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Managed and unmanaged whale mortality in the California Current Ecosystem

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ABSTRACT

Whales serve important biological and cultural functions in the California Current ecosystem (CCE). Due to concerns regarding anthropogenic impacts on whales, the California Ocean Protection Council articulated a goal to achieve zero mortality for CCE whales, with a target of creating a statewide plan by 2022. Achieving zero mortality is a laudable but difficult goal as success depends on understanding the existing sources of mortality, the opportunities for policy change, and coordination of activities across the entire CCE. This review synthesizes the available research on drivers of mortality for nine whale species in the CCE and existing policy that addresses those drivers. Five main threats contribute to whale mortality in the CCE and are currently targeted through relevant policy responses: entanglement, vessel strikes, noise, water quality, and marine debris. Three threats remain largely unaddressed in management, despite their contribution to lethal and sublethal impacts on whales: nutritional stress, disease, and predation. Ultimately, sources of whale mortality are interconnected and their impacts span both geographic and jurisdictional boundaries, necessitating a holistic approach to managing whale mortality in the CCE.

1. Introduction

The California Current ecosystem (CCE) is a highly productive marine environment that comprises several ecologically and economically important temperate habitats. Each provides numerous social-ecological benefits from British Columbia, Canada to Baja California, Mexico [32]. The CCE also serves as a migration corridor, sporadic foraging grounds, and year-round habitat for a number of protected whale species that often overlap with anthropogenic activity (Fig. 1; [10]). Changes within the ocean environment can augment interactions between whales and humans, which may lead to whale mortality events such as entanglements and vessel strikes [149].

The presence of resident and transient whales is important to the overall structure and function of the CCE as well as the human values derived from it. Eighteen species of whale have been observed along the west coast of the United States [117], with humpback (*Megaptera novaeangliae*), gray (*Eschrichtius robustus*), blue (*Balaenoptera musculus*), and fin (*B. physalus*) whales being the most encountered species. Whales influence multiple marine ecosystem functions including carbon storage and fisheries production [87,128]. They facilitate oceanic nutrient cycling through input via feces and urine, nutrient dispersion, and deep-sea food provisioning through carcass deposition [37,143,166]. Whales are also key players in marine food webs, making up an important prey source for other CCE predators and exerting selective pressures on their own prey as well [143,152].

In addition to their key ecological roles, whales have long been important to humanity. Modern society tends to appreciate whales for their intrinsic values as well as non-consumptive uses, including whale

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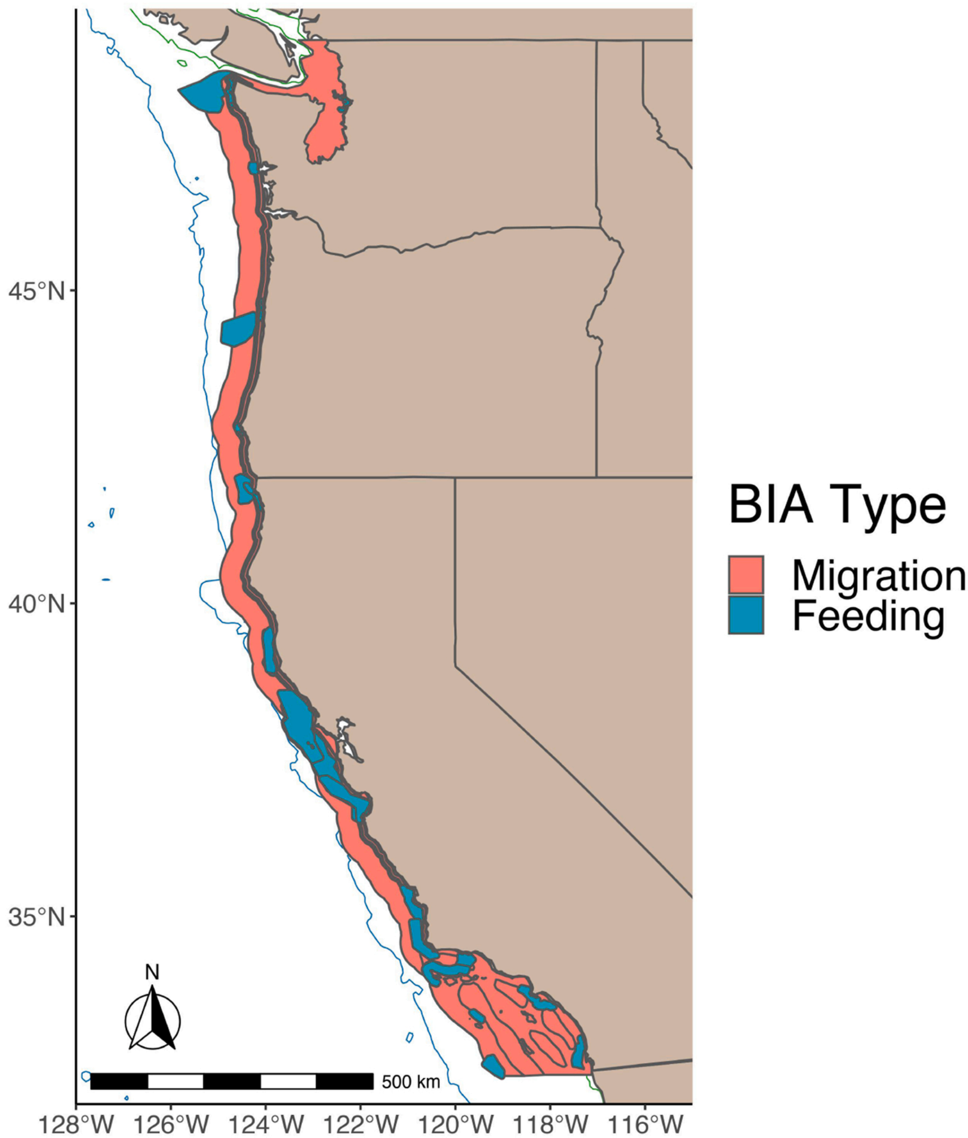

Fig. 1. A Map of the California Current extending from Vancouver Island, Canada in the north to Baja California, Mexico in the south. Lines of bathymetry show the location of the 40-fathom line (−73 m, green) and the continental shelf margin (−2000 m, blue). Shaded areas show the Biologically Important Areas (BIAs) that have been identified for three large whale species in this review, including areas where blue, humpback, and gray whales feeding aggregations are regularly detected (in blue) and the gray whale migration corridor (in pink). Other whale species included in this review use these waters but information on their BIAs is unavailable. Data source: [15,16].

watching [33,94,158]. However, whales have historically been ascribed subsistence and spiritual value by the people living alongside the CCE, with some contemporary Indigenous peoples in the CCE still enacting traditional whale hunts [98]. In the recent past, large whales were a key economic resource for coastal and non-coastal peoples. Commercial whaling led to the decimation of up to 90% of global whale populations [143,176] and, in response, the development of extensive policy and management decisions, including a moratorium on commercial whaling by the International Whaling Commission (IWC) [74,107].

As some whale populations, such as gray whales [142], have rebounded in the absence of whaling pressure, other threats to their recovery have emerged. For example, whale entanglement in fishing gear within the CCE has increasingly affected blue, gray, and humpback whales over the past decade [118]. Vessel strikes also cause significant mortality. Based on recorded events, vessel strike has particularly affected endangered fin and humpback whales [62] and non-endangered gray whales [163]. Recorded instances of entanglement and vessel strike represent a small percentage of the number of events taking place [146]; together, entanglement in fishing gear and strikes from vessels have been identified as key factors inhibiting the recovery of CCE whales [19,71,89]. However, other human activities may interact additively or synergistically with other stressors faced by whales and may be responsible for unknown levels of mortality. For example, an Unusual Mortality Event impacting eastern North Pacific gray whales from 2019 to 2020 was not tied to entanglement or vessel strike but has been linked to starvation compounded by human disturbance (e.g., low prey availability, stress from navigating around ships, fishing activities, construction on the migration route) [28]. Furthermore, anthropogenic climate change is expected to disrupt numerous ocean dynamics, negatively impacting whale recovery [31] while simultaneously impacting other coastal industries [149].

In response to rising levels of mortality for CCE whales, the California Ocean Protection Council (OPC) recently unveiled a new management target. In their strategic plan [19], OPC articulated the goal to develop a statewide strategy by 2022 to protect California's whales and sea turtles. The target of the management plan is to achieve zero mortality for these populations. In the strategic plan, points related to "Vision Zero" highlight actions related to entanglement (including collaboration and support with the state's fishing gear working group, testing fishing gear innovations that reduce entanglement threats, and funding the transition away from drift gillnet fishing) and vessel strikes (develop a permanent statewide vessel speed reduction program). In addition, the plan mentions the need to research and analyze "impacts of whale strikes from the shipping industry and other sources of whale (and turtle)

Target 3.3.5: Develop a statewide whale and sea turtle protection plan by 2022 with a target of zero mortality (Vision Zero). As a component of this overall plan, develop and initiate a funding strategy to reduce the risk of entanglement in California fishing gear by 2020.

Partners: CDFW [California Department of Fish & Wildlife], FGC [Fish & Game Commission], ARB [Air Resources Board]

Actions

- Collaborate with the California Dungeness Crab Fishing Gear Working Group to reduce the risk of whale entanglement in California fishing gear; fund priority projects recommended by the Working Group to address data gaps and enhance results. (OPC Lead)
- Provide funding for the state's drift gillnet transition program — consistent with SB 1017 (Allen, 2018) — and work towards the target of elimination of large mesh drift gillnets off the California coast by 2024. (OPC Lead)
- Support research and analysis of impacts of whale strikes from the shipping industry and other sources of whale and turtle mortality, including noise and marine debris from land-based sources. (OPC Lead)
- Support the testing of fishing gear innovations, such as "pop-up" fishing technologies, in 2021. (OPC Lead)
- With ARB, coastal air districts, ports, and the National Marine Sanctuary Program, develop a permanent, statewide, Vessel Speed Reduction Program that incentivizes the shipping industry to prevent whale strikes, reduce coastal air pollution, and minimize marine noise pollution.

Fig. 2. OPC's strategic goal for Vision Zero mortality [19].

mortality, including noise and marine debris from land-based sources" (Fig. 2; [19]). However, effectively determining the total impact of human actions on whale populations and achieving Vision Zero requires accounting for all known sources of whale mortality, their relation to each other, and any deficiencies in existing whale protection policies.

This synthesis aims to respond to this need, through reviewing academic literature and government technical memoranda to identify factors that contribute to CCE whale mortality and policy responses designed to address these factors. Results point to a nuanced landscape of whale mortality, where many factors contribute to whale mortality, through the accumulation of direct and indirect sources (Fig. 3). Discrete sources of mortality (e.g., entanglement, vessel strikes) are being addressed to varying extents with targeted policy responses and may offer the opportunity for effective responses that reshape these pressures on shorter-term timeframes. Chronic and diffuse mortality pressures (e.g., nutritional stress, disease) are more complex and indicative of broadscale changes in ocean conditions. Unlike discrete counterparts, these mortality sources often lack clear levers to pull or avenues for effective policy responses and may appear out of reach for the task of addressing whale mortality. Considering these "managed" and "unmanaged" sources in concert offers a holistic view of mortality, offering a better-informed starting point for policy efforts to reduce whale mortality overall.

2. Literature review

This synthesis draws on published literature and policy documents to review the biology and management of whale mortality in the CCE. Nine large whale species are considered in this work, including: humpback, gray, blue, fin, minke (*B. acutorostrata*), sei (*B. borealis*), sperm (*Physeter macrocephalus*), North Pacific right (*Eubalaena japonica*), and killer whales (*Orcinus orca*). In May 2020, authors met in a virtual workshop to develop search terms around sources of whale mortality, and to determine geographic range and species foci (see Supplement). In May - June 2020, authors used Web of Science to pull a corpus of literature based on search terms. Using the screening tool Covidence (www.covidence.org), two reviewers screened each abstract for inclusion in this review based on relevant topic, geographic scope, and species. Literature was also added to the review on an ad hoc basis from reviewer suggestions, new publications in the field, and to expand geographic scope where informative.

Authors identified relevant policy documents and other agency publications (e.g., press releases, management updates) through targeted searches of state and federal agency websites. NMFS Marine Mammal Health and Stranding Response Program (MMHSRP) West Coast Region Marine Mammal Stranding Network provided data on entanglement and stranding. Entanglement data includes reports of living or dead whales observed at sea or on shore with human-made materials (including rope, net, monofilament line, traps, debris, etc.) attached to them. Entanglement observations are reported to the NMFS West Coast Region and confirmed by NOAA staff or another expert through direct observation, review of photos/videos, or other criteria [146]. Entanglement data covered the years 1982–2019 and included reports from the U.S. (California, Oregon, and Washington). The dataset also includes confirmed entanglements reported from Canada and Mexico if the source of entangling material could be confirmed as originating in the U.S. Stranding data includes reports of living or dead whales observed on the shore, as well as dead whales observed at sea [115]. The stranding dataset covered the years 2006–2019 and included reports from California, Oregon, and Washington. Only confirmed records from 2010 were used in this analysis due to improved confidence and data quality (pers. comm., NOAA affiliates).

3. Managed sources of mortality

3.1. Entanglement

3.1.1. Biology

Entanglement in fishing gear is implicated as a primary source of mortality in the two most recent status reviews of baleen whales [30, 176] and is often-cited in mortality studies both within and beyond the CCE as a source of concern (e.g., [149,184]). Entanglement can result in mortality in various ways, including drowning, suffocation, and health decline as a result of injury or restricted movement [14,22,108]. Studies on the U.S. East Coast demonstrate that drag from fishing gear can be energetically costly and physiologically stressful for individual whales

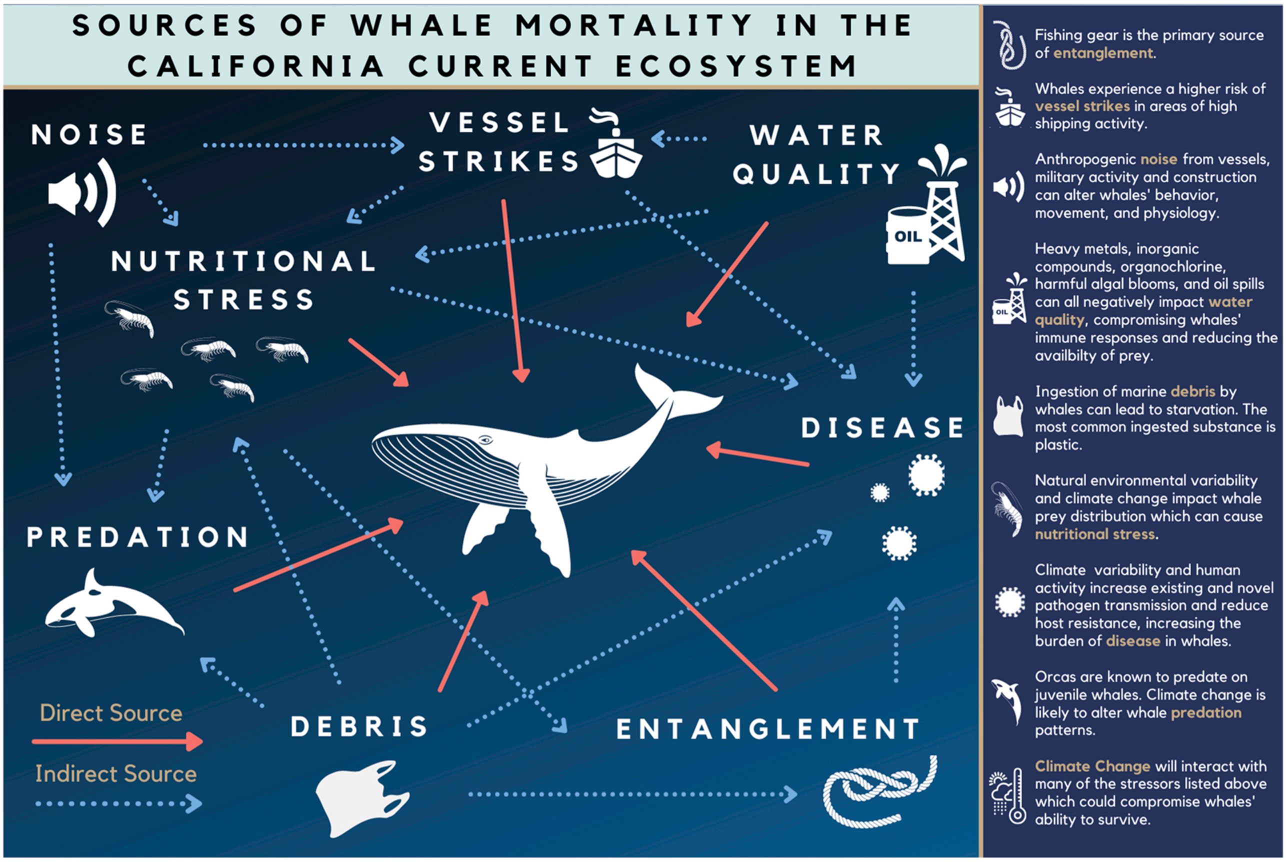

Fig. 3. Interacting sources of mortality in California Current Ecosystem Ecosystem. .

[95,181], and can have population-level impacts by reducing reproductive capacity of female whales and increasing the impact of parasites and the likelihood of disease [24,182].

On the U.S. West Coast between 2010 and 2019, an average of 28.4 entanglement cases (i.e., confirmed reports of whales with attached human-made materials) were reported annually [146]. There has been a general increase in reported entanglements on the U.S. West Coast since 2013 with some variability (Fig. 4A). Variability may be attributed to multiple factors including changes in abundance and distribution of whales and prey, environmental conditions, fishing and other human activities, and public reporting rate [146]. Out of confirmed cases, 89.4% of entangled whales were alive at time of reporting; this may suggest that whales are sometimes able to disentangle or that many entangled whales die and sink undetected [146].

Of the nine whale species in this analysis, there were reported entanglements for seven (gray, humpback, minke, fin, sperm, blue, and killer whales) between 2010 and 2020. Humpback and gray whales are the most frequently entangled species on the West Coast (64.6% and 28.8% of all 274 entangled cases identified to species, respectively). Most unidentified whales (N = 10) are also likely gray or humpback [21]. Greater case numbers for these species are likely influenced by their proximity to shore, relatively long periods of overlap with entangling gear during annual migrations, and greater population size. Body morphology [146] and foraging behaviors, including feeding off the bottom in the case of gray whales and acrobatic maneuvering in the case of humpbacks, may also be contributing factors. Entanglements on the West Coast have been reported in all months, though patterns vary by species. Humpback whale entanglements are high through the summer and fall, peaking in August, while gray whale entanglements peak in the spring (Fig. 4C). Most entanglements are observed in California, the West Coast state with the longest coastline (Fig. 4D). Most entanglements in California are observed from central and southern California, but this may be due to increased reporting near high-use ocean areas with more “eyes on the water” [146].

Most entanglements (52.8%) cannot be traced to specific fisheries, gear types, or areas of occurrence. Of known sources, pot/trap gear and netting have been the gears most frequently associated with whale entanglements on the U.S. West Coast (Fig. 4B; [146]). Gillnets are historically a common source of entanglement for gray whales, likely due to whale abundance and spatial overlap with gillnet fisheries [22,146], but gillnet entanglement rates have been decreasing since 2000, coincident with increasing gillnet regulations in the late 1990 s [146]. Humpback whales are most commonly entangled in commercial Dungeness crab gear, representing 62.9% of the 89 cases where gear type could be identified. The number of confirmed entanglements associated with pot/trap gear was particularly high in 2016 [146,149]. An important yet poorly understood subset of entanglements result from lost, abandoned, or discarded gear [12,59]. Distinguishing between entanglements related to lost gear versus active gear is difficult because whales can carry gear for long periods of time, giving the gear time to degrade [146]. The most recent estimate for West Coast Dungeness crab fisheries is 11% gear loss (estimated for Puget Sound fishery; [8]), though this rate varies based on whale presence, oceanic conditions, and fishing practices. Determining the area where a whale was first entangled is challenging, as gear is not always retrievable or clearly marked. Just 21% of confirmed entanglements in the U.S. West Coast were linked to known gear origin; the majority of these were cases of gear originating from the same region where the entanglement event was detected. In a small number of cases whales carried U.S. fisheries gear across national borders, resulting in confirmed entanglements in Canada or Mexico stemming from U.S. fisheries (Fig. 4C; [146]). It is possible that some entangling gear originates from fishing outside of the U.S.; however,

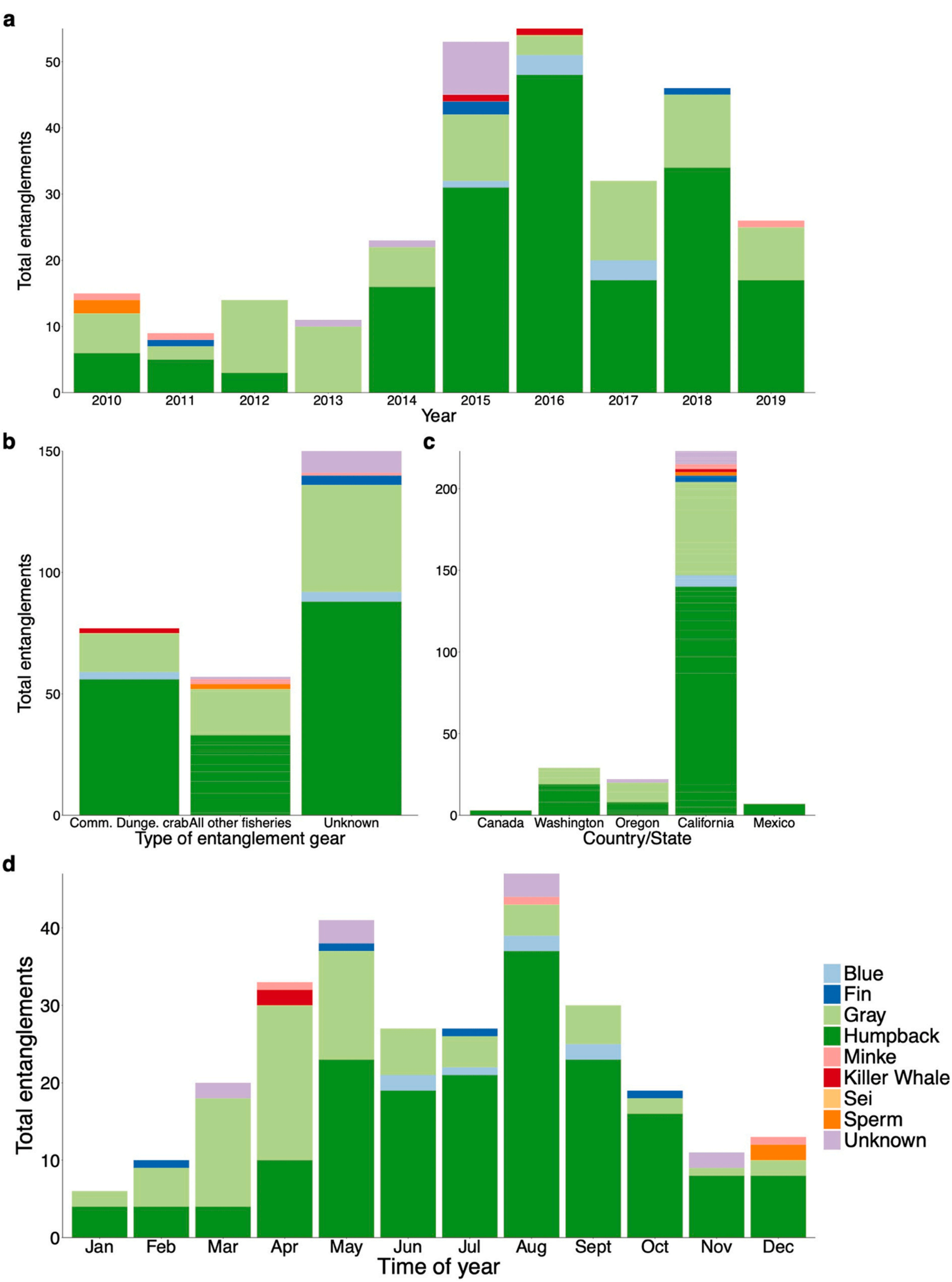

Fig. 4. Confirmed whale entanglements in the U.S. West Coast region, 2010–2019 (MMHSRP, 2021): (a) Total entanglements over time; (b) Entanglements by gear type in the U.S. West Coast region, including commercial Dungeness crab, all other fisheries, and unknown gear sources. All known gear was linked to U.S. fisheries. Most unknown gear included rope, buoys, and other types of marine debris that could not be linked to a fishery; (c) Entanglements by state or country (Canada and Mexico), ordered north to south. Cases reported from outside of the U.S. (Canada and Mexico) are included only when the source of entanglement is confirmed to be U.S. fisheries gear; (d) Entanglements by month.

Table 1
Drivers, objectives, policies, jurisdictions, and case examples of existing whale mortality management.

Driver	Objective	General Policy	Jurisdiction and Example Case
Entanglement 	Reduce amount of gear	Gear buyback: government program to purchase licenses or gear from fishers	State, e.g., S.B. 5447, WA Dungeness License Buy-back Program [155]
		Fishers collect and sell or keep derelict gear post-season	State, e.g., H.B. 3262, OR Post-Season Derelict Gear Recovery [73]
	Modify existing gear	Require line and/or buoy marking to improve identification of entanglement sources	State, e.g., WAC 220–340–430, WA Crab Fishery Gear Requirements [190]
		Mandate acoustic deterrents on some gear to maximize whale avoidance	National, e.g., Taking of Marine Mammals Incidental to Commercial Fishing Operations, 50 C.F.R. § 229 [174]
		Line length limitation: restrict maximum line length in fixed gear fisheries	State, e.g., WAC 220–340–430, WA Crab Fishery Gear Requirements [190]
	Time area restriction	Area fishing limits during peak whale abundance	State, e.g., Rule 635–005–0460, OR Area Limits [122]
		Dynamic fishing closures and timing of season open/close	State, e.g., Cal. Code Reg. 14 § 132.8, CA Risk Assessment and Mitigation Program [17]
Vessel strike 	Reduce strike probability	Area to Be Avoided (ATBA): mandatory or voluntary, permanent or dynamic designation of areas prohibiting the passage of vessels	International, e.g., Amendment to TSS: Santa Barbara Channel, International Maritime Organization ([4]
		Traffic Separation Scheme (TSS): mandatory measure that creates traffic lanes for vessels, can route ships to areas of less whale density	International, e.g., Amendment to TSS: San Francisco, IMO [5]
		Pilotage for ships entering/exiting select waters including harbors	Local, e.g., Port of Los Angeles [135]
		Notice to mariners around existing regulations (VSRs, ATBAs) and active presence of whales in area	National, e.g., Santa Barbara VSR [92]
		Vessel Speed Reduction (VSR) zones: voluntary or mandatory, permanent or dynamic measures to reduce vessel speeds and decrease the likelihood of a strike occurring	National, e.g., California National Marine Sanctuaries VSR [92]; Local, e.g., Port of Long Beach [134]
	Reduce strike lethality	VSR zones: see above; implemented to decrease the severity of a strike	See above
Noise 	Reduce exposure to shipping noise	Emissions Control Area (ECA): mandatory measure requiring vessels to use cleaner-burning fuel when transiting area; can lead to vessel speed reduction or vessels avoiding area	International, e.g., North American ECA) [41]
		ATBA, TSS to concentrate shipping noise away from whales	International, e.g., IMO Channel Islands National Marine Sanctuary ATBA [119]
		Seasonal VSRs to limit noise impacts during particularly sensitive time periods	International, e.g., VSR trials in cross-boundary Salish Sea (Port of Vancouver ECHO Program) to reduce noise during Southern Resident killer whale foraging [81]
		International resolutions for nations to develop guidelines and enforcement around reducing underwater noise pollution	International, e.g., Guidelines for reduction of underwater noise from commercial shipping, IMO [76]
	Reduce exposure to construction noise	Require operational adjustments to construction project: ramp-up; sound attenuation devices; acoustic deterrents	National, e.g., NMFS stipulations in incidental harassment authorization for San Francisco Bay wharf maintenance ([173]
		Require protected species observers (PSOs) to detect whale presence and shift construction activities	National, e.g., NMFS trainings for PSOs [9]
Water Quality 	Reduce and collect pollution at sea	Non-binding frameworks and strategies to advance marine pollution research and reduction	International, e.g., UN Environment Programme [179]
		Regulations and resolutions to limit discharge of ship-based pollution (oil, toxics, macroplastics, sewage)	International, e.g., MARPOL (Protocol of 1978) [137]; National, e.g., Save Our Seas 2.0 Act, S. 1982 [150]; State, e.g., State Water Resources Control Board [170]
	Reduce plastic production	Use tax, fees, or bans on certain plastic products	National, e.g., U.S.A. Microbead-Free Waters Act, H.R. 1321 [105]; State, e.g., S.B. 270, CA Single-Use Carryout Bags [154]; Local, e.g., San Francisco Checkout Bag Charge, 172–19 [26]
		Plastics buyback: deposit refunds for some plastics	State, e.g., H.B. 3145, Oregon Bottle Bill [72]
		Extended producer responsibility programs	State, e.g., CA Plastic Pollution Producer Responsibility Act, SB 54 [153]

there are no confirmed cases of this in the dataset.

3.1.2. Policy

Global attention to marine mammal bycatch in fisheries and aquaculture has promoted the development of fishing alternatives, including gear modifications and time-area closures, designed to reduce this risk [44]. To reduce large whale entanglement, gear modification is typically focused on reducing the amount of slack rope in the water column in order to minimize the potential for entangling a passing whale (Table 1; [84,44,89]). For trap fisheries, methods to reduce entanglement include using sinking groundline between traps in a trawl and shortening rope length [89], limiting traps-per-trawl in relevant fisheries [84], reducing the number of traps allowed per fishing license or reducing the number of active fishing licenses [6], or switching to ropeless gear where the vertical line is stored at seafloor with the trap and released upon fisher retrieval [171].

Other gear modifications reduce the severity of entanglement should it occur. Ropes with lower breaking points, weak links, and time tension line cutters have been proposed to increase the possibility for a whale to shed entangling gear [44,84,171,191]. Acoustic pingers attached to gear may warn whales away from line and are required in some California fisheries (Table 1; [20]), but limited evidence suggests that large baleen whales do not respond to pingers [65,133].

In addition to gear modifications, temporal and spatial restrictions on fishing effort reduce overlap between whales and active fishing gear (Table 1; [44]). Closures can be permanent, seasonal, or dynamic, depending on the residence time of whales in the area [71,89,165], but lack of knowledge about whale distribution is a major challenge in designing and implementing effective closures [63,91]. Increased monitoring (including shore-based, vessel-based, aerial, acoustic, satellite, and GPS tag monitors) and predictive modeling will help provide higher resolution data on whale distribution [66].

Collaboration between managers, researchers, and fishing industry members can help in identifying feasible solutions and providing support for fishery practice transitions to reduce the risk of entanglement [89]. Both major avenues of entanglement risk reduction face implementation challenges. Gear changes have been critiqued for practical infeasibilities (e.g., ropeless gear leads to increased risk of multiple fishers' overlapping gear), high cost to fishers in terms of time and money, and safety concerns for fleets navigating new gear [89,161], while fishery closures represent a loss of potential income to fishers [55]. These changes can also have unintended consequences: for example, increasing trap number per trawl in New England fisheries pushed fishers to deploy stronger line, potentially exacerbating entanglement severity [109]; while fishery closures on the West Coast shifted pressure to new fisheries [55]. However, collaborative working groups that set industry regulations, like California's Dungeness Crab Fishing Gear Working Group and the Risk Assessment Mitigation Program (RAMP), offer a formalized route for experimentation and collaboration that may help overcome barriers and prevent unintended consequences [161]. Ongoing work to invest in industry-informed gear innovation and identify opportunities for financial assistance for gear changes can aid transitions in the fishing industry [111]. Additionally, seafood certification programs, like the Marine Stewardship Council, can create "whale safe fishery" certifications to drive consumer interest and incentivize costly changes to fishing practice [89].

3.2. Vessel strike

3.2.1. Biology

Vessel collisions are a leading source of large whale mortality around the globe [157,176]. On the U.S. West Coast, vessel strikes are especially prevalent in Southern California, where levels of strike are suggested to be a major factor limiting whale population growth and recovery [141]. Strikes cause direct injury to the animal through sharp or blunt force injuries, resulting in immediate or delayed mortality [108,184]. Longer-term, sub-lethal consequences of vessel strikes are poorly understood, but locomotive impairments caused by collisions can increase energy expenditures and contribute to death by starvation and decrease individual fitness [157].

In the MMHSRP National Stranding Database, out of 79 strandings documented from 2010 through 2019, gray (38%), humpback (22.8%), fin (21.5%), and blue (8.86%) whales comprised the bulk of recorded vessel strike strandings (Fig. 5; [97]). In California, the highest vessel collision risk occurs offshore in designated shipping lanes from San Francisco to Long Beach ports [141]. Shipping lanes and major ports in the Santa Barbara and Southern California Bight are a collision hotspot: blue whales face the highest mortality risk in Santa Monica Bay in the Southern California Bight, and other species are likely at elevated risk due to the proximity of shipping lanes to important ecological areas for whales [139,141]. Fin whales face the highest risk of collision along the Central Coast, and humpbacks experience the highest risk off San Francisco [140].

Vulnerability to mortality by strike includes complex interactions between ecology, whale behavior, and vessel practices that warrant deeper species-specific studies [157]. For example, blue and humpback whales migrate and forage closer to shore compared to fin whales, which makes them more susceptible to vessel collisions when shipping lanes are moved inshore, as occurred in 2009 [110,141]. Fin whales are twice as susceptible to ship strikes during night hours due to their nocturnal increase in surface water use. This leads to increased risk in winter based on long nights, though in the Southern California Bight, this diurnal effect does not occur, and mortality risk is the same during day and night year-round [82]. Blue whales are especially vulnerable to vessel collisions [141], possibly because they do not avoid areas of high vessel traffic [100] and they forage along the shelf break where many shipping lanes run parallel [70].

3.2.2. Policy

Vessel strike management is typically discussed in terms of reducing (1) the risk of a strike occurring through re-routing vessel traffic patterns away from areas with high whale presence and (2) the potential for a strike to be lethal through reducing the speeds at which vessels travel (Table 1; [162]).

Both streams of management require up-to-date knowledge on where whales are found. There are increasing efforts to improve the communication of whale presence and density data in a usable form for vessel operators beyond "Local Notices to Mariners" deployed by the Coast Guard [101]. App-based devices can help community scientists collect these observations and share them with vessel operators. For example, apps like WhaleAlert (http://www.whalealert.org/) allow users to report whale sightings. Tools like Whale Safe (http://www.whalesafe.com) incorporate multiple streams of data—including sightings, acoustic monitoring data [13], and habitat models [1]—to track and communicate whale presence and shipping industry compliance with whale protection measures ([193]).

To reduce the risk of a strike, vessel traffic in "Traffic Separation Schemes" and "Areas To Be Avoided" have been shifted to limit overlap of vessels and high whale densities [139]. Re-routing is not always possible (e.g., in narrow port entrances), requiring mariner awareness to reduce strike when whales and vessels overlap. In shipping lanes, vessel operators identify whale location and then make real-time operational changes, like redirection or speed reduction, to avoid a collision (Table 1). Technical tools, like thermal trackers, can help vessel operators detect whales more effectively [197] and on-board observers can help alert operators to whale presence when conditions allow [49].

While reducing strike risk relies primarily on spatial management and mariner awareness, reducing lethality is primarily a function of vessel speed. Speed restrictions are typically implemented as speed reduction zones, designed to give whales more time to avoid coming vessels and lower the risk of vessels striking whales, as well as the risk of killing whales if strikes occur [186]. Speed restriction zones can be

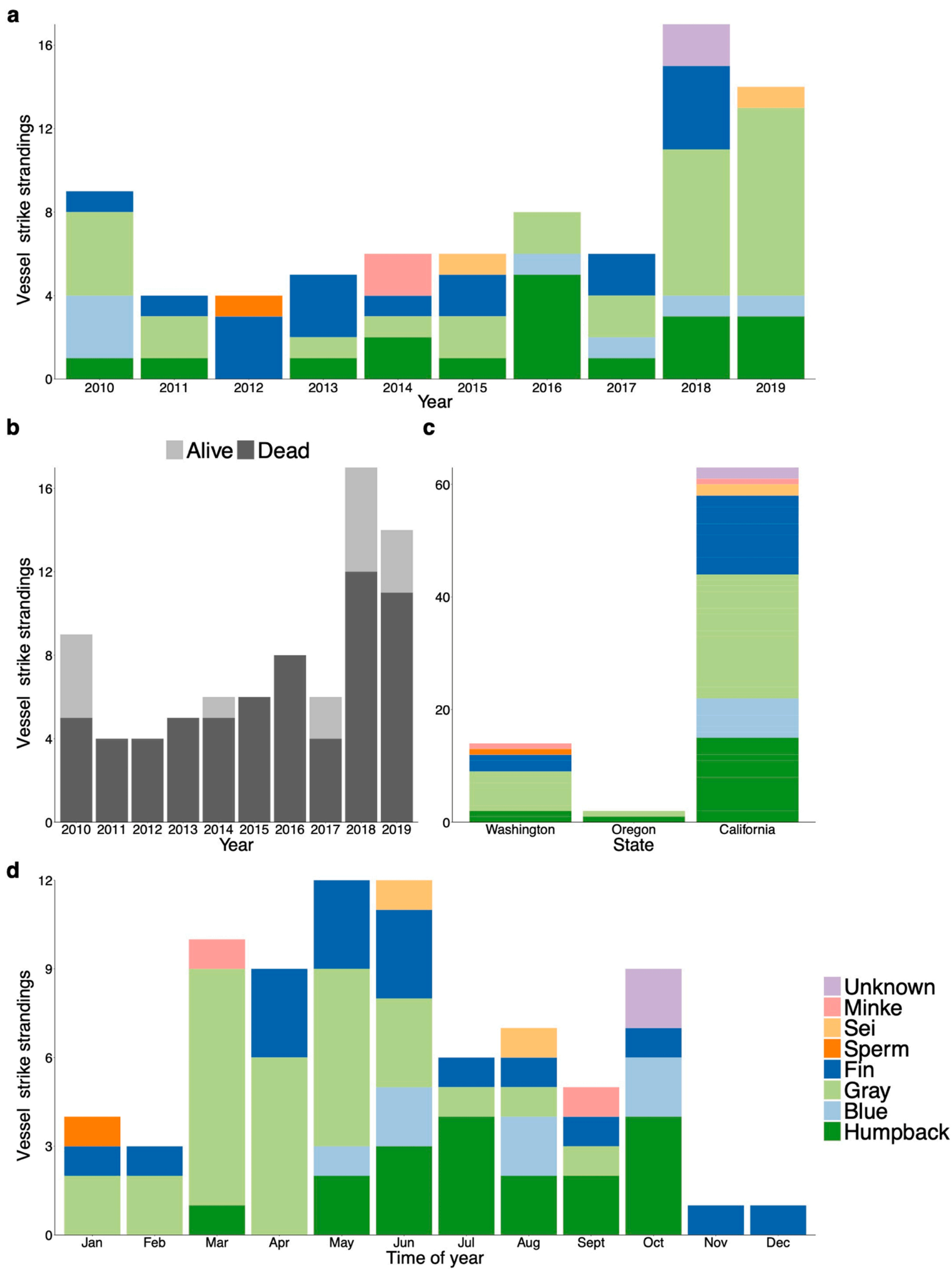

Fig. 5. California, Oregon, and Washington stranding records exhibiting evidence of vessel strikes, 2010–2019 (MMHRSP, 2021). (a) Total vessel strike strandings over time, (b) confirmed dead or alive from observation status, (c) by state (no data available from Canada or Mexico in this dataset), and (d) by month.

designed as permanent, seasonal, or dynamic, instated in response to likely whale presence ([68]). Speed reduction programs on the U.S. West Coast are voluntary, but some offer financial incentive or positive publicity for vessels that comply [110]. One such program is the partnership between Channel Islands National Marine Sanctuary and the Santa Barbara Air Resources Board, which trialed an incentives-based speed reduction program in which shipping industries received a payment for each vessel trip that complied with voluntary speed limits, with some evidence of positive compliance [53]. Recently, incentives have shifted to public ratings for cooperative shipping industries; again, this seems to promote compliance with voluntary speed restrictions (most recent year: [192]). Outside of the CCE, measures designed and implemented through collaboration between government regulators and the shipping industry have resulted in compliance with proposed measures [27] and reduction in risk to whales [34]. However, where such policies have been implemented on the U.S. East Coast, both voluntary and mandatory speed restriction policies show mixed evidence of compliance ([116, 183,186] and some benefit to whales [85], suggesting a need for deeper understanding of how incentives, monitoring, and enforcement affect efficacy of these policies.

3.3. Noise

3.3.1. Biology

Anthropogenic noise, such as the sounds associated with vessel engines, propellers, depth sounders, sonar, fishing pingers, seismic exploration, construction, and wind farm operations, are ubiquitous throughout the ocean [38]. Noise can cause sublethal effects that alter a whale's behavior, movement, physiology, or acoustic interactions [121].

Along the California coast, vessel noise is considered a key contributor to anthropogenic noise due to the numerous commercial ports in Northern and Southern California. The engines of large, low-RPM vessels, like cargo ships, tankers, and cruise ships, produce sounds in a range frequency that overlaps with large whale vocalizations, effectively masking whales' auditory signals, affecting their navigation, and inhibiting predator avoidance [61]. Southern California waters also experience noise from military sonar, which likely affects many marine species, however research on species-specific response to military sonar is patchy [126]. In experimental exposures to sonar conducted in California, behavioral changes have been observed in blue whales [54,60, 167] and gray whales [52].

Behavioral responses to noise can enhance the risk of other whale mortality stressors. In noisy areas, whales may be unable to detect or differentiate the sound of oncoming vessels due to ambient noise and other vessels further in the distance [57]. Whales demonstrate vessel avoidance, but inconsistently; the speed of the vessel, ambient acoustic environment, and ongoing mating or feeding behaviors may prevent a whale from responding to a vessel in time to avoid collision [42]. Uncertainty remains around the relationship between higher noise volume and increased strandings, species-specific susceptibility, and seasonality of noise impacts.

3.3.2. Policy

Two major managed sources of noise include vessel traffic and energy exploration and construction [96,104]. Managing noise from

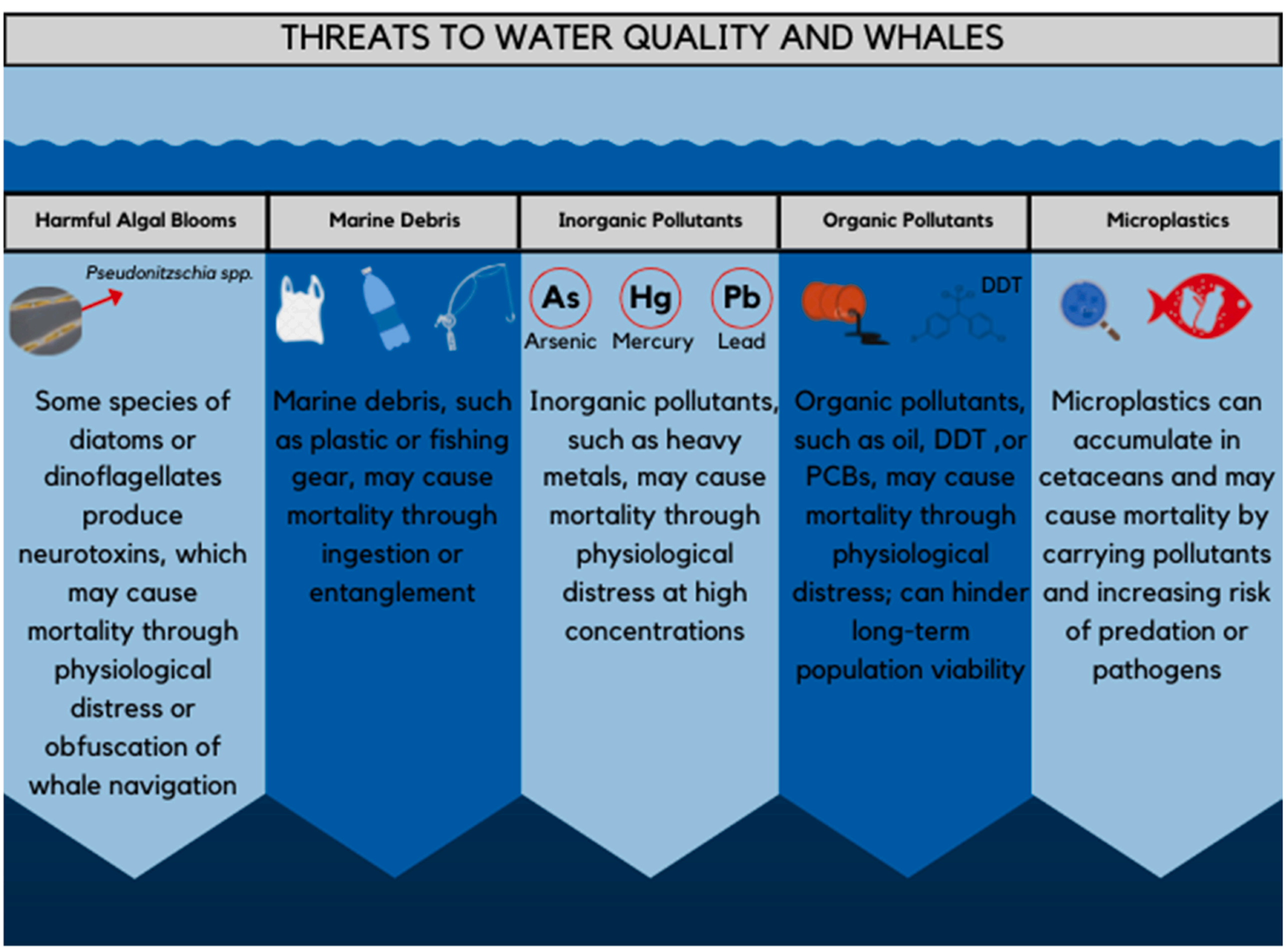

Fig. 6. Whales can be impacted by adverse water quality through a variety ofsources. Macroplastics and microplastics, as well as harmful algal blooms, canphysiologically stress whales and increase pollution burdens, leading to lowerreproductive success and greater risk of mortality. [Print in color.]

vessels involves implementing vessel speed reduction zones, traffic separation schemes, and timed port entry and exit, thereby reducing noise intensity or duration and creating quiet zones in areas and seasons deemed to be particularly important to whales (Table 1; [138]). Many of these responses also reduce the risk of vessel strike. With speed restrictions, there is a need to assess the whale behavioral and health trade-offs of allowing high-intensity noise for shorter durations (e.g. vessels traveling at full speed) versus lower-intensity noise for longer durations (e.g. vessels traveling at reduced speed) [101]. For individual vessels, hull maintenance and ship quieting technology can further reduce noise production [104], and programs like Green Marine incorporate these activities into their voluntary environmental certifications for shipowners (green-marine.org). However, it is unknown whether quieting vessels will increase risk of vessel strike if the distance at which whales can detect approaching vessels decreases [42].

Discrete noise sources in energy exploration and development include seismic surveys and construction or pile-driving (Table 1). Noise attenuation methods, including bubble curtains or solid barriers, can abate noise from fixed sources [40]. New technology, like the use of vibroseis in place of traditional airgun seismic surveys or suction anchors in place of pile driving, can reduce overall noise production [104,169]. Data-sharing between entities can reduce the number of surveys that need to be conducted [40,104];. NOAA deploys protections under federal resource protection law to regulate the use of discrete noise sources and grants permits for incidental take if noise is deemed necessary for commercial fishing, scientific research, or national defense purposes (Table 1; [67,96]). Permitting incentivizes industry groups to invest in noise reduction technologies [39].

3.4. Water quality and marine debris

3.4.1. Biology

3.4.1.1. Plastics and marine debris. Water quality concerns that may impact whales encompass a number of factors, including marine debris, organic and inorganic pollutants, and algal toxins (Fig. 6). According to NOAA, marine debris is “any persistent solid material that is manufactured or processed and, directly or indirectly, intentionally or unintentionally, disposed of or abandoned into the marine environment [.]”. Due to their widespread use and durability, plastics are a major source of marine debris [113]. Macroplastics (> 20 mm in size, e.g., packaging, land-based products, fishing gear, rope) and microplastics (< 5 mm in size, e.g., microbeads from cosmetics, synthetic fibers, fragments from degrading macroplastics) originate from land and sea and can distribute widely across the world’s oceans [113,114]. Debris concentrations are often associated with shipping lanes, fishing areas, and oceanic convergence zones [164].

Marine debris primarily leads to mortality in whales through ingestion and entanglement [12]. Over half of all cetacean species (56%) are documented to have ingested debris, including blue, fin, minke, sperm, killer, and gray whales. In a global review, cetacean debris ingestion was documented more frequently than entanglement, with rates of ingestion increasing over the past two decades [12]. Ingestion of debris can directly lead to mortality through internal injuries, gastric impaction (excessive accumulation of ingested material in the stomach), and blockage causing starvation [12,78,189]. Researchers have also hypothesized that oral debris entanglement can lead to mortality in whales by interfering with their hydrostatic oral seal [86]. Species that use suction, lunge, or ram feeding are more likely to incidentally ingest debris than other species [86,164,189]. Rates of debris ingestion vary across regions, within species, and among species. In a global synthesis of stranding data, ingestion rates ranged from 0% to 31%; mortality rates for stranded cetaceans that had ingested debris ranged from 0% to 22% but were typically in the 3–10% range [12]. Quantification of debris impacts often relies on stranding data, which is only a small fraction of all mortality and may be biased although more work is being done on analyzing plastics and plastic compounds from feces when recoverable [144]. Stranding data may overestimate plastic ingestion, as animals that ingest debris may be more likely to strand than animals that die of other sources or may ingest plastic during the stranding process [12,189]. In addition, microplastics accumulate inorganic toxins, and consumers can ingest these microplastics directly (filter feeding) or through prey, thus ingesting toxins [56].

3.4.1.2. Inorganic and organic pollutants. Heavy metals and inorganic compounds are commonly found in whale tissues, sometimes in high enough concentrations to cause physiological distress [3,35,79,103,151]. Whales can be exposed to these pollutants through digestion of prey, ingestion of water, or accidental consumption of sediment [151]. Whales that occupy higher trophic levels are more sensitive to contaminant burdens [3,35,79,196]. One exception to this observation is the gray whale, which feeds at a lower trophic level, but accumulates high concentrations of contaminants from plankton and sediments that it ingests from benthic suction-feeding [79]. The western coast of the United States has high concentrations of organochlorines [2]. Despite evidence indicating that organochlorine levels in cetacean blubber have actually decreased over the last forty years [2], many populations remain vulnerable to the long-term effects of DDT, PCB, and PBDEs. Chronic exposure to organochlorines at high levels has the potential to affect long-term population viability [35,79], causing declines in populations that already are at high risk of collapse [35,196] or slowing or reversing the recovery of more robust populations.

3.4.1.3. Harmful algal blooms. Saxitoxin and domoic acid, both associated with harmful algal blooms (HABs), have been suggested to confound whale navigation and increase physiological stress [90,145,176], leading to an increased chance of stranding, vessel strikes, or mortality. In Southern California, the temporal distribution of marine mammal stranding corresponds to peak *Pseudonitzschia* blooms [177], and domoic acid has been detected in gray, humpback, and minke whales [46,177]. Minke whale fecal analysis indicates that domoic acid intoxication likely occurs through ingestion of northern anchovy prey, expanding upon the understanding of how HABs, domoic acid, and cetaceans are connected [46]. However, dying or deceased cetaceans are less likely to become beachcast along the California coast, preventing researchers from determining how susceptible these species are to domoic acid toxicity [177].

3.4.2. Policy

Preventing plastic and marine debris requires management of land-, sea-, and ship-based pollution sources across multiple jurisdictions [125,129,195]. International entities coordinate global frameworks to reduce marine debris, prioritizing litter, nutrient management, and wastewater (Table 1; [179]). Policies to reduce single-use plastics are increasingly prevalent (Table 1; [156]). In the U.S., national, state, and municipal policies often act to ban or disincentivize plastic use in an uncoordinated manner (Table 1; [88,195]). Technological interventions (e.g., booms, drones, waterwheels) and manual beach clean-ups collect existing plastic litter at local scales [80,156]. No formal policies and few technological interventions exist for the prevention and collection of microplastics [129,156].

Anthropogenic pollutants, including heavy metals and inorganic compounds, lack comprehensive prevention. The International Convention for the Prevention of Pollution from Ships (MARPOL) targets garbage, oil, noxious liquid substances, and other harmful or persistent substances carried by vessels and prohibits their dumping at sea [77]. Nationally, classifying a pollutant as a toxin under the U.S. EPA introduces regulation on the pollutant’s use and disposal, and heightens the consequence for parties responsible for emitting these substances into marine environments [129]. Preventing HABs involves addressing a suite of enabling factors that promote the growth and toxicity of these organisms; for a discussion of environment-wide management see “Climate Change”, below.

4. Unmanaged sources of mortality

Entanglements, vessel strikes, noise, and poor water quality stem directly from human activities, cause significant whale mortality in the CCE, and are managed by existing policy to variable extents and effects. However, other drivers such as thermal and nutritional stress, disease, and predation have indirect linkages to human activities (e.g., climate change, habitat degradation), contribute to overall whale mortality in the CCE, but are largely unmanaged by existing policy. In addition, there is often less information on how these sources impact whales, specifically. These indirect sources of mortality are nonetheless critical to understand and address as they likely alter and exacerbate the impact of the managed drivers described above (e.g., [149]). Attention to the combined effects of multiple stressors, including managed and unmanaged sources of mortality, is a key challenge in modern conservation [131]. However, for whales, policy and management responses designed to address indirect sources of mortality, or joint effects from multiple stressors, are nascent or nonexistent. As these stressors are intertwined with global ocean changes, effective responses to lessen the impact on CCE whales would likely require long timeframes and complex-system approaches that stretch beyond the CCE.

4.1. Nutritional stress

The abundance and distribution of prey species changes in the California Current Ecosystem (CCE) due to natural environmental variability [47,148] and climate change [29]. Changes in the timing and distribution of prey leave whales with three options to mitigate nutritional stress. Whales can shift foraging from less productive to more productive feeding grounds in time or space, they can engage in prey switching, or some combination of the two [149]. Whale species vary in their ability to employ these strategies. Prey specialists, such as blue whales (prey: krill species; [99]), North Pacific right whales (prey: *Calanus marshallae*; [160]), and some killer whales (prey: Chinook salmon; [64]) do not engage in prey switching and are unlikely to develop behavioral plasticity in prey choice quickly enough to keep up with anthropogenically driven changes in prey patterns. Species that do engage in prey switching or are prey generalists (e.g., humpback whales) may be able to compensate for shifts in prey abundance, but changes in spatial foraging patterns may put these species at elevated risk of entanglement or other threats if prey patches overlap with these stressors [149].

Just as certain whale species are more vulnerable to nutritional stress, certain life stages are also more vulnerable. Juvenile baleen whale mortality due to starvation is elevated because they have lower energy reserves than adults [23,132,176,187]. Lack of prey is less likely to be an immediate cause of mortality for adult whales but can lead to reduced reproductive rates particularly when bad years occur more commonly [130,176,187], and more time is spent away from breeding/calving grounds [127]. Impacts on pre-reproductive individuals and reproductive rates are likely to alter long-term recovery patterns for these species in ways that cannot be captured by mortality or stranding data alone.

Policy approaches to address nutritional stress vary depending on the prey species in question. Existing fishery management plans are cognizant of ecosystem effects of fishing and may represent an avenue towards managing nutritional stress in whales. For example, the Pacific Fishery Management Council sets rules for the harvest of prey species in the CCE through the Coastal Pelagic Species Management Plan [124]. While not explicitly whale-focused, the plan includes harvest controls (or, in the case of krill, moratoria) for a number of prey species with fishery restrictions justified by the importance of maintaining prey biomass for groundfish, seabirds, and marine mammals [120,123]. Washington State’s Southern Resident Orca Task Force, in contrast, is explicitly whale-focused: it has prioritized actions related to reduce bycatch and increase hatchery production of Chinook salmon to reduce nutritional stress for endangered Southern Resident killer whales [168].

4.2. Disease

Whales’ immense migratory trajectories can facilitate the introduction and spread of pathogens across oceans. However, due to their mobility and protected status, current understanding of whale disease remains quite limited. To increase availability of information about cetacean diseases, the IWC launched the Cetacean Diseases of Concern program in 2008. One lethal disease that has been globally observed in baleen and toothed whales alike and has been associated with mass die-offs is the cetacean morbillivirus. Because this is a respiratory virus, transmission among individuals likely occurs during social aggregations, though there has been some evidence of transmission between mother and fetus. Cetaceans that survive the disease have an increased likelihood of developing other, potentially fatal infections [180].

Often, diseases in whales are linked with immunotoxicants. Specifically, the widespread use of biological samples to measure the accumulation of pollutants in marine mammals has demonstrated that environmental contaminants such as heavy metals adversely affect immune function in whales and other large mammals [35,75]. Additionally, past stressors can increase susceptibility to disease. For example, impacts from vessels or wounds incurred from entanglement in marine debris can create opportunities for infection [83,108]. As climate change progresses, disease transmission is also likely to increase [147]. However, because whales’ residential ranges are so massive, it is unlikely they will be able to find spatial refuges from these effects [58].

4.3. Predation

Predation upon whales is known to occur, with killer whales dominating inter-cetacean predation interactions. Observations have shown killer whales prey upon most juvenile whales in the CCE [106], including humpback whales [48], gray whales [11], and other baleen whales [50,102]. While the transient populations of killer whales in the Northeast Pacific prefer to prey upon marine mammals [175], adult baleen whales are not an important prey source for killer whales in high-latitude feeding grounds, and most predation events involve young cetaceans [102]. However, these prey preferences may change as humans continue to alter the ocean by, for example, precipitating collapse of alternative prey populations [43] or altering migratory routes to overlap with killer whale presence [50].

Sharks may pose a source of whale predation. Shark scavenging on whale carcasses has been documented within the CCE [93,199]. Evidence of shark predation on living whales has been documented globally, for example through detecting shark bite scars on living humpback whales in Australian oceans [112] and recently, through the first published eye-witness observations of white shark predation on a humpback whale off South Africa [36]; however in the CCE, instances of shark predation on living whales are not evident in published literature.

4.4. Climate change

Climate change is altering spatial and temporal patterns of productivity in the California Current [25] and is likely to affect whale condition, reproduction, and mortality rates [149]. These stressors may be further compounded by other anthropogenic drivers, like fishing, which change spatial and temporal patterns or prey or reduce overall prey availability [159,172]. Climate change may also worsen the organic contaminant burdens in whales. For example, some killer whales intake PCB from salmon, but as ocean temperatures warm and the lipid content of salmon potentially decreases, killer whales might increase their salmon consumption and subsequent PCB burden [79]. This climate change-induced sensitivity is poorly understood and not limited to organochlorines. Climate-related ecological and oceanographic changes are expected to alter whale mortality rates due to decreased foraging habitat [69], disease and parasitism [176], predation [45], and bycatch/entanglement [149,194]. The prevalence of these synergistic effects on whale mortality rates emphasizes the need for a better understanding of how climate change interacts with other anthropogenic impacts on whales. Moreover, intersecting sources of mortality, augmented by climate change point to the necessity of a multi-stressor approach to minimizing whale mortality in the CCE.

5. Discussion

The CCE is home to many resident and migratory whale species that are vulnerable to mortality caused by human activity. Current whale population estimates are a vestige of the whaling industry that disbanded over 40 years ago, and are thus protected by major legislation, such as the Endangered Species Act and Marine Mammal Protection Act, that target specific sources of mortality–such as entanglement in fishing gear and vessel strikes–but do not necessarily address other "unmanaged" sources of mortality, including marine debris ingestion and climate change. In the face of persistent anthropogenic harm to whales, California's Ocean Protection Council (OPC) has articulated a bold intention for whales in California waters: zero mortality. In the coming years, OPC aims to develop a statewide management plan towards Vision Zero by supporting innovations that reduce whale entanglement and vessel strikes, as well as furthering research into these and other sources of whale mortality. This review aimed to identify the key drivers of whale mortality and associated policy measures, and to call attention to existing knowledge gaps. What emerged was an intricate web of mortality sources that likely require a multi-dimensional, rather than single-stressor, management approach (Fig. 3).

5.1. Multi-stressor human impacts exacerbate whale mortality

The impact of whale mortality sources varies spatially and by species. For example, entanglement reporting is highest in central and southern California, and humpback and gray whales are the most likely species to become entangled. Sources of mortality also vary through time. This review confirms the pattern of higher entanglement rates during the spring and summer months when migrating whales come into contact with trap fishing gear. On a longer time horizon, mortality attributed to vessel strike varies interannually and was highest over a fifteen-year period in 2018 and 2019. State and federal law directly manage some sources of mortality, such as entanglement, vessel strike, and noise pollution. However, predation, nutritional stress, and disease are also important drivers of whale population dynamics throughout the California Current but tend to lack policy responses designed to ameliorate the stress on whales. The rates and distribution of these drivers are changing due to human activity, and notably through the symptoms of climate change. Finally, whale mortality events may not be attributable to a single cause. Forensic challenges and the often-cumulative nature of drivers of mortality make it difficult to determine what factors contributed most to the death of an individual, even in cases where the proximal cause is known.

In general, human-caused whale mortality is an issue of multiple stressors. Exposure to contaminants, nutritional stress, elevated disease incidence, and other factors may all contribute to the condition of an individual whale, leading to increased chance of death by non-lethal vessel strike or entanglement. Conversely, non-lethal vessel strike or entanglement may reduce the ability of an individual to contend with diminished food availability or disease. Furthermore, migration requires whale populations to cross multiple jurisdictional boundaries; whale mortality in one jurisdiction is influenced by exposure and threats in another. Despite the interrelated effects of multiple stressors, modern management approaches tend to address a single source of mortality at a time and apply to a limited region (Table 1). Policy efforts focus particularly on entanglement and vessel strikes. The overwhelming emphasis on discrete sources of mortality may be due in part to the relative ease of crafting policy to address a single driver, but also because of a lack of research providing a cumulative and integrative view of what drives whale mortality rates. This review highlights a need for increased research attention to currently unmanaged stressors, in order to understand and respond to how these stressors contribute in direct and indirect ways to overall whale mortality. If whale mortality derives from a complex web of multiple drivers, acting additively or synergistically, effective policy solutions need to recognize and respond to the multiple sources of mortality and their relations to one another. This response will require the involvement and coordination of multiple partners and agencies, both for advancing research and implementing management actions.

5.2. Policy approaches to a multi-stressor, multi-jurisdictional challenge

Existing partnerships offer a model of how to leverage jurisdictional overlap to match the complexity of whale mortality. Partnerships can begin by coordinating efforts across geographic borders, to better fit the extent of mortality stressors. For example, a Tri-State Agreement requires fisheries agencies in California, Oregon, and Washington jointly manage Dungeness crab fishing in the U.S. CCE. This partnership offers an avenue to address whale mortality via entanglement at a multi-state spatial scale, as well as opening the possibility for sharing best practices and learning across different fishing groups [124].

In addition to coordination across geographic borders, coordination among agencies and organizations with differing management mandates can reveal opportunities to address whale mortality. For example, 2014 saw the creation of a novel partnership between the Santa Barbara Air Pollution Control District, the Channel Islands National Marine Sanctuary, and the Environmental Defense Center. These partners worked with shipping industry members to develop an incentives-based Voluntary Speed Reduction program for vessels transiting in the Santa Barbara Channel, to improve local air quality and address risks to whales from vessel strike and noise exposure. Programs like "Protecting Blue Whales and Blue Skies" and WhaleSafe are supported by partnerships that draw on best available scientific knowledge, local knowledge, and innovative technology to mitigate mortality risk [62,136,193].

In addition to working across geographic boundaries and agency jurisdictions, partnerships are beginning to address the intersections between mortality stressors. The Risk Assessment and Mitigation Program (RAMP), developed in partnership with the California Dungeness Crab Fishing Gear Working Group and state agencies, is a leading example. First piloted in 2017, RAMP is a management tool whereby commercial and recreational fishers, environmental organizations, and fisheries managers assess the cumulative entanglement risk to whales and make in-season management changes. While RAMP focuses on reducing mortality via entanglement, the considered risk factors include both managed (e.g., fishing dynamics) and unmanaged (e.g., forage conditions) factors, offering a pathway for multiple stressors to lead to management decisions [18]. RAMP is valuable, too, for its dynamic, responsive decision-making structure. Such schemes, in which behavior change to reduce risk to whales responds to updated measures of whale presence, will likely protect more whales at lessened cost to human activities compared to fixed strategies, particularly during times of unpredictable ocean conditions [68].

6. Conclusion

This synthesis points to a necessary ideological shift in whale mortality research and management. While mortality threats of the last century (namely commercial whaling) were amenable to narrowly-focused attention, the contemporary seascape of whale mortality necessitates a broader response based in systems thinking. For California to truly meet the intention of Vision Zero and minimize human-driven whale mortality in the CCE, the complex, multi-stressor nature of whale mortality must be addressed. Policies that operate across jurisdictions and leverage partnerships between and among managers and resource users may help to meet this need. Developing such creative solutions requires input from different perspectives across the ocean community, including managers, industry members, researchers, policymakers, and coastal communities. Engagement with different ocean-user communities can reveal feasible interventions and temper unforeseen social and ecological consequences. RAMP, in particular, serves as a promising model for convening diverse views and, ultimately, developing a tool to proactively reduce the risk of whale entanglement. Future efforts could build on RAMP's framework, extending this collaborative and tool-based approach to additional sources of whale mortality and their interactions.

Engagement with different ocean-user communities can reveal feasible interventions and temper unforeseen social and ecological consequences. RAMP, in particular, serves as a promising model for convening diverse views and, ultimately, developing a tool to proactively reduce the risk of whale entanglement. To facilitate the development of similar programs in the future, this review provides a conceptual model in Fig. 3 that may serve as a foundation towards considering multiple stressors in whale mortality management. The model highlights the importance of assembling diverse ocean users, researchers, and regulators who may together describe the stressors and interactions facing a particular whale population and identify ways to navigate inevitable gaps in existing knowledge (e.g., [131]). Even when such collaborations do not immediately reveal solutions to reducing whale mortality, they have the potential to build a more complete understanding of the stressors at play and take an important first step towards improving ocean habitability for whales. This shift aligns with ongoing changes to ocean management paradigms, which signal a transition from sector-based to integrated approaches (e.g., marine spatial planning, ecosystem-based management, social-ecological systems). A research and policy response that coordinates across different regions, industries, and environmental mandates offers the layered approach needed to effectively address the complexity of persistent whale mortality.

CRediT authorship contribution statement

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Authorship order was determined through consensus, following the methods developed and taught by members of the Civic Laboratory for Environmental Action Research (Liboiron et al. [200]).

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2022.105039.

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