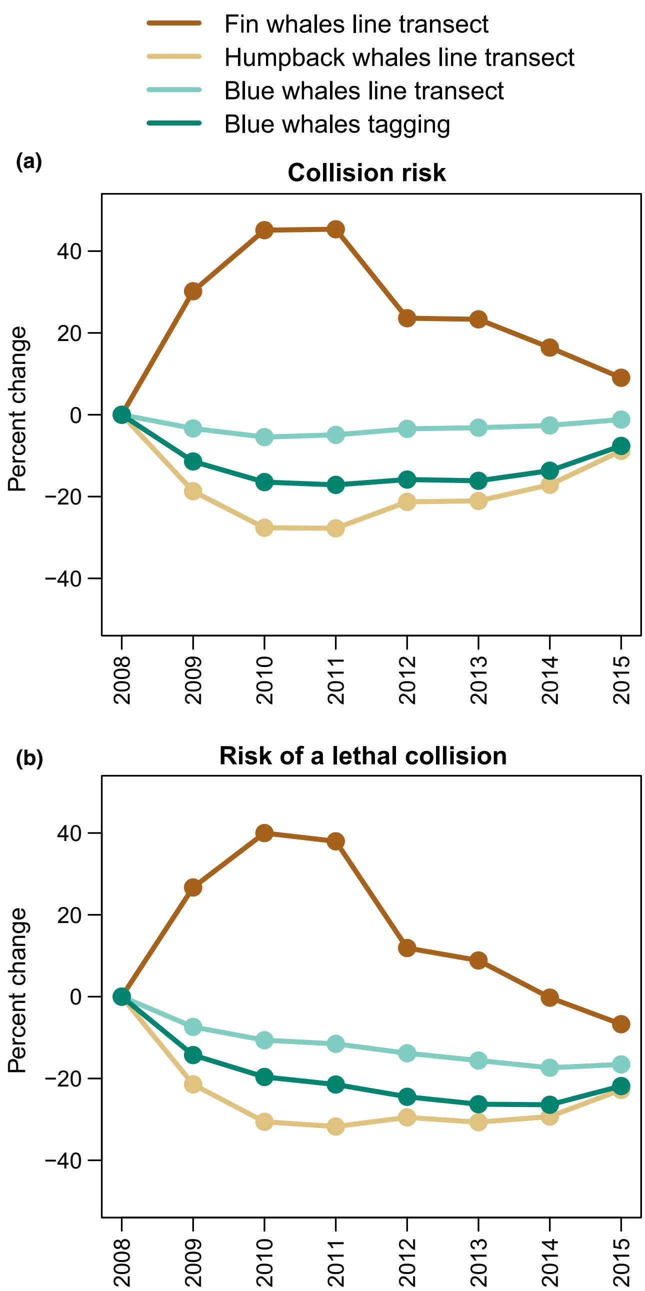


FIGURE 4 We assessed the percent change in (a) collision risk and (b) the risk of a lethal collision relative to 2008 using ship traffic data from 2008 to 2015 to understand how changes in traffic initiated by the shipping industry affected risk

risk of a lethal collision was lower in the later part of the time series (for example, risk of a lethal collision for blue whales was lower in 2015 than 2008) because ship speeds became progressively slower.

Comparisons between collision risk from existing traffic and the four management strategies show that concentrating traffic does not always reduce risk (Figure 5). In particular, collision risk for all species increased when traffic was concentrated on the northwestern route. Concentrating traffic on the western route reduced collision risk compared to collision risk from existing traffic for all species, except blue whale distributions derived from tagging, which showed an approximately 3% increase between 2012 and 2014 and a 1% increase in 2015. Concentrating traffic on the southwestern route increased risk for fin whales, which occur farther offshore, and had mixed results for the other species. Expanding the ATBA reduced collision risk compared to collision risk from existing traffic for all species. For all management strategies, the change in risk was generally the largest between 2009 and 2011 and smaller between 2012 and 2015.

Reducing ship speeds throughout the Bight resulted in the largest decrease in the risk of a lethal collision in the early part of the time series when ships were travelling fastest (Figure 6a). However, a speed reduction to 12 knots still provides an approximate 11%–13% decrease in the risk of a lethal collision for all species in 2015 and a speed reduction to 10 knots provides an approximate 22%–24% decrease. The effectiveness of only slowing ships down in the Channel depended on the percentage of traffic in the Channel (Figure 6b). The effect was largest when the highest numbers of ships were in the Channel in 2008. When a majority of ships used the western approach (2009–2011) and, concomitantly, would not be subject to speed restrictions in the Channel, the effect was smaller.

4 | DISCUSSION

Our results suggest that a large decrease in ship-strike risk can be achieved by speed reductions. Ship speeds declined in the Bight from 2008 to 2015 because air pollution regulations and economic factors made slow-steaming strategies more cost effective (Moore et al., 2018). Consequently, the reduction in the risk of a lethal collision from slowing ships down was largest in 2008 and smallest in 2015 (Figure 6a). Although the reduction in the risk of a lethal collision was smallest in 2015, speed reductions throughout the Bight still provided a large decrease in ship-strike risk in this year: an approximate 12% decrease in the risk of a lethal collision for all species for a speed reduction to 12 knots and an approximate 23% decrease in risk for a speed reduction to 10 knots. The effects of speed reductions on collision risk and the probability that a collision is lethal should continue to be assessed. The effects of speed reductions were similar for all species because the data used to parameterize the Conn and Silber (2013) relationship did not allow them to account for potential differences in vulnerability between species (for example, McKenna, Calambokidis, Oleson, Laist, & Goldbogen, 2015).

The potential conservation gains from speed reductions are corroborated by the effectiveness of slowing ships down for right

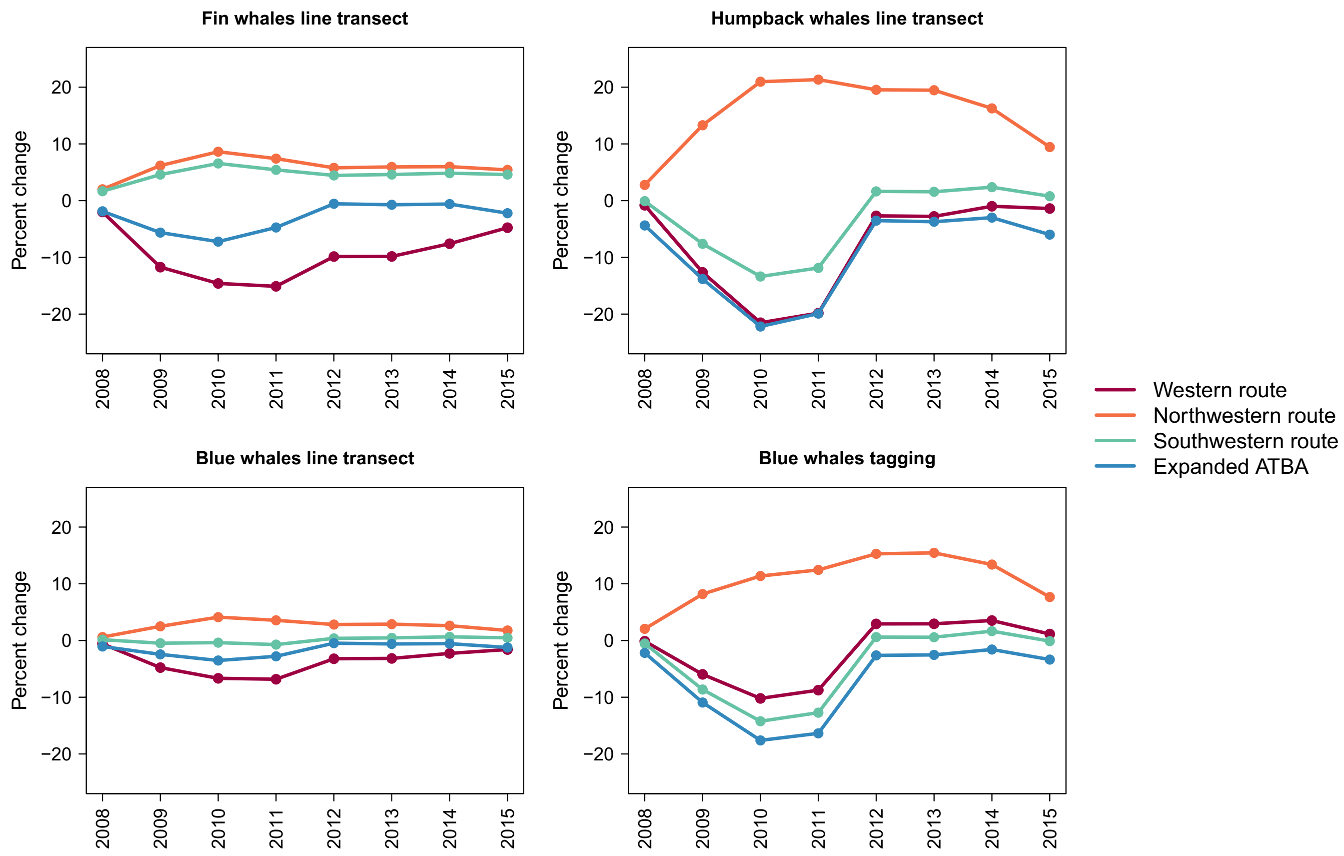


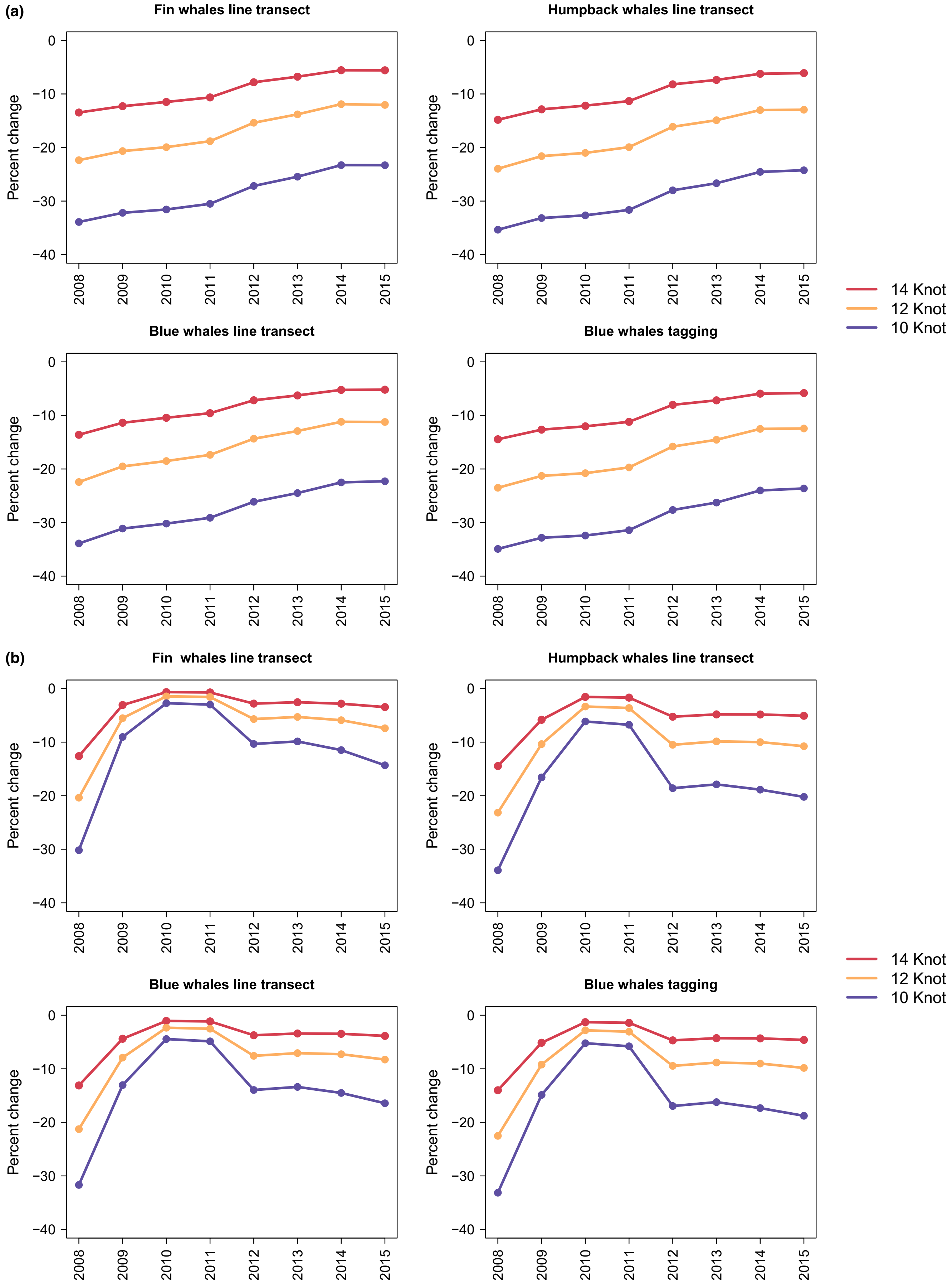
FIGURE 5 The percent change between collision risk from existing ship traffic and traffic estimated for the management strategies

whales on the East Coast of the United States (Conn & Silber, 2013). There are three management options for reducing ship speeds: voluntary, mandatory, and incentivized. Studies on the West and East Coasts of the United States have shown little compliance with voluntary speed reductions (for example, Freedman et al., 2017; McKenna, Katz, Condit, & Walbridge, 2012; Silber, Adams, & Bettridge, 2012). However, compliance was higher (although not 100%) when mandatory speed reductions were implemented and enforced on the East Coast (Silber, Adams, & Fonnesbeck, 2014). Recent efforts in the Channel to offer incentives to ships that travel slower have been broadly effective, but only reach a small percentage of ships travelling in this region (Freedman et al., 2017) and require continued financial support. Our analyses assume 100% compliance with speed reductions. In reality, the percent compliance with speed reductions will depend on whether speed reductions are voluntary, mandatory, or incentivized.

The shipping industry opposed speed reductions (NOAA, 2016) and the United States Navy was concerned that speed reductions applied only in the Channel could increase traffic in the western approach, which overlaps with their training range (NOAA, 2016). Our analyses suggest that speed reductions applied throughout the Bight would provide maximum conservation gains. In particular, our analyses of speed reductions applied only in the Channel in 2015 (Figure 6b) resulted in an approximate 7%–11% decrease in the risk of a lethal collision for a speed reduction to 12 knots (compared to a 12% decrease when speeds are reduced throughout the Bight) and an approximate 14%–20% decrease in risk for a speed reduction to 10 knots (compared to a 24% decrease when speeds are reduced throughout the Bight). If ship traffic changed from the 2015 patterns in response to speed restrictions in the Channel (for example, ships travelling south of the Channel), these risk estimates would change.

Higher densities for all species extend west from San Miguel Island (Figure 3). An important feeding area for blue and humpback whales was identified in this region using data from non-systematic surveys (Calambokidis et al., 2015). Our analyses suggest the importance of reducing the overlap between this region and ship traffic using a western approach. Concentrating traffic on the northwestern route, which captures the primary 2009–2011 traffic patterns, increased risk for all species relative to existing traffic because it increased the overlap between traffic and this important feeding area. Concentrating traffic on the western route or expanding the ATBA reduced risk relative to existing traffic because both strategies remove traffic from this important feeding area. The reduction in collision risk compared to existing traffic was largest between 2009 and 2011 (Figure 5), when a high percentage

FIGURE 6 (a) The percent change between the risk of a lethal collision from existing ship traffic and traffic assuming speeds were reduced to 14, 12, and 10 knots throughout the Bight. (b) The percent change between the risk of a lethal collision from existing ship traffic and traffic assuming speeds were reduced in the Channel


(a)
Fin whales line transect
Humpback whales line transect
Blue whales line transect
Blue whales tagging
Percent change
0
−10
−20
−30
−40
2008
2009
2010
2011
2012
2013
2014
2015
14 Knot
12 Knot
10 Knot
(b)
Fin whales line transect
Humpback whales line transect
Blue whales line transect
Blue whales tagging

of ships travelled through this area to avoid air pollution regulations. The effectiveness of the western route and ATBA expansion was reduced in 2015 when a high percentage of traffic had returned to the Channel. Creating a western route was opposed by the United States Navy and the shipping industry (NOAA, 2016). However, expanding the ATBA was broadly supported by all stakeholders.

Our results suggest that speed reductions throughout the Bight and expanding the ATBA may provide an optimal solution for addressing stakeholder needs and reducing ship-strike risk. These strategies reduce risk for blue whales using both the line-transect and tagging data, even though the tagging data suggest higher blue whale use of the Channel and the line-transect data suggest higher densities south of the Channel. They also reduce risk for fin and humpback whales. However, expanding the ATBA without creating a western route creates the possibility for higher overlap between fin whales and traffic in the western approach. Continued monitoring of ship traffic will be critical to determine whether additional strategies are needed to reduce this overlap.

Our analyses assume that ships travel in a straight approach between the western edge of the expanded ATBA and the TSS. If ships do not follow this straight approach, they may increase their overlap with high density whale areas. Consequently, extending the TSS to the edge of the expanded ATBA is likely to provide added risk reductions. The resolution of the whale data is too coarse to estimate the change in risk from extending the TSS. Combining an ATBA expansion with a TSS extension was broadly supported by stakeholders. Speed reductions should reduce risk year-round, according to the relationship between speed and the probability that a collision is lethal (Conn & Silber, 2013). The effect of expanding the ATBA between January and June should be evaluated because the line-transect data used to derive the whale distributions were collected between July and December and studies have found seasonal changes in fin (Scales et al., 2017) and humpback (Becker et al., 2017) whale distributions off California. These evaluations should use data collected throughout the Bight to ensure they capture potential seasonal changes in whale distributions and include changes in ship traffic in the Channel and western approach.

We found changes in ship-strike risk for multiple whale species associated with changes in ship traffic caused by air pollution regulations and economic factors. Although our analyses focus on whale populations in the Bight, they are relevant globally as stakeholders consider strategies to balance human use of the marine environment with protecting human health and marine resources. For example, the IMO is considering strategies to reduce greenhouse gas emissions from shipping and has established a new global limit on sulphur content in ship fuel that will take effect on 1 January 2020. Additionally, air pollution regulations for ships have been considered in the Mediterranean Sea and off Japan, Australia, Singapore and China (Moore et al., 2018), as well as the Baltic and North Seas (Åström, Yaramenka, Winnes, Fridell, & Holland, 2018). Our results suggest that it is critical to evaluate the potential consequences of these actions on ship-strike risk. The methodology developed for the Bight can be used to evaluate these potential consequences and to design strategies for reducing the risk of ships striking whales.

ACKNOWLEDGEMENTS

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DATA ACCESSIBILITY

The predictions from the Becker et al. (2016) habitat models can be downloaded from https://cetsound.noaa.gov/cda. The blue whale home ranges from Irvine et al. (2014) are available as a Figshare Dataset (Irvine et al. 2019; https://doi.org/10.6084/m9.figshare.8269721.v2). The Moore et al. (2018) shipping data are available as a Mendeley data set (Moore 2018; https://doi.org/10.17632/4tgwv45bz8.1).

ORCID

Jessica V. Redfern https://orcid.org/0000-0003-4042-3668
Thomas J. Moore https://orcid.org/0000-0002-0243-6049
Elizabeth A. Becker https://orcid.org/0000-0002-8858-122X
John Calambokidis https://orcid.org/0000-0002-5028-7172
Ladd M. Irvine https://orcid.org/0000-0001-5135-3496
Daniel M. Palacios https://orcid.org/0000-0001-7069-7913

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BIOSKETCH

Dr. Jessica V. Redfern leads the Marine Mammal Spatial Habitat and Risk Program in the Marine Mammal and Turtle Division at the Southwest Fisheries Science Center in La Jolla, California. This group of modellers, ecologists, and oceanographers uses ecosystem data to predict the location of marine mammals, identify priority habitat, and conduct spatially explicit risk assessments. Jessica's current projects include assessing the risk of ships striking whales in areas with high shipping traffic around the world and using ecosystem data to interpret trends in the abundance of dolphins that have been impacted by tuna purse-seine fishing in the eastern tropical Pacific.

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