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Estimating reductions in the risk of vessels striking whales achieved by management strategies

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ABSTRACT

Methods to evaluate strategies to reduce the risk of vessels striking whales are needed to balance species protections with economic consequences. Previously used simplistic methods do not include important elements of vessel-strike risk. More complex methods often include parameters that have not been estimated for whales. Additionally, the whale and vessel metrics used in all methods are important because they may lead to biases in estimated risk reductions. We build a simple metric, Total PLETHd, from three components: (1) the relationship between vessel speed and the probability that a strike is lethal (PLETH), (2) vessel transit distance, and (3) whale distributions. Total PLETHd is calculated by multiplying estimates of whale distribution by the sum of transit distance multiplied by transit PLETH. We use this metric to assess risk reductions for North Atlantic right, humpback, fin, and sei whales on the United States East Coast. We found that a 10 kt speed restriction was necessary for reducing risk and that speed restrictions applied in broad areas defined by whale habitat were almost as effective as restrictions applied throughout all East Coast waters. While our areas were primarily defined to protect right whales, our results suggest they also protect humpback, fin, and sei whales. Total PLETHd represents an improvement over previous methods for estimating risk reductions because it addresses limitations in these methods. It can be used to estimate risk reductions for multiple species associated with management strategies, including changing vessel routes and implementing speed restrictions in different areas and time periods.

1. Introduction

Vessel strikes of large whales remain a conservation challenge throughout the world. For example, the International Maritime Organization (IMO) adopted nine proposals between 1997 and 2009 to reduce the risk of vessels striking large whales (hereafter, vessel-strike risk). The proposals focused on four species in three regions: North Atlantic right whales (*Eubalaena glacialis*; hereafter, right whales) in United States (U.S.) and Canadian waters and fin (*Balaenoptera physalus*), sperm (*Physeter macrocephalus*), and long-finned pilot whales (*Globicephala melas*) in the Mediterranean Sea (Silber et al., 2012b). Measures used to reduce vessel-strike risk typically involve changing vessel routes and slowing vessels down. The goal of measures that change vessel routes, such as shifting the location or configuration of traffic separation schemes (i.e., shipping lanes) or establishing areas to be avoided, is to reduce the co-occurrence of whales and vessels. The goal of measures that slow vessels down is to reduce the risk of lethal vessel strikes because studies have found that the probability of a lethal strike increases with vessel speed (Conn and Silber, 2013; Vanderlaan and Taggart, 2007). Additionally, slower speeds may allow whales and vessel operators more time to engage in avoidance behavior (e.g., Gende et al., 2019; Vanderlaan and Taggart, 2007).

Measures used to reduce vessel-strike risk may increase costs to the shipping industry through longer transit distances (e.g., from longer routes) or longer transit times (e.g., from slower speeds). These economic consequences must be balanced with the protection the measures

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provide to species. Consequently, methods to evaluate the conservation success or risk reduction achieved by these measures are critically important. Previously used methods have ranged from relatively simple, such as estimating the co-occurrence of whales and vessels (e.g., Redfern et al., 2013; Williams and O'Hara, 2010), to more complex, such as estimating mortality using encounter rate theory (e.g., Crum et al., 2019; Garrison et al., 2022; Martin et al., 2016; Rockwood et al., 2020).

Existing simple methods do not include some important elements of vessel-strike risk. For example, co-occurrence methods do not incorporate the role of vessel speed. Some methods that analyze vessel speeds to assess reductions in the probability of a lethal vessel strike achieved by speed restrictions do not incorporate spatial and temporal variability in whale distributions (e.g., Conn and Silber, 2013; Wiley et al., 2011). Existing methods that are more complex often require parameter estimates that are not easy to obtain for large whales. For example, encounter rate theory can be used to estimate the number of whale mortalities caused by vessel strikes, but requires estimates of whale swim speed, the probability of a whale being in the vertical strike zone (i.e., close enough to the surface to be at risk of a strike), and the probability of collision avoidance by whales and vessels. Rockwood et al. (2017) found that mortality estimates for blue (*Balaenoptera musculus*), humpback (*Megaptera novaeangliae*), and fin whales on the U. S. West Coast derived using encounter rate theory increased by 37 % when they changed the depth of the strike zone from one to two times the vessel draft. Crum et al. (2019) omitted the probability of a whale being in a strike zone and the probability of whale or vessel avoidance in their analyses of right whale vessel-strike mortality risk in a breeding area on the southeastern coast of the U.S. because they did not have estimates for these parameters. Simulations of whale movements have also been used to estimate mortality caused by vessel strike (van der Hoop et al., 2012). These methods are computationally expensive (Crum et al., 2019) and also require parameter estimates (e.g., turning angles associated with different behaviors) that may vary by habitat.

The whale and vessel metrics used in both the simple and complex methods are important because they may lead to biases in the risk estimates. For example, the right whale density model (Roberts et al., 2020) used by Garrison et al. (2022) did not accurately predict the total population size of right whales because it estimated density using independent sub-region models and did not cover the entire range of the species. Consequently, Garrison et al. (2022) estimated relative numbers of mortalities, rather than absolute values. The choice of vessel metrics is also critically important. Wiley et al. (2011) calculated the probability of lethal strikes using vessel speeds on individual transits and then averaged the probabilities for transits in each grid cell. The grid cell probabilities were then averaged to obtain values for the entire study area. These summary metrics were selected to ensure that vessel traffic patterns in the full study area were given equal weight. However, this summarization of vessel traffic may cause bias in the estimated risk because it does not correct for the length of each transit (i.e., short and long transits are assumed to contribute equally to vessel-strike risk; see supplemental material for examples). Similarly, Rockwood et al. (2017) used averages of parameters from all vessels (e.g., vessel speed and size) in a grid cell in their analyses of vessel-strike mortalities. Rockwood et al. (2020) noted that these averages can cause bias because they ignore the non-linear relationship between vessel parameters and vessel-strike mortality. They modified the approach of Rockwood et al. (2017) by estimating the number of mortalities for each vessel transit independently and then summing the mortalities in each grid cell.

We developed a simple metric, Total PLETHd, that can be used to assess changes in vessel-strike risk from different speed restrictions, in different areas, in different time periods, and for multiple species. This metric addresses many of the limitations in the previously used simple methods for estimating reductions in vessel-strike risk. It also retains simplicity by omitting parameters that are not well known for large whales. While we agree with calculating estimates of whale mortality caused by vessel strikes when possible, we wanted to provide an alternative metric that is easier to calculate and can be applied in a broad array of study areas, particularly areas where information about whale species is not available to parameterize more complex methods (e. g., swim speed, time spent close to the surface, etc.). Total PLETHd is built from three components (see methods for details): (1) the relationship between vessel speed and the probability that a vessel strike is lethal ("PLETH"), (2) vessel transit distance ("d"), and (3) whale distributions. The first and second components are obtained by summing (the "total" in Total PLETHd), rather than averaging.

We used Total PLETHd to assess the reduction in the risk of lethal vessel strikes to large whales in the U.S. East Coast Exclusive Economic Zone (hereafter, EEZ) through broad-scale vessel speed restrictions. Along the U.S. East Coast, Seasonal and Dynamic Management Areas were implemented by the U.S. National Oceanic and Atmospheric Administration (NOAA) in 2008 to protect right whales (NOAA, 2008). Seasonal Management Areas were established where the risk of a vessel striking a right whale is expected to be higher due to whale or vessel traffic density. Consequently, these areas differ in size (e.g., from approximately 1,500 to 23,000 km^2), are active during different times of year, and are implemented for different lengths of time (e.g., 2–5 months). When active, all vessels >65 ft (except vessels owned, operated by, or operated under contract to the U.S. government and law enforcement vessels engaged in enforcement or search and rescue) are required to travel at 10 kts or less in these areas. Smaller vessels are requested, but not required, to travel at 10 kts or less. Dynamic Management Areas are established in real-time when three or more right whales are seen within close proximity and remain in effect for 15 days. All mariners are encouraged to avoid these areas or reduce vessel speeds to 10 kts or less when transiting through them. However, these measures are voluntary and there is little cooperation with these requests to slow down (NOAA, 2020; Silber et al., 2012a).

Analyses of right whales struck within Seasonal Management Areas (Laist et al., 2014) and analyses comparing the number of right whales struck before and after management measures were implemented (NOAA, 2020) suggest that these measures have helped to reduce vessel strikes of right whales. However, there were 14 documented lethal (mortalities and serious injuries) vessel strikes of 13 right whales from 2008 through May 2023 in the U.S. (NOAA, 2020, 2023b), which suggests that further action is required to support the recovery of the species by reducing vessel strike risk. At least four of these strikes (two before 2019 and two after 2020) involved vessels smaller than 65 ft (NOAA, 2020, 2023b), which are not subject to the mandatory speed restrictions. Some of these strikes may also be the result of climate-driven changes in right whale habitat use that have occurred since 2010 (Meyer-Gutbrod et al., 2021; Record et al., 2019). As a result of these changes in habitat use, the Seasonal Management Areas may be too small and occur for too short a period of time to effectively protect right whales. Other whale species on the U.S. East Coast are also at risk of vessel strike (NOAA, 2023a; van der Hoop et al., 2013; van der Hoop et al., 2015) and it may be possible to enhance current regulations to improve protections for other species. We used Total PLETHd to quantify the risk reductions achieved by speed restrictions of 14, 12, and 10 kts and the effect of implementing these speed restrictions for the entire EEZ and in smaller regions containing higher whale densities. We considered North Atlantic right, humpback, fin, and sei (*Balaenoptera borealis*) whales in our analyses.

2. Materials and methods

2.1. Whale densities

Our study area is the U.S. East Coast EEZ, which extends ~200 nautical miles from the coastline between the northern boundary of Maine and the southern tip of Florida (Fig. 1). This area contains habitat for right, humpback, fin, and sei whales (Roberts et al., 2016a). Monthly predicted densities were acquired from the Duke University Marine

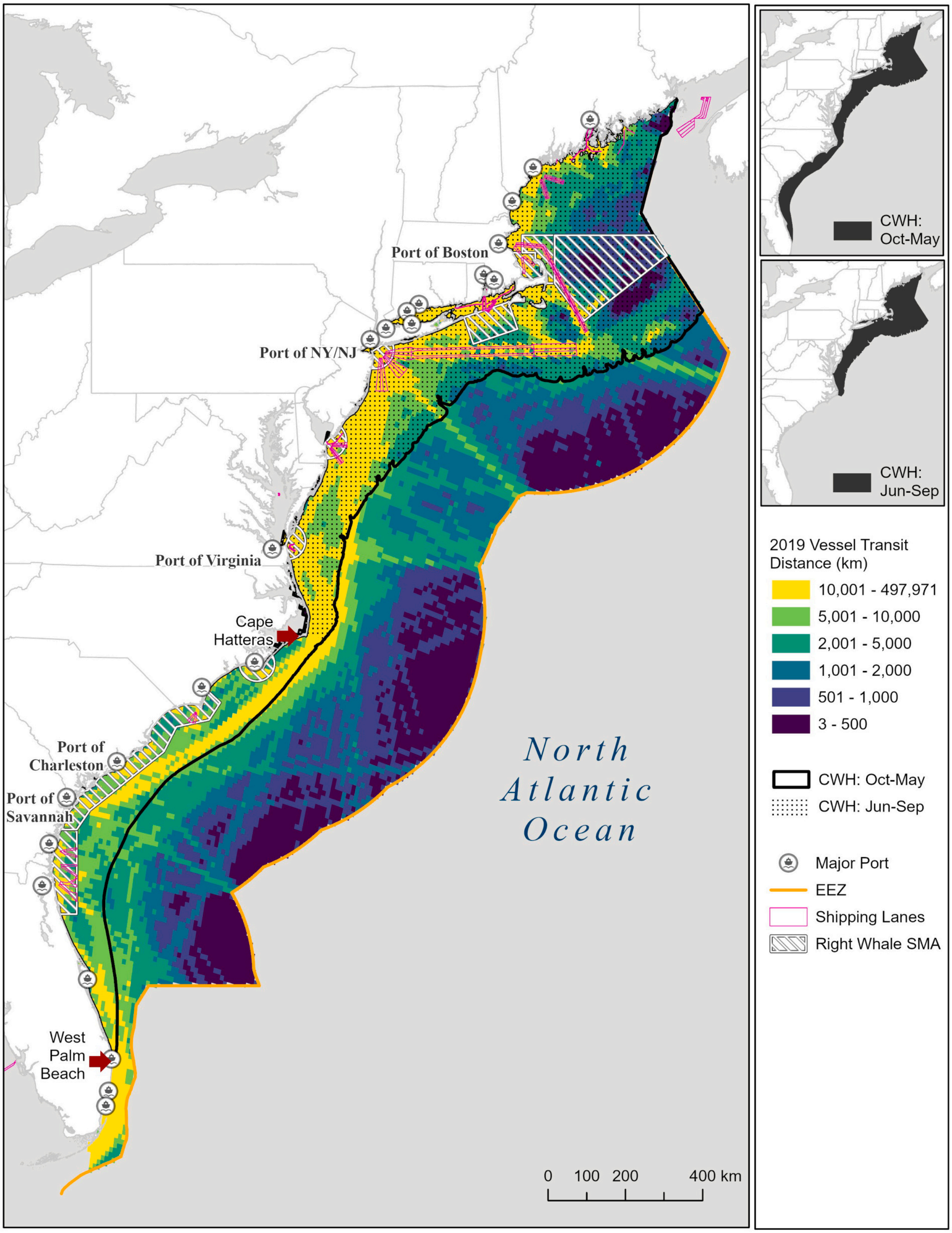

Fig. 1. The study area is delineated by the U.S. East Coast Exclusive Economic Zone (EEZ) (orange line) and overlaps with right whale Seasonal Management Areas (SMA). Vessel transit distance from 2019 is shown in a blue to yellow color ramp indicating low to high vessel traffic, respectively. Core whale habitat (CWH): Jun–Sep (see text for details and inset map) is depicted with black dots and represents CWH from June to September. Core whale habitat (CWH): Oct–May is outlined in solid black and represents core whale habitat from October to May. It includes the area of CWH from June to September, but extends along the continental shelf break to West Palm Beach, FL (see inset map). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Geospatial Ecology Laboratory website (https://seamap.env.duke.edu/models/Duke/EC/) for these four whale species: right whale (v. 11.1), humpback whale (v. 10), fin whale (v. 11), and sei whale (v. 8) (Roberts et al., 2016a; Roberts et al., 2016b, 2017; Roberts et al., 2018; Roberts et al., 2020, 2021). Densities represent the number of individual animals per 100 km^2. Densities of humpback, sei, and fin whale were predicted using models developed from approximately 1.1 million linear km of line-transect aerial and shipboard cetacean surveys conducted from 1998 to 2016 and were provided at a 10 km × 10 km gridded spatial resolution. Right whale densities were predicted for 2010–2018; these predicted densities are recommended for management purposes because they represent a period of habitat changes and population decline. The right whale density predictions were provided at a 5 km × 5 km gridded spatial resolution.

Density was modeled similarly for all species using the methodology of Roberts et al. (2016a). The goal of Roberts et al. (2016a) was to develop a consistent set of cetacean density models for U.S. Atlantic and Gulf of Mexico waters. They applied distance sampling (Buckland et al., 2001) and density surface modeling (Miller et al., 2013) to marine mammal survey data and candidate environmental covariates. Availability and perception biases were corrected for all species. Models for each species were updated as additional survey data, covariates, and information about species distribution changes became available (e.g., Roberts et al., 2020, 2021). These predictions represent the best available spatially explicit whale density estimates in our study area.

The grid for the predicted whale densities was not the same as the grid for the shipping data; therefore, we used the area-weighted average method of Woodman et al. (2019) to summarize the monthly predicted whale densities in the shipping grid cells. We only included shipping grid cells in our analyses that had at least 50 % of their area covered by whale density grid cells. We created total whale density estimates for each month by summing whale density estimates for all species. Total whale density is used to calculate Total PLETHd (Section 2.3) and ensures that all species are given equal weight in the risk assessment (Section 2.4).

2.2. Vessel traffic

Our study area is highly industrialized and is characterized by large amounts of vessel traffic. The U.S. East Coast contains several major ports, including the Port of Boston, Port of New York/New Jersey, Port of Savannah, Port of Virginia, Port of Charleston, and Florida Ports (Fig. 1). In addition to commercial shipping and transport, this area has other forms of vessel traffic, including fishing, cruise ships, working vessels, and passenger vessels. We used automatic identification system (AIS) data received by both low-orbiting satellite constellations (ORBCOMM) and terrestrial stations (USCG Nationwide Automated Identification System) to characterize vessel traffic. AIS is a maritime safety communications system that provides vessel information, including vessel identity, type, position, course, and speed. Use of AIS was adopted by the IMO in 2000 and became mandatory by December 31, 2004. Requirements for large vessels carrying AIS transceivers are determined at international levels by the IMO. At the national level in the U.S., the Coast Guard determines AIS carriage requirements for multiple vessel classes. Specifically, the Coast Guard requires any vessel that meets the following criteria to carry an operational AIS transceiver: vessels that are ≥65 ft in length; towing vessels of ≥26 ft in length and >600 hp; vessels certified to carry >150 passengers; vessels that contain dangerous or flammable cargo; and vessels that can restrict or affect navigation of other vessels (U.S. Coast Guard Navigation Center, see https://www.navcen.uscg.gov/ais-requirements). Vessels that are not required to carry AIS transceivers may voluntarily use them. We used AIS data from January 1, 2019 through December 31, 2019. We selected this time period because it was the most recent data available and was the best representation of current vessel traffic patterns. We processed the AIS data in a PostgreSQL database with a PostGIS spatial extension.

We obtained relevant vessel information, which included vessel type and size, from the AIS data and a third-party vessel database. The AIS data contain a field in which mariners enter vessel type and navigation status. The available options for this field are limited and the data provided by mariners often contains omissions and inaccuracies. Consequently, we used a third-party vessel database (https://ihsmarkit.com/industry/maritime.html) containing vessel characteristics for all propelled, seagoing merchant vessels of 100+ gross tonnage to supply missing or inaccurate vessel type information in the AIS data. Vessel types in the database are classified using a multi-leveled scheme with over 200 vessel type codes. For our analyses, we classified vessels into the following vessel types: bulk carrier, container, dredging, fishing, general cargo, law, medical, military, other, other cargo, other passenger, passenger (cruise), passenger/general, pilot, pleasure, pollution control vessel, port tenders/offshore work vessel, research, vehicle carrier, sailing, search and rescue, tanker, towing/pushing, and undetermined. We grouped these vessel types into five categories to assess broad differences in traffic patterns: Commercial, Fishing, Other, Working Exempt, and Working Non-Exempt (Table 1). Some categories contain vessel types that encompass a wide range of sizes and characteristics (e.g., the Other vessel category contains cruise ships and sailing vessels). Exempted vessels are not subject to the NOAA speed restrictions implemented in 2008 and include vessels engaged in enforcement or search and rescue activities, military vessels, and vessels owned, operated, or contracted by the federal government.

Each AIS data point is time stamped and indicates a vessel's speed over ground (SOG) and position. We connected temporally consecutive AIS data points belonging to the same vessel to create transit segments when the elapsed time between points was <2 h for terrestrial data and <4 h for satellite data. Transit segments were removed from the analyses when the reported SOG was missing, the reported SOG was ≥ 50 kts, or SOG calculated using the travel time and distance was ≥ kts. We clipped the transits using a 10 km × 10 km grid that was projected using a polar azimuthal equal-area projection for the Northern hemisphere (Brodzik et al., 2012). Our EEZ study area contained 9,156,100 grid cells. We calculated the distance for each of the clipped transit segments.

We summed vessel transit segment distances for the full year and for each month to understand temporal changes in traffic. We also summed vessel transit segment distances within grid cells, within the EEZ, and within core whale habitat (see Section 2.4). Finally, we explored how each vessel category contributed to total vessel traffic and we summarized the speeds traveled by each vessel category in 2 kt bins to understand how transit speeds differed between vessel categories and how transit speeds contributed to the risk of a lethal strike.

Table 1
Categories of vessel types that were used to summarize the automatic identification system (AIS) data.

	Vessel categories				
	Commercial	Fishing	Other	Working Exempt	Working Non-Exempt
Vessel types	Bulk carrier	Fishing	Other passenger	Military	Towing/pushing
	Container		Pleasure	Search & rescue	Port tenders/offshore work vessel
	General cargo		Sailing	Law	Dredging
	Vehicle carrier		Passenger (cruise)	Research	Pilot
	Tanker		Other	Medical	Pollution control vessel
	Other cargo		Undetermined		Resol-18

2.3. Total PLETHd

We developed a simple metric, Total PLETHd (Eqs. 1 and 2), to assess changes in risk for multiple whale species in large study areas. We used parameter estimates from Conn and Silber (2013) to estimate the relationship between vessel speed and the probability that a vessel-whale collision would be lethal, where $PLETH = \frac{1}{1+exp^{-(-1.905+0.217speed)}}$. We calculated PLETH for each segment of a vessel's transit. We distance weighted the PLETH for each segment by multiplying PLETH by the transit distance for each segment within a cell. We then summed all distance-weighted PLETH values within each cell, so that longer transit segments would have a greater influence than shorter transit segments. This additive approach is similar to the approach used by Rockwood et al. (2020) and to the mortality hazard defined by Conn and Silber (2013) as the sum in an area of independent hazards associated with the speed and length of individual transits. We then multiplied the summed, distance-weighted PLETH values by the total whale density estimate in each cell to incorporate heterogeneity in whale distributions, similar to previous studies that estimate risk using the co-occurrence of whales and vessels (e.g., Redfern et al., 2020; Redfern et al., 2013; Redfern et al., 2019; Williams and O'Hara, 2010), resulting in a Total PLETHd value for each cell (Eq. 1).

$$Total\ PLETHd_c = \rho_c \sum_{i=1}^{N} (PLETH_i \bullet d_i) \quad (1)$$

where ρ_c is the total whale density estimate in the cell c, i indexes transit segments in cell c, N is the number of transit segments in cell c, $PLETH_i$ is the probability of lethality calculated using the speed traveled on transit segment i, and d_i is the distance traveled on transit segment i. The total whale density estimate in each cell, ρ_c, represents the density for all species and was calculated for each month by summing whale density estimates for all species. Consequently, all whale species were weighted equally when calculating Total PLETHd. To obtain Total PLETHd for a given management strategy m (e.g., a management area, time period, or vessel category), we summed Total PLETHd$_c$ across all cells within the management strategy (Eq. 2).

$$\text{Total PLETHd}_m = \sum_{j=1}^{C} \text{TotalPLETHd}_{cj} \quad (2)$$

where j indexes cells associated with management strategy m, C is the number of cells associated with management strategy m, and Total PLETHd$_c$ in cell j is defined by Eq. 1.

2.4. Risk assessment

The monthly predicted whale densities represent expected long-term patterns in whale distributions. Long-term distribution patterns are the appropriate temporal resolution to use when evaluating broad, seasonal management measures. When estimating the reduction in risk achieved by management measures that change ship traffic, it is appropriate to use the most recent year of ship traffic data because it is the best approximation for current ship traffic. We calculated monthly Total PLETHd for the observed speeds within each grid cell (Eq. 1) in the EEZ to characterize spatial and temporal differences in risk. A grid cell was considered to be in the EEZ if its centroid fell within the EEZ boundary. When mapping monthly Total PLETHd, we scaled Total PLETHd for each cell between 0 and 1 using the minimum and maximum Total PLETHd values in the study area across all months.

We also calculated the percent reduction in Total PLETHd for multiple management strategies (Eq. 2). Specifically, we calculated Total PLETHd for the entire EEZ at observed speeds and at hypothetical speed restrictions of 14, 12, and 10 kts. Speed restrictions were calculated by changing the speed for all transit segments with observed speeds above the restricted value to the restricted value. For example, to calculate a 10 kt speed restriction, any segment whose speed was >10 kts was replaced with 10 kts.

We also calculated Total PLETHd assuming speed restrictions were only applied in important whale habitat. We defined important habitat as the set of grid cells with the highest 50 % of predicted densities for each species in each month. Cells that met the definition of important habitat for fin, sei, or humpback whales were assigned a value of 1. Cells that met the definition of important habitat for right whales were assigned a value of 3. For each species, cells that did not meet the definition of important habitat were assigned a value of 0. We summed the grid cell values for all species in each month. The summed values ranged from 0 to 6. We visually inspected the monthly maps and defined core whale habitat (CWH) as areas delineated by geomorphic features (e.g., bathymetric features and coastal cities) that contained a majority of grid cells with a value of 3 and higher. Using cells with a value of 3 and higher prioritizes including grid cells with the highest 50 % of predicted right whale densities in CWH. We prioritized right whales when defining CWH because right whales are critically endangered and vessel strikes are contributing to the risk of extinction for this species. A grid cell was considered to be in CWH if its centroid fell within the CWH boundaries.

We calculated the risk reduction achieved by the different speed restrictions and the application of speed restrictions throughout the EEZ or only in CWH for each month and summed the monthly values to characterize annual risk reductions. Monthly estimates of risk and vessel traffic in CWH were defined using the CWH associated with each month (Fig. 1). Although current federal speed restrictions on the U.S. East Coast typically apply to vessels >65 ft, we used vessels of all sizes in our analyses and assumed that all vessels adhere to the hypothetical speed restrictions. Finally, we summarized Total PLETHd by vessel category to measure the contribution of each vessel category to risk. All data processing, analyses, and mapping were completed using Python v. 3.10 and ArcGIS Pro v. 2.9.

3. Results

3.1. Whale densities and core whale habitat

Total whale density estimates were calculated for each month by summing whale density estimates for all species and used to calculate Total PLETHd. From June through September, predicted densities of right, humpback, fin, and sei whales were highest in northern shelf waters (i.e., north of Cape Hatteras, NC; Supplemental Information A). From October through May, high predicted densities extended south for all species (Supplemental Information A). Predicted densities of sei whales and, to a more limited extent, right whales also extended farther offshore in the south during these months.

Two CWH areas were defined to capture these distribution patterns (Fig. 1 and Supplemental Information A). Core whale habitat from June through September covers 231,286 km^2 (25 % of the EEZ) and extends from the northern boundary of the EEZ to Cape Hatteras, NC. Its eastward extent is defined by the continental shelf break (Fig. 1). Core whale habitat from October through May covers 339,136 km^2 (37 % of the EEZ). It includes the northern area, but extends along the continental shelf break to West Palm Beach, FL (Fig. 1).

3.2. Vessel traffic

Vessel traffic (as defined by transit distance) was higher in summer months and lower in winter months (Fig. 2A). The highest concentrations of vessel traffic occurred closer to shore (within approximately 150 km of the coast) and through, or in route to, shipping lanes and/or ports (Fig. 1). For the full year, 71 % of vessel traffic was found in CWH. Other (e.g., cruise and other passenger vessels; see Table 1) and Commercial (e.g., container, cargo, and tanker vessels; see Table 1) vessel categories contributed the most to vessel traffic in the EEZ (39 % and 35 %, respectively) and in the CWH (43 % and 26 %, respectively). Fishing, Working Non-Exempt, and Working Exempt contributed 11 %, 12 %,

Fig. 2. The volume of vessel transit distance in the U.S. East Coast Exclusive Economic Zone (EEZ) and in Core Whale Habitat (CWH; see text for details) by month (A) and by vessel category (B; Table 1): Other (e.g., cruise and other passenger vessels), Commercial (e.g., container, cargo, and tanker vessels), Fishing, Working Non-Exempt (e.g., dredging, pilot, and pollution control vessels), and Working Exempt (e.g., military vessels and vessels engaged in enforcement or search and rescue activities).

and 2 % of vessel traffic, respectively, in the EEZ and 15 %, 14 %, and 2 %, respectively, in the CWH (Fig. 2B).

Approximately 50 % of vessel traffic in the Other vessel category traveled at 0–10 kts, 14 % at 10–14 kts, 13 % at 14–20 kts, and 23 % at 20+ kts (Fig. 3A). Across all vessel categories, the Other vessel category contained 81 % of the vessel traffic traveling at the fastest speeds (20+ kts) in the EEZ (Fig. 3). Fifteen percent of Commercial vessel traffic traveled at 0–10 kts, 40 % at 10–14 kts, 41 % at 14–20 kts, and 4 % at 20+ kts (Fig. 3B). Most of the vessel traffic for Fishing, Working Non-Exempt, and Working Exempt (i.e., 87 %, 73 %, and 55 %, respectively) occurred at speeds <10 kts (Fig. 3C, D, and E).

3.3. Risk assessment

Observed Total PLETHd varied in space and time. In the EEZ and CWH, higher Total PLETHd was observed from May through July and lower Total PLETHd was observed from November through February (Fig. 5A). Total PLETHd was higher in the north than the south, in all months (Fig. 4). In the south, Total PLETHd was highest from December through March (Fig. 4). The CWH contained a majority of the risk (i.e., Total $PLETHd_{CWH}$ > 75 % of Total $PLETHd_{EEZ}$) in all months.

Contributions to Total PLETHd by vessel category followed the same patterns in the EEZ and CWH. Commercial vessels contributed the most to Total PLETHd (EEZ–46 %, CWH–42 %), followed by Other (EEZ–29 %, CWH–31 %), Fishing (EEZ–17 %, CWH–19 %), Working Non-Exempt (EEZ–6 %, CWH–6 %), and Working Exempt (EEZ–2 %, CWH–2 %) (Fig. 5B).

Applying hypothetical speed restrictions of 14, 12, and 10 kts to vessel traffic in the EEZ resulted in 5 %, 10 %, and 18 %, respectively, reductions in Total PLETHd (Table 2). Applying hypothetical speed restrictions to vessel traffic in the CWH resulted in 4 %, 8 %, and 15 %, respectively, reductions in Total PLETHd. Applying speed restrictions only within CWH captured the majority of the risk reduction (84–87 %) obtained when speed restrictions were applied in the entire EEZ (4–15 % risk reduction in CWH versus 5–18 % risk reduction in the EEZ).

4. Discussion

4.1. Using speed restrictions to minimize the risk of a lethal vessel strike

Our results suggest that a 10 kt speed restriction applied in areas defined by core habitat for multiple whale species (CWH) was almost as effective at reducing the risk of a lethal vessel strike as applying speed restrictions throughout all East Coast EEZ waters. From June to September, CWH occurs in northern shelf waters and captures the highest vessel-strike risk for right, humpback, fin, and sei whales (Fig. 4). From October through May, CWH includes all U.S. shelf waters to capture the increased vessel-strike risk for these species in the south during this time period (Fig. 4). The CWH covers 25 % and 37 % of the EEZ during these respective time periods. Along the U.S. East Coast, Seasonal Management Areas were implemented by NOAA in 2008 to protect right whales (NOAA, 2008). These Seasonal Managements Areas are smaller and implemented for shorter time periods than our CWH and require most vessels 65 ft or longer to transit at 10 kts or less. However, 14 vessel strikes of 13 right whales resulting in mortality or serious injury have been documented from 2008 through May 2023 in the U.S. (NOAA, 2020, 2023b), which suggests that further action is required to support the recovery of the species by reducing vessel strike risk. One action proposed by NOAA is expanding these speed restriction areas in space and time (NOAA, 2022). Our CWH is similar to the expanded speed restriction areas and support the study by Garrison et al. (2022) that shows that a 10 kt speed restriction in the expanded areas reduces vessel strike risk for right whales. Our results also suggest that these areas provide protections for humpback, fin, and sei whales. Finally, our study shows that Commercial and Other (e.g., cruise and other passenger vessels; see Table 1) vessel categories would be the most impacted by speed restrictions.

Reducing vessel speeds to 14 kts within the entire EEZ provided little risk reduction (i.e., 5 %). However, a 10 kt speed restriction reduced the risk by 18 %. The larger reduction in risk at 10 kts versus 14 kts is a result of the lower probability of a lethal strike (PLETH) for vessels traveling at 10 kts (i.e., PLETH = 0.57 at 10 kts; PLETH = 0.76 at 14 kts; Conn and Silber, 2013). It is also a result of observed vessel speeds. In particular, the observed speeds for a majority of vessel traffic (68 % in the EEZ) are ≤ 14 kts (Fig. 3) and are not affected by the 14 kt speed restriction. We also looked at risk reduction in CWH and used the shelf break to define the eastward boundary of CWH. While this boundary captures a majority of the areas with higher whale densities, it misses an area of higher densities that occurs beyond the shelf break in the mid-Atlantic from October to May. The importance of this area should be considered in future analyses. Right whales were weighted more heavily than other species in the definition of CWH because they are listed as Critically Endangered on the IUCN Red List of Threatened Species (Cooke, 2020). This weighting was used to ensure that cells with higher predicted right whale densities were protected by vessel speed restrictions. Garrison et al. (2022) used encounter rate theory to estimate the reduction in right whale mortalities that could be achieved by implementing speed restrictions in broad areas along the U.S. East Coast. Their broad areas were defined as the areas of highest risk to right whales. Our CWH was defined using the highest densities of right, humpback, fin, and sei whales and is similar to the broad areas identified by Garrison et al. (2022), which suggests that these broad areas may provide ancillary

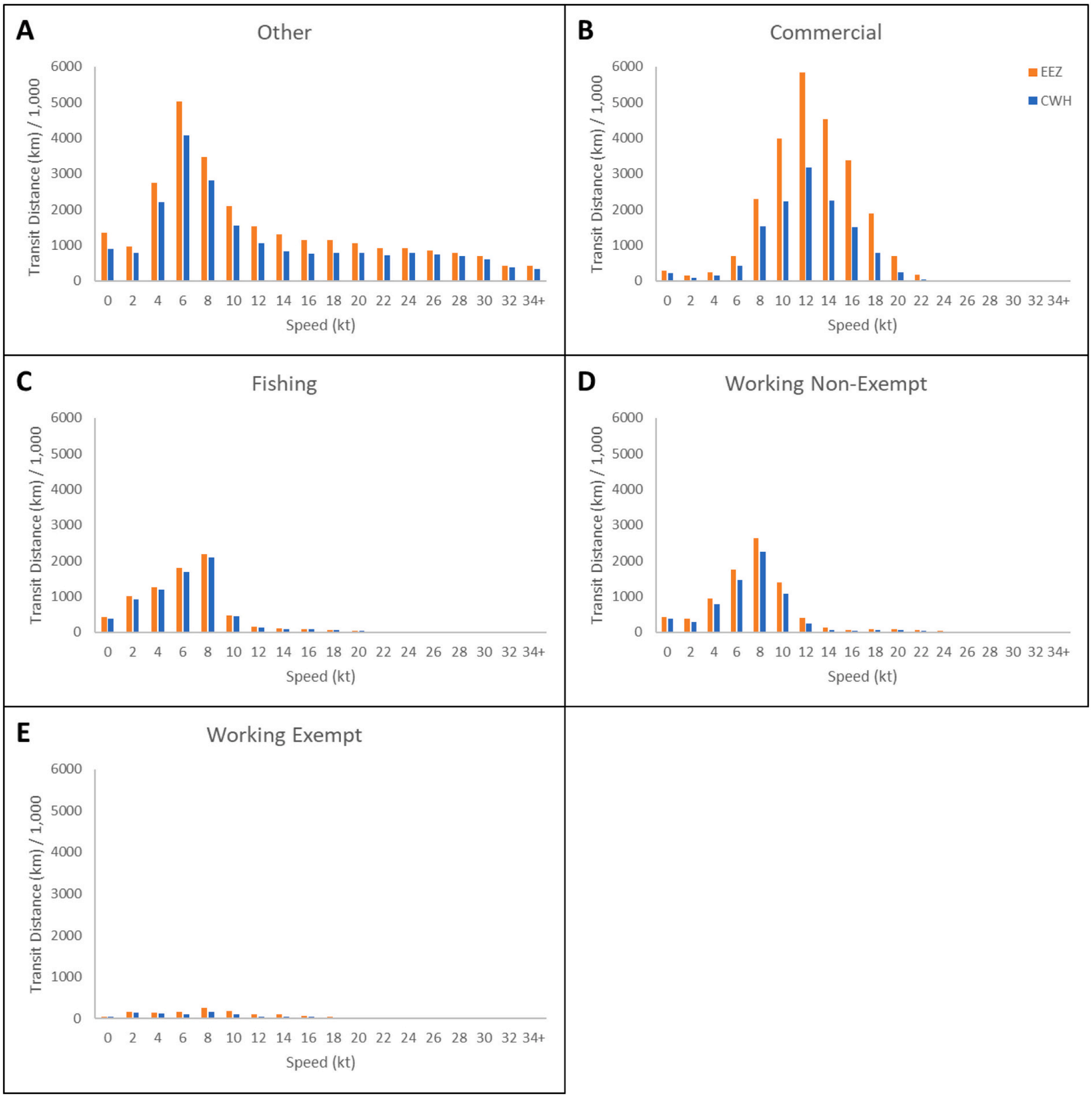

Fig. 3. Vessel transit distance in the U.S. East Coast Exclusive Economic Zone (EEZ), shown in orange, and in Core Whale Habitat (CWH), shown in blue, summarized in 2 kt speed bins for vessel categories (Table 1): Other (A; e.g., cruise and other passenger vessels), Commercial (B; e.g., container, cargo, and tanker vessels), Fishing (C), Working Non-Exempt (D; e.g., dredging, pilot, and pollution control vessels), and Working Exempt (E; e.g., military vessels and vessels engaged in enforcement or search and rescue activities). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

benefits for these other species.

We found that reducing vessel speeds within CWH captured the majority of the risk reduction (84–87 %) obtained when speed restrictions were applied in the entire EEZ (i.e., 4–15 % risk reduction in CWH versus 5–18 % risk reduction in the EEZ). The CWH captured a high percentage of the total risk reduction in the EEZ because it contained higher whale densities and higher densities of vessel traffic. Consequently, speed restrictions can be effective when applied in areas that are smaller than the EEZ, but broader than the current Seasonal Management Areas, which range in size from approximately 1,500 to 23,000 km^2 and were implemented in 2008 to protect right whales in areas where the risk of vessel strike was expected to be higher due to whale or vessel traffic density (NOAA, 2008).

Our results are similar to the results obtained by Garrison et al. (2022) using an encounter rate model developed for right whales. Specifically, Garrison et al. (2022) also found that implementing speed restrictions in areas broader than the Seasonal Management Areas, but smaller than the entire EEZ, accounted for the majority (i.e., 89 %) of their total possible risk reduction. However, they found an approximately 28 % reduction in right whale vessel strike risk when 10 kt speed restrictions were implemented in their broad areas, which are similar to our CWH, compared to our 15 % risk reduction. Their estimated risk reduction may be higher because our analyses included right, humpback, fin, and sei whales. Humpback, fin, and sei whales can occur beyond the shelf, which could have resulted in higher risk estimates offshore and, concomitantly, lower risk reduction when implementing a 10 kt speed restriction in CWH.

We estimated reductions in risk using Total PLETHd and weighted all species equally when calculating Total PLETHd. Whether right whales should be given higher weights in the Total PLETHd calculation can be considered in specific management applications. We weighted species equally when we calculated Total PLETHd to determine whether

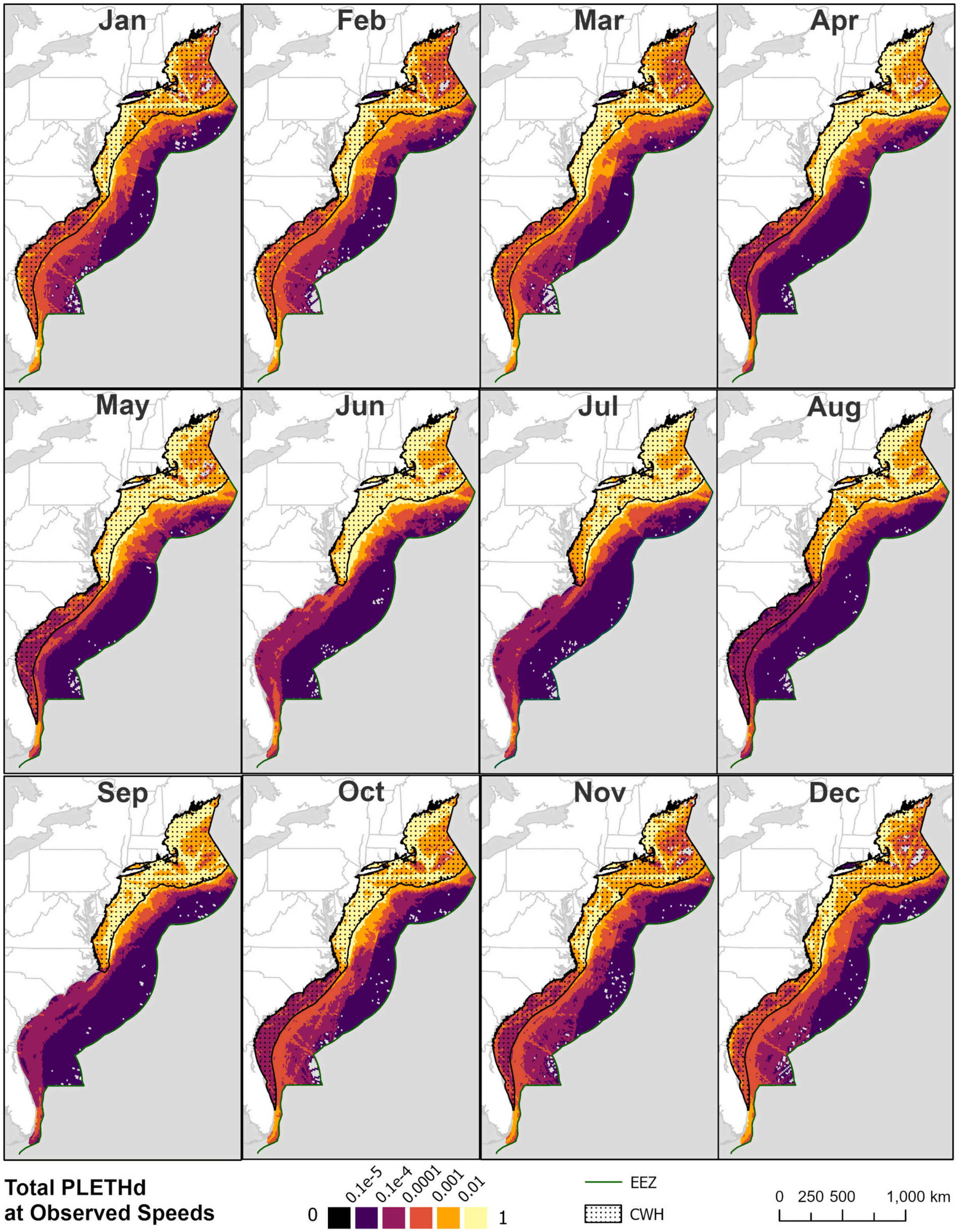

Fig. 4. Observed Total PLETHd (2019) by month represented with a black to yellow color ramp indicating lower to higher risk, respectively. Total PLETHd was scaled between 0 and 1 for each cell using the minimum and maximum Total PLETHd values in the study area across all months. The study area is delineated by the U.S. East Coast Exclusive Economic Zone (EEZ; green line) and Core Whale Habitat (CWH; black dots; see text for details). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

applying speed restrictions in the CWH, which was defined to ensure speed restrictions were implemented in areas of higher right whale densities, provided ancillary benefits to other large whale species. Total PLETHd could also be calculated for each species to compare the risk reduction achieved among species. Specific management applications should also consider the variability in risk reductions associated with the uncertainty in the predicted whale densities. The low and high confidence intervals for the predicted whale densities in each grid cell could

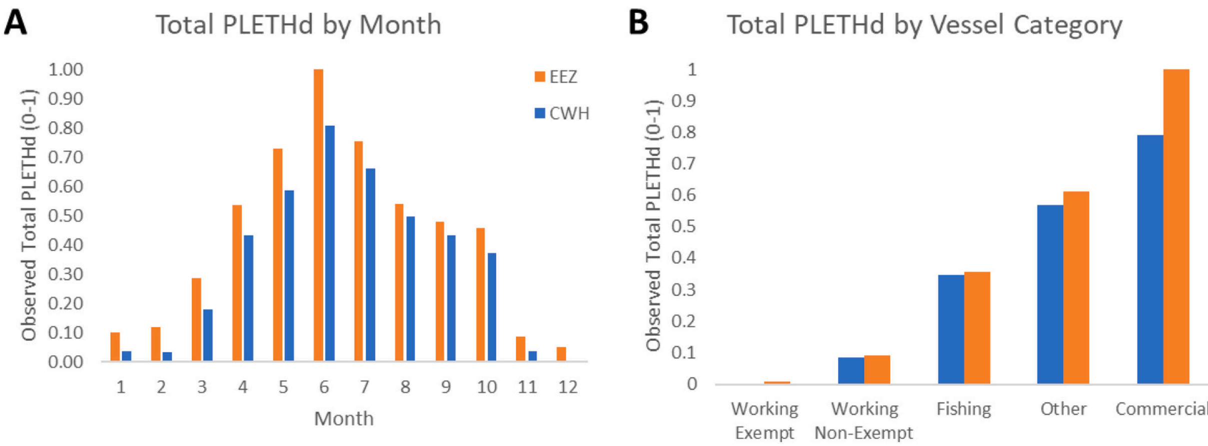

Fig. 5. Observed Total PLETHd (2019) in the U.S. East Coast Exclusive Economic Zone (EEZ) and in Core Whale Habitat (CWH; see text for details) by month (A) and by vessel category (B). Total PLETHd was scaled between 0 and 1 using the minimum and maximum Total PLETHd values in the EEZ and CWH across months or vessel categories.

Table 2
Annual Total PLETHd reduction (%) at hypothetical speed restrictions imposed on vessel traffic throughout the U.S. East Coast Exclusive Economic Zone (EEZ) and only in Core Whale Habitat (CWH).

Speed restriction	Total PLETHd reduction *Speed restricted in EEZ*	Total PLETHd reduction *Speed restricted in CWH*	Total PLETHd reduction in the EEZ captured by applying speed restrictions only in CWH
14 kt	5 %	4 %	87 %
12 kt	10 %	8 %	85 %
10 kt	18 %	15 %	84 %

be used in the Total PLETHd calculations to assess variability in risk reductions.

When identifying areas for speed restrictions, managers should consider the extent to which traffic will be affected and the type of vessels that will be affected. The majority of vessel traffic (71 % as defined by the amount of transit distance) was contained in the CWH, even though the CWH only covered a small percentage of the area within the EEZ. Therefore, reducing the area in which speed restrictions are applied does not necessarily correspond to the same reductions in the amount of vessel traffic that is affected. In our study area, Commercial and Other vessel categories contributed the most to risk because they had the highest amounts of vessel traffic and some of the highest vessel speeds; consequently, these vessel categories would be the most impacted by speed restrictions. The Other vessel category contains a broad range of vessel types and these vessel types could be assessed individually in future analyses.

When evaluating potential risk reductions, managers must consider whether speed restrictions should be mandatory or voluntary. Over a decade of research on the U.S. East and West Coasts shows low cooperation with voluntary speed restrictions (e.g., Freedman et al., 2017; McKenna et al., 2012; Morten et al., 2022; NOAA, 2020; Silber et al., 2012a). Mandatory speed restrictions achieved high compliance when they were implemented and enforced on the East Coast (Silber et al., 2014). A recent assessment of compliance with these mandatory speed restrictions (NOAA, 2020) showed 81 % compliance between 2018 and 2019, but that compliance varied spatially and by vessel category. These studies suggest that mandatory speed restrictions are needed to achieve risk reductions. Our calculations assume 100 % compliance with speed restrictions. Realized risk reductions are likely to be smaller than our estimates because compliance with mandatory speed restrictions may be <100 %. Additionally, speed restrictions on the U.S. East Coast are currently applied in much smaller areas and enforcement of speed restrictions in larger areas and compliance with these speed restrictions will need to be assessed.

4.2. Total PLETHd

Total PLETHd provides a relative estimate of vessel-strike risk. It cannot be used to estimate the number of mortalities caused by vessel strikes because it excludes many of the parameters needed to estimate mortalities. Specifically, Total PLETHd excludes parameters that are frequently unknown for large whales and can vary among habitats, including whale swim speed, the proportion of time a whale spends close enough to the surface to be at risk of a strike, and the probability of collision avoidance by whales and vessels. Although Total PLETHd cannot be used to estimate mortality, Total PLETHd represents an improvement over previously used methods for estimating risk reductions because it addresses many of the limitations in these methods. Consequently, Total PLETHd may be an appropriate metric to estimate risk reductions from management strategies in areas where less information about large whale species (e.g., swim speed, time spent close to the surface, etc.) is available.

Total PLETHd incorporates elements of several methods for calculating the risk of vessel strikes to whales. Similar to the methods developed by Wiley et al. (2011) and Conn and Silber (2013), Total PLETHd uses the relationship between vessel speed and the probability that a vessel strike is lethal (PLETH). Multiple PLETH curves have been developed and provide different probability estimates for a lethal strike at the same speed. For example, Vanderlaan and Taggart (2007) estimate a 0.31 probability of a lethal strike for a vessel transiting at 10 kts. In contrast, Conn and Silber (2013) estimate a 0.57 probability of a lethal strike for a vessel transiting at 10 kts. We used the most recently developed PLETH curve (Conn and Silber, 2013), which uses approximately twice the amount of vessel-strike data as Vanderlaan and Taggart (2007) and represents the best available probability estimates at the time these analyses were conducted. As new PLETH curves become available, they can be used in the Total PLETHd calculations, which enables Total PLETHd to be easily updated. The effect of vessel size on the probability that a vessel strike is lethal is not included in existing PLETH curves or in our analyses. It could be incorporated in the future by adjusting the PLETH component of Total PLETHd.

Total PLETHd is calculated by summing (the "total" in Total PLETHd) the vessel transit distance ("d") multiplied by the probability that a vessel strike is lethal ("PLETH") calculated at the speed traveled on the transit. This additive approach is similar to the approach used by Rockwood et al. (2020) and to the mortality hazard defined by Conn and

Silber (2013). This additive approach is an improvement over unweighted averaging because an unweighted average does not take into account the amount of vessel traffic in a given area or time period. For example, an unweighted average treats all transits as equal, regardless of their length. It also treats all areas and time periods as equal, regardless of the amount of traffic they contain. Consequently, the use of unweighted averages can lead to underestimates of risk.

The final component of Total PLETHd is multiplying the summed, distance-weighted PLETH values by an estimate of whale distribution throughout the study area. This component is similar to previous studies that estimate risk using the co-occurrence of whales and vessels (e.g., Redfern et al., 2020; Redfern et al., 2013; Redfern et al., 2019; Williams and O'Hara, 2010) and enables Total PLETHd to incorporate temporal and spatial heterogeneity in whale distributions. Our analyses used predicted whale densities, but any estimate of whale distribution throughout a study area (e.g., probability of occurrence or encounter rates) could be used. However, it is important to understand how the estimate of whale distribution changes what is estimated by Total PLETHd. For example, using the probability of occurrence to calculate Total PLETHd does not account for different numbers of whales that may be present in different areas that have the same probability of occurrence. Uncertainty in estimates of whale distribution can easily be incorporated in Total PLETHd. For example, the expected range of Total PLETHd values could be calculated using the high and low confidence intervals estimated for predicted whale densities. Alternatively, multiple Total PLETHd values could be calculated using simulated whale distributions and summary statistics could be generated for the Total PLETHd values.

5. Conclusion

There is a significant, positive relationship between vessel speed and the probability that a vessel strike is lethal for a whale (Conn and Silber, 2013; Vanderlaan and Taggart, 2007). Previous studies suggest that vessel speed restrictions have reduced the risk of lethal vessel strikes (Conn and Silber, 2013; Laist et al., 2014). However, the current spatial and temporal scales at which speed restrictions are implemented along the U.S. East Coast are inadequate because lethal vessel strikes of large whales remain an important management issue (NOAA, 2020, 2023a, 2023b; van der Hoop et al., 2013). Therefore, new strategies to reduce this source of mortality must be considered. It has been suggested that speed restrictions be implemented in larger areas and for longer periods of time (Laist et al., 2014; van der Hoop et al., 2015). Our results showed that a 10 kt, rather than 14 kt, speed restriction was necessary for reducing risk and that speed restrictions applied in CWH were almost as effective as speed restrictions applied throughout the U.S. East Coast EEZ. The CWH represents broad areas and long time periods that were primarily defined to ensure protection of right whales. Our results also suggest that a 10 kt speed restriction in CWH provides protections for humpback, fin, and sei whales. From June to September, CWH occurs in northern shelf waters and captures the highest vessel-strike risk for right, humpback, fin, and sei whales (Fig. 4). From October through May, CWH includes all U.S. shelf waters to capture the increased vessel-strike risk for these species in the south during this time period (Fig. 4). Finally, our study shows that Commercial and Other (e.g., cruise and other passenger vessels; see Table 1) vessel categories would be the most impacted by speed restrictions.

Total PLETHd provides a relatively simple risk metric that can be used to estimate potential risk reductions associated with alternative management strategies, including changing vessel routes, implementing different speed restrictions (e.g., 10 versus 14 kts), and implementing speed restrictions in different areas and for different time periods. It incorporates spatial and temporal differences in vessel speeds, vessel traffic, and whale distributions. Solutions to human-wildlife conflicts often require stakeholder support. Total PLETHd can help achieve support for management strategies to reduce vessel-strike risk because it is easy to use and produces results that are easy to interpret. Economic trade-off analyses (e.g., Samhouri et al., 2021; White et al., 2012) can be used to combine risk reductions estimated by Total PLETHd with the costs associated with vessels traveling at slower speeds. These analyses allow stakeholders to identify solutions that balance species protection with potential costs to the shipping industry.

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CRediT authorship contribution statement

Jessica V. Redfern: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Writing – original draft, Writing – review & editing. **Brooke C. Hodge:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Writing – original draft, Writing – review & editing. **Daniel E. Pendleton:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Writing – original draft, Writing – review & editing. **Amy R. Knowlton:** Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing. **Jeffrey Adams:** Conceptualization, Data curation, Formal analysis, Writing – review & editing. **Eric Patterson:** Conceptualization, Writing – review & editing. **Caroline Good:** Conceptualization, Writing – review & editing. **Jason J. Roberts:** Conceptualization, Data curation, Formal analysis, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jessica Redfern reports financial support was provided by Marine Mammal Commission. Jessica Redfern reports financial support was provided by Lindy Johnson Fund at the New England Aquarium. The results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect the views of NMFS, NOAA, or the Department of Commerce.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2023.110427.

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