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Best Practices for Assessing and Managing Bycatch of Marine Mammals

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Bycatch in marine fisheries is the leading source of human-caused mortality for marine mammals, has contributed to substantial declines of many marine mammal populations and species, and the extinction of at least one. Schemes for evaluating marine mammal bycatch largely rely on estimates of abundance and bycatch, which are needed for calculating biological reference points and for determining conservation status. However, obtaining these estimates is resource intensive and takes careful long-term planning. The need for assessments of marine mammal bycatch in fisheries is expected to increase worldwide due to the recently implemented Import Provisions of the United States Marine Mammal Protection Act. Managers and other stakeholders need reliable, standardized methods for collecting data to estimate abundance and bycatch rates. In some cases, managers will be starting with little or no data and no system in place to collect data. We outline a comprehensive framework for managing bycatch of marine mammals. We describe and provide guidance on (1) planning for an assessment of bycatch, (2) collecting appropriate data (e.g., abundance and bycatch estimates), (3) assessing bycatch and calculating reference points, and (4) using the results of the assessment to guide marine mammal bycatch reduction. We also provide a brief overview of available mitigation techniques to reduce marine mammal bycatch in various fisheries. This paper provides information for scientists and resource managers in the hope that it will lead to new or improved programs for assessing marine mammal bycatch, establishing best practices, and enhancing marine mammal conservation globally.

Keywords: bycatch, management, assessment, marine mammal, framework, MMPA import rule, fisheries, USA Marine Mammal Protection Act

INTRODUCTION

Human activities can intentionally or unintentionally harm marine mammals. Commercial hunting led to the decline of most species of large whales and many species of pinnipeds, and led or contributed to the extinction of a few species, namely Steller's sea cow (*Hydrodamalis gigas*), the Caribbean monk seal (*Neomonachus tropicalis*), the Japanese sea lion (*Zalophus japonicus*), and the sea mink (*Neovison macrodon*) (Le Boeuf et al., 1986; Mead et al., 2000; Turvey and Risley, 2006; Lowry, 2017). The risk to marine mammals from commercial hunting has been greatly reduced for most species since the establishment of agreements, such as the International Convention for the Regulation of Whaling, and various decisions under those conventions, such as the 1982 moratorium on commercial whaling. Now, for many species of marine mammals, the greatest threat is from fisheries bycatch, when marine mammals die from injuries sustained from becoming hooked, entrapped, or entangled in fishing gear (Read et al., 2006; Read, 2008). Many species of marine mammals have experienced severe declines in abundance caused by fisheries bycatch. For example, entanglement in fishing gear was a major contributor to the recent extinction of the baiji or Yangtze river dolphin (*Lipotes vexillifer*) (Smith et al., 2017), and this same threat is largely or entirely responsible for the Critically Endangered status and near-extinction of the vaquita (*Phocoena sinus*) (Rojas-Bracho and Taylor, 2017; Taylor et al., 2017) and the Atlantic humpback dolphin (*Sousa teuszii*) (Collins et al., 2017). Brownell et al. (2019) concluded that bycatch in gillnets is the greatest threat to most of the 13 small cetaceans presently listed as Critically Endangered on the International Union for Conservation of Nature (IUCN) Red List.

Therefore, it is important to evaluate whether the number of marine mammals killed by fisheries bycatch is leading to population declines (or impeding recovery) and this can only be accomplished by conducting an appropriate assessment. An assessment, often called a *stock* or *population assessment*, is an evaluation of the status of the population relative to management or conservation goals. Most commonly, marine mammal assessments involve quantitative methods to estimate the extent of population depletion, or to estimate how much human-caused mortality, intentional or incidental, can be allowed while achieving management or conservation goals (Wade, 2018). Moreover, it is important to develop assessment methods that are practical and can be applied worldwide given that marine mammal bycatch is a global problem.

Assessment methods for marine mammal populations have changed substantially over recent decades. In the early 1960s, the rapid decline in the numbers of whales of hunted species spurred the International Whaling Commission (IWC) to invite fisheries stock assessment scientists (i.e., the "Committee of Three"; Nagtzaam, 2009) to help evaluate the status of whale stocks and recommend quotas, leading to some of the first quantitative stock assessments ever conducted for whales. Similar methods were then adopted for what were perhaps the first assessments of the impact of bycatch on marine mammal populations, those of Smith (1979, 1983) for dolphin populations in the eastern tropical Pacific Ocean killed in a tuna purse seine fishery. These assessments were "back-calculations" in which a population model, an estimate of current abundance (and trends, if available), and a complete historical record of estimates of bycatch mortality were used to calculate the pre-exploitation population size. The ratio of current to pre-exploitation abundance (referred to as the 'depletion level') was used to summarize population status. This type of assessment was used to address one of the primary objectives of the United States Marine Mammal Protection Act (MMPA), which directs that marine mammals should not be permitted to diminish below their "optimum sustainable population" (OSP), defined as being between the maximum net productivity level (MNPL) and the maximum number of individuals that the environment can support (the carrying capacity of the environment, K). Under the MMPA, a population that falls below MNPL (often considered to be 50% of K) is designated as *Depleted,* and management actions designed to protect and recover *Depleted* populations may be taken.

Scientists and managers rarely have enough data to assess the depletion level of bycaught species, because there is seldom a record of bycatch going back in time to the start of all fisheries. For example, over the first 22 years where the MMPA was in force in the United States, only 12 (8%) of all marine mammal populations in US waters were assessed relative to MNPL (Taylor et al., 2000). Basing management on a finding of *Depletion* is also not proactive in preventing depletion in the first place. Using fisheries assessment terminology, a depleted population is analogous to a population that is *overfished*. What is missing from this approach is a way to evaluate whether the level of bycatch is high enough to eventually lead to depletion, which is analogous to a fish population that is experiencing *overfishing* (Methot et al., 2014).

A different and simpler approach to assessing marine mammal bycatch is to develop a bycatch reference point based on data that can be collected and analyzed at any time, especially data that can be used to estimate abundance (Taylor et al., 2000). Marine mammal scientists have developed methods for conducting population surveys and estimating abundance (Hammond et al., 2021). Similarly, fisheries observer programs have collected data on marine mammal bycatch in many types of fisheries for decades, and robust statistical techniques have been developed to estimate the annual bycatch in a fishery (Moore et al., In review, Frontiers in Marine Science)[1]. Once estimates of abundance are available, it is relatively straightforward to calculate a bycatch reference point, which can be compared to the estimated bycatch mortality to determine if the bycatch level is too high (i.e., if it is likely to slow

[1]Moore, J. E., Heinemann, D., Francis, T. B., Hammond, P. S., Long, K. J., Punt, A. E., et al. (2010). *In internal review. Estimating bycatch mortality for marine mammal stock assessment: concepts and best practices. To be submitted to a Special Research Topic in the Marine Megafauna section of the journal Frontiers in Marine Science.*

recovery or lead to the long-term decline of the population or stock productivity).

The 1994 amendments to the US MMPA mandated, for the first time in the United States, the use of a reference point to evaluate human-caused mortality (e.g., bycatch), termed the Potential Biological Removal (PBR) level. Outside the United States, several similar bycatch reference points have been used, such as for evaluating bycatch of harbor porpoises (*Phocoena phocoena*) in gillnet fisheries in the Baltic and North seas (ASCOBANS, 2000), bycatch of New Zealand sea lions (*Phocarctos hookeri*) in a squid trawl fishery (Gales, 1995; Harcourt, 2001), and bycatch of several species of dolphin in the tuna purse seine fishery in the eastern tropical Pacific[2]. Many of these reference points parallel those used for fisheries stock assessment; for example, the concept of MNPL, which underpins the PBR approach, is nearly identical to the concept of Maximum Sustainable Yield Level often used in assessments of fish stocks.

The PBR reference point was developed to assess mortality of marine mammal populations, but PBR and similar mortality reference points have been recommended more generally for management of exploited species (Milner-Gulland and Akçakaya, 2001). PBR has been used to evaluate bush-meat hunting in tropical forests (Parry et al., 2009; Weinbaum et al., 2013) and to assess fisheries bycatch of seabirds (e.g., Dillingham and Fletcher, 2008; Barbraud et al., 2009; Zydelis et al., 2009). Several reference points have been proposed, more broadly, to evaluate bycatch of all marine megafauna, not just marine mammals (Moore J. E. et al., 2013; Curtis et al., 2015).

The urgent need for quantitative assessments of marine mammal bycatch in fisheries is bound to substantially increase worldwide. The import provisions of the US MMPA require that imported fish and fish products be evaluated with respect to US standards for managing marine mammal bycatch; the regulations to implement this requirement were issued in 2016 (50 CFR §216.24; hereafter referred to as the "MMPA Import Provisions"). These regulations require nations that export fish and fish products to the United States, and that are identified by the National Oceanic and Atmospheric Administration (NOAA) as having fisheries that are known or likely to involve marine mammal bycatch (called "export fisheries"), have a regulatory program governing marine mammal bycatch that is comparable in effectiveness to the regulatory program governing US commercial fisheries. A fishery may also be classified as an export fishery if there is insufficient information on marine mammal bycatch rates to determine whether the fishery has no known or remote likelihood of marine mammal bycatch and thus could be exempt from the requirement. To receive an authorization to export fish or fish products to the United States, an export fishery must be governed by a regulatory program that meets certain conditions for assessing marine mammal populations by estimating bycatch, calculating bycatch limits, and reducing bycatch below such limits in export fisheries or by implementing alternative measures (e.g., eliminate the potential for bycatch). By the end of 2022 the United States intends to make comparability findings for all export fisheries to determine whether a harvesting nation's marine mammal bycatch program is comparable in effectiveness to that of the United States. If an export fishery fails to receive a comparability finding, the products from that fishery would be prohibited from entering the United States. One of the first steps NOAA took in implementing the MMPA Import Provisions was to create a List of Foreign Fisheries[3], which currently includes more than 1,800 fisheries from 131 nations listed as export fisheries, all of which will have to be evaluated for comparability to US standards[4].

The motivation for this paper is, in part, the recognition that in many parts of the world, the MMPA Import Provisions will mean that fisheries managers need to conduct marine mammal assessments for the first time (Williams et al., 2016). In the United States, the change to using a reference point for evaluating bycatch, rather than depletion level, immediately resulted in an increase in the number of populations assessed from 12 to 112, primarily because PBR is a relatively easy method to implement (Taylor et al., 2000). By describing the simplest framework for managing marine mammal management based on the use of a reference point, we hope to increase the number of populations that are assessed worldwide.

Collectively, we, the authors, have >250 years of contributing to marine mammal assessments, and we attempt to synthesize lessons learned in a way that we hope will be useful to those who are relatively new to managing marine mammal bycatch. We have focused in the Introduction on the rationale for using reference points to evaluate bycatch levels, primarily because using reference points requires the least amount of data compared to other, more complicated assessment methods. However, calculating a reference point is just one, albeit important, part of a larger and more complex process. Considerable information gathering and scientific research must occur before a reference point can be calculated. Then, once a reference point has been calculated and bycatch levels assessed, other steps must occur before bycatch can be reduced. Therefore, we describe and provide guidance on the entire framework, including (1) planning for an assessment of bycatch, (2) collecting appropriate data (e.g., abundance and bycatch estimates), (3) conducting the assessment of bycatch (by calculating a reference point), and (4) using the results of the assessment to guide marine mammal bycatch reduction (**Figure 1**). Although many of the examples discussed stem from the US approach to addressing marine mammal bycatch, our intention is to provide a general framework for assessing marine mammal bycatch more broadly.

We briefly discuss alternative, more complicated assessment methods, and we also discuss an alternative approach of mitigating bycatch without conducting an assessment, though adopting this approach can be problematic. Although **Figure 1** contains eight discrete steps, in some cases, where some information is already known about both the affected marine mammal community and fishing activity, it may be possible to start the process at later steps.

[2] Agreement on the International Dolphin Conservation Program, https://www.iattc.org/PDFFiles/AIDCP/_English/AIDCP.pdf

[3] https://www.fisheries.noaa.gov/foreign/international-affairs/list-foreign-fisheries

[4] 85 FR 63527, October 8, 2020, https://www.govinfo.gov/app/details/FR-2020-10-08/2020-22290

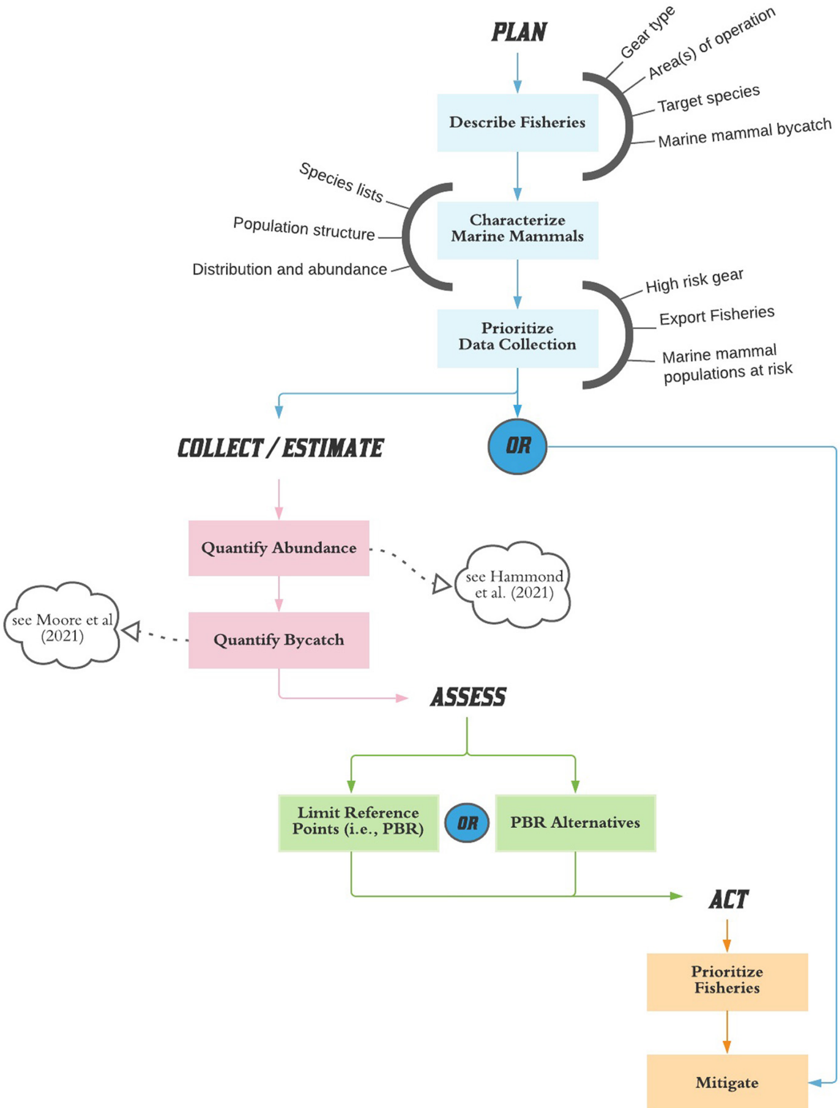

FIGURE 1 | A flow chart illustrating the process for assessing and managing bycatch of marine mammals. Names of flowchart components correspond to the names of the section headers in the paper.

PLANNING FOR AN ASSESSMENT OF BYCATCH

Identify Fisheries That May Interact With Marine Mammal Populations

The first step is to summarize what is known about the fishing gear used in a specific area. Fisheries are sometimes categorized (and managed) by target species, and therefore might deploy multiple gear types, but for evaluating bycatch of marine mammals it is important to identify fisheries by individual gear type because of the different risks posed by each gear type. Enough is known about marine mammal bycatch worldwide to reasonably predict which types of fishing gear will have the highest bycatch risk for particular marine mammals (Read, 2008; Brownell et al., 2019). Identifying fisheries that use high-risk gear and show substantial spatial and temporal overlap with the distribution of marine mammals provides a strong indicator of the likelihood of a bycatch problem. For example, global bycatch risk for odontocetes (toothed whales, dolphins, and porpoise) from small-scale gillnet fisheries has been estimated from species occurrence and bycatch susceptibility combined with estimates of fishing pressure (Temple et al., 2021). High-risk gear types, such as gillnets, purse seines, and trawls, not only have the capacity to take large numbers of marine mammals, but the potential for mortality is also very high due to the length of time the gear is fished and the inability of captured marine mammals to reach the surface to breathe. Other gear types, such as longlines, traps/pots, and pound nets, have variable impacts depending on which marine mammals occur in the fishing area (**Box 1**).

BOX 1 | Default priority level for data collection for different fishing gear types, based on likely risk for marine mammal bycatch. This is intended as a starting point, given that there can be different risks to different species depending on the fishing location, amount of fishing effort, how the gear is configured and fished, and other considerations. For example, the risk from buoy lines of trap/pot gear can be a high priority for large whales, such as the considerable risk such gear poses to North Atlantic right whales. In contrast, the same trap/pot gear may be a low priority for species such as seals and sea lions. Similarly, the risk from longline gear is particularly high for species that depredate longline gear, such as pilot whales, false killer whales, and sperm whales, but may be a low priority for species such as large whales.

Gear type	Risk priority	Considerations
Gillnet	High	All types, including drift, set, anchored, and trammel, are generally high risk for all species of marine mammals.
Trawl	High	Bottom or mid-water. Risk can vary depending on the speed of the trawl and size of the opening, with higher risk associated with faster tow speeds and wider trawl mouths.
Purse seine	High	Risk is variable, but can be high particularly if there is intentional encirclement, such as of dolphin schools in the eastern tropical Pacific or if the fishery targets fish that are also marine mammal prey, leading to inadvertent capture of marine mammals.
Trap/pot	Medium	Risk is species dependent. Buoy lines from trap/pot gear can be a high risk for large whales, such as right and humpback whales, and in the United States there is bycatch of bottlenose dolphins in some pot gear. Additionally, some pinnipeds can become entangled and drown after entering pots.
Longline	Medium	Bottom or pelagic. Many species can be captured, but higher risk is mainly associated with species that frequently depredate catch (e.g., pilot whales, sperm whales, killer whales, false killer whales).
Fyke (trap) net	Medium	Can pose substantial risk for species like harbor porpoises and seals.
Dredge	Low	Though similar to trawling, lower tow speed and narrow opening usually leads to low risk.
Hook and line	Low	Includes trolling. There are reports of bycatch with what are likely depredating sea lions, dolphins, and killer whales.
Demersal seines	Low	Includes Danish and Scottish seines.
Pound net	Low	There are reports of interactions with some dolphin species and harbor porpoises.
Cast and ring net	Low	
Jigs	Low	
Handline	Low	

After gear types have been identified, fisheries are often described by area of operation and/or target species. There is not necessarily a single best way to do this; it may be most sensible to anticipate what categorization would facilitate implementation of mitigation measures, should they be necessary. Once a list of fisheries has been developed, available information on the number of boats or individual fishery participants, the level of fishing effort, and the seasonal and spatial distribution of that fishing effort should be summarized to give an indication of the potential for bycatch of marine mammals (see for example, the US “List of Fisheries”)[5].

Next, available information on marine mammal bycatch in each specific fishery should be compiled. Assuming that bycatch has not been directly studied or observed previously, indirect or anecdotal information may be available, which can sometimes provide a good indication of substantial marine mammal bycatch in a specific fishery or area (**Box 2**). Records of marine mammal strandings are sometimes available, either through systematic stranding programs, anecdotal reports to fisheries agencies, accounts published in scientific literature, or reports in traditional and social media outlets. Stranded animals or even live pinnipeds when hauled-out, can be evaluated for evidence of fishing gear interactions (e.g., net marks on the body, recovered hooks/line/net) that sometimes can identify whether an animal died due to an interaction with fishing gear, and can implicate which type of gear was involved (Page et al., 2004; Moore M. J. et al., 2013; Ashe et al., 2021). Even if stranded animals do not provide enough information to identify gear type, sometimes the spatial and temporal co-occurrence of strandings and the operation of a fishery can suggest a fishery has substantial bycatch that should be investigated further. Examination of beach-cast carcasses can reveal that fisheries interactions exist, but may be unreliable for estimating the extent of bycatch

BOX 2 | How does one know whether marine mammal bycatch occurs in a fishery?

- Talk to fishermen – not all people associated with a fishery are willing to self-report marine mammal bycatch, but some do.
- Are there regular strandings of marine mammals on the coast in certain areas where fisheries operate?
    - Detailed examination of fresh carcasses can reveal marking and other information that indicates whether fishing gear, and what type, caused the death of an animal.
- Are there fisheries using gear types known to be high risk for marine mammal bycatch?
    - Some types of gear, such as gillnets, nearly always catch marine mammals if they co-occur.
- Search the popular media or social media for anecdotes from the public, and look for accounts published in scientific literature or other forums.
- Rapid assessment techniques can be used if no other information is available.

[5]https://www.fisheries.noaa.gov/national/marine-mammal-protection/list-fisheries-summary-tables

mortality, not least because the probability of a carcass stranding can vary among species by orders of magnitude (Williams et al., 2011).

A formal fishery observer program to estimate marine mammal bycatch rates (described below under "Quantifying marine mammal bycatch") is the most reliable way to evaluate whether a fishery has substantial bycatch, but when setting initial priorities, some other rapid-assessment methods can be used to identify if bycatch occurs. Fishermen can be requested or mandated to self-report bycatch of marine mammals. However, because self-reporting rates are often low, the use of such data typically results in negatively biased estimates of bycatch rates (Walsh et al., 2002; Emery et al., 2019; see Mangi et al., 2016), but such data can be valuable to identify whether bycatch occurs. Similarly, dockside interviews with fishermen can be conducted to collect information about marine mammal bycatch. Such interviews, especially if conducted by people known and trusted by the fishing community, can often reveal much about marine mammal bycatch (e.g., Moore et al., 2010; Pardalou and Tsikliras, 2018). Methods can be combined; for example, Mustika et al. (2014) describe a pilot study to identify the extent of small cetacean bycatch in Indonesia through fishermen interviews and stranding data. Another possibility arises if a marine mammal survey is conducted; data on direct occurrence of fishing boats can then also be collected to document the distribution of fisheries and their co-occurrence with marine mammals, to identify important areas of overlap (e.g., Goldsworthy and Page, 2007; de Boer et al., 2016; Baird et al., 2021). Similarly, Braulik et al. (2018) describe an approach for a rapid assessment that integrated collection of data on cetaceans from visual, acoustic, and interview surveys with existing information from multiple sources, to provide low-resolution data on the relative abundance of cetaceans as well as on threats such as bycatch.

Hines et al. (2020) have developed a geographic information systems tool based on open-source software for analyzing bycatch in small-scale fisheries, called Bycatch Risk Assessment (ByRA). The tool combines data on spatial locations of fishing vessels from marine mammal surveys with information from interviews with fishermen or other experts to create a GIS layer of fisheries risk, which is combined with a habitat model from survey data and environmental variables to predict the distribution of marine mammal species. Bycatch risk is evaluated based on the spatial and temporal coincidence of ranked probabilities of overlap between a species' occurrence and fishing; such analyses can be used to set priorities for collecting data on bycatch rates and fishing effort, and can identify areas deserving of management efforts and further research. Verutes et al. (2020) show an example of the use of the ByRA tool in a case study examining risk to Irrawaddy dolphins (*Orcaella brevirostris*) and dugongs (*Dugong dugon*) from five small-scale fishing gear types in Malaysia and Vietnam.

Initially Characterize the Marine Mammal Community

The marine mammal community needs to be described and characterized to create a list of all the marine mammal species that occur in the region, and a description of the population structure (number and boundaries of discrete populations) within each species in the region. Information about a population learned from any surveys (formal or informal) should be summarized, especially related to the population's distribution and abundance. It is also important to summarize anything known about the population structure. Many types of information can be used to identify populations of a species, including distribution (especially a hiatus in occurrence), movements, population trends, morphology, life history, genetics, acoustic signatures, chemical signals including contaminants, and habitat preferences (Martien et al., 2019). Additional information should be summarized, such as anything known about the spatial and seasonal occurrence of each population.

Even if no formal surveys have been conducted, it should at least be possible to describe which species are known to occur in a region, and in which marine zone each species is expected to be found, including the (1) Coastal (Littoral), (2) Shelf (Neritic), (3) Continental slope, or (4) Oceanic zones. For example, sperm whales (*Physeter macrocephalus*) are rarely found in the Coastal or Shelf marine zones. Anecdotal information is often available to document occurrence of most species. In most coastal areas, people who are on the water regularly, such as fishermen, will be familiar with which marine mammal species occur in their area. Because pinnipeds haul-out on land to give birth, molt, or rest, the pinniped species that occur in an area are usually well known, though their at-sea distribution may be unknown. Similarly, the occurrence of coastal cetaceans that can be seen from shore, such as bottlenose dolphins (*Tursiops* spp.), humpback dolphins (*Sousa* spp.), franciscana (*Pontoporia blainvillei*), harbor porpoise (*Phocoena phocoena*), or Burmeister's porpoises (*Phocoena spinipinnis*) will likely be well known in a region. However, given that fisheries often occur throughout a nation's Exclusive Economic Zone (EEZ), which extends up to 200 nautical miles from shore, it will be necessary to characterize the marine mammal community within the EEZ. Unless dedicated surveys have occurred in those areas, little documentation may exist about which species occur there, particularly for relatively cryptic species such as beaked whales. There are several resources that can be used to create a complete list of species likely to be found in a certain region, which can serve as a starting point (**Supplementary Material S1**).

Although information about bycatch of marine mammals in specific fisheries will have already been summarized in the previous step (above), it is also useful to summarize information about bycatch specific to each species. For example, a summary of fisheries known to take a particular marine mammal may point to a priority species if it is killed as bycatch in many large fisheries. Additionally, some information might be available for a species that is not tied to a specific fishery; this might include stranding records that indicate bycatch of the species, but not which specific gear or fishery.

Any information about other sources of anthropogenic mortality should also be included. Finally, anything known about the conservation or management status of the population should be summarized, including IUCN Red List status, and, if relevant, any status relative to domestic legislation or assessment frameworks.

Prioritizing Data Collection

Data on abundance and bycatch are essential to assessing and mitigating bycatch impacts. If those data are not available, programs to estimate abundance and fisheries bycatch will need to be developed. Because it is usually impractical to immediately collect all necessary data, some decisions will need to be made about which marine mammal surveys to first conduct, and which fisheries to first observe. Obviously, creating a meaningful list of priorities will be more difficult the less that is known, but even with little information, it is still possible to establish priorities based on several considerations. Here, we start with how to set priorities that are most feasible in a situation where little or no abundance or bycatch data are available.

The most important initial step is to compile information about the types of fisheries that occur in an area, and identify those that are likely to have the greatest potential for bycatch of marine mammals. If little information is available about bycatch rates, or even if bycatch occurs, we recommend the risk categories based on gear type (**Box 1**). Where no evidence of bycatch is known, but monitoring has been sparse or non-existent, it is important not to assume that bycatch does not occur. In general, one needs to be cautious because no data or incomplete data does not necessarily indicate a lack of bycatch impacts. Basing priorities on overlap between fisheries known to have substantial marine mammal bycatch in other regions ('risky fisheries') and marine mammal density distribution will avoid this pitfall (e.g., Hines et al., 2020), though this is often insufficient (Williams et al., 2014). Nonetheless, in the absence of other information, the overlap between risky fisheries and the range of marine mammal species can represent a starting point for collecting data.

For nations exporting seafood products to the United States, if NOAA's List of Foreign Fisheries (LOFF) identifies a fishery as an export fishery, this is a good indicator to begin assessing that fishery for marine mammal bycatch. The LOFF uniformly classified all gillnet, driftnet, set net, fyke net, trammel net and pound net fisheries as export (rather than exempt) fisheries because the likelihood of marine mammal bycatch is more than remote. For other gear types, including trap/pot, longline and troll line, purse seine, and all trawl, the LOFF classified these as export fisheries with limited exceptions; these limited exceptions include when a harvesting nation provided information that the fishery did not overlap with marine mammals, had very low documented bycatch rates, was analogous to a US commercial fishery that had low documented bycatch rates, or had implemented mitigation measures to prevent bycatch. On the LOFF, highly selective fisheries that have a remote likelihood of marine mammal bycatch (i.e., low priority for data collection or not a priority at all) are exempt fisheries and include the following gear types: hand collection, diving, manual extraction, hand lines, hook and line, jigs, dredges, clam rakes, beach-operated hauling nets, ring nets, beach seines, small lift nets, cast nets, small bamboo weir, floating mats for roe collection, and most forms of aquaculture.

Gillnet fisheries have long been recognized to have high bycatch mortality rates in nearly all configurations, including drift gillnets and anchored/set gillnets (Perrin et al., 1994; Reeves et al., 2013). Substantial bycatch has been documented in areas where coastal gillnet fisheries overlap distributions of coastal marine mammals, such as harbor porpoises or bottlenose dolphins (Brownell et al., 2019), and proximity to the shore often leads to evidence of such bycatch from strandings usually with visible net marks on the body (de Quiros et al., 2017). However, it is well known that pelagic gillnets can also have high bycatch of marine mammals, such as >100,000 cetaceans per year in tuna gillnets in the Indian Ocean (Anderson et al., 2020), so any type of gillnet fishery is potentially high risk. Some types of purse seine fisheries can have substantial bycatch particularly if there is intentional encirclement, such as of dolphin schools in the eastern tropical Pacific (Perrin, 1969; Wade, 1995) or if the fishery targets fish that are also marine mammal prey, leading to inadvertent capture of marine mammals. Midwater or surface trawl fisheries will sometimes have high marine mammal bycatch, depending on the gear, with larger openings and higher trawl speeds increasing risk; for this reason, some pair-trawl configurations have had particularly high bycatch and bycatch mortality rates (e.g., De Boer et al., 2012). Some bottom (demersal) trawl gear can have relatively high risk to marine mammal species that forage on or near the sea floor (e.g., Franco-Trecu et al., 2019).

Other gear types can pose a medium to high risk to marine mammals depending upon their configuration and operation. Longline fisheries can have substantial bycatch of marine mammals, especially odontocetes (toothed whales) known to take bait or target fish from fishing gear (Hamer et al., 2012). Many hooked and/or entangled marine mammals are able to reach the surface to breathe, but even those that are released alive or self-release with some gear remaining attached (e.g., a hook and some amount of line) may have suffered serious injuries that are likely to lead to death. Pot fisheries can trap and drown sea lions in the pot itself (Campbell et al., 2008). Trap/pot fisheries can entangle baleen whales (Johnson et al., 2005) and small cetaceans in buoy lines that fishermen use to locate and retrieve traps/pots from the bottom, or in ground lines used to connect traps/pots; when these pot fisheries occur at high densities, they can pose substantial risk to large whale populations (e.g., Kraus et al., 2005). After becoming entangled, baleen whales generally swim off with gear attached that can impede feeding, reproduction, and/or swimming, cause substantial injuries and suffering, and ultimately lead to death (van der Hoop et al., 2016). When marine mammal populations are small, such as the North Atlantic right whale (*Eubalaena glacialis*), mortality of a few individuals a year can have substantial population-level impacts.

Several gear types are thought to have low to medium risk of bycatch, depending on the specific gear and mode of operation. Dredge gear is somewhat similar to demersal trawl gear, but it has smaller openings, lacks large trawl doors, and is usually towed at a lower speed, so the risk to marine mammals is generally thought to be lower. Pound nets can trap small coastal cetacean and pinniped species; there have been some cases where substantial catches have occurred locally. Similarly, beach seines generally pose medium or low risk to marine mammals, but they can substantially impact small, localized populations of small cetaceans (Pierce et al., 2020). Troll fisheries tend to pose lower risk to marine mammals, though there are cases where trolling with hook-and-line gear could be considered impactful especially if the vessel uses dolphins to locate fish and maneuvers through a group of marine mammals (Baird and Webster, 2020). Hook-and-line fisheries are considered low risk, although there are some well documented cases where depredation in recreational fisheries has led to interactions and serious injuries, such as for bottlenose dolphins (*Tursiops truncatus*) in the Gulf of Mexico (Wells et al., 2008) and killer whales (*Orcinus orca*) in British Columbia. Other types of fishing gear or methods (e.g., jigs, handlines), many manually deployed, may also be considered low-risk because of the short duration of deployment or because marine mammals generally do not occur in areas where these gears are deployed.

The spatial and temporal distribution of effort in high- and medium-priority gear-type fisheries should be compared to the known or suspected distribution of marine mammal populations. Any obvious hotspots of co-occurrence of high densities of marine mammals and high-priority fisheries can contribute to a preliminary list of the highest priority areas to investigate. Similarly, co-occurrence with medium-priority fisheries will provide a preliminary list of the second highest priority areas. After this initial evaluation, any additional information can be used to finely tune priorities for data collection. Evidence of concurrent strandings or anecdotal reports of bycatch in identified areas could elevate the priority of a specific area or fishery. As mentioned above, it could be helpful to formalize this step in a GIS-based decision framework, such as the toolbox described by Hines et al. (2020). If fisheries bycatch mortality of a certain species is known to occur at an appreciable but unquantified rate, a decline has been noted in the relative abundance of that species, and there are no other obvious explanations for what has caused that decline, this would indicate that data collection on bycatch rates of that species is a high priority.

The next step is to evaluate other considerations. Marine mammal populations that are small or declining, and/or have already been identified as a conservation concern, would be a higher priority to assess than those with a larger population size or increasing trends. The goal is to develop a list of priorities for fisheries to monitor and marine mammal populations to assess given potential bycatch impacts.

COLLECTING APPROPRIATE DATA

Quantify Marine Mammal Bycatch

It is critical to estimate the magnitude of annual bycatch in fisheries to assess marine mammal bycatch using a mortality reference point. Fully describing how to observe fisheries, collect effort data, and estimate bycatch rates and total bycatch are beyond the scope of this paper. See text footnote 1 provide a comprehensive guide to these processes, including identifying minimum requirements for obtaining credible estimates of bycatch and best practices. See text footnote 1 also focus on empirical studies that have generated quantitative results (with uncertainties and limitations specified). Here, we briefly outline the primary steps involved in quantifying bycatch to describe the scope of the process.

The standard way to quantify marine mammal bycatch in a fishery is through a two-part process, including (1) observing fishing operations and bycatch for a portion of a fishery, and (2) collecting effort data for the entire fishery. With these two types of data, a bycatch rate for the observed portion of the fishery can be estimated, and it can be applied to some measure of total fishing effort to estimate total marine mammal bycatch. Among the primary approaches to data collection are on-board observer programs (commercial or research vessels), on-board camera systems, observer programs from secondary platforms (if observers cannot be placed on fishing boats), logbook records (self-reporting), and structured interviews with fishermen, including dockside surveys.

The proportion of fishing effort that needs to be observed will vary among fisheries. In general, the larger a fishery is (more vessels and/or fishing trips), the smaller the percentage of the total fishing effort that must be observed to adequately characterize bycatch rates. It is important that the observations randomly sample the entire fishery to produce unbiased estimates of bycatch mortality. This often requires understanding the fishery in great detail to, for example, ensure that fishing in all spatial areas or seasons are sampled (e.g., such as ensuring that fishing trips originating from all fishing ports are sampled). It is common to use stratified sampling designs, for example, to observe various-sized vessels as separate strata with different observation rates, or to sample at higher rates in areas with the greatest amount of fishing effort, or in areas that are suspected or known to have the highest rate of marine mammal bycatch.

Estimating or quantifying bycatch in fisheries that are not directly observable is particularly challenging; the most common example is entanglement of large whales in buoy lines attached to pot gear. Evidence that large whales are entangled in lines can be seen from specific types of scars seen on the whales (Knowlton et al., 2012), but this cannot determine which fisheries are responsible for the entanglement. Typically, pot gear can be left in the water unattended for considerable periods of time, so quite often no fishing vessel is in the vicinity of the gear when a large whale entanglement occurs. Entangled whales are often later encountered, either alive, floating dead, or stranded, so one approach is to mark the gear in a way that allows the specific fishery to be identified from lines and other gear still attached to the whale (e.g., Johnson et al., 2005).

It may also be necessary to address situations where marine mammals are observed injured and released alive, but their fate post-release is unknown and they may ultimately die. There are guidelines in the United States for assessing injuries and determining whether a given injury is likely to lead to death (National Marine Fisheries Service, 2012). For some injuries it is possible to estimate the proportion of marine mammals injured that ultimately died from the injury based on extensive population monitoring and known outcomes for individuals that were documented as injured in fishing gear (National Marine Fisheries Service, 2012).

There are several ways to analyze bycatch data, and statistical methods are rapidly improving (see text footnote 1). Simple ratio estimators are sufficient in a properly designed study; so-called design-based methods assume that bycatch in the observed portion of the fishery can be extrapolated to the whole fishery because the fishery is sampled in a representative way. Other approaches, generally referred to as model-based estimators, will work better when sampling cannot meet this standard. In some situations, model-based estimators can improve precision and reduce bias in bycatch estimates. There are strengths and weaknesses of each approach; see text footnote 1 for further discussion.

Some elements of characterizing a fishery (see **Supplementary Material S2**) are essential for estimating bycatch (e.g., fishing effort) whereas others are more relevant for developing mitigation measures (e.g., nature of interactions, such as whether hooked or entangled, the amount of gear remaining on the animal, whether depredation occurred), so it is worth collecting those types of data, too, even if they are not directly used for estimating bycatch. Observer programs may need to be modified to provide sufficient data to evaluate whether mitigation measures are effective in reducing the bycatch to below the reference point or to meet conservation goals.

Quantify Abundance of Marine Mammal Populations

A fundamental requirement to assess the status of a population is the availability of a nearly unbiased estimate of absolute abundance. Hammond et al. (2021) provide a comprehensive guide to estimating the abundance of marine mammal populations, and they identify minimum requirements for obtaining credible estimates of abundance and suggest best practices. That review also describes many examples of studies that have resulted in credible abundance estimates (with uncertainties and limitations specified). Here, we briefly outline some common abundance quantification techniques and applications; see Hammond et al. (2021) for guidance on how to select a method for a particular situation.

For cetaceans, several techniques and field methods are used depending on the marine mammal species and regions (as an illustration, see **Supplementary Material S4** for a summary of the methods used for all marine mammal populations in the United States). Most cetacean abundance estimates are made using either line transect (distance sampling) methods (74% of US stocks, **Supplementary Table 1**) (Buckland et al., 2001) or mark-recapture methods (25% of US stocks, **Supplementary Table 1**) based on the identification of individuals (Hammond et al., 1990). Line-transect surveys involve conducting a survey with observers along transects that sample the area for which an abundance estimate is desired, while collecting data on the perpendicular distance (the distance away from the trackline) of each marine mammal group that is seen. The platform to use for cetacean line-transect surveys varies depending upon the region to be surveyed (e.g., ships in oceanic regions; ships and airplanes in continental slope and shelf regions; ships, small boats, and airplanes in coastal and nearshore regions). Table 1 in Hammond et al. (2021) provides a list of example studies of line-transect methods used to estimate the abundance of cetacean populations from small boats, ships, and airplanes.

There is an extensive literature and history of using mark-recapture methods to estimate abundance of terrestrial wildlife, where animals are captured, marked in some way (such as with a tag), released, and then recaptured at a later sampling time (e.g., Otis et al., 1978; Schwarz and Seber, 1999; Chao, 2001). Many of these methods have been adapted for use with marine mammals and are usually based on the sighting and resighting of individuals over time. Individuals are normally identified from natural markings observed in photographs, but sometimes through genotyping of skin biopsies (e.g., Hamner et al., 2014) or from marks placed on animals. Identification of cetaceans can be based on scars, notches in the dorsal fin/ridge, color patterns, the shape of the dorsal fin or flukes or other natural marks. Table 2 in Hammond et al. (2021) provides a list of example studies where mark-recapture analyses have been applied to photo-identification data to estimate the abundance of marine mammal populations.

Other methods for estimating cetacean abundance exist. For example, boat surveys are often used to count freshwater dolphins and porpoises, without using line transect methods, but instead use correction factors applied to the counts. Alternatively, in a few cases the abundance of baleen whale populations that migrate close to headlands (e.g., gray whales, *Eschrichtius robustu*s, and some populations of humpback whales, *Megaptera novaeangliae*) can be estimated using land-based counts.

The abundance of a pinniped population is often estimated based on a count of individuals when they are hauled out on land or ice. Depending upon the species, the counts can be conducted from land, boats, drones, or airplanes. The surveys may be timed to coincide with times when the most individuals are hauled out, such as during molting, and all age classes are counted (54% of US pinniped stocks, **Supplementary Table 1**). These counts are often corrected for the proportion of animals that are hauled out at the time of the survey, which can be estimated using telemetry data from tags placed on the animals. Abundance can also be estimated from counts of the number of pups on a rookery (21% of US pinniped stocks, **Supplementary Table 1**); this method can be useful when not all age and sex classes haul out at the same time. A population model, using estimates of survival and birth rates, must be used to extrapolate a pup count to an estimate of total abundance. Data needed to estimate those parameters can be difficult to collect, and parameters may change over time, so this method is not used as commonly as haul-out counts. The abundance of several ice seal species has been estimated using line- or strip-transect surveys conducted from airplanes (10% of US pinniped stocks, **Supplementary Table 1**). This can also include the use of tag telemetry data to estimate the proportion of the population that is hauled out on the ice at the time of the survey. Mark-recapture methods have also been used to estimate the abundance of some pinnipeds, using marks applied to the animals or natural coloration patterns [see Table 2 in Hammond et al. (2021) for examples].

The abundance of sirenians or marine mustelids (e.g., sea otters, *Enhydra lutris*) is usually estimated in a similar manner to cetaceans, using line-transect or strip-transect surveys from airplanes or boats.

CONDUCTING AN ASSESSMENT OF BYCATCH

The United States Example – The Stock Assessment Process and the PBR Reference Point

Moore M. J. et al. (2013) and Curtis et al. (2015) offered a set of guidelines for conducting reference-point based management, outlining a general assessment framework of which the US PBR approach can be considered a special case. Their reviews include extensive discussion of the basis for different conservation objectives and risk tolerances that can be used to tune the reference point estimators as a function of these and species conservation status (e.g., IUCN Red List status). For convenience, and because it would be relevant to the MMPA Import Provisions, we briefly summarize how the PBR bycatch reference point is derived for US marine mammal populations, and how assessments are conducted.

The US MMPA requires a "Stock Assessment Report" for each marine mammal population[6] in US waters (see **Supplementary Material S3** for a list of contents for such reports), which makes transparent how much (or little) is known about each population and whether bycatch is a concern. To assist in this, the National Marine Fisheries Service has published "Guidelines for Preparing Stock Assessment Reports pursuant to the 1994 amendments to the MMPA,"[7] which we refer to as 'the Guidelines.' The Guidelines serve as a practical guide for how assessments are conducted in the United States, and here we highlight some of the important issues.

Understanding population structure is an essential first step in conducting an assessment. The Guidelines expand on the MMPA definition of a stock: "*For the purposes of management under the MMPA, a stock is recognized as being a management unit that identifies a demographically independent biological population*." Data on population structure are often lacking, but defaulting to a single population for an entire ocean basin is likely inappropriate given what is known about population structure for most species. The Guidelines note that for some species genetic and other biological information has confirmed the likely existence of stocks of relatively small spatial scale, and therefore a species' range within an ocean should be divided into stocks that represent defensible management units. A guide for how to delineate demographically independent populations of marine mammals can be found in Martien et al. (2019).

Once stocks are defined, it is possible to summarize information on abundance, fisheries bycatch mortality, and other information. Calculating the bycatch reference point PBR depends upon three values:

$$\mathrm{PBR} = \mathrm{N_{min}} \cdot 1/2\mathrm{R_{max}} \cdot \mathrm{F_r},$$

where N_{min} is a minimum estimate of abundance that provides assurance the true population size is larger, R_{max} is the maximum net reproductive rate, and F_r is the recovery factor (in the United States the F_r must range between 0.1 and 1.0, but in theory it can approach 0). In the Guidelines, N_{min} is defined to be the 20th percentile of an abundance estimate. The 20th percentile was specified using simulations that showed that populations that experienced mortality at the level of a PBR calculated with that value of N_{min} would stay at or recover to MNPL with 95% probability (Wade, 1998; Taylor et al., 2000). This type of simulation performance testing is known as management strategy evaluation, which has become common in fisheries management and conservation (Bunnefeld et al., 2011).

The Guidelines provide default values for R_{max} (0.04 for cetaceans and manatees; 0.12 for pinnipeds and sea otters) and require reliable stock-specific information to use an estimated R_{max} in lieu of the defaults. In practice, relatively few population assessments use stock-specific estimates of R_{max}. Notable exceptions include some endangered small populations that are not recovering (e.g., southern resident killer whales), and populations of humpback whales that have been documented to increase at rates greater than 0.04.

The intent of the US MMPA in including F_r when calculating PBR was to ensure the recovery of a population to its Optimum Sustainable Population level (by providing a precautionary buffer against potential biases or other non-ideal circumstances) and to expedite recovery (minimize recovery time) for endangered, threatened, and/or depleted populations. Therefore, the Guidelines specify that the default value for F_r for populations of unknown status (i.e., not known to be above MNPL) should be 0.5; this value was chosen because Wade (1998) indicated this value would make the PBR, and the achievement of the objectives of the MMPA, robust to common biases and issues with the estimates of PBR and bycatch levels. The Guidelines note that "*Recovery factors of 1.0 for stocks of unknown status should be reserved for cases where there is assurance that N_{min}, R_{max}, and the estimates of mortality and serious injury are unbiased and where the stock structure is unequivocal*." Species listed as endangered under the US Endangered Species Act (ESA) are given a value for F_r of 0.1 to promote recovery and minimize the probability of extinction. Although there is not a one-to-one correspondence between listings under the US ESA and the IUCN Red List, it is our view that it would be a reasonable starting point to set $F_r = 0.1$ for any species or population listed as Critically Endangered or Endangered on the IUCN Red List.

[6]The US MMPA defines the terms "population stock" and "stock" to be synonymous; that is, "The term "population stock" or "stock" means a group of marine mammals of the same species or lower taxon in a common spatial arrangement, that interbreed when mature." We use the term population throughout unless referring to a specific US MMPA directive that uses the word stock.

[7]https://www.fisheries.noaa.gov/national/marine-mammal-protection/guidelines-assessing-marine-mammal-stocks

The US MMPA requires that all human-caused mortality and serious injury[8] of the population be estimated, including bycatch mortality, and that all fisheries interacting with marine mammals be described, including number of vessels/participants in a fishery and seasonal/area differences in fishery mortality. The Guidelines recommend, where appropriate to improve precision, using average annual mortality over the last 5 years that are available. A stock is designated as *Strategic* if this level of annual mortality exceeds PBR. In the US, PBR is not used as a cap, such that a fishery would close if incidental mortality and serious injury exceeded PBR. Instead, fisheries with bycatch of a *Strategic* stock may be subject to specific requirements (see below), including those for reducing bycatch to below that stock's PBR.

Alternative Assessment Methods

It is worth considering other assessment methods, if they are available and appropriate. In data-poor situations, for example, methods can be developed that rely only on trends in abundance (e.g., Punt et al., 2021b). Those methods ultimately provide lower and more variable reference points for bycatch mortality and are more sensitive to uncertainties than the PBR method. Methods based on trends also have the disadvantage that if that mortality is reduced, an increasing trend does not guarantee the population has recovered significantly. The reverse situation is different – if a decline in population size of 50% or greater has been observed, it is safe to assume that the population is below MNPL, and therefore depleted. If fisheries bycatch mortality is known to occur at an appreciable but unquantified rate and there are no other explanations for what has caused a decline, this would indicate that data collection on bycatch rates is a high priority (see above).

Alternative methods are also available in more data-rich situations. For example, Brandon et al. (2017) show that incorporating multiple abundance estimates for data-rich populations can lead to increased stability of calculated values for PBR through time, which could reduce regulatory uncertainty that may be associated with some human activities managed using the PBR reference point. With more data or resources, assessments that are more sophisticated (and complicated) than simple reference points such as PBR are possible (e.g., Goldsworthy and Page, 2007; Punt et al., 2020, 2021a).

USING THE RESULTS OF THE ASSESSMENT TO GUIDE MARINE MAMMAL BYCATCH REDUCTION

Identifying High Priorities for Bycatch Reduction

Once the assessments have been completed, it is important to identify which fisheries are priorities for bycatch reduction, as there are usually insufficient resources to attempt to mitigate bycatch in all fisheries immediately. For example, the US MMPA specifies the highest priorities for bycatch reduction are fisheries with bycatch mortality exceeding a stock's PBR, marine mammal stocks with small population size, and those stocks that are declining most rapidly.

Fisheries can also be ranked by the level of bycatch mortality as a percentage of a given population's PBR. If bycatch levels exceed PBR, the fishery would be a high priority for monitoring and mitigation whereas if bycatch levels were more than 50% of PBR (but less than PBR), that fishery would be a medium priority for monitoring and mitigation. Obviously, this type of ranking can be extended if appropriate, to recognize the higher priority of situations where bycatch mortality is even greater (e.g., 2 or 3 times PBR). Another type of high priority fishery is one that has relatively high levels of bycatch of an endangered species or population.

Complications arise when assessments indicate bycatch exceeds reference points for several species. Clearly, if a single fishery has bycatch that exceeds the reference point of multiple populations, that fishery should be a high priority for management action or bycatch reduction. For example, in the United States, a plan was developed to reduce bycatch of Baird's beaked whales (*Berardius bairdii*), Cuvier's beaked whales (*Ziphius cavirostris*), *Mesoplodon* species of beaked whales, short-finned pilot whales (*Globicephala macrorhynchus*), pygmy sperm whales (*Kogia breviceps*), sperm whales, and humpback whales in the California/Oregon swordfish drift gillnet fishery. The large number of species taken at relatively high levels in a high-risk gear type made it clear that this fishery was a priority for bycatch reduction.

In the absence of high-quality survey data on abundance and/or bycatch, population projections can be used to test bycatch scenarios and identify priorities for bycatch reduction. Simulation-based tools provide a way to examine potential outcomes and inform management decisions related to bycatch limits or bycatch reduction measures, such as gear modifications meant to reduce risk to an acceptable level. Scenario analysis, in which populations are projected forward under different management decisions, allows stakeholders to see the relative impacts of these management decisions even when data are sparse for populations of interest. For example, Siple (2021) developed the Marine Mammal Bycatch Impacts Exploration Tool (MMBIET) and a corresponding R package for projecting marine mammal populations subjected to different bycatch levels (**Figures 2**, **3**). Projections can be used to determine performance in terms of population recovery and expected long-term depletion levels. In terms of reference points, the tool calculates N_{min} based on an abundance estimate and its coefficient of variation, and then calculates PBR based on a value for R_{max} (with default values based on the assumptions in the MMPA) and F_r chosen by the user (**Figure 2A**). Projection outputs and performance can then be plotted and explored (**Figure 2B**). While this tool is useful for exploring risk, the values it provides will only be as good as its inputs (e.g., if the current abundance of the population is incorrectly specified, MMBIET may provide an incorrect estimate of PBR or incorrect times to recovery). Thus, interactive tools such as MMBIET allow users to explore scenarios and identify robust management strategies, provided they are used correctly.

[8] "Serious injury" is defined to be an injury that is likely to lead to death.

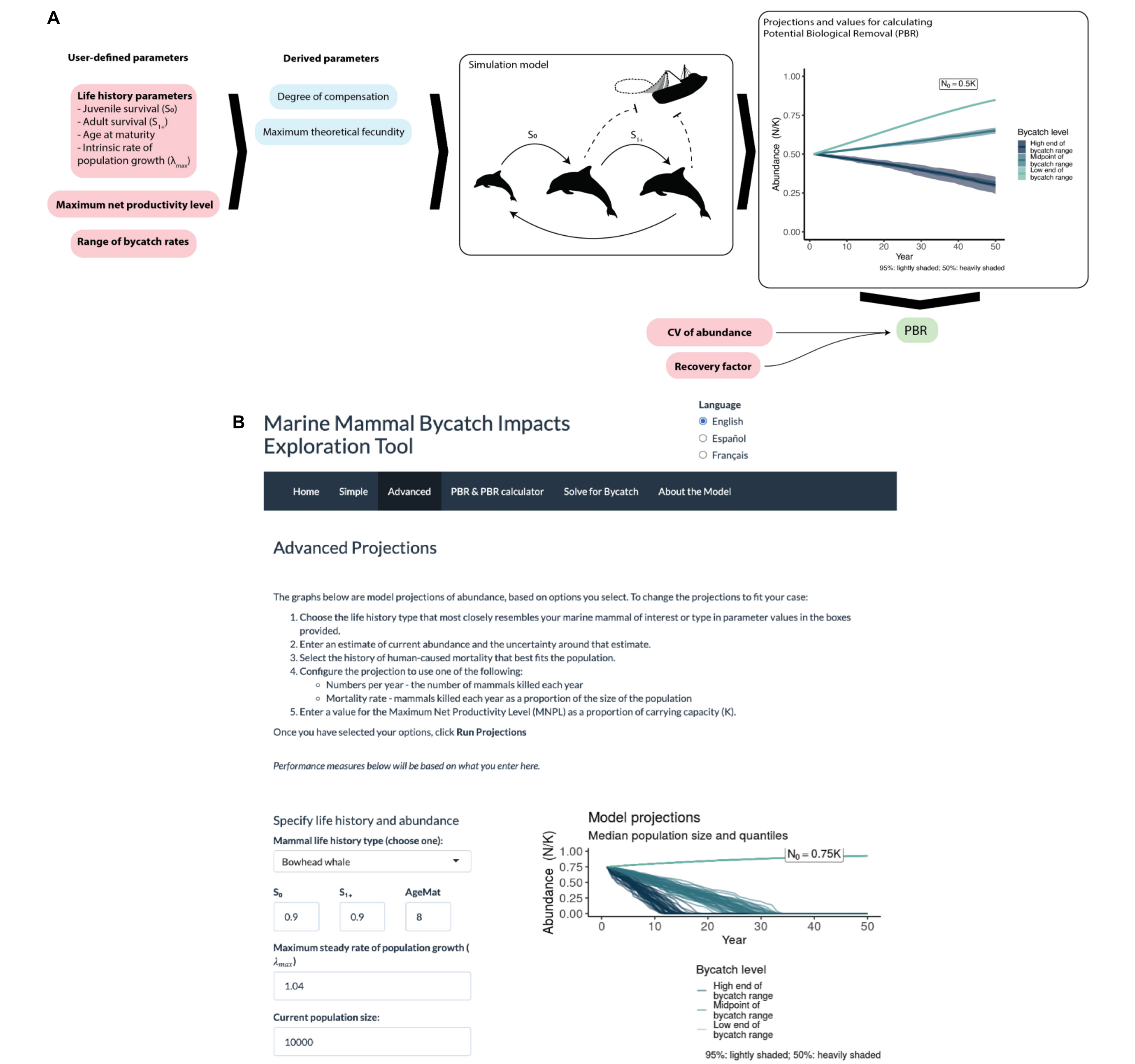

FIGURE 2 | (A) Flow of inputs and information in the Marine Mammal Bycatch Impacts Exploration Tool (MMBIET; Siple, 2021). Pink boxes indicate user-specified inputs; blue boxes indicate derived life history parameters. Users provide life history information by selecting a default life history type or by specifying parameter values manually. They also choose the Maximum Net Productivity Level (MNPL) and a range of bycatch rates to explore. The tool uses these values to conduct projections of marine mammal abundance into the future. The simulated abundance and CV of abundance selected by the user are used to calculate Potential Biological Removal (PBR). **(B)** Example screenshot from MMBIET. Open source code can be found at www.github.com/mcsiple/mmrefpoints.

Similarly, demonstrated co-occurrence of high-risk fisheries and marine mammal populations, either through qualitative evaluation or structured methods such as GIS mapping tools (e.g., Hines et al., 2020; Verutes et al., 2020; Welch et al., 2020), can help identify priority spatial areas for bycatch reduction. Bycatch mitigation, which often takes many years to accomplish, could begin in these areas while research continues. Eventually, it will be necessary to quantify bycatch rates to evaluate how much bycatch needs to be reduced to ensure it is below a reference point such as PBR. Valuable information can be gained in the meantime by initiating work on fisheries that are predicted to have unsustainable levels of bycatch.

Mitigating Marine Mammal Bycatch

Once fisheries have been prioritized, the next step is to set specific goals for mitigating bycatch. A reasonable immediate goal would be to reduce the bycatch level to below the reference point. However, reducing the bycatch to just barely below the reference

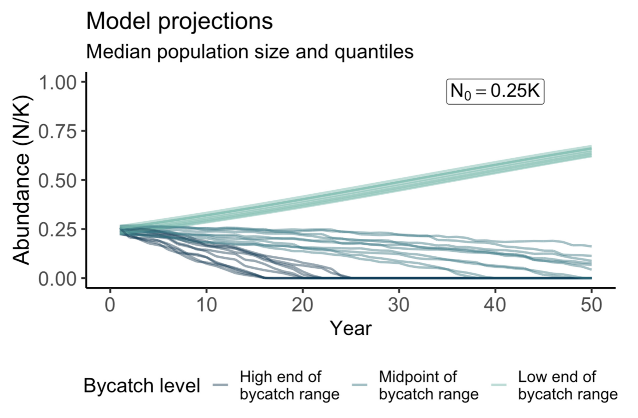

FIGURE 3 | An example of model projections for a bottlenose dolphin population, starting at 25% of carrying capacity, with a bycatch rate between 10 individuals per year (light green lines) to 1,300 individuals per year (dark blue lines). The lowest bycatch rate, which is below PBR for this theoretical population (PBR = 183 individuals), leads to a recovery to MNPL, which is set at half of the carrying capacity (*N/K* = 0.5). For these projections, the starting population size is 20,000 individuals, the CV of abundance is 0.1, and the CV of bycatch is 0.5.

point is not ideal, due to uncertainty in estimating abundance and mortality. Thus, it would be better to attempt to reduce bycatch to a level well below the reference point. Under the US MMPA, the immediate goal is reducing bycatch to below a stock's PBR, but the long-term goal is to reduce it even further to insignificant levels (i.e., 10% of PBR).

To implement effective bycatch reduction measures for fisheries, it is useful or even necessary to involve many stakeholders in the process, including fishing industry representatives, government fisheries managers and scientists, non-governmental organizations, and academic scientists. For this reason, the 1994 US MMPA amendments established a framework for reducing fisheries bycatch mortality that exceeded a stock's PBR level; this framework relies on stakeholder-based "Take Reduction Teams" to recommend consensus-based Take Reduction Plans that include mitigation measures for reducing bycatch mortality of particular marine mammal stocks in certain fisheries. Including fishermen, who bring expert knowledge and creativity, on Take Reduction Teams is critical to the success of take reduction planning.

There are various ways to mitigate marine mammal bycatch, and several recent reviews of methods are available (FAO, 2018, 2021; Leaper and Calderan, 2018; Hamilton and Baker, 2019). One with generally good success is time and/or area closures, meaning, for example, to prohibit fishing in "hotspots" or areas of substantial overlap in spatial distribution between fishing effort and marine mammal abundance at certain times of the year. If such hotspots in co-occurrence can be identified, closing the areas to fishing would, in some situations, reduce bycatch considerably. FAO (2018) provides nine examples of time/area closures from six countries. If needed, time/area closures can sometimes be implemented fairly rapidly with a high chance of success at reducing bycatch. For example, the International Council for the Exploration of the Sea (ICES) recommended emergency temporal closures of all fisheries of concern (trawls, gillnets, trammel nets, and purse seines) and the application of pingers on pair trawlers to mitigate bycatch outside the closure periods to immediately reduce bycatch of common dolphins in the Bay of Biscay (ICES, 2020). One implementation challenge is the potential for edge effects, where fishing effort is concentrated along the border of the closed area; in such cases, the bycatch reduction may not be as great as would be expected if fishing effort were dispersed across the remaining open areas.

There may be undesirable economic impacts on a fishery if fishing cannot occur in other areas or in different time periods, so stakeholders often favor modifying fishing gear and practices to avoid the potentially large economic impacts of time/area closures. This can include changing hook types or gillnet mesh size, or switching to buoyless (often referred to as ropeless) trap/pot fishing (e.g., Myers et al., 2019). Gear modification is an available and common mitigation approach in the absence of assessment (see below). For example, much research has focused on modifying longline gear to reduce the likelihood that animals get hooked (e.g., Bigelow et al., 2012; McLellan et al., 2015).

Acoustic alarms, such as pingers, have been used to alert certain species of marine mammals to nets in the water or to scare them away from nets (e.g., Carretta et al., 2008; Palka et al., 2008; FAO, 2021). However, their effectiveness in mitigating bycatch varies between locations and species (Berrow et al., 2008; Carretta and Barlow, 2011; Dawson et al., 2013). A review of multiple studies concluded that pingers were effective in reducing bycatch of harbor porpoises, beaked whales, common dolphins and franciscanas, but were not effective for bottlenose dolphins, and the authors concluded it was not possible to predict efficacy for other species; they suggested pingers might be most effective for species that are neophobic or easily startled such as the harbor porpoise (Dawson et al., 2013). Additionally, if there is a high density of fishing effort in a particular geographic region, one would need to consider the benefits of bycatch reduction versus the cost to the marine mammals of being displaced by pingers away from a significant portion of their habitat, which may be important for foraging or other essential activities. For example, harbor porpoises are highly susceptible to bycatch in gillnet fisheries, with most animals suffocating in the nets, and pingers have been shown through multiple experiments to effectively reduce bycatch; in such cases it may be more beneficial to implement mitigation measures despite any sub-lethal impacts such as displacement.

Another type of mitigation that can be applied in the absence of an assessment is gear switching, where a fishery switches from a relatively high-threat to a relatively low-threat gear type. Bycatch of vaquitas in gillnets in the upper Gulf of California has led to a severe reduction in the population to the point where just a few animals remain. The species is critically endangered, and it faces imminent extinction (D'Agrosa et al., 2000; Taylor et al., 2017). A small shrimp trawl that can be towed from artisanal-style fishing boats was recommended to replace the gillnets. Similarly, Berninsone et al. (2020) evaluated switching from gillnets to longlines to mitigate bycatch of franciscanas in Argentina.

In some cases, certain gear/fishery types have been eliminated altogether. For example, the US Atlantic Offshore Cetacean Take Reduction Team was convened to reduce the incidental mortality and serious injury of several species of marine mammal in the Atlantic pelagic driftnet, pelagic longline, and pair trawl fisheries. The pair trawl fishery was an experimental fishery for tuna, and because of the large separation between the vessels and the high tow speeds (2.5–5 knots), the fishery had a high dolphin bycatch rate. For a variety of reasons, the pair trawl fishery was not authorized as a permanent fishery. The pelagic driftnet fishery (targeting swordfish) was eventually closed to reduce marine mammal bycatch (McDonald et al., 2016). Effectively, two gear types with high bycatch rates were eliminated, leaving mitigation and bycatch reduction to focus on the longline fishery[9].

Mitigation methods, such as the use of electronic acoustic pingers, can be prohibitively expensive to implement. Awareness of this has led to recent research to develop lower-cost solutions, such as glass and plastic recycled bottle alarms and acoustic reflectors to use on gillnets instead of electronic pingers (FAO, 2018). Additional details on mitigation methods can be found in FAO (2018, 2021), which provide a thorough discussion of techniques used to address marine mammal bycatch, including a comprehensive review of mitigation techniques (Appendix 3 of FAO, 2018), and a table documenting 69 studies where an attempt was made to reduce marine mammal bycatch (Appendix 4 of FAO, 2018). Werner et al. (2015) provided specific advice for mitigating marine mammal bycatch and depredation in longline fisheries.

Consideration needs to be given to the timing and sample size to detect any change in the bycatch rate, assess eventual effectiveness, and determine whether the mitigation is successful in meeting conservation goals. It may be difficult to measure a statistically significant reduction in the bycatch rate immediately if bycatch rates are high relative to the mortality reference point, but observations of bycatch are still relatively rare; managers should consider this when evaluating the effectiveness of mitigation measures. Additionally, effectiveness should be regularly assessed at meaningful intervals to ensure that any bycatch reduction continues through time.

There are implementation considerations for all mitigation measures that managers should be aware of and plan for before implementation begins. Such considerations span many sectors – regulatory, enforcement, socioeconomic, and safety to name a few – and include subjects such as the mechanisms to enact new measures (e.g., regulations, proclamations, voluntary compliance), safety of fishermen when using modified gear or fishing practices, enforcement strategies (e.g., via marine patrol, vessel monitoring systems), supply chain impacts (e.g., time needed to manufacture a new gear modification), the time and money it will take for fishermen to incorporate gear modifications into existing gear, etc.

Mitigating Without Assessment

It may be appropriate to pursue bycatch mitigation directly without conducting an assessment. The main issue here would be determining how much mitigation to do; in other words, how do you know how much bycatch needs to be reduced if you have not calculated a bycatch reference point?

Some marine mammal species only occur in an area seasonally because they migrate to another location for a portion of the year, such as humpback whales that arrive at some nearshore areas in low latitudes for part of the winter. If a nearshore fishery overlapped with the distribution of a marine mammal population and was known to cause bycatch, that area could be closed for the entire time period in which the marine mammals are present. In this case, the bycatch would be entirely mitigated (reduced to zero), and it would not be necessary to calculate a mortality reference point as a reduction target. This is of course a relatively extreme mitigation strategy and considerable thought would need to be given as to whether the fishery could adapt.

Another example would be a change in fishing gear. For example, species that depredate longline gear, such as killer whales, pilot whales, and sperm whales, can be bycaught (by hooking or entanglement, or both). Switching to pot gear would eliminate bycatch in the longline gear but it would be necessary, of course, to evaluate whether pot fishing poses entanglement risk to large whales as well as whether it provides revenue similar to that provided by the longline fishery.

Another example would be mitigating bycatch of cetaceans in gillnet gear. As mentioned earlier, in many locations "pingers" have been used to reduce bycatch rates of cetaceans, but they have not been effective for all species. Therefore, it may not be possible to conclude that mandating the use of pingers would be sufficient mitigation without first conducting an assessment of effectiveness. It is possible that showing that circumstances are similar to those of another location where pingers have been evaluated as effective would give reasonable confidence that pingers would reduce mortality, such as successful examples with harbor porpoise bycatch reduction. However, it would still be difficult to determine whether the reduction was sufficient without an actual assessment to provide a quantitative target for bycatch reduction.

One successful example of mitigating without assessment occurred in the southern and western Australian rock lobster fisheries, which killed Australian sea lions (*Neophoca cinerea*) that became trapped and drowned when entering pots; rather than attempt to observe the fishery and estimate bycatch, a sea lion excluder device was mandated in the fishery and that essentially eliminated bycatch (Campbell et al., 2008).

DISCUSSION

We have outlined the full process of assessing bycatch of marine mammals in fisheries. We have tried to concisely provide enough

[9]https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-take-reduction-plans-and-teams

detail to make clear the issues and problems. Where detail is important, we have tried to provide clear pointers to the published literature and other sources of information that are particularly useful.

Although the need for more and better assessments of marine mammal bycatch worldwide has long been recognized, this paper was motivated by the recent US MMPA Import Provisions. The scale of marine mammal bycatch assessments that countries will need to perform to continue exporting seafood to the United States has increased, possibly by an order of magnitude. Countries have already been taking at least a few of the steps described above, particularly with the need to describe fisheries that interact or may interact with marine mammal populations, information that is needed for the List of Foreign Fisheries.

Challenges and Future Work

If we consider fisheries worldwide, the sheer magnitude of managing bycatch is daunting. There are thousands of fisheries, and relatively few of these have been monitored for marine mammal bycatch. Initiating observer programs to estimate bycatch mortality in so many fisheries and countries represents an enormous task that would require a substantial increase in expertise capacity, training, and financial and other resources. Other authors (e.g., Read, 2008) have noted this, and it likely partially explains why so little progress, relative to the level of need, has been made in assessing and thereby reducing bycatch worldwide over the last few decades.

Many areas throughout the world have never been surveyed to estimate marine mammal abundance (Kaschner et al., 2012). The marine mammal and wildlife biology research communities have conducted workshops to train scientists and managers in important techniques, such as line-transect analysis[10] and mark-recapture analysis[11]. The number and scope of marine mammal surveys and abundance estimates from South America have increased rapidly over the last several decades, in part due to education efforts of the Latin American Society for Aquatic Mammals (SOLAMAC). However, conducting marine mammal surveys to estimate abundance for all areas where problematic fisheries exist still represents an enormous task. The level of training will likely need to be expanded substantially.

There is also a clear need for capacity building of expertise in bycatch mitigation techniques. Workshops and reports by various organizations (e.g., FAO, 2018, 2021; Leaper and Calderan, 2018) are helping to disseminate information, but it will likely also take practical workshops or demonstrations of specific techniques, such as gear modification, for these methods to become more widely used in a timely manner.

Marine mammal bycatch in small-scale fisheries (often also termed 'artisanal' fisheries) is increasingly being recognized as an important conservation issue, but the products from such fisheries are not usually exported to the United States, so the US MMPA Import Provisions would not have direct relevance to many such fisheries. Small-scale fisheries are typically defined as fishing conducted from small, sometimes sail-powered, vessels with little advanced technology, as opposed to large-scale company-owned commercial fishing conducted from large modern vessels, though the exact definition is not such a simple dichotomy (Smith and Basurto, 2019). Nonetheless, small-scale fisheries have been estimated to represent as much as half of total global fisheries production and employ more than 99% of the world's fishermen, but bycatch is likely more a function of fishing gear type and target species, rather than whether a fishery is small- or large-scale (Jones et al., 2018). Bycatch risk from small-scale gillnet fisheries has been predicted to predominantly occur in tropical and sub-tropical regions dominated by low- and middle-income nations (Temple et al., 2021). Managing marine mammal bycatch in small-scale fisheries in developing nations is particularly difficult, given the dispersed nature of such fisheries and lack of resources, and because there is often little or no infrastructure in place for management. However, the level of marine mammal bycatch in small-scale fisheries, especially gillnets, can be high (Palacios and Gerrodette, 1996; Read, 2008; Brownell et al., 2019). Several important efforts are being made to build capacity in developing nations. One example is *The Consortium for the Conservation of the Atlantic Humpback Dolphin*, which was initiated in response to growing concerns regarding the declining conservation status of this species. Part of its focus has been to create the incentives, resources, and capacity needed for local stakeholders to engage in research and monitoring, such as marine mammal stranding response training for 'ecoguards' in Gabon, and a guide to identify marine mammals of the Atlantic coast of Africa[12]. More general efforts include *The Global Marine Animal Stranding Toolkit*[13] designed to provide training for responding to marine mammal strandings, including evaluation of human interactions such as bycatch. Another is a practical guide for the safe handling and release of bycaught small cetaceans from fishing gear produced by the Convention on the Conservation of Migratory Species of Wild Animals (CMS) and the World Wide Fund for Nature (Hamer and Minton, 2020). The International Whaling Commission (IWC) has established an *Expert Advisory Panel on Entanglement Response*[14] for large whales, which is developing best practices and conducting workshops around the world to train people to remove fishing gear from living whales. The IWC has also started a *Bycatch Mitigation Initiative*[15], whose initial focus is on small-scale/artisanal fisheries in coastal areas of developing countries; this initiative is expected to provide technical advice and capacity development/training. Many more such efforts will be needed to address bycatch in small-scale fisheries throughout the world.

Conclusion and Hopes for a Brighter Future for Marine Mammal Populations

The MMPA Import Provisions do not apply to all fisheries in the world that have bycatch of marine mammals; it

[10]https://workshops.distancesampling.org/
[11]http://www.phidot.org/forum/viewforum.php?f=8
[12]https://www.sousateuszii.org/resources/
[13]https://www.gmast.org/
[14]https://iwc.int/entanglement-response-network
[15]https://iwc.int/bycatch

applies only to fisheries that export to the United States. However, this represents a substantial increase in the number of fisheries that might be managed to limit marine mammal bycatch. To estimate bycatch and abundance of marine mammals for the more than 1,800 fisheries on NOAA's List of Foreign Fisheries would be a very large undertaking. To continue to export seafood to the United States, any given fishery would need to have its bycatch of marine mammals assessed as part of a regulatory program (or implement alternative measures to reduce bycatch) to apply for and receive a comparability finding. Additionally, by implementing a regulatory program to comply with the MMPA Import Provisions, countries may increase capacity to assess and manage marine mammal bycatch in all their fisheries (i.e., non-export fisheries).

It is not clear where funding and expertise to accomplish all this work will come from, although the US National Marine Fisheries Service has indicated a willingness to provide technical assistance contingent on available funding and resources[16]. For that reason, we have tried to provide guidance to ensure that the most important situations are given priority, similar to the framework for reducing marine mammal bycatch in the United States.

Williams et al. (2016) noted that the MMPA Import Provisions could have significant conservation benefits for marine mammal populations, but only if it is accompanied by substantial investments to boost scientific and compliance capacity. Otherwise, if these investments are not made, it could have little effect other than inflicting economic hardship on fishing communities, many of which are already poor and struggling. Similarly, after assessing the risk of marine mammal bycatch in small-scale fisheries in Southeast Asia, Johnson et al. (2017) concluded that export countries will have trouble achieving and documenting compliance with the rule within the 5-year exemption period.

Although we have highlighted the important issue of building capacity for conducting assessments of marine mammal bycatch throughout the world, even areas with considerable capacity have not necessarily achieved meaningful bycatch reduction. For example, several authors recently argue that the European Union (EU) has failed to adequately assess and mitigate bycatch of small cetaceans (Bearzi and Reeves, 2021; Carlén et al., 2021; Dolman et al., 2021; Rogan et al., 2021); they suggest this is due to diffuse management authority, a lack of political will, and the fact that the EU has no overarching quantitative conservation objectives. Rogan et al. (2021) suggest the EU establish a comprehensive plan that would include quantitative management objectives, generate estimates of abundance and bycatch mortality, and establish biological reference points to guide management actions; such a plan would incorporate much of the scheme we suggest here (**Figure 1**) and would be consistent with best practice guidelines for reference point-based management (Curtis et al., 2015).

Even when a specific management scheme is in place, such as in the United States, it can still be difficult to achieve substantial reduction of bycatch. US Take Reduction Plans have successfully reduced bycatch to below PBR for most stocks (McDonald et al., 2016), but there is at least one notable exception. Despite implementing multiple mitigation measures over two decades, bycatch mortality and serious injury of North Atlantic right whales continues to exceed the stock's PBR, and the population is declining (Kraus et al., 2016; Pace et al., 2017). The right whale case has been particularly complex, involving multiple fisheries and gear types, additional human-caused mortality from vessel strikes, and recent shifts in the whales' distribution to areas with unmitigated threats attributed to climate change, highlighting the challenges of bycatch reduction even for high-capacity regulatory programs.

The Food and Agriculture Organization of the UN (FAO), CMS, and other groups, including some non-governmental organizations, have been advocating for marine mammal bycatch reduction and supporting development of mitigation measures. These efforts have had some success in identifying key issues, and reducing bycatch in some areas. Our hope is that by providing a summary of best practices for an entire framework for managing marine mammal bycatch, this paper will contribute to the spread of effective management efforts to address the leading source of human-caused mortality of marine mammals.

AUTHOR CONTRIBUTIONS

All the authors contributed to the concept and overall outline of the manuscript, helped identify what specific content should be in each section, contributed to the manuscript revision, and read and approved the submitted version. KL and PW led the writing of the manuscript. MCS wrote sections of the manuscript. KL produced the **Supplementary Material S2, S3**. PW produced the **Supplementary Table 1**. GMS produced the **Supplementary Table 2**. TF and MCS created the figures. KL and PW created the **Boxes 1**, **2**.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.757330/full#supplementary-material

[16]https://media.fisheries.noaa.gov/dam-migration/mmpa_import_rule_compliance_guide_april_2019_eng_508.pdf

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