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Assessing the Risk of Ships Striking Large Whales in Marine Spatial Planning

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Abstract: *Marine spatial planning provides a comprehensive framework for managing multiple uses of the marine environment and has the potential to minimize environmental impacts and reduce conflicts among users. Spatially explicit assessments of the risks to key marine species from human activities are a requirement of marine spatial planning. We assessed the risk of ships striking humpback (Megaptera novaeangliae), blue (*Balaenoptera musculus*), and fin (*Balaenoptera physalus*) whales in alternative shipping routes derived from patterns of shipping traffic off Southern California (U.S.A.). Specifically, we developed whale-habitat models and assumed ship-strike risk for the alternative shipping routes was proportional to the number of whales predicted by the models to occur within each route. This definition of risk assumes all ships travel within a single route. We also calculated risk assuming ships travel via multiple routes. We estimated the potential for conflict between shipping and other uses (military training and fishing) due to overlap with the routes. We also estimated the overlap between shipping routes and protected areas. The route with the lowest risk for humpback whales had the highest risk for fin whales and vice versa. Risk to both species may be ameliorated by creating a new route south of the northern Channel Islands and spreading traffic between this new route and the existing route in the Santa Barbara Channel. Creating a longer route may reduce the overlap between shipping and other uses by concentrating shipping traffic. Blue whales are distributed more evenly across our study area than humpback and fin whales; thus, risk could not be ameliorated by concentrating shipping traffic in any of the routes we considered. Reducing ship-strike risk for blue whales may be necessary because our estimate of the potential number of strikes suggests that they are likely to exceed allowable levels of anthropogenic impacts established under U.S. laws.*

Keywords: commercial shipping, generalized additive models, habitat modeling, risk analysis

Evaluación del Riesgo de Colisiones de Barcos y Ballenas en la Planificación Marina Espacial

Resumen: *La planificación marina espacial proporciona un marco de referencia integral para el manejo de usos múltiples del ambiente marino, y tiene el potencial para minimizar los efectos ambientales y reducir conflictos entre los usuarios. Las evaluaciones espacialmente explícitas de los riesgos para especies marinas clave derivados de las actividades humanas son un requerimiento de la planificación marina espacial. Evaluamos el riesgo de colisión de barcos con ballenas Megaptera novaeangliae, Balaenoptera musculus y B. physalus en rutas de navegación alternas derivadas de patrones del tráfico marino en el sur de California (U.S.A.). Específicamente, desarrollamos modelos del hábitat de ballenas y asumimos que el riesgo de colisión con barcos en las rutas alternativas fue proporcional al número de ballenas que los modelos pronosticaron*

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que iban a ocurrir en cada ruta. Esta definición de riesgo asume que todos los barcos viajan en una sola ruta. También calculamos el riesgo asumiendo que los barcos viajan en rutas múltiples. Estimamos el potencial de conflictos entre la navegación y otros usos (entrenamiento militar y pesca) debido al traslape con las rutas. También estimamos el traslape entre rutas de navegación y áreas protegidas. La ruta con el menor riesgo para M. novaeangliae tenía el mayor riesgo para B. physalus y viceversa. El riesgo para ambas especies puede ser disminuido mediante la creación de una nueva ruta al sur de las Channel Islands y distribuyendo el tráfico entre esta ruta nueva y la existente en el Canal de Santa Bárbara. La creación de una ruta más larga puede reducir el traslape entre la navegación y otros usos al concentrar el tráfico de navegación. Las ballenas B. musculus se distribuyen más homogéneamente que M. novaeangliae y B. physalus en nuestra zona de estudio; por lo tanto, el riesgo no podría disminuir con la concentración del tráfico de navegación en ninguna de las rutas que consideramos. La reducción del riesgo de colisión de las ballenas puede ser necesario porque nuestra evaluación del número potencial de choques sugiere que es probable que excedan los niveles permisibles de impactos antropogénicos establecidos por las leyes de E.U.A.

Palabras Clave: Análisis de riesgo, modelado del hábitat, modelos aditivos generalizados, navegación comercial

Introduction

Marine spatial planning (MSP) provides a comprehensive framework for managing multiple uses of the marine environment (e.g., shipping, military training, and fishing) and has the potential to minimize environmental impacts and reduce conflicts among users (Crowder et al. 2006). MSP must be based on ecological principles to sustain ecosystem integrity. For example, one outcome of decision making should be healthy populations of top predators and prey species that affect the structure and stability of food webs and species that have strong effects on community structure and function (Foley et al. 2010). Spatially explicit risk assessments are a basic requirement of MSP because they link the distribution of these key species to the potential effects and distribution of anthropogenic activities (Stelzenmüller et al. 2010; Grech et al. 2011).

An example of the connections between users of the marine environment and the possibility for conflict recently occurred in Southern California (U.S.A.) (Figs. 1a & b) when the California Air Resources Board implemented the Ocean-Going Vessel Fuel Rule (hereafter, fuel rule). The fuel rule was intended to reduce emissions of particulate matter, sulfur oxides, and nitrogen oxides by requiring large, commercial ships to use cleaner-burning fuels when traveling within approximately 44 km (24 nautical miles) of the mainland coast (Soriano et al. 2008). Before implementation of the rule, a majority of ships traveled through the traffic separation scheme (TSS) adopted by the International Maritime Organization in the Santa Barbara Channel. Following implementation, a higher proportion of ships began traveling south of the northern Channel Islands (McKenna et al. 2012) to reduce the time spent using more expensive, cleaner fuels.

This shift resulted in increased shipping traffic in military ranges and raised concerns for maritime safety because the movement of ships outside a TSS is less predictable and thus increases the potential for collisions and oil spills. The U.S. Coast Guard (2010) initiated a study of the routes to the 2 largest ports in Southern California (Los Angeles and Long Beach) (Fig. 1c). Public comments submitted as part of this study included 2 primary concerns. The U.S. Navy and Air Force said any disruption of their military activities from increased shipping traffic could add to operational costs and limit capacity to support national security. Several nonprofit groups, the U.S. National Marine Fisheries Service, and the Channel Islands National Marine Sanctuary requested that the Coast Guard consider the risk of ships striking large whales.

Large whales are vulnerable to collisions with all vessel types, sizes, and classes throughout the world's oceans (Laist et al. 2001). Waters off Southern California include seasonal feeding areas for humpback (*Megaptera novaeangliae*) and blue (*Balaenoptera musculus*) whales (Calambokidis & Barlow 2004; Calambokidis et al. 2009), and aggregations of fin whales (*Balaenoptera physalus*) have been observed year-round (Forney et al. 1995). All 3 species are listed as endangered under the U.S. Endangered Species Act. The U.S. Marine Mammal Protection Act requires calculation of potential biological removal, defined as "the maximum number of animals that may be removed annually by anthropogenic causes while allowing the population to reach or maintain its optimum sustainable population." The phrase *optimum sustainable population* is defined as "the number of animals which will result in the maximum productivity of the population or the species, keeping in mind the carrying capacity of the habitat and the health of the ecosystem of which they form a constituent element" (16 U.S.C. 1362[3][9]). For the population of blue whales along the U.S. West Coast, the potential biological removal is 3 individuals (Carretta et al. 2011). Ship strikes of blue whales have been documented for almost 2 decades along the California coast, but the issue received increased attention in 2007 when at least 4 blue whales were killed by ship strikes off Southern California (Berman-Kowalewski et al. 2010).

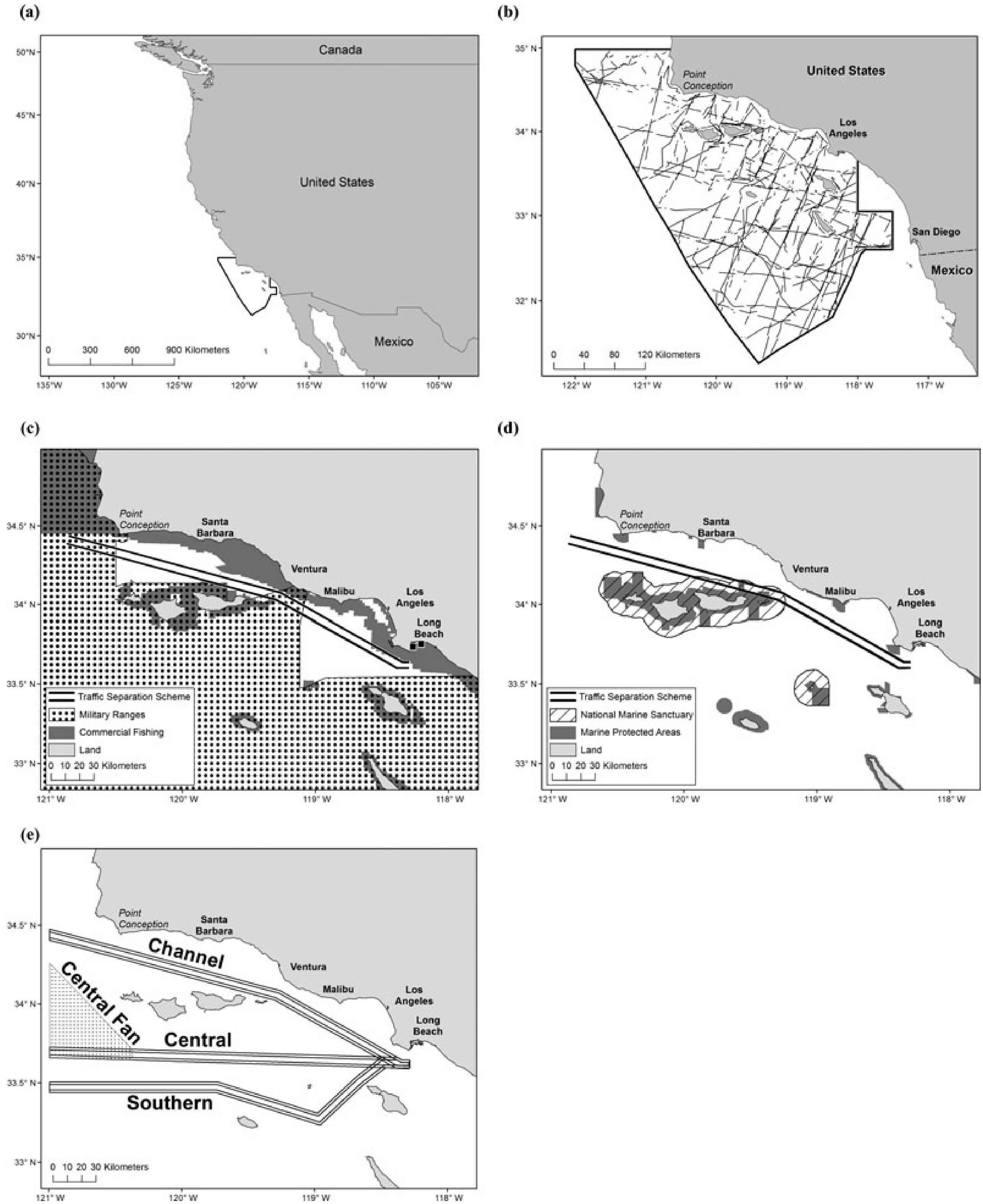

Figure 1. (a) Location of the Southern California study area (outlined in black) on the southwestern coast of the United States, (b) transects surveyed on cruises conducted primarily between August and November in 1991, 1993, 1996, 2001, 2005, 2008, and 2009, (c) primary human uses of the study area (shipping is represented by the 2 largest ports [black squares] and the traffic separation scheme), (d) Channel Islands National Marine Sanctuary and protected areas, and (e) alternative shipping routes considered in our analyses (Central Fan represents the option of establishing only the eastern portion of the Central route; thus, the fan [stippled] represents a range of possible approaches to this route).

We conducted a spatially explicit assessment of the risk of ships striking (hereafter, ship-strike risk) humpback, blue, and fin whales off the coast of Southern California. Specifically, we modeled the number of whales as a function of habitat variables and assumed ship-strike risk for alternative shipping routes was proportional to the number of whales predicted by the models to occur within each route. The proportion of whales within a shipping route that will be struck is a function of whale densities, volume of shipping traffic, ship speed, and whale behavior. Information is lacking on the functional form of these relations and other factors that may affect ship-strike risk. Consequently, we quantified the co-occurrence of whales and shipping traffic as has been done in recent ship-strike studies (Vanderlaan et al. 2009; Williams & O'Hara 2010) and studies used to modify the TSS to the port of Boston through Stellwagen Bank National Marine Sanctuary to reduce ship-strike risk for right whales (*Eubalena glacialis*) (Merrick 2005). We assumed all ships traveled within a single route and approximated the multi-route traffic patterns observed off Southern California after implementation of the fuel rule. If whale distributions are the only criteria used to select optimal shipping routes, conflicts may arise between shipping and other uses (Figs. 1c & d). Therefore, we also estimated the potential for conflict due to overlap between the routes and areas used for other purposes (e.g., military training, fishing, and protection of resources).

Methods

Data Collection

We used whale sightings and oceanographic data collected by the National Marine Fisheries Service's Southwest Fisheries Science Center from primarily August through November in 1991, 1993, 1996, 2001, 2005, 2008, and 2009. Surveys conducted from 1991 to 2008 covered broad regions of the U.S. West Coast. The 2009 survey focused primarily on Southern California and represents approximately 40% of the total effort and a high proportion of the whale sightings (Supporting Information). On all surveys, line-transect methods were used to collect marine mammal data during daylight hours. We used approximately 9300 km of survey effort (Fig. 1b) collected in Beaufort sea states of 5 or lower. Survey effort consisted of 2 observers using pedestal-mounted 25 × 150 binoculars to search for marine mammals from the flying bridge of the ship; a third observer searched by eye or with 7× handheld binoculars and recorded both sightings and survey conditions.

When marine mammals were detected, the vessel approached the group as needed to identify the species and estimate group size. Observers independently recorded their best, high, and low estimates of group size for each sighting. For mixed species sightings, observers also estimated the percentage of each species in the group. To obtain a single estimate of group size for each sighting, we averaged the best estimate from each observer or the best estimate multiplied by the percentage of each species. If no observers gave a best estimate, we averaged the low estimates.

Oceanographic sampling was systematically conducted during each survey. A thermosalinograph measured sea surface temperature and salinity every 2 minutes or more frequently. Surface chlorophyll concentration and mixed-layer depth were measured at approximately 55-km or shorter intervals. We defined mixed-layer depth as the depth at which the temperature was 0.5°C less than sea surface temperature. We obtained mixed-layer depth estimates from expendable bathythermograph drops and conductivity, temperature, and depth casts.

Whale Models

The shape of the study area (Fig. 1b) was determined by the availability of habitat data. We divided transects into continuous-effort segments of approximately 5 km as described by Becker et al. (2010). For each species, we used generalized additive models (GAMs) to relate the number of individuals in each segment to the following habitat variables: sea surface temperature and salinity, log-transformed surface chlorophyll concentration, mixed-layer depth, and distance to the 200-m isobath. This isobath represents the shelf break for many areas of the California coast and is an important habitat feature for many species of large whales (Fiedler et al. 1998; Becker et al. 2010). Relatively strong correlations were observed between surface chlorophyll concentration and sea surface temperature (–0.71), mixed-layer depth and sea surface temperature (–0.44), and mixed-layer depth and the distance to the 200-m isobath (0.55).

The distance traveled on effort in each segment was an offset in the models because the amount of effort varied among segments. Survey year was a linear term in the model for each species to account for long-term changes in whale abundance (Calambokidis & Barlow 2004; Moore & Barlow 2011). We used kriging to interpolate the oceanographic variables throughout the study area. Specifically, variograms were fit to the data collected from 1991 to 2008 along broad regions of the U.S. West Coast. We did not include 2009 data in the variograms because this survey occurred in a smaller area and sampling was conducted at a finer resolution. We used bilinear interpolation to extract values from the kriged grids at the midpoint of the transect segments. The 200-m isobath was derived from ETOPO1 (Amante & Eakins 2009), a 1 arc-minute global-relief model. We used negative values of the distance to the 200-m isobath in waters shallower than 200 m to differentiate shelf from slope waters.

We fit Poisson GAMs, in which overdispersion was corrected with a quasi-likelihood model, using the software package S+ (Version 8.1 for Windows, Tibco Software, Somerville, Massachusetts). The variables included in each model and the degrees of freedom for cubic smoothing splines were selected by an automated forward-backward stepwise approach and Akaike's information criterion (AIC) (Becker et al. 2010). Each model was fit 3 times, starting with a null model that included only the intercept. We used the dispersion parameter from the null model to calculate AIC values in the algorithm step.gam, which tested all predictor variables for inclusion in the second model as cubic smoothing splines with 2 or 3 degrees of freedom. For the third model, we used the dispersion parameter from the second model to calculate the AIC values in the algorithm step.gam, which tested all predictor variables for inclusion as linear terms or cubic smoothing splines with 2 or 3 degrees of freedom.

To ensure all potentially important variables were included in the final models, we evaluated the following for the 5 candidate models with the lowest AIC values in the second call to step.gam: $\Delta_i = \text{AIC}_{\text{candidate}} - \text{AIC}_{\text{best}}$, Akaike weights, cumulative Akaike weights, and evidence ratios (Symonds & Moussalli 2011). All variables and the highest degrees of freedom for each variable in any candidate model with $\Delta_i < 2$ were included in the final model (Becker et al. 2012). We used the percentage of explained deviance to assess model fit and annual ratios of observed to predicted number of whales to assess the accuracy of the predictions.

We used the models to predict the number of whales in each cell of a 2 × 2 km grid of the study area. Specifically, we made predictions for each year of survey data on the basis of the kriged oceanographic variables extracted at the center of each cell by bilinear interpolation and the distance to the 200-m isobath calculated at the center of each cell. We calculated whale density in each cell by dividing the predicted number of whales by 2 × effort × ESW × $g(0)$, where effort was assumed to be 1 km because effort was included as an offset in the model; the effective strip width (ESW) was 1.715 for fin and blue whales and 2.894 for humpback whales (Barlow 2003); and the trackline detection probability, $g(0)$, was 0.90 for all species (Barlow 2003). We summarized whale density throughout the study area by calculating the weighted average of the annual predictions, where the weights were the proportion of survey effort in the study area for each year. The average predictions do not account for within-year variation in species distributions; rather, they represent expected long-term patterns in humpback, blue, and fin whale distributions between August and November.

Spatial autocorrelation in species distributions can limit the interpretation of habitat relationships and restrict the transferability of habitat models in space and time (Dormann 2007). For each species, we developed Moran's I correlograms, with lags from 0 to 50 km in approximately 5-km increments, for the number of whales observed in the segments to test for spatial autocorrelation. Weights within each lag were defined by the inverse distance between points. For each lag, 95% confidence intervals were derived from 500 simulations in which the number of whales was randomly permuted. Spatial autocorrelation at individual lags was assumed to be significant if the observed Moran's I value was not included in the confidence interval.

Risk

We used Automatic Identification System (AIS) data collected between 15 September and 30 November in 2008 and 2009 (McKenna et al. 2012) to analyze traffic patterns for commercial ships that were at least 100 m in length. Specifically, we created linear ship transits by joining successive position reports with the same ship identifier that occurred no more than 1 hour apart and had less than a 30-degree difference between headings. These criteria minimized inaccuracies in the transits caused by uncertainty in ship locations. The transit analyses do not account for seasonal variations in shipping traffic; rather, they represent traffic patterns observed during a period that coincides with the whale surveys.

The 4 alternative shipping routes we considered (Fig. 1e) were derived from the 2008 and 2009 ship transits. The Channel route is a TSS adopted by the International Maritime Organization. The Central route spans our study area in a region of ship traffic south of the northern Channel Islands. The Central Fan represents the option of establishing only the eastern portion of the Central route; consequently, the fan represents a range of possible approaches to this route. We derived the boundaries of the fan from the 2009 ship transits. The location of the Southern route was constrained by the protected areas around Santa Barbara, Santa Catalina, and San Nicolas Islands. The lengths of the Channel, Central, and Southern routes are similar. All shipping routes were composed of an inbound lane, an outbound lane, and a middle traffic separation zone, following conventions for the TSS in the Santa Barbara Channel. For all routes, we assumed that no ships traveled in the traffic-separation zone.

We overlaid the number of whales predicted by the models in 2 × 2 km grid cells on a map of each shipping route. The predicted number of whales within the inbound and outbound lanes was summed to obtain the total number of whales within each route. We assumed all traffic occurred within a route and that ship density was one for all routes except the Central Fan route. To account for the lower ship density expected in the fan portion of the Central Fan route, we calculated ship density as the ratio of the area in the Central route that occurred in the fan to the area of the fan. We multiplied the predicted number of whales within each route by ship density to estimate ship-strike risk. Thus, ship-strike risk is a measure of the co-occurrence of whales and shipping traffic. We summarized the results by calculating the weighted average and standard error of the annual risk estimates, where the weights were the proportion of survey effort in the study area for each year. We defined the relative risk for each route as the difference between the average route risk and the average Channel route risk divided by the average Channel route risk.

Assuming all shipping traffic occurs in each route is helpful for identifying the route that has the smallest overlap with whale distributions. However, ship transits derived from the 2008 AIS data show that approximately 77% of shipping traffic occurred in the Channel route, approximately 12% of traffic occurred in the Central Fan route, and the remaining 11% was broadly distributed. Following implementation of the fuel rule in 2009, approximately 29% of shipping traffic occurred in the Channel route, 39% of traffic occurred in the Central Fan route, and the remaining traffic was broadly distributed south of the northern Channel Islands. Consequently, we also evaluated risk assuming traffic occurred in both the Channel and Central Fan routes, which captured the majority of the observed traffic in both years. This assumption resulted in Channel traffic estimates of 87% and Central Fan traffic estimates of 13% in 2008. In 2009 the Channel estimate was 43% and the Central Fan estimate was 57%.

Habitat-modeling studies suggest annual predictions of species distributions may contain substantial error, but average predictions can provide accurate summaries of expected long-term patterns in species distributions (e.g., Barlow et al. 2009). Consequently, we calculated the risk associated with a predominantly Channel traffic pattern (approximated from AIS data collected in 2008 before implementation of the fuel rule) and risk associated with a multi-route traffic pattern (approximated from AIS data collected in 2009 after implementation of the fuel rule) as the sum of the traffic percentage for each route multiplied by the average of the annual risk estimates calculated assuming all traffic occurs in the route. We also used the annual risk estimates to calculate the standard error of the risk associated with the multi-route traffic patterns. This approach allowed us to directly compare the risk estimates for the traffic patterns to the risk estimates that assume all traffic occurs within a single route.

Route-Use Overlap

The primary human uses of Southern California waters are shipping, military training, and fishing (Fig. 1c). We obtained dominant use areas for commercial fishing from the California Ocean Uses Atlas Project (NMPAC & MCBI 2010). Protected areas off Southern California (NMPAC 2011; CDFG 2012) have been designated by both state and federal governments for a suite of reasons ranging from water quality to protection of marine life (Fig. 1d). Waters off Southern California also contain the federally managed Channel Islands National Marine Sanctuary (Fig. 1d). Automatic Identification System data show that ships transit through a majority of these areas (McKenna et al.2012). Shipping traffic in the sanctuary is predominantly confined to the TSS, which overlaps with sanctuary boundaries. For each of these uses, we calculated the area that occurs in the inbound and outbound lanes of the shipping routes.

Results

The final models for each species (Table 1) differed in the variables selected or the shape of the relations (Supporting Information) and thus predicted distinct high-density areas for each species (Fig. 2). The habitat relations for all species were similar to those observed during fine-scale surveys off Southern California (Fiedler et al. 1998) and along the entire U.S. West Coast (Becker et al. 2010). Humpback whale habitat occurred in the northernmost portion of our study area (Fig. 2a), in productive coastal waters characterized by cold temperatures, low salinities, and high chlorophyll concentrations (Supporting Information). The habitat model explained 31.2% of the deviance. Although predictions of humpback whale numbers across all years were accurate, annual ratios of observed to predicted number of whales indicated the habitat model did not accurately explain the number of humpback whales in individual years (Supporting Information). Significant, positive spatial autocorrelation (Moran's $I = 0.010$–0.043) was observed for humpback whales across the distances considered (0–50 km).

Blue and fin whales were more broadly distributed (Figs. 2b & c), and the habitat models for these species explained lower percentages of deviance (14.9% for blue whales and 17% for fin whales) compared with humpback whales. However, ratios of observed to predicted number of whales for both species indicated greater accuracy in the predictions for individual years than the humpback whale model (Supporting Information). High densities of blue whales occurred along the 200-m isobath in waters that had intermediate mixed-layer depths and high concentrations of surface chlorophyll (Supporting Information). This habitat occurred close to shore and extended somewhat into the Santa Barbara Channel in the north. It also occurred in offshore waters farther south (Fig. 2b). Blue whales showed significant, positive spatial autocorrelation at 5 km (Moran's $I = 0.066$). Fin whale habitat (Fig. 2c) occurred in offshore waters, which were characterized by cold surface temperatures, intermediate mixed-layer depths, and intermediate concentrations of surface chlorophyll (Supporting Information). Fin whales

Table 1. Summary of generalized additive models relating the number of humpback, blue, and fin whales to year, distance to the 200-m isobath in kilometers (isobath), and oceanographic variables[a]

Species and candidate model	*df*	*Explained deviance*	*AIC*	Δ_i	*Akaike weight*	*Cumulative Akaike weight*	*Evidence ratio*
Humpback whale							
s(LNSC,2)	2.93	0.287	451.14	0	0.277	0.277	
s(LNSC,3)	3.89	0.297	451.24	0.09	0.264	0.541	1.05
SST+*s*(LNSC,2)	3.93	0.297	451.28	0.14	0.259	0.800	1.07
SSS+*s*(LNSC,2)	3.93	0.295	452.37	1.22	0.150	0.950	1.84
isobath+*s*(LNSC,2)	3.93	0.289	456.07	4.93	0.024	0.974	11.76
Blue whale							
isobath+*s*(MLD,3)+*s*(LNSC,3)	7.88	0.139	1005.37	0	0.392	0.392	
s(isobath,3)+*s*(MLD,3)+*s*(LNSC,3)	9.86	0.149	1006.14	0.76	0.268	0.660	1.46
s(isobath,2)+*s*(MLD,3)+*s*(LNSC,3)	8.86	0.143	1006.62	1.24	0.210	0.870	1.86
isobath+SSS+*s*(MLD,3)+*s*(LNSC,3)	8.88	0.140	1010.10	4.73	0.037	0.907	10.62
s(isobath,2)+SSS+*s*(MLD,3) + *s*(LNSC,3)	9.85	0.144	1010.93	5.55	0.024	0.932	16.05
Fin whale							
SST+*s*(MLD,3)+*s*(LNSC,3)	7.87	0.170	1656.59	0	0.99	0.99	
s(SST,2)+*s*(MLD,3)+*s*(LNSC,3)	8.88	0.171	1666.90	10.31	0.01	0.99	173.41
SST+SSS+*s*(MLD,3)+*s*(LNSC,3)	8.87	0.170	1668.20	11.61	0.00	1.00	331.89
isobath+SST+*s*(MLD,3)+*s*(LNSC,3)	8.87	0.170	1668.89	12.31	0.00	1.00	470.75
SST+*s*(MLD,3)+*s*(LNSC,2)	6.88	0.155	1670.63	14.04	0.00	1.00	1119.67

[a]*Abbreviations: SST, sea surface temperature (°C); SSS, sea surface salinity (psu); MLD, mixed-layer depth (m); LNSC, logarithm of surface chlorophyll concentration; df, degrees of freedom; AIC, Akaike's information criterion;* $\Delta_i = AIC_{candidate} - AIC_{best}$*. Terms are represented as smoothing spline functions with associated df (e.g., s(SST,2)) or linear terms (e.g., SST). All candidate models include a linear year term and are corrected for effort with an offset; the year and offset terms are not shown in the table. The 5 candidate models with the lowest AIC values are presented for each species. The final model for each species includes all variables and the highest df for the smoothing spline for each variable found in any candidate model with* $\Delta_i < 2$.

showed significant, positive spatial autocorrelation at 45 km (Moran's $I = 0.016$).

Ship-strike risk was highest for humpback whales under the assumption that all traffic occurred in the Channel route (risk = 3.58) and lowest under the assumption that all traffic occurred in the Southern route (risk = 0.93) (Fig. 3 & Table 2). The opposite pattern was observed for fin whales; risk was 6.39 for the Channel route and 13.70 for the Southern route (Fig. 3 & Table 2). For both species, risk assuming some distribution of traffic among routes occurred between these 2 extremes. Following implementation of the fuel rule (approximated from the multiroute traffic pattern observed in 2009), risk decreased from 3.32 to 2.41 for humpback whales and increased from 6.85 to 8.41 for fin whales (Table 2). The change in risk occurred because a higher proportion of ships began traveling south of the northern Channel Islands instead of using the TSS in the Santa Barbara Channel. Predictions of high densities of blue whales spanned the study area (Fig. 2b) and resulted in similar risk estimates among all routes and little change in risk following implementation of the fuel rule (Fig. 3 & Table 2). The variance in risk was high for all species (Table 2) because of interannual variability in distribution and availability of habitat.

We calculated the potential for conflict due to overlap between the shipping routes and areas used for other purposes. The Channel route had the least overlap with military ranges, but it was the only route that overlapped with the National Marine Sanctuary and other marine protected areas (Table 2). Fishing areas had the highest overlap with the Channel route; however, better fishing data are needed to determine how much fishing actually occurs within the TSS. The largest overlap was between the Central Fan route and military ranges because of the large area traversed by ships before entering the route.

Discussion

An average of 1 humpback whale, 1.8 blue whale, and 1.2 fin whale ship strikes were documented per year along the California coast from 2005 to 2010 (NMFS 2011). The documented number of strikes is an underestimate of the actual number of strikes because ship strikes have a low probability of detection (Laist et al. 2001). For example, Kraus et al. (2005) estimated a carcass-detection rate of 17% for right whales. The carcass-detection rate for humpback, blue, and fin whales could be <17% because right whales tend to float after death. If the carcass-detection rate is lower for these species, the actual number of strikes would be higher. To correct the observed number of ship strikes, we assumed a 17% carcass-detection rate and estimated that 5.9 humpback whales, 10.6 blue whales, and 7.1 fin whales were struck by ships each year. Potential biological removals, calculated on the basis of the definition in the U.S. Marine Mammal Protection Act, are 11.3 humpback whales and 16 fin whales for the U.S. West Coast population

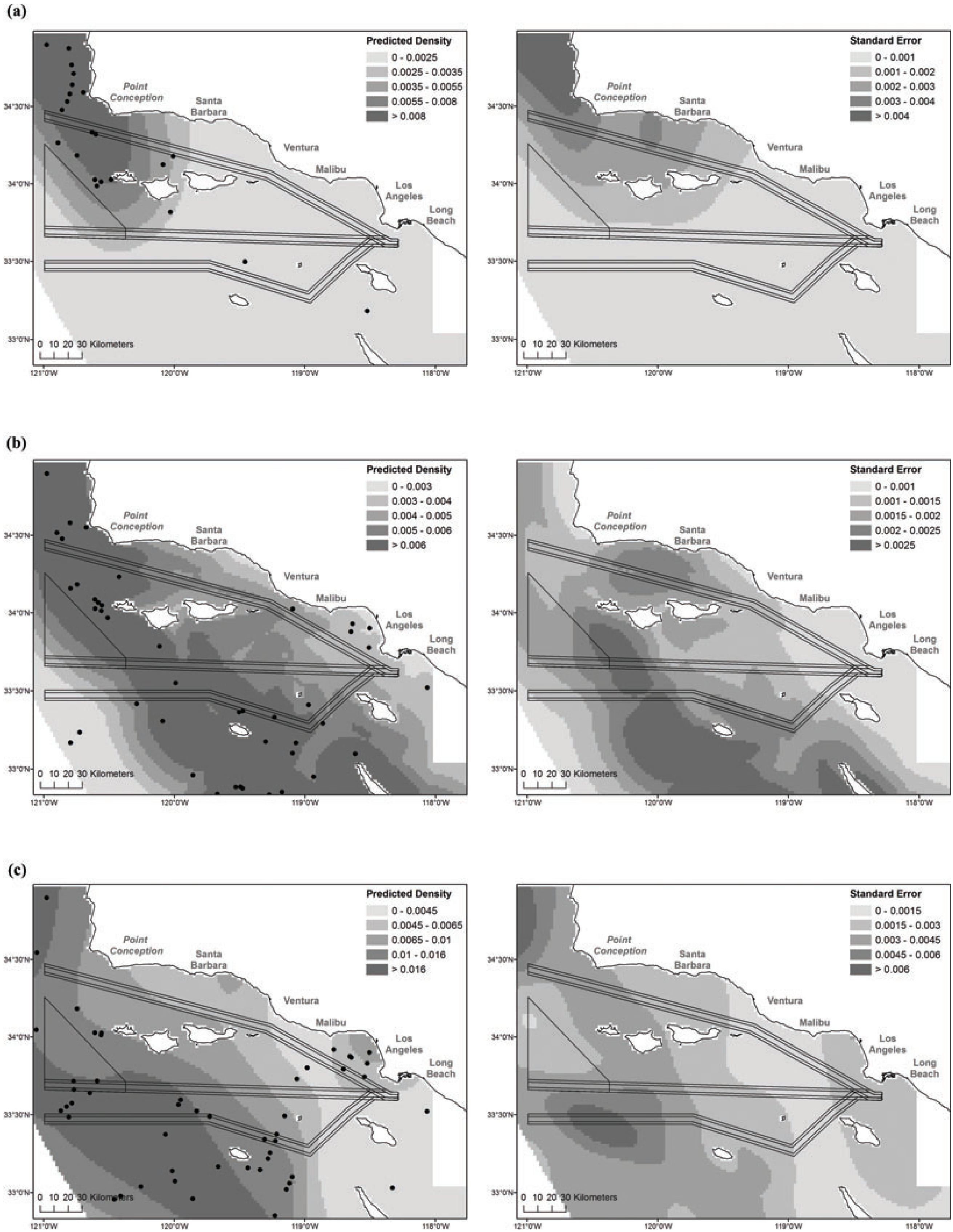

Figure 2. Mean predicted densities and standard errors for (a) humpback, (b) blue, and (c) fin whales (black dots, sightings) in the subset of the study area that overlapped with the shipping routes (black lines).

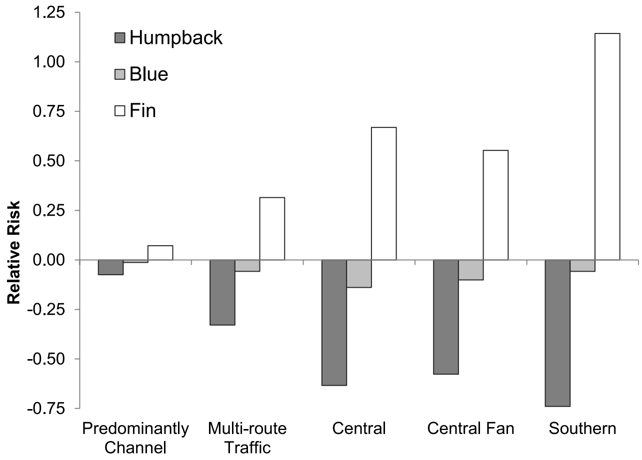

Figure 3. Relative ship-strike risk for 3 whale species. We calculated risk assuming all shipping traffic occurs in the Channel route (traffic separation scheme adopted by the International Maritime Organization). We compared this risk to risk calculated assuming all traffic occurs in alternative routes (Fig. 1e). Also compared are relative ship-strike risk for the predominantly Channel traffic pattern observed in 2008 and the multi-route traffic pattern observed in 2009. Negative values imply risk is higher in the Channel route than the alternative route, whereas positive values imply the alternative route has higher risk than the Channel route.

(Carretta et al. 2011). The estimated number of ship strikes for these species is below their potential biological removals and thus suggests the number of strikes may be sustainable. Even conservative estimates of the number of blue whale ship strikes, however, are higher than the potential biological removal of 3 individuals. Consequently, blue whale ship strikes likely exceed allowable levels established under U.S. laws.

Although these calculations only include ship strikes and a full assessment of the status of these species must also include fisheries entanglements and other anthropogenic effects, the potential population-level consequences of these removals are corroborated by observed trends in abundance. Increases in abundance over time have been observed for both humpback (Calambokidis & Barlow 2004) and fin whales (Moore & Barlow 2011) along the California coast. In contrast, there is no evidence that the blue whale population in the North Pacific is growing. There is evidence that blue whale occurrence off California has declined, but these declines are likely caused by a northward shift in their feeding areas (Calambokidis et al. 2009). Given the likelihood that blue whale ship strikes exceed allowable levels established under U.S. laws, further research is needed to determine whether ship strikes could be limiting population growth for blue whales and how to reduce ship-strike risk. Blue whales were distributed more evenly than humpback and fin whales off Southern California. Consequently, shifting traffic among the routes considered in our analyses did not reduce risk. Possibilities for reducing risk include fine-scale alterations of the existing TSS (e.g., narrowing the Channel route to minimize overlap with the 200-m isobath) and alternative management strategies, such as the seasonal management areas that have been used on the U.S. East Coast to reduce ship-strike risk for right whales (Lagueux et al. 2011).

For humpback and fin whales, these analyses represent a powerful tool for balancing user-user and user-environment conflicts when evaluating optimal shipping routes. Our results showed that the Central Fan route (Fig. 1e) had the highest spatial overlap with military ranges (Table 2). The distribution of southern shipping traffic following implementation of the fuel rule was even broader than this route (McKenna et al. 2012) and resulted in a magnified potential for user-user conflict. User-environment conflicts were also magnified because ship-strike risk for fin whales is not uniform throughout

Table 2. Ship-strike risk[a] to whales off Southern California calculated from annual predictions of the number of whales in each route and potential conflicts between use of alternative shipping routes (Fig. 1e) and other primary types of uses.[b]

Shipping routes[c]	*Humpback whales (SE)*	*Blue whales (SE)*	*Fin whales (SE)*	*Military (km^2)*	*Fishing (km^2)*	*Sanctuary (km^2)*	*Other protected areas (km^2)*
Channel route	3.58 (1.32)	5.91 (1.05)	6.39 (1.78)	289.84	61.77	185.94	38.30
Central Fan route	1.52 (0.43)	5.32 (1.11)	9.93 (1.86)	2563.28	0.77	0	0
Central route	1.31 (0.40)	5.09 (1.16)	10.66 (2.13)	650.23	0.77	0	0
Southern route	0.93 (0.24)	5.57 (1.52)	13.70 (2.89)	876.26	3.75	0	0
Predominantly channel	3.32 (1.20)	5.84 (1.02)	6.85 (1.67)				
Multi-route traffic	2.41 (0.80)	5.58 (1.00)	8.41 (1.56)				

[a] *We assumed risk was proportional to the mean predicted number of whales in each route. Risk was calculated assuming all traffic occurs within a route and by approximating traffic patterns observed before and after implementation of a rule intended to reduce air pollution by requiring ships to use cleaner-burning fuels when traveling close to the mainland coast.*
[b] *Estimated as the overlap between each route and areas used for other purposes.*
[c] *The predominantly Channel traffic pattern observed in 2008 was approximated on the basis that 87% of traffic occurred in the Channel route and 13% of traffic occurred in the Central Fan route. The multi-route traffic pattern observed in 2009 was approximated on the basis that 43% of traffic occurred in the Channel route and 57% of traffic occurred in the Central Fan route.*

the region of increased southern shipping traffic (e.g., the Southern route has a higher risk than the Central route [Table 2]). The general increase in ship-strike risk for fin whales associated with implementation of the fuel rule is consistent with fin whale stranding records. The number of documented fin whale ship strikes in 2009 was the second largest in 20 years of stranding records (NMFS 2011).

One possible way to reduce both of these conflicts is to designate a new TSS at an optimal location south of the northern Channel Islands and determine whether this new TSS should replace or be established in conjunction with the existing TSS in the Santa Barbara Channel. Our analyses of 4 alternative shipping routes show a contrast in ship-strike risk for humpback and fin whales (Fig. 3) because they have opposing areas of higher densities off Southern California (Figs. 2a & c). Specifically, selection of the route that has the lowest risk for one species (i.e., the Southern route for humpback whales or the Channel route for fin whales [Table 2]) resulted in maximizing risk for the other species. Having all shipping traffic occur in either the Central or Central Fan route reduced risk for fin whales (10.7 and 9.9, respectively) relative to having all traffic occur in the Southern route (13.7). It also provided a decreased risk for humpback whales that was only slightly less than the decrease achieved in the Southern route (Fig. 3).

The changes in risk observed after implementation of the fuel rule, however, suggest that distributing traffic between the Channel route and either the Central Fan or Central route may balance the risks for humpback and fin whales. Specifically, our comparison of risk following implementation of the fuel rule, assuming 43% of traffic occurred in the Channel route and 57% occurred in the Central Fan route, to risk assuming all traffic occurs in the Channel route showed intermediate changes in risk for both species (Fig. 3). The decrease in relative risk for humpback whales was −0.33 (range among routes: −0.07 to −0.74) following implementation of the fuel rule and the increase in relative risk for fin whales was 0.32 (range among routes: 0.07–1.14). Interannual variability in this region was too high to allow us to differentiate risk between the Central and Central Fan routes for either species. However, there were clear differences in the amount of overlap between these routes and other users. The Central Fan route has a shorter designated route than the Central route, which allows ships to choose their approach to the route and results in higher overlap with military ranges. Consequently, it may be useful to consider other users' needs when determining the length of the route in this area. For example, it may be more important to exclude shipping from certain areas within the military ranges. More data are needed to better understand the actual allocation of fishing effort and its overlap with the shipping routes.

We identified spatial autocorrelation at varying distances in the observations of all 3 species across the 7 years of surveys in our study area. The whale-habitat models are expected to reflect this autocorrelation. Although spatial autocorrelation does not necessarily generate bias in ecology analyses (Diniz-Filho et al. 2003), it can limit the interpretation of species-habitat relations and restrict the transferability of habitat models in space and time (Dormann 2007). Consequently, our models should not be used to make predictions outside the study area, where spatial autocorrelation may differ, or to infer mechanistic relations between whale distributions and individual habitat variables. It is also possible that spatial autocorrelation may differ in the future (e.g., in association with longer-term oceanographic variability); therefore, these models and the risk assessment should be updated periodically.

The uncertainty in our risk estimates was due primarily to interannual variability in species distributions and can be reduced by extending the time series of line-transect data and improving the habitat variables through finer-resolution sampling and incorporation of prey data. Seasonality in the risk estimates should also be assessed because fin whales are present off Southern California all year and some blue and humpback whales may have arrived before or remained after the period in which our data were collected. The risk estimates could also be expanded to incorporate the amount of time whales spend at the surface, how encounters with ships affect whale behavior, and effects of ship speed and traffic volume. Other potential threats to large whales in the California Current include noise from commercial shipping, entanglements in fishing gear, ocean-based pollution, and climate change (Halpern et al. 2009). These threats can be integrated in analyses of cumulative effects to assess consequences for the population viability of large whales.

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Supporting Information

Sample sizes and ratios of observed to predicted number of whales (Appendix S1) and functional forms for variables included in the generalized additive models (Appendix S2) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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