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REVIEW

Marine mammal conservation: over the horizon

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ABSTRACT: Marine mammals can play important ecological roles in aquatic ecosystems, and their presence can be key to community structure and function. Consequently, marine mammals are often considered indicators of ecosystem health and flagship species. Yet, historical population declines caused by exploitation, and additional current threats, such as climate change, fisheries bycatch, pollution and maritime development, continue to impact many marine mammal species, and at least 25% are classified as threatened (Critically Endangered, Endangered or Vulnerable) on the IUCN Red List. Conversely, some species have experienced population increases/recoveries in recent decades, reflecting management interventions, and are heralded as conservation successes. To continue these successes and reverse the downward trajectories of at-risk species, it is necessary to evaluate the threats faced by marine mammals and the conservation mechanisms available to address them. Additionally, there is a need to identify evidence-based priorities of both research and conservation needs across a range of settings and taxa. To that effect we: (1) outline the key threats to marine mammals and their impacts, identify the associated knowledge gaps and recommend actions needed; (2) discuss the merits and downfalls of established and emerging conservation mechanisms; (3) outline the application of research and monitoring techniques; and (4) highlight particular taxa/populations that are in urgent need of focus.

KEY WORDS: Conservation · Marine mammals · Priority setting · Management · Research techniques · Threats

1. INTRODUCTION

Marine mammals, including 126 extant species of cetaceans (whales, porpoises and dolphins), pinnipeds (true seals, fur seals, sea lions and walruses), sirenians (dugongs and manatees), sea otters *Enhydra lutris* and polar bears *Ursus maritimus* known to date, can play important ecological roles and are often considered indicators of marine ecosystem health (Bossart 2011, Parsons et al. 2015, Society for Marine Mammalogy 2019). Their typically large body sizes and broad range of diets influence community structure and functioning through processes such as top-down control, nutrient recycling and bioturbation (Estes & Duggins 1995, Bowen 1997, Roman et al. 2014, Kiszka et al. 2015, Albouy et al. 2017). Yet,

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historical declines caused by exploitation, and additional current threats, such as climate change, fisheries bycatch, pollution and maritime development, continue to jeopardize many marine mammal species (Kovacs et al. 2012, Magera et al. 2013, Parsons et al. 2015, Albouy et al. 2017, Avila et al. 2018). These stressors, combined with life-history traits such as low reproductive rates and the specificity of the breeding or foraging requirements of some species (Davidson et al. 2012, Maxwell et al. 2013), have led to ~25% (n = 32) of marine mammal species currently being classified as threatened (Critically Endangered, n = 2; Endangered, n = 17; and Vulnerable, n = 13) on the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species (www.iucn.org; last accessed April 2020). Marine mammals can be difficult to monitor, and changes in their population status are challenging to detect (Kaschner et al. 2011, Lotze et al. 2011, Davidson et al. 2012). As a result, an additional 21% (n = 26) of species are deemed Data Deficient by the IUCN.

Many species and populations of marine mammals are declining, and some have been extirpated from parts of their range (e.g. dugong *Dugong dugon* and Ganges river dolphin *Platanista gangetica*) or have gone extinct (e.g. Steller's sea cow *Hydrodamalis gigas,* Caribbean monk seal *Monachus tropicalis* and Yangtze River dolphin or baiji *Lipotes vexillifer*; Turvey et al. 2007, McClenachan & Cooper 2008, Davidson et al. 2012). Yet in some cases, management interventions, such as hunting bans and greater protection, have led to population increases/recoveries in recent decades, and are heralded as conservation successes (e.g. northern elephant seals *Mirounga angustirostris*, humpback whales *Megaptera novaeangliae* and Guadalupe fur seals *Arctocephalus townsendi*; Magera et al. 2013).

With the advent of the Decade of Ocean Science for Sustainable Development beginning in 2021 (United Nations 2019), we sought to bring together a global network of scientists interested in marine mammal conservation to look over the horizon and explore emerging challenges and solutions. In this review, we (1) outline key threats to marine mammals from anthropogenic activities, identify knowledge gaps and recommend responses; (2) discuss the merits and downfalls of existing and future conservation mechanisms; (3) outline the application of research and monitoring techniques; and (4) highlight particular taxa/populations that are in urgent need of focus. Given that they make up the majority of this animal group, we generally focus on cetaceans and pinnipeds.

2. KEY THREATS TO MARINE MAMMALS

The threats posed to marine mammals by anthropogenic activities can be numerous and complex (Avila et al. 2018). Approximately 98% of marine mammal species are at some level of risk in 56% of the ocean, mainly in coastal waters (Avila et al. 2018; Fig. 1). Here, we provide a brief background of the key threats affecting marine mammals around the globe. In Table 1 we summarise knowledge gaps relating to these threats and recommend actions to resolve them.

2.1. Climate change

Specialised diets, restricted ranges, high site fidelity and dependence on specific habitats, which are often reached via extensive migrations, are thought to make many marine mammal species particularly vulnerable to anthropogenic climate change (Würsig et al. 2001, Simmonds & Isaac 2007, Laidre et al. 2015, 2018, Silber et al. 2017). While the full nature and scope of climate-driven effects are uncertain for many species (Schumann et al. 2013, Fuentes et al. 2016a), impacts have already been detected for some and forecasted for others (Schumann et al. 2013, Fuentes et al. 2016a, Regehr et al. 2016, Laidre et al. 2018, Moore & Reeves 2018). These impacts may be geographic (e.g. habitat loss and range shifts) or trophic-related (e.g. variation in food availability, trophic dynamics and competition), with consequences for phenology (e.g. changes to breeding and migration timing) and ultimately, fitness (e.g. effects on reproductive success, health, body condition and population vital rates; Simmonds & Isaac 2007, Burek et al. 2008, Kovacs et al. 2011, Edwards 2013, Ramp et al. 2015, Fuentes et al. 2016b, Silber et al. 2017, Hauser et al. 2018, Boyd et al. 2019, Hamilton et al. 2019, Avila et al. 2020, Laidre et al. 2020a). Marine mammal populations most vulnerable to these influences are likely to be those that (1) are dependent on or associated with sea ice in the polar regions (e.g. polar bears, walruses and ice seals; Moore & Reeves 2018, Bestley et al. 2020); (2) are reliant on upwelling boundary currents (e.g. rorqual whales; Díaz López & Methion 2019); (3) have restricted ranges and small populations (e.g. vaquita *Phocoena sinus*; Simmonds & Isaac 2007); or (4) are reliant on low-lying islands, atolls and coral reef habitats (e.g. Hawaiian monk seal *Neomonachus schauinslandi*; Baker et al. 2012).

The capacity of marine mammals to adapt to climate change is poorly understood. Some species may

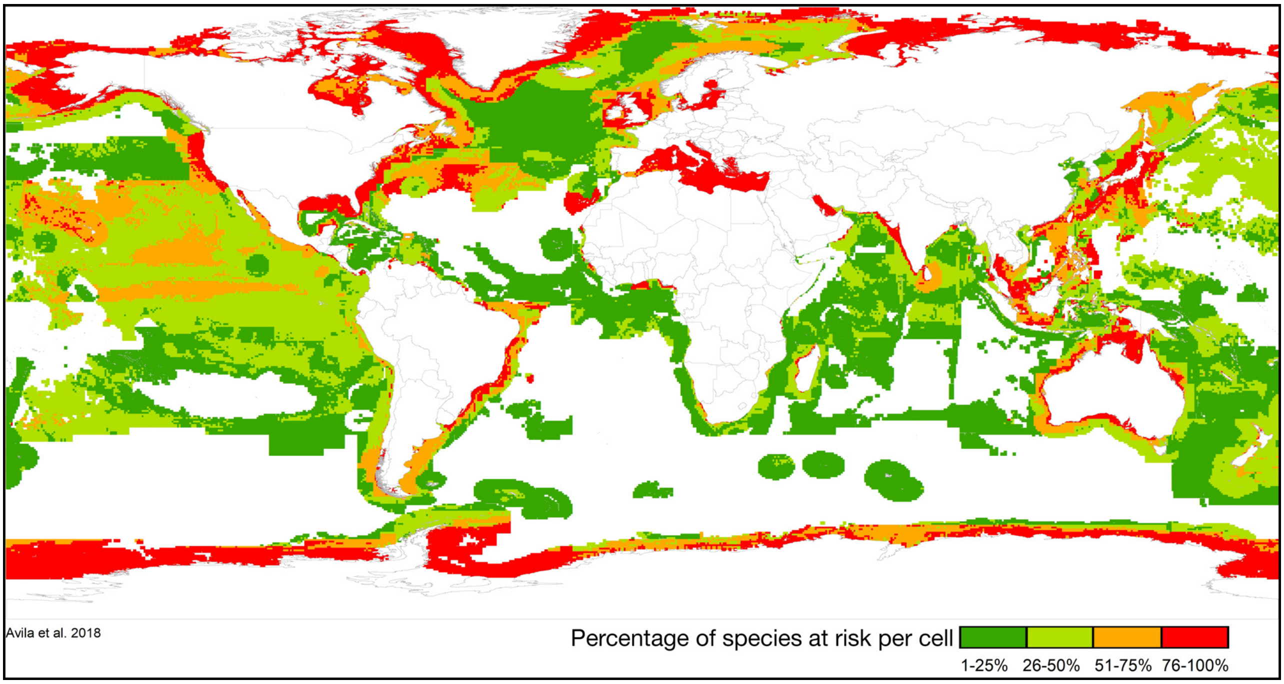

Fig. 1. Cumulative risk map showing the proportion of species of the total of species predicted to be present per cell with at least 1 documented threat. Red areas represent high-risk areas or hotspots (see Avila et al. 2018 for more details)

be able to modify their behaviour in response to changes (e.g. by shifting their range or diet; Moore & Huntington 2008, Evans et al. 2010, Schumann et al. 2013, Ramp et al. 2015). In some cases, the impacts of climate change may be initially positive but later unknown (Moore & Reeves 2018, Laidre et al. 2020b). For example, evidence of a number of positive impacts linked to thinner sea-ice (range expansion, improved body condition and stable reproductive performance) has been identified for a subpopulation of polar bears (Laidre et al. 2020b). However, the rapid pace of climate change and the large number of potential cumulative and synergistic stressors make predicting specific impacts challenging (Laidre & Heide-Jørgensen 2005, Burek et al. 2008, Moore 2008, Patyk et al. 2015).

2.2. Fisheries

2.2.1. Fisheries bycatch

Marine mammal bycatch, i.e. the incidental capture or entanglement of animals in active fishing gear, is a critical yet seemingly intractable problem (Reeves et al. 2013, Brownell et al. 2019), and is currently the threat affecting the greatest number of marine mammal species worldwide (101 species recorded, but likely more; Avila et al. 2018). From small-scale to large commercial fisheries, in national and international waters, developed and developing countries, in urban and isolated areas, marine mammals are being caught in nets and other types of fishing gear (Tulloch et al. 2020b). Gillnet or entangling net fisheries are the greatest global concern (Dawson et al. 2013, Reeves et al. 2013, Brownell et al. 2019), but interactions also occur with other fishing gears such as longlines, purse-seines, trawls and pots/traps (FAO 2018, Hamilton & Baker 2019). Additionally, electric fishing is an emerging threat in freshwater habitats (Turvey et al. 2007).

Several species of cetaceans (e.g. vaquita and North Atlantic right whale *Eubalaena glacialis*; Kenney 2018, Jaramillo-Legorreta et al. 2019) and pinnipeds (e.g. Mediterranean monk seal *Monachus monachus*; Karamanlidis et al. 2008) have been driven close to extinction due, in part, to fisheries bycatch. The baiji was declared extinct in the Yangtze River in 2006 as a result of unsustainable bycatch and other human activities (Turvey et al. 2007). Other species have also been reduced to critically low levels (e.g. New Zealand sea lion *Phocarctos hookeri*, Australian sea lion *Neophoca cinerea* and some sirenian populations; Hamer et al. 2013, Chilvers & Meyer 2017).

Table 1. Key threats to marine mammals, the associated knowledge gaps and the actions needed to address them

Key threats	Knowledge gaps	Required actions
Climate change	• Functional responses to environmental change through physiological, phenological and behavioural mechanisms • Indirect impacts on prey and habitat availability	• Long-term monitoring • Assess tolerance zones of marine mammals and their prey • Predictive modelling of species distributions and trophic networks under different climate scenarios • Determine cascading effects from impacts of prey and habitat availability
Fisheries bycatch	• Bycatch rates • Fate of animals post-capture and release (e.g. mortality rates) • Social and economic consequences of mitigation measures	• Deploy on-board monitoring systems (for bycatch rates and species) • Use re-sighting or satellite tagging to gain estimates of post-release mortality • Develop more low/no cost mitigation methods • Gain perspectives on governance structures, cultural beliefs and perceptions of fishers • Create more awareness of the dimension of the problem among seafood consumers and fishers
Reduction of prey availability due to overfishing	• Quantitative estimates of the biological interactions between marine mammals and fisheries	• Gain information on key marine mammal diet parameters, such as composition and prey consumption rate, for a greater number of species • Expand the use of ecosystem models to assess the competitive interactions between marine mammals and fisheries
Commercial and subsistence take	• Population impacts of commercial whaling • Local drivers and motivators of take • Sustainability of subsistence take of sirenians • Quantity estimates of illegal take	• Establish mechanisms to regulate commercial whaling • Develop mitigation alternatives • Create more awareness of the dimension of the problem • Work with local communities to obtain data and enable sustainability assessments • Encourage governments to implement measures to deter illegal take
Use of marine mammals as bait in fisheries	• Quantity of aquatic mammals targeted or salvaged, particularly in Africa and South America • Which marine mammal populations are affected by this practice	• Quantitative assessment of the take and its impact on the local populations • Monitor effectiveness of mitigation measures, e.g. campaigns to change local perceptions, alternative livelihoods for fishers, enforced legislation and management of target fisheries
Coastal and freshwater development	• Degree of displacement of the local populations • Impact on the population size • Consequences of cumulative effects caused by multiple impacts • Extent of loss of critical sirenian habitat	• Assess habitat degradation and monitoring • Examine the effects in the long term of the overlap between vessel traffic and marine mammals • Improve regulation of coastal and riverine construction and development • Assess cumulative impact in coastal populations • Identify and monitor changes in critical sirenian habitats and their ecosystem services, and work with local communities and managers to protect them

(*continued on next page*)

Table 1 (continued)

Key threats	Knowledge gaps	Required actions
Marine renewable energy installations (MREIs)	• Occurrence and behaviour of marine mammals using sites targeted for MREIs • Consequences of behavioural impacts of MREIs for marine mammals, in terms of fitness and population dynamics • Impacts from deployment of MREIs • If and how animals respond spatially to tidal stream turbines in 3D space	• Investigate the energetic/fitness consequences of disturbance (i.e. population consequences of disturbance) from construction and operation • Examine if, how and why marine mammals seek out MREIs, and how they serve as attractants • Investigate device noise, audibility and sound propagation in energetic marine environments
Noise	• No audiograms, and therefore no information on hearing sensitivities, exist for some species (particularly baleen whales) • Validity of mitigation measures is incomplete for the diversity of habitats and species to which they are applied • What represents healthy or attractive acoustic habitats for marine mammals • Population consequences of disturbance	• Validate reliability of frameworks to infer ecologically relevant metrics, such as consequences for individual fitness • Scale noise impacts to populations in space using process-based modelling frameworks, such as individual-based models • Study, understand and mitigate new industrial consequences as the ice-cover in the Arctic changes
Plastic pollution	• Potential for nanoplastics (sub-micron sized plastic particles) to pass through the gut wall and into the blood stream, and reach organs, such as the liver or the lymphatic system • Extent to which plastic ingestion exposes marine mammals to chemicals on or within them compared to their usual dietary and environmental input • Effects of plastic ingestion on animal health and exposure to disease • Population-level impacts and global trends of entanglement in plastic debris	• Develop methods and technology to detect nanoplastics in biological tissue of wild animals • Examine concentration of chemical contaminants (e.g. plasticizers such as phthalates) in animal tissue and blood alongside plastic debris in digestive tract and environmental loads • Explore global strandings datasets for plastic pollution interactions and pathological information to better understand potential impacts on animal health
Chemical contaminants	• Environmental exposure of marine mammal populations to newly listed persistent organic pollutants, such as poly- and perfluoroalkyl substances and short-chain chlorinated paraffins, as well as chemicals of emerging concern, such as nanoparticles and pharmaceuticals and personal care products • Marine mammal effect assessment • Effect of climate change on transport, fate and effects of environmental contaminants and their toxicological impact in populations	• Examine impacts of emerging contaminants on animal health • Improve regulations on chemical disposal and reduce the amount of chemicals entering the environment
Pathogen pollution	• Exposure of marine mammals to pathogens from domestic animals (e.g. dogs, cats and livestock) • Influence of sea farms on the health of wild animal populations • Prevalence of reverse zoonosis of human virus (e.g. SARS-CoV-2) from various input pathways (e.g. poorly managed wastewater)	• Evaluate the impact of domestic animals on health of wild marine mammals and establish protocols to diminish such interactions • Further explore potential virus transmission routes (e.g. eDNA analysis of wastewater outflows) and examine marine mammals for the presence of human-borne viruses • Evaluate the susceptibility of marine mammals to SARS-CoV-2 and other coronaviruses

In many regions, fisheries bycatch of marine megafauna is poorly monitored or regulated, especially in international waters (e.g. Anderson et al. 2020), so the population-level impacts are not well understood (Lewison et al. 2014). Where monitoring is carried out, gaps in data on fishing effort, marine mammal encounter frequency, bycatch rates, species identification and the fate of animals post-capture and release limit our ability to assess the risk of fisheries bycatch, understand the cumulative impacts from fisheries that overlap with the distributions of individual populations and constrain management action (Hines et al. 2020).

2.2.2. Reduction of prey availability due to overfishing

Indirect interactions between marine mammals and fisheries are complex, poorly understood and largely unmanaged (Trites et al. 1997). Relatively little is known about exploitative competition between marine mammals and fisheries , i.e. the overlap in resource use between them (e.g. Pauly et al. 1998, Kaschner & Pauly 2005, Machado et al. 2016).

Multiple studies have shown that prey species reduction by fisheries can (at least partially) contribute to the decline of marine mammal populations, particularly small cetaceans and pinnipeds (e.g. Plaganyi & Butterworth 2005). For example, in the Mediterranean Sea, the population decline of short-beaked common dolphins *Delphinus delphis* has been mainly attributed to the decline of small pelagic fish stocks in the Ionian Sea (Bearzi et al. 2006, Piroddi et al. 2011). Along the coast of British Columbia, Canada, and Washington State, USA, the decline of reproductive rates and survival of fish-eating killer whales *Orcinus orca* has been correlated with the reduced abundance of Chinook salmon *Oncorhynchus tshawytscha*, which is at least partially due to overfishing of salmon stocks (Nehlsen et al. 1991, Ford et al. 2010). Among pinnipeds, population declines due to prey depletion from fisheries have been documented, or strongly suspected, for several species, including harbour seals *Phoca vitulina* in the western Gulf of Alaska (Pitcher 1990) and southern sea lions *Otaria flavescens* off the coast of Argentina (Koen-Alonso & Yodzis 2005) and Uruguay (Riet-Sapriza et al. 2013). At least 19 species of marine mammals, mainly odontocetes, are currently known to experience biological interactions with fisheries; high-risk areas are mostly in the northern Mediterranean Sea and along the eastern coast of South America (Avila et al. 2018). However, the magnitude of impact on marine mammal populations from fisheries-related prey depletion might be underestimated and requires further investigation. In addition, herbivorous species of marine mammals (e.g. sirenians) may experience depletion of food availability as a result of fishing activities. For example, some fisheries damage the seagrass meadows on which dugongs feed (Marsh et al. 2011).

2.3. Exploitation

2.3.1. Commercial and subsistence take

Many taxa marine mammal taxa are subject to direct human exploitation. For example, Robards & Reeves (2011) estimated that people in 114 countries have consumed meat and other products from ~87 species of marine mammals since 1990. A global moratorium on whaling was enacted in 1983, and no commercial whaling has been permitted under the International Whaling Commission (IWC) in international waters. Commercial whaling within nations' exclusive economic zones (EEZs) was/is allowed under IWC, and both subsistence and scientific whaling have continued in some countries. For example, in 2019, 360 individuals from 4 baleen whale species were caught by Denmark (Greenland), St Vincent and the Grenadines, Russia and the USA for subsistence purposes (www.iwc.int/table_aboriginal; last accessed 23 September 2020) and 640 individuals from 2 baleen whale species were caught for scientific purposes by Japan in the 2018/19 Antarctic season (www.iwc.int/table_permit; last accessed 23 September 2020).

The take of small cetaceans for food, bait and traditional uses has long been a cause of concern for the IWC as well as other intergovernmental and non-governmental organisations. Most countries have, at some time, used small cetaceans for food, but the scale and extent of such utilization is variable. Present-day artisanal hunting has been identified in some areas, for example, St Vincent and the Grenadines, as an essential source of protein for local communities (Fielding 2014), and subsistence hunting by indigenous residents across the Arctic is a vital part of communities and contributes to economic, cultural and spiritual well-being (Laidre et al. 2015). Few countries regulate small cetacean hunts, and globally, the number of small cetaceans taken, deliberately or otherwise, is unknown.

Pinniped hunting is extensive in the Arctic region and, although controversial, is regulated through a variety of legal frameworks. Canada permits the largest marine mammal hunt in the word with allowable takes of up to 350 000 ind. yr^{-1} (Hammill & Stenson 2005), although actual takes vary greatly (www.dfo-mpo.gc.ca/fisheries-peches/seals-phoques/seal-stats-phoques-eng.html; last accessed 23 Sept 2020). Comparable commercial hunts for multiple species of small cetaceans set quotas at approximately 22 000 ind. yr^{-1} (www.jfa.maff.go.jp/j/whale/w_document/pdf/h17_progress_report.pdf; last accessed 23 Sept 2020).

All 4 species of sirenians are subject to subsistence take (Marsh et al. 2011). In most countries, this harvest is illegal, but in Australia, and some Pacific countries, indigenous people are permitted to hunt dugongs for traditional purposes.

Illegal take likely poses a significant threat to many marine mammal populations but the extent is largely unknown.

2.3.2. Use of marine mammals as bait in fisheries

The use of marine mammals as bait is a geographically extensive activity, affecting at least 42 species in 33 countries, predominantly in Latin America, Asia and West Africa (Cosentino & Fisher 2016, Mintzer et al. 2018). Small cetaceans and pinnipeds are primarily used for shark, crab and lobster fisheries in the marine environment, and riverine dolphins are used for catfish fisheries in freshwater systems (Avila et al. 2008, Quintana-Rizzo 2014, Mintzer et al. 2018, Campbell et al. 2020, Castro et al. 2020). Marine mammals as bait are either (1) deliberately targeted, where animals are the main objective for fishers, (2) non-targeted-deliberate, bycaught or stranded animals are recovered and killed, and (3) non-targeted salvaged acquisition, when an incidentally caught animal is used (Hall 1996, Marsh et al. 2011, Robards & Reeves 2011). The majority of interactions are thought to be deliberately targeted (83% of cases; Mintzer et al. 2018). The general appeal of marine mammal bait to fishers is that it is considered effective (due to its fatty, bloody and durable consistency), and readily available at little or no cost (often being collected en route to fishing grounds; Mangel et al. 2010, Barbosa-Filho et al. 2018).

2.4. Industrial development

2.4.1. Coastal and freshwater development

Many marine mammal species have experienced significant declines due to cumulative impacts of anthropogenic activities in coastal and freshwater environments, especially those with small populations, high site fidelity and reliance on coastal and riverine habitats (Schipper et al. 2008, Pompa et al. 2011, Avila et al. 2018).

The expansion and intensity of anthropogenic activities in these areas generates a wide array of stressors, which may impact marine mammals both directly or indirectly (Aguirre & Tabor 2004, Maxwell et al. 2013). Industrial activities include the construction of infrastructure such as ports and dams, as well as facilities related to aquaculture, energy production and military activity. Human encroachment on breeding and haul-out habitat is thought to have played a contributory role in the decline and extinction of the Caribbean monk seal and Japanese sea lion *Zalophus japonicas*, and likely threatens other extant pinniped species (Kovacs et al. 2012). For freshwater species, such as river dolphins in South Asia and South America, and manatees in Africa and South America, large-scale diversions of river flows by dams, barrages and canals for irrigation, hydropower generation and urban/industrial water supply have led to habitat loss (with fragmentation of population connectivity and increased pollution), and effects on food abundance and distribution (Smith et al. 2009, Marsh et al. 2011, Choudhary et al. 2012, Braulik et al. 2014, Araújo & Wang 2015, Pavanato et al. 2016, Arraut et al. 2017). Reduced freshwater flows have also negatively affected the productivity of downstream estuarine and coastal habitats for other dolphin species (Smith et al. 2009).

Additionally, the global increase in maritime and riverine vessel traffic is causing greater underwater noise (see Section 2.5.1) and vessel–animal collisions (Laist et al. 2001, Van Waerebeek et al. 2007, Manuel & Ritter 2010, Avila et al. 2018, Dey et al. 2019).

2.4.2. Marine renewable energy installations

Marine renewable energy installations (MREIs; wind, wave and tidal-stream devices), can help reduce hydrocarbon use and therefore mitigate climate change (Magagna & Uihlein 2015). However, installation, operation and decommissioning of these devices can potentially impact wildlife, including marine mammals (Boehlert & Gill 2010). Installation of wind turbines using pile-driving is associated with high sound levels, leading to avoidance or displacement of marine mammals out to considerable ranges (>20 km; Tougaard et al. 2009, Russell et al. 2016). Construction and maintenance of MREIs also results in increased vessel traffic and increased potential for vessel collision, particularly with whales (Inger et al. 2009, Bailey et al. 2014), as well as noise impacts (David 2006, Graham et al. 2019). Floating wind turbines are an emerging technology that allow for deployment in waters too deep for pile-driven seabed-mounted turbines. Advantages of floating turbines include reduced construction noise, reduced vessel traffic and lower installation costs. However, mid-water column infrastructure (chains and power cables) could pose higher entanglement risk (Harnois et al. 2015), and could snag abandoned fishing gear in the water column, exacerbating this risk (Benjamins et al. 2014). Devices to extract wave energy, although less common than floating wind turbines, are likely to have similar sub-surface risks. Devices that extract energy from tidal streams are effectively submarine versions of wind turbines, although the blades are generally shorter and slower turning. However, marine mammal injury from collision with tidal turbine blades is a significant conservation and consenting concern (Wilson et al. 2007, Onoufriou et al. 2019). Hastie et al. (2018) demonstrated that harbour seals avoid areas during playback of tidal turbine operational noise, but a priority for future research is to determine the avoidance behaviour of marine mammals in relation to actual operating turbines, and the potential for such devices to cause exclusion from foraging areas, or barriers to transit, particularly in multi-device arrays.

2.5. Pollution

2.5.1. Noise

Anthropogenic underwater noise is recognised as a pervasive pollutant impacting marine mammals globally (Williams et al. 2015, Cholewiak et al. 2018). Sources range from the intentionally generated (e.g. seismic exploration, sonar, particularly naval, and acoustic deterrent devices; Elliott et al. 2019) to the incidental (e.g. commercial and private vessels, pile-driving, explosives, icebreaking, dredging and point sources like offshore structures, such as MREIs, as well as coastal roads, bridges and aircraft; Richardson et al. 2013). The consequences for marine mammals depend heavily on the nature of the source, particularly its amplitude, frequency and temporal components (e.g. continuous, impulsive, predictable and familiar). Impacts range from direct tissue trauma, particularly auditory damage (Southall et al. 2008), to behavioural responses and stress (Gomez et al. 2016, Dey et al. 2019) which may themselves lead to significant injury (Jepson et al. 2003), or habitat exclusion and masking of ecologically relevant sounds like communication (Clark et al. 2009).

2.5.2. Plastic

At least 42% of extant marine mammal species have been found to ingest or become entangled in plastic pollution (Senko et al. 2020). Plastic may be consumed via 2 main pathways, direct or indirect ingestion. The former can occur as a result of indiscriminate feeding strategies (e.g. filter feeders; Besseling et al. 2015), mistaken identity (Secchi & Zarzur 1999, de Stephanis et al. 2013) or due to naivety and curiosity, as may be the case in young animals (Baird & Hooker 2000). Indirect ingestion can occur as a result of trophic transfer where prey containing microplastics (plastic <5 mm in size) are consumed (Nelms et al. 2018, 2019a,b). Ingestion of macroplastics (>5 mm) can cause lacerations, ulcerations, obstructions and lesions, and may lead to sublethal effects such as dietary dilution, dehydration and starvation (Kastelein & Lavaleije 1992, Stamper et al. 2006, Levy et al. 2009, Alexiadou et al. 2019). Although ingestion of macroplastics can result in mortality, the population-level effects for most species are unknown (Alexiadou et al. 2019, Senko et al. 2020). Some, already vulnerable, species and populations (i.e. those that are of conservation concern due to other stressors) are likely to be most at risk. Foraging ecology and/or habitat use also appear to be a risk factor. For example, deep-diving odontocetes, such as beaked and sperm whales, seem to have the propensity to consume, and become compromised by, plastic pollution (Secchi & Zarzur 1999, Stamper et al. 2006, Jacobsen et al. 2010, Kaladharan et al. 2014, Lusher et al. 2015, Abreo et al. 2016, Alexiadou et al. 2019).

Entanglement in plastic pollution, such as derelict fishing gear (or ‘ghost gear’; i.e. gear that is abandoned, lost or deliberately discarded), packaging and strapping, can lead to lacerations, constriction, higher energetic costs associated with increased drag, an inability to forage and/or escape predators and other threats (such as ship strikes) and drowning (Allen et al. 2012, van der Hoop et al. 2017, Jepsen & de Bruyn 2019). Although cetaceans are known to become entangled in debris (Baulch & Perry 2014), pinnipeds seem to be more susceptible, and 67% of species (n = 22 of 33) have been recorded with entanglements (Laist 1997, Jepsen & de Bruyn 2019).

2.5.3. Chemical contaminants

Contaminants are recognised as significant stressors of marine mammal health worldwide, including in remote polar environments (Brown et al. 2018). Persistent organic pollutants (POPs), heavy metals, and pharmaceuticals and personal care products (Bengtson Nash 2018) represent just a small selection of legacy and emerging contaminants of concern. Genotoxicity, immunosuppression and endocrine disruption are among the toxic effects commonly associated with legacy POPs and heavy metals, but our understanding of how exposure to complex environmental chemical mixtures is expressed in wild marine mammal populations is poor (Desforges et al. 2017). Oil spills from offshore extraction and transportation can negatively affect marine mammals through direct contact with crude oil and damage to foraging areas and prey stocks. For instance, the 1989 'Exxon Valdez' oil spill in Alaska killed tens of killer whales and thousands (1000–2800) of sea otters, and other individuals may have migrated out of the affected area (Helm et al. 2015). Similarly, the 2010 *Deepwater Horizon* oil spill in the Gulf of Mexico caused a dolphin mortality event (>1000 dead individuals were recorded; www.fisheries.noaa.gov/national/marine-life-distress/sea-turtles-dolphins-and-whales-10-years-after-deepwater-horizon-oil; last accessed 11 December 2020), while surviving animals exhibited moderate to severe lung disease and evidence of hypoadrenocorticism consistent with immunotoxic effects of oil (Daly et al. 2016).

2.5.4. Pathogens

Increased urbanisation of coastal areas, movement of ballast waters and global movement of people have contributed to an increase in detection of terrestrial pathogens in marine life. The term 'pathogen pollution' has been coined to describe the emergence of organisms typically considered pathogens of land animals in the ocean ecosystem. Protozoa such as *Giardia*, shed in mammalian faeces, have been detected in marine mammals from the Arctic to Antarctica (Fayer et al. 2004). *Toxoplamsa gondii*, a parasite dependent upon cats for sexual reproduction and shed in faeces of felids, is an important cause of mortality in Endangered Hawaiian monk seals and California sea otters in the USA, and for Māui dolphins *Cephalorhynchus hectori maui* in New Zealand (Roe et al. 2013, Barbieri et al. 2016).

The recent outbreak of COVID-19 (SARS-CoV-2 virus) has highlighted concerns of reverse zoonosis, where human-borne viruses are passed to wild animals. Marine mammals may be exposed to the virus via sources such as inadequately managed wastewater and direct human contact (e.g. handling by field researchers), and are potentially highly susceptible to infection (Barbosa et al. 2021, Mathavarajah et al. 2021).

3. CONSERVATION MECHANISMS

The diversity of threats facing marine mammals requires an equally diverse suite of conservation tools to address them. Here we outline a range of established and emerging conservation mechanisms and discuss their merits and downfalls.

3.1. Practical management options

3.1.1. Bycatch mitigation

Many non-technical and technical marine mammal bycatch mitigation methods have been proposed or tested with varying degrees of success and implementation (for detailed reviews, see FAO 2018 and Hamilton & Baker 2019). Non-technical methods include spatial closures (permanent, seasonal or dynamic) to reduce or eliminate the overlap between the fishing activity and at-risk species (Gilman et al. 2006, NMFS 2010, van der Hoop et al. 2013, Hazen et al. 2018); gear switching from high- to low-risk practices (e.g. from gillnets to longlines); binding and non-binding measures (e.g. national legislation, international agreements and consumer campaigns); and Food and Agriculture Organization of the United Nations (FAO) best practice advice.

Technical methods to reduce bycatch come in many forms but their efficacy tends to be species-specific. Acoustic deterrents are perhaps the most tested and include alarms (pingers) applied to fishing nets (Carretta & Barlow 2011, Dawson et al. 2013), playback of predator sounds (Werner et al. 2015) and passive acoustics, such as nets with enhanced acoustic reflectivity (Trippel et al. 2003, Larsen et al. 2007, Bordino et al. 2013). Pingers have had promising results in deterring several species of cetaceans (e.g. Burmeister's porpoises *Phocoena spinipinnis*) from small-scale driftnets (Clay et al. 2018) but have also been shown to attract some pinnipeds ('dinner bell' effect; Carretta

& Barlow 2011). Recently, light-emitting diodes reduced gillnet bycatch of small cetaceans in Peru by 70% (Bielli et al. 2020). For pinnipeds, attempts at reducing deaths have involved seal and sea lion exclusion devices on trawl nets and cod pots, with varying success (Königson et al. 2015, Lyle et al. 2016, Meyer et al. 2017). Other fishing gear modifications include weakened gear (e.g. thinner net twine, narrower gauge longline hooks, weak links or reduced strength rope on pots and traps that allows animals to break free; Northridge et al. 2003, Knowlton et al. 2016); net illumination (Bielli et al. 2020); ropeless traps/pots (DeAlteris 1999); and shielding of target catch, such as with 'cachalotera' (from 'cachalote', meaning sperm whale in Spanish; Moreno et al. 2008) or 'umbrella and stones' devices (to reduce sperm whale *Physeter macrocephalus* and seabird depredation of fish caught by bottom-set longlines; Goetz et al. 2011).

Changes to fishing operations can also help avoid or mitigate bycatch. Examples of this can be found in tuna purse-seine fisheries through the elimination of setting on dolphin pods and whales (Gilman 2011) or using back-down procedures and Medina panels that allow encircled dolphins to escape (Hall & Roman 2013).

Implementation costs, including the tracking of potential impacts on target species catch rates and catch value, need additional consideration. A promising approach is to apply return-on-investment approaches to select the most cost-effective mitigation, which can vary with region, fishery and species, often in complex ways (Tulloch et al. 2020a). Low-cost solutions for the vast small-scale coastal net fisheries common in the developing world also require particular attention (Brownell et al. 2019). Fishers involved in incidences of bycatch are at risk of penalties and punishments, where enforcement exists. For socio-economically marginalized fishers (e.g. in Africa or South Asia), and/ or where monitoring is weak or non-existent, the costs of honest reporting of accidental bycatch cases might be too high and affect livelihoods negatively. In such scenarios, fishers mostly tend to hide bycatch cases, which can result in severe under-reporting and poor ability to enact change (Lewison et al. 2011, Teh et al. 2015). Inclusion and empowerment of fishing communities is essential for managing, reporting and ultimately preventing bycatch.

3.1.2. Creating alternative livelihoods for fishers

Elimination of human-induced mortality is urgently needed for small isolated populations of marine mammals (Wade 1998, Brownell et al. 2019). This goal is challenging for fisheries in developing countries where extensive multi-gear fisheries are active, some throughout the year. Professional fishing is not only about food security and income generation but is also a source of cultural identity. Successfully changing the behaviour of fishers to new gears and/or areas that reduce bycatch, to not using marine mammals as bait and potentially reducing their dependence on fisheries, requires not only awareness, education and exposure to ecosystem-based thinking, but requires alternative modes of income generation and sources of food. As these processes require a rigorous social and economic assessment of individual situations, providing alternative livelihoods should be considered as a socio-ecological process of transformation, rather than a conservation challenge per se (Mozumder et al. 2018).

Focus on the fishing community to maximise the likelihood of successful transition to alternative livelihoods and economic and sociological expertise is key (Amevenku et al. 2019). Failure to understand and incorporate the needs of the fishers and their community will inevitably lead to suboptimal outcomes in the long term because too few fishers will be able to transition to the new livelihoods needed to achieve required levels of bycatch reduction (Sorice & Donlan 2015). In small-scale fisheries, fishing is often part of a 'portfolio' of activities, especially in Asia where fishing is a seasonal activity. Fishers seek other opportunities in off-seasons, indicating that alternatives to fishing may be already available to these communities.

There are a few examples of alternative livelihood programmes that have been specifically designed to protect a species of conservation concern from fishing. The alternative livelihoods programme developed by the National Oceanic and Atmospheric Administration (NOAA) for the vaquita (Vaquita SAFE 2019) is a prominent but unsuccessful example. In some situations, dolphin-watching may provide an alternative livelihood (Sutaria 2009, Beasley et al. 2014, Mustika et al. 2017). Women's collectives that provide a wide portfolio of income generation at the household level through diverse activities, such as seaweed drying, pond aquaculture, vegetable and fruit farming and handicrafts, along with the education and movement of youth from fishing to different occupations, have been established in several marine fishing communities in India (Patterson et al. 2008, Periyasamy et al. 2014, Kadfak 2020), but the performance of such initiatives has not yet been evaluated.

3.1.3. Spatial management for conservation

Spatial management is one of the most common approaches in marine mammal conservation, varying widely in spatial scope and target, including marine protected areas (MPAs), single-sector spatial management or dynamic management approaches. MPAs are the most well-known spatial management tool, with their goals and protection levels ranging from no-take marine reserves where all extractive activities are prohibited (IUCN Category Ia: Strict Nature Reserve), to MPAs where only a subset of activities are prohibited (IUCN Category VI: Protected areas with sustainable use of natural resources; Day et al. 2019). MPAs may be designed to protect marine mammals either directly by targeting threats, or indirectly through management goals that may reduce impacts on marine mammals, such as prohibition of fisheries that result in bycatch of marine mammals or that compete with their food resources (Peckham et al. 2011). Since many marine mammals are wide-ranging species, smaller MPAs may not be of sufficient size to encompass critical habitat (Agardy et al. 2011); however, many marine mammal species do aggregate during key life-history stages or during seasonal cycles (e.g. foraging and breeding), and these areas can potentially be effectively encompassed by MPAs (Cordes et al. 2011, Gormley et al. 2012).

Dynamic ocean management, whereby managed boundaries shift over short time scales, or near-real time, in response to changing conditions or animal movements (Maxwell et al. 2015), is an approach that is increasingly being employed, as it is more responsive to highly mobile species and results in less active management of human uses of the ocean (see e.g. Wiley et al. 2013, Dunn et al. 2016, Hazen et al. 2017, 2018). Furthermore, mobile and flexible MPAs may be a critical tool for accommodating shifting marine mammal distributions as a result of climate change (Avila et al. 2018, Maxwell et al. 2020).

A relatively new advance in spatial management for marine mammals is the concept of Important Marine Mammal Areas (IMMAs; Corrigan et al. 2014). IMMAs are defined as discrete portions of habitat, important to marine mammal species that have the potential to be delineated and managed for conservation. How IMMAs concord with existing legislative controls within and across national jurisdictions is still being developed, and IMMAs have the potential to be delineated and managed for conservation by management agencies, whether government, intergovernmental organisations or conservation groups, though this is not mandated.

While spatial management can be effective for marine mammals (Notarbartolo di Sciara et al. 2016), several limitations exist. For example, marine mammals are often impacted by multiple human threats simultaneously, resulting in additive or cumulative impacts on individuals and populations (Maxwell et al. 2013). Additionally, threats that exist within MPAs, such as pollution or climate change, may originate outside of spatial boundaries and may be beyond the jurisdiction or capabilities of management agencies (Maxwell et al. 2014). Furthermore, population-level impacts of management actions can be difficult to assess, given the highly mobile nature and long generation times of some marine mammal species. Determining the efficacy of these management actions requires greater attention (Ashe et al. 2010).

3.1.4. *Ex situ* conservation

Ex situ management, i.e. the maintenance of a species outside its natural habitat for conservation purposes, has saved species such as the Arabian oryx *Oryx leucoryx* and the California condor *Gymnogyps californianus* from extinction. Classically in this approach, individuals are removed from their natural habitat to a safe area, a breeding programme is established, and offspring are returned to the wild after threats there have been reduced or eliminated. *Ex situ* management can be controversial, because such efforts may be perceived to divert resources from efforts to conserve species in their natural habitats (Bowkett 2009, Ralls & Ballou 2013). In addition, *ex situ* operations are expensive, logistically challenging, require long-term commitment and are risky for captured individuals. Typically they are only considered when extinction risk is high (Martin et al. 2012, Canessa et al. 2016).

The increasing urgency for actions to tackle the current biodiversity crisis has led to changes in the definition of *ex situ* conservation, and the distinction between *in situ* and *ex situ* has become blurred. The IUCN (IUCN/SSC 2014) now defines *ex situ* as:

> conditions under which individuals are spatially restricted with respect to their natural spatial patterns or those of their progeny, are removed from many of their natural ecological processes, and are managed on some level by humans.

This new approach to *ex situ* conservation, which includes elements of management by humans within marine mammal habitats (as distinct from *ex situ* captive breeding), is feasible for some marine mammals, especially those with terrestrial elements to their life history. Temporary holding of stranded pinnipeds to treat injuries, diseases, malnutrition or impacts from oil with release into their natural range following disease screening now occurs in many parts of the world. For example, in 2012, almost a third (32 %) of all living Hawaiian monk seals were alive due to past human interventions, such as disentanglement, translocation, nutritional support and vaccination (Harting et al. 2014). In California, 71 % of abandoned sea otter pups reared in captivity by surrogate otter mothers and released at weaning survived to adulthood (Nicholson et al. 2007). In China, Yangtze finless porpoise *Neophocaena phocaenoides* have been translocated from the mainstream river to protected oxbow pools where they are now reproducing (Wang 2015).

In the future, new approaches will need to combine *ex situ* conservation with *in situ* management to prevent the loss of marine mammal diversity. Disentanglement, medical treatment, vaccination and translocation will likely be increasingly integrated into population-level management of pinnipeds *in situ*. For cetaceans, capture myopathy and captive maintenance remain challenges. For example, attempts to capture Critically Endangered vaquita for temporary protection were halted after the death of an animal from capture myopathy (Rojas-Bracho et al. 2019) but may have potential for more robust species. The scale, size and number of facilities needed to adequately house sufficient animals to maintain genetic diversity in a captive population make captive breeding programmes for reintroduction unlikely for the larger marine mammal species. The successful release of captive-born cetaceans into the wild poses an additional challenge due to their complex patterns of social behaviour. To date, only 1 formal attempt has been described, with unclear results: a group of bottlenose dolphins, including 4 captive-born juveniles, were released from an aquarium in Western Australia in 1992; 1 calf was recaptured due to poor health, 1 is assumed to have died, and the fate of the other 2 is unknown (Gales & Waples 1993).

3.1.5. Animal welfare science and its application to conservation outcomes

It is increasingly acknowledged that conservation efforts for wild marine mammal populations need to be inclusive of animal welfare (McMahon et al. 2012, Dubois & Fraser 2013), and that the welfare science of individuals can inform conservation management of populations (Beausoleil et al. 2018). However, animal welfare can be mistaken for animal rights, and subsequently misunderstood as either morally or emotionally motivated. Papastavrou et al. (2017) demonstrated how conservation and welfare share similarities in their scientific biases and proposed that they should be considered in unison in marine mammal conservation management. These arguments align with international legislations such as the US Marine Mammal Protection Act (1972) and New Zealand Marine Mammal Protection Act (1978) which define disturbance and harm at the individual level (welfare), even though the aim of conservation management is to prevent population impacts. Indeed, the potential benefits of integrating welfare science, including individual health studies, into conservation management efforts are starting to be recognised in marine mammal conservation (Pirotta et al. 2017). While many biologists still appear to be discomforted by the now widespread discussions of welfare in terms of an individual's subjective experience, i.e. 'feelings' (Beausoleil et al. 2018), recent failed attempts to safely live-capture vaquita in an attempt to conserve the species (Rojas-Bracho et al. 2019) serve as a reminder of why welfare must be positioned within scientific discourse, planning and assessment. While some conservationists, veterinarians and welfare scientists still consider their own disciplines in isolation, an increasing need to find commonalities in our language, understanding and application is necessary if we are to positively affect conservation outcomes for marine mammals (Stockin 2019). The recent application of the 5 domains model to assess welfare implications of tourism on a critically endangered whale population is just one example (Nicol et al. 2020).

3.2. Monitoring and sampling

Effective management of marine mammals with diverse habitat ranges depends on the sharing of species- and population-specific data, environmental information and data on local, regional and global threats. Forums such as the IWC have long facilitated data sharing, and there is now strong evidence suggesting data syntheses are effective at identifying research and conservation priorities (Campbell et al. 2015, Nguyen et al. 2017, Hindell et al. 2020). Recommendations for how to achieve this include:

(1) Create data management plans that include definitions of the types of data, their source, formats, interfaces, and scientific robustness (e.g. anecdotal records, incidental sightings or systematic monitoring).

(2) Map out potential data sources.

(3) Pool information to produce datasets.

(4) Accompany all datasets with metadata descriptions based on standardised formats and vocabularies, such as MVB (vocab.nerc.ac.uk/collection/MVB) and use the Biodiversity Information Standards to offer online management and sharing of data from multiple sources.

(5) Store and securely back up the data for providers and users.

(6) Provide protection/privacy policies for re-use of the available data and determine whether it should be open access (see Lennox et al. 2020 for issues regarding release of sensitive biological data).

(7) Encourage the use of free apps/platforms to collect citizen science data and map sightings.

(8) Promote pathways by which scientists, students and industry can provide input to any resultant repository database(s).

(9) Enable frameworks for the access and sharing of data with different stakeholders/users in the short and long term, while adhering to the 'Findable, Accessible, Interoperable, Reusable' (FAIR) principles for scientific data management and stewardship (Wilkinson et al. 2016).

(10) Provide services that acknowledge or display contributors, in particular the promulgation of data digital object identifiers (DOIs), to encourage data publication.

(11) Promote e-learning platforms for training, especially for remote areas or those with less access to technological resources.

Building the capacity of scientists with skills in Open Science, programming for analysis, research data management, data visualization, information security, machine learning and author carpentry, and computational infrastructures (www.codata.org/) will facilitate data handling required for effective marine mammal research and conservation. To do this effectively, we need to create strong and relevant communication and messaging platforms for all marine mammal scientists. Datasets should be made available within a global repository of metadata (e.g. global databases that can integrate both species and environmental parameters such as the Ocean Biogeographic Information System, OBIS; https://obis.org/), ensuring that existing data can be discovered, accessed and used to support management decisions, such as designating IMMAs (De Pooter et al. 2017). A forum for such a repository could be hosted within an extant international consortium, such as the IWC, Intergovernmental Oceanographic Commission of United Nations Educational, Scientific and Cultural Organisation (IOC-UNESCO; https://ioc.unesco.org/), OBIS, World Register of Marine Species (WoRMS; http://www.marinespecies.org/) or the IUCN, thereby ensuring longevity and that the quality of the data is maintained and linked to other platforms worldwide.

3.3. Policy, guidance and assessment

3.3.1. IUCN Red List

The IUCN Red List (https://www.iucnredlist.org/) is the globally recognised standard for characterizing conservation status of species and ecosystems, and has many strengths. Rigorous application of the clearly defined quantitative Categories and Criteria by recognised experts in the field provides a common currency that a variety of global stakeholders respect, roughly understand and rely upon. Red List classifications are cited in many contexts, including popular media, environmental impact assessments and national and international laws, policies and treaties (Hoffmann et al. 2008). Assignment of a 'Threatened' classification status can spur conservation action and lend urgency and credibility to regional recovery programmes, management plans, research projects and funding, to support practical conservation efforts. Furthermore, in many cases, the need to obtain quantitative population data and evaluate threats for either national or international Red List assessments can provide incentive for the expert compilation of unpublished, but reliable, data on certain species or populations, or drive new research which, in turn, informs on-the-ground conservation efforts (Hoffmann et al. 2008).

While the Red List is generally viewed as authoritative, critics argue that its emphasis on robust data on abundance and threats may distract energy and funding away from more practical on-the-ground threat reduction and conservation interventions (e.g. Knight et al. 2010). Furthermore, the utility of global species-level assessments has been questioned on the grounds that they may provide a false sense of security for wide-ranging species with geographically isolated (sub)populations, which themselves are threatened or in decline (Godfrey & Godley 2008, Desforges et al. 2018). Some feel that efforts to address this concern for marine mammals have resulted in a somewhat haphazard collection of (sub)population-level assessments, usually conducted only for those populations that are well studied, are seriously threatened and have a 'champion' with the expertise and motivation to prepare and submit an assessment.

Among other perceived limitations, as an assessment tool only, the Red List lacks ‘teeth’ and has no mechanism or power to implement or enforce change at the level of a range state, which is where most of the regulatory capacity lies (Hoffmann et al. 2008). However, from its inception, the Red List has been designed as a widely accepted and practical way to help stakeholders of all types to set priorities for conservation action. Without such a standardised tool, governments, funding bodies, industry and others responsible for allocation of resources or development of conservation policy, would arguably have difficulty sifting through and synthesizing scientific and popular literature to guide their decisions.

The Red List can and should evolve, and complementary tools can make it more effective to achieve conservation aims. Recently, in an effort to move beyond an exclusive reliance on quantitative population and trend data, Red List assessments for cetaceans have included greater consideration of the nature and pervasiveness of threats and their potential population-level impacts (Minton et al. 2017, Wang & Reeves 2017, da Silva et al. 2018, Braulik & Smith 2019), providing a more precautionary and holistic approach. Combined with national assessments, and other complementary tools, such as place-based assessments (e.g. IMMAs, Ecologically or Biologically Significant Marine Areas, or Key Biodiversity Areas), the Red List can serve to catalyse and inform legislation, threat-mitigation efforts and management measures that lead to population increase and recovery (Zamin et al. 2010). As the human footprint on our planet expands to include almost every marine mammal habitat, putting more and more populations at risk, the IUCN Red List remains more relevant for marine mammal conservation than ever.

3.3.2. Science outreach and advocacy: international agreements and frameworks

It is frequently argued that the role of science stops with providing the evidence, leaving policy-makers to decide how to act. Many marine mammal scientists are likely guilty of statements such as ‘this research is essential to underpin the implementation of the Marine Strategy Framework Directive’, implicitly assuming that marine mammal conservation is enhanced as a result of research. However, to be effective, scientists must, from the outset, engage with all relevant stakeholders, ranging from policy-makers to the general public: locally, nationally and internationally. Following the precautionary principle, scientific advice should be offered even when data are imperfect (as they usually are), noting that incomplete knowledge does not justify inaction by managers.

An effective approach to successful conservation science is to embed it within the adaptive management framework (McFadden et al. 2011). Adaptive management capitalises on opportunities to improve the effectiveness of management strategies as new knowledge is gained (McCarthy & Possingham 2007) and so extends conservation science into management strategy evaluation and decision-support systems, with feedback and linkages between scientific advice, its implementation (partial or complete) and evaluation and re-evaluation of outcomes. Such systems can propose a range of possible science-based management measures, providing evidence about the likely environmental, social and economic outcomes of their implementation, and critically evaluate the likely nature and extent of non-compliance with measures and its consequences (e.g. the Conservation Evidence assessments: www.conservationevidence.com). However, this requires adaptation by scientists, consent of managers and policy-makers, and support from governments, stakeholders and the general public. It also presupposes a joined-up approach to environmental legislation, for example such that fisheries and conservation management are integrated rather than dependent on different legislation and government departments. An ecosystem-based approach to managing charismatic species is key in order to truly understand and mitigate the impacts of multiple threats on marine mammal populations. This could be supported by a risk-based approach, which explicitly recognises the monetary and cultural values attached to marine mammals as a component of healthy marine ecosystems, objectively measures the likelihood and extent of costs and benefits, to identify how and where resources can be most effectively deployed using a return-on-investment approach to achieve conservation objectives (Tulloch et al. 2020b). This can help to avoid focussing conservation actions on a few charismatic species or a few protected areas while the wider ecosystems on which they depend continue to be degraded.

3.3.3. Regulatory versus incentive-based approaches

The marine mammal conservation science community has historically focussed on documenting the status of, and threats to, various taxa (Read et al. 2006, Avila et al. 2018) and recommending potential regulatory or management solutions to the many conservation concerns. This approach has often not resulted in the uptake of the solutions proposed, even in nations where the conservation priority is codified in legal and policy instruments (Reeves et al. 2003). There are relatively few examples of demonstrated impact from uptake of science-based recommendations into regulation or management (although see Gormley et al. 2012). The potential socio-economic and resultant political impact associated with regulating activities is often deemed unacceptable by decision makers, and so a zero-sum trade-off results. While good governance may be necessary for marine mammal conservation, it may not always be sufficient.

Faced with similar challenges in other sectors, civil society actors (e.g. non-government organisations and progressive companies) have sought to create positive incentives via markets to recognise and reward those who act in a sustainable or responsible manner. These actors leveraged increasing societal expectations for sustainability, coupled with increasing market demand for secure supply chains, and eventually led to the development of a suite of voluntary sustainability certification and labelling programmes for products, including timber, coffee, palm oil and fish (e.g. Agnew et al. 2014). Such organisations develop standards that entities who wish to be certified need to meet in order to access the potential benefits of certification (e.g. access to new markets or price premiums). When these potential benefits exceed the marginal cost of actions that result in more sustainable outcomes, organisations who seek certification are incentivised to implement such solutions. For example, implementing harvest-control rules to restrict fishing effort as the stock approaches the target level, increasing levels of observer coverage to assess bycatch species and conducting benthic surveys to improve assessments of habitat impacts.

We suggest that the uptake of marine mammal conservation-focussed recommendations may benefit from considering how market (or indeed other) incentives could aid in addressing the socio-economic impacts of regulatory or other measures whose consequences may impede conservation outcomes. However, in situations where individuals in small populations of marine mammals are killed incidentally, the time required to implement incentive-based mechanisms is likely to be too long to prevent local extinction. For example, all 11 examples of Critically Endangered small cetacean populations impacted by gill netting identified by Brownell et al. (2019) have such small populations that even 1 human-caused mortality will increase the risk of extinction (see International Whaling Commission 2018). In such cases, incentives alone are unlikely to prevent extinction although they may be a component of a more comprehensive approach. Interdisciplinary research to identify the scenarios under which either regulatory or incentive-based measures, or both in combination, may yield successful outcomes would be valuable. Such research should be undertaken well before emergency conservation actions are required. Additionally, improved communication between scientists and the general public may enhance awareness of conservation issues, improve support for proposed solutions and result in greater conservation success.

4. RESEARCH AND MONITORING TECHNIQUES

In recent decades, the range of methods used to observe and understand marine mammals has evolved rapidly. Here we outline examples of key technological, molecular and social techniques and discuss their future application and priorities for development.

4.1. Technology

4.1.1. Satellite and drone imagery

Over the past 5 decades, the use of earth observation satellites and other emerging technologies has grown exponentially. Decreasing costs, increasing resolution of sensors, expanding global coverage, and the availability of public archives of imagery (e.g. Google Earth) now make it possible for researchers to use remote sensing tools to safely and efficiently study marine mammals (Moxley et al. 2017, Johnston 2019, Schofield et al. 2019).

Earth observation satellites: Several studies have successfully employed satellite data to investigate marine mammal distribution and density. WorldView imagery has been used to study distributions of Weddell seals *Leptonychotes weddellii* (LaRue et al. 2011) and polar bears (LaRue & Stapleton 2018), and to detect and count mysticete whales in several locations around the world (Fretwell et al. 2014, Cubaynes et al. 2019, Bamford et al. 2020). Deep learning methods to automate detection and enumeration in satellite data are in development (Guirado et al. 2019).

The capacity for studying and conserving marine mammals via satellites will continue to grow, due to the continued launch of large earth observation satellites (>50 kg) to support habitat and conservation studies (Probst et al. 2017), as well as the proliferation of small satellites (<50 kg; i.e. cubeSats, microSats and nanoSats, see Spaceworks, https://www.spaceworks.aero/nano-microsatellite-forecast-8th-edition-2018/). These efforts will provide improved imaging and increased coverage for purposes of tracking animals with the Argos System (Bille et al. 2018).

Unoccupied aircraft systems: At present, unoccupied aircraft systems (UASs or 'drones') are used to detect and count marine mammals in shore-based colonies, on sea ice and at sea (Moreland et al. 2015, Seymour et al. 2017, Angliss et al. 2018, McIntosh et al. 2018), assess size and body condition (Durban et al. 2015, Sweeney et al. 2015, Christiansen et al. 2018, Allan et al. 2019), monitor vital signs (Horton et al. 2019), study respiratory microbiomes and virology (Apprill et al. 2017, Pirotta et al. 2017, Geoghegan et al. 2018), document behaviour (Torres et al. 2018) and detect and assess injury rates (Martins et al. 2019). These on-demand sampling approaches are increasingly coupled with automated approaches for analysis (e.g. Fearnbach et al. 2018, Burnett et al. 2019), including deep learning techniques (Gray et al. 2019). Alongside these biological and ecological applications, efforts focussed on understanding and mitigating disturbance of marine mammals by aerial and underwater drones are underway (Smith et al. 2016, Arona et al. 2018, Thaler et al. 2019). Finally, there is a growing interest in using drones to study human interactions with marine spaces and species, although key privacy and security concerns must be addressed (Nowlin et al. 2019).

Drones provide on-demand remote sensing at incredibly high resolutions, overcoming many challenges presented by satellite remote sensing (Johnston 2019). Furthermore, UAS surveys can be cheaper and less logistically challenging than occupied aircraft surveys, and may present opportunities to reduce risk to researchers and study subjects (Johnston 2019). As costs decline further and platform and sensor capacities rise, UAS technology represents a dramatic democratization of remote sensing in marine mammal research and conservation. Unfortunately, at present, the legal rules associated with the use of UAS in marine mammal research are complicated, constantly in flux, and in some locations, their use is prohibited. This ever-changing legal landscape is one of the major factors that limits adoption of UAS technology in marine mammal research.

4.1.2. Biologging and telemetry

Biologging is the use of animal-borne electronic tags to record data about individuals and their environment (Rutz & Hays 2009; Fig. 2). Biotelemetry refers to the remote transmission of such data when tags cannot be recovered (Hart & Hyrenbach 2009, Hussey et al. 2015). Biologging was pioneered on marine mammals over 50 yr ago (Kooyman 1966), and the field has since developed to facilitate data collection from all marine mammal taxa around the globe (McIntyre 2014). We are in a 'Golden Age' of biologging science, with rapid advances in technology and analytical approaches (Ropert-Coudert et al. 2009, Wilmers et al. 2015). Besides the long-established location and dive sensors, an array of additional sensors, including conductivity, temperature, depth (Boehme et al. 2009); accelerometers (Ydesen et al. 2014), magnetometers (Mate et al. 2017) and jaw movement (Liebsch et al. 2007); video (Goldbogen et al. 2013); stomach temperature (Andrews 1998); sound level (Johnson & Tyack 2003); active acoustics (Lawson et al. 2015); and, most recently, near-infrared spectroscopy to measure haemodynamics (McKnight et al. 2019), can be incorporated into biologging devices. Such data and associated analytical tools have provided key information for marine mammal conservation, including inference of important foraging areas (Hindell et al. 2020), and how individuals respond to anthropogenic disturbance (Russell et al. 2016, Isojunno et al. 2017) and environmental change (Hindell et al. 2017, Harcourt et al. 2019b).

As biologging technology and analytical approaches continue to develop, 5 key areas are essential to maximise progress for marine mammal conservation:

(1) Improved on-board compression and abstraction techniques for high-resolution data to optimise transmission (Photopoulou et al. 2015, Cox et al. 2018). This will reduce reliance on archival tags, which are currently only appropriate for certain life stages and species that can be easily re-encountered, generating demographic bias in the literature (McIntyre 2014).

(2) Improved tag hydrodynamics and bio-compatibility with minimally invasive attachments to limit energetic consequences of carrying a tag (Kyte et al. 2019), thus helping to mitigate tag effects in biologging data and welfare concerns (Wilson & McMahon 2006, Horning et al. 2017).

(3) Development of long-lasting miniature tags, allowing individuals to be tracked over multiple years, facilitating estimation of vital rates including survival and recruitment age to improve our understanding of population dynamics (Horning & Hill 2005).

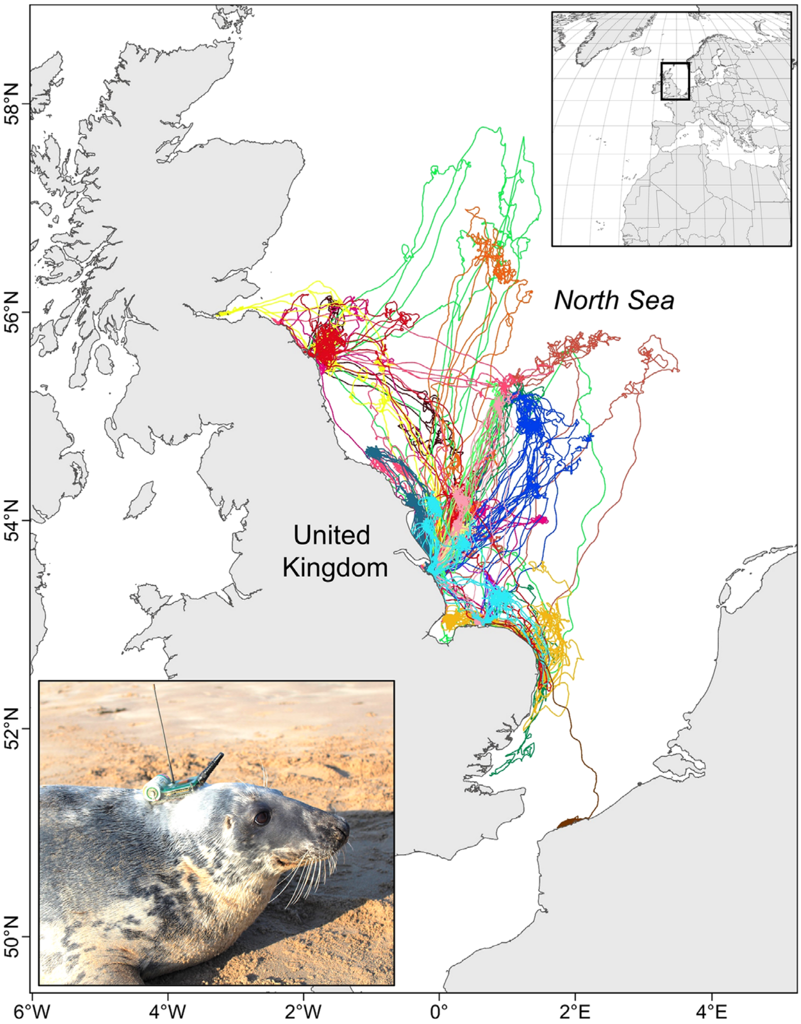

Fig. 2. Biologging devices provide a suite of data useful for marine mammal conservation. For example, satellite telemetry devices deployed on grey seals in the southern North Sea record and transmit data on their location, dive activity and haul-out behaviour, which can be used to answer a range of questions relevant to conservation management. Photo and tracks credit: Sea Mammal Research Unit

(4) Integration of physiological sensors alongside simultaneous collection of behavioural and environmental data to allow estimation of the true impacts of anthropogenic disturbance on marine mammals at sea (Hays et al. 2016, Pirotta et al. 2018).

(5) Improved integration of biologging and biotelemetry data into international marine policy frameworks for effective conservation (Dunn et al. 2019).

4.1.3. Habitat preference modelling

Habitat preference modelling (HPM) aims to quantify the link between species presence or abundance and environmental covariates (Fig. 3). For marine mammals, modelled relationships are often used to predict the at-sea distribution of populations (Gregr et al. 2013). For pinnipeds, HPM can also be used to predict distributions on land (Dendrinos et al. 2007). Predicted distributions are used to identify priority areas for conservation management (Bailey & Thompson 2009, Embling et al. 2010). Although traditionally such models are based on census or visual survey data (Baumgartner et al. 2003), advances in ecological modelling techniques have facilitated HPM for acoustic survey (Marques et al. 2009, Pirotta et al. 2011, Stanistreet et al. 2018, Merkens et al. 2019) and individual tracking data (Aarts et al. 2008, Wilson et al. 2018).

To maximise the potential of HPM for marine mammal conservation, we identify 4 general (1–4), and 2 data-specific (5–6), challenges, and suggest priorities for future work:

(1) Climate change increases the challenges associated with HPM but also its necessity (Hazen et al. 2013, Silber et al. 2017). Such modelling often involves extrapolating predictions beyond the environmental parameter space in which the model was fitted (Bouchet et al. 2020). Researchers should highlight areas of extrapolation and use multiple climate scenarios to assess the robustness of predictions.

(2) To enhance our ability to predict distributions, we must improve our understanding of the mechanistic relationships between species and the physical (e.g. water depth) and biological (e.g. drivers of prey/predator distributions) processes that shape habitats (Palacios et al. 2013). This shift towards ecosystem-level modelling requires data on diet composition and flexibility (Smout & Lindstrøm 2007) but could facilitate more dynamic management strategies (Maxwell et al. 2015).

(3) Where possible, HPM should be activity-specific (Palacios et al. 2019). Not accounting for activity-specific (e.g. foraging, resting and breeding) preferences may result in inaccurate overall preference

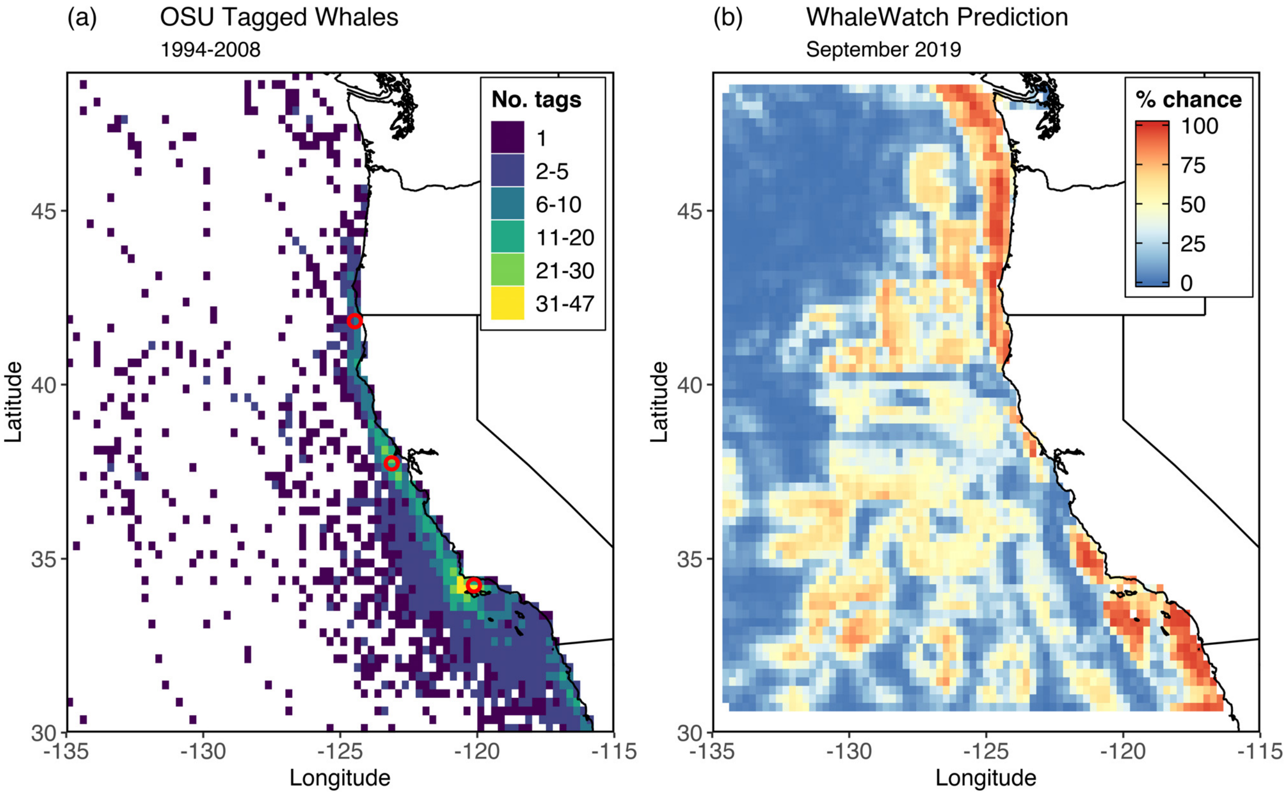

Fig. 3. (a) Locations of 104 blue whales *Balaenoptera musculus* were tracked using satellite-monitored radio tags off the US West Coast between 1994 and 2008, with colour shading indicating the number of tagged whales occurring inside 25 km grid cells to highlight the hotspots of highest observed aggregation. Red circles indicate the 3 areas where the tags were deployed (see Bailey & Thompson 2009 for details). Tracks credit: Oregon State University (OSU). (b) Prediction of the likelihood of blue whale occurrence (% chance) based on habitat preference modelling of static and dynamic habitat variables in the California Current ecosystem for September 2019, on a 25 km resolution grid, from the WhaleWatch model available from NOAA at https://www.fisheries.noaa.gov/west-coast/marine-mammal-protection/whalewatch (see Hazen et al. 2016 for details)

relationships and inadequate protection (Tyne et al. 2015).

(4) Future research should aim to improve the interface between population models and HPM to directly link population dynamics and habitat trends with species distributions (Hindell et al. 2017).

(5) Models using survey data should propagate uncertainty in detection probabilities to inform uncertainty surrounding predictions (Marques et al. 2009).

(6) HPM for presence-only (i.e. tracking) data often requires various subjective assumptions. More robust predictions depend on understanding the impacts of such assumptions and would benefit from combining multiple data sources to evaluate methods (Mikkelsen et al. 2016, Woodman et al. 2019), and linking inference from the typical HPM landscape-scale models with models of individual movement paths (Signer et al. 2017, Michelot et al. 2019).

4.1.4. Real-time acoustic data

In contrast to light, sound travels well underwater and has become a key source of information on marine mammal species presence, system attributes and harmful anthropogenic activities. Options for deploying acoustic monitoring sensors into appropriate locations are diverse (Van Parijs et al. 2009) and typically rely on passive-acoustic monitoring using hydrophones. The simplest approach is to suspend one or multiple hydrophones in the water, using any platform, from canoes to ships. Vessels can be expensive, however, and impractical for long-term use. Continuous monitoring can be achieved if hydrophones can be cabled to shore. Though more convenient, cables are costly and vulnerable to damage from storms or fishing activities, and require substantial, often military, infrastructure (e.g. Tyack et al. 2011). With the advent of small, low-power electronics, miniaturisation has revolutionised acoustic monitoring, and many options are now available to remotely capture and archive sound without vessels or cables (Sousa-Lima et al. 2013). Hydrophones and recorders are commonly packaged as free-standing units and left alone in the water to record for days, months or longer and can be stationed at any depth by using acoustic release mechanisms (Mellinger et al. 2007). Memory size, battery life, desired sampling rate and duty cycling determine device duration. Units are most often left at sea moored or drifting, alone or in arrays (Van Parijs et al. 2009, Wilson et al. 2014). Further miniaturisation has even made it possible to attach them to the animals themselves (Johnson & Tyack 2003, Fregosi et al. 2016). Passive acoustic monitoring is not suitable for species such as pinnipeds that do not reliably indicate their presence through vocalisations. For these species, active sonar is emerging as a potentially useful monitoring technique (Hastie et al. 2019).

There are a number of situations where stored sound is insufficient and real-time information is needed. Examples include those where animal presence and location are used to observe how they respond to the presentation of particular signals (Tyack et al. 2011) or where industrial activities need be curtailed when animals are present (Verfuss et al. 2016). For such applications, real-time sound might be transferred through cables or via satellite or cellular networks (Lee et al. 2018). Real-time acoustic monitoring of right whales on the east coast of the USA is used to notify mariners of their location, thus reducing the risk of ship strikes (Soldevilla et al. 2014). The high-frequency and cryptic nature of many marine mammal signals, however, mean that sophisticated data compression and automated detectors are required (Gillespie et al. 2009). Here, the ongoing artificial intelligence revolution in signal detection and species classification methods has exciting potential for marine mammal studies. The proliferation of above- and below-water unmanned vehicles has meant that acoustic sensors can be attached and manoeuvred into and through a wide variety of challenging habitats at less cost than traditional approaches (Verfuss et al. 2019). Especially exciting is the possibility of communication and responsive sampling or movement between unmanned vehicles so that all the benefits of applications like arrays can be harnessed without the limitations of being fixed in space. At such a point, listening to marine mammals could be as mobile as the animals themselves. An operational challenge for the marine research community will be to keep abreast of the ever-changing tools long enough to apply, test, debug, validate and optimise them so that they can be used to usefully answer urgent questions required for marine mammal conservation and management.

4.1.5. Electronic monitoring of fisheries

Electronic monitoring (EM) systems are increasingly being used to complement conventional human on-board observer programmes and to initiate at-sea monitoring of fishing practices where none previously existed, and can produce estimates of marine mammal bycatch with high precision and possibly higher accuracy than estimates derived from conventional at-sea observer programmes (Kindt-Larsen et al. 2012, Bartholomew et al. 2018). EM systems typically use on-board cameras, global positioning systems, sensors and data loggers to collect information on fishing, trans-shipment and supply vessels (Restrepo et al. 2018). Properly designed EM systems have several advantages over conventional human observer programmes, in particular, greatly reducing 3 main sources of statistical sampling bias (Monteagudo et al. 2015, Kennelly & Hager 2018, Gilman et al. 2019):

(1) Observer effect: Fishers may alter their fishing practices and gear in response to the presence of a human observer or EM system. The higher the observer and EM coverage rate, the lower the bias from an observer effect, where 100% observer coverage would eliminate this source of bias. Having all vessels outfitted with EM equipment and analysing a random sample or all of the EM imagery could eliminate this source of bias.

(2) Observer displacement effect: Management authorities may not place observers on vessels that are too small to accommodate an additional person, or because they are unsafe, or it may be logistically challenging for placement. Vessel specification requirements for EM systems are much lower than for a human observer. EM therefore enables avoiding an observer displacement effect so that sampling is random and balanced proportionately across ports and vessel categories.

(3) Coercion and corruption: At-sea observers collect sensitive information, and the vessel captain and crew may hinder the observer from properly conducting their monitoring activities, threaten the observer's safety or attempt to bribe the observer to not report damaging information. Some observers may deliberately misreport sensitive data fields due to friendships with fishers.

EM also provides more accurate data by enabling multiple areas of vessels to be monitored simultaneously and near-continuously, allowing questionable data to be audited. Logbook data self-reported by fishers can be much less reliable than EM data, in particular for discards and bycatch of species of conservation concern, as fishers may have economic or regulatory disincentives to record accurate data, or may be inattentive (e.g. Walsh et al. 2002). Camera set-up, however, can be a weakness for EM systems, as areas on deck or water where crew handle and release non-retained catch may not be within EM camera fields of view (Monteagudo et al. 2015, Larcombe et al. 2016, Bartholomew et al. 2018, Briand et al. 2018). For marine mammals, and other species that crew release, blind spots may prevent EM systems from detecting the capture event, or when detected, could prevent EM analysts from determining the species, condition, handling and release methods employed by crew, or what gear remained attached to the animal upon release (McElderry et al. 2010, 2011, Gilman et al. 2020). Minor modifications, such as adding a dedicated camera on the outboard side of the rail near the hauling station (Gilman et al. 2019), obtaining crew cooperation to bring bycatch into the EM camera field of view prior to release, and, if needed, adjusting deck lighting to ensure that areas within the EM cameras' fields of view are adequately lit, could all help address the issues of visibility and detection by cameras (Gilman et al. 2019).

4.1.6. Spatial Monitoring and Reporting Tool patrols

Spatial Monitoring and Reporting Tool (SMART) is a suite of best practices and a free, user-friendly software program (https://smartconservationtools.org/) used by protected-area managers and local communities to document, adaptively manage and evaluate the performance of wildlife enforcement and monitoring patrols. The software can also integrate data collected from other sources, such as informant networks and vessel monitoring systems. Although SMART has been used mostly for terrestrial wildlife enforcement and monitoring patrols, it is also becoming a valuable conservation tool in the marine environment (Cronin et al. 2019). SMART is being pioneered for marine mammal conservation in the waterways of the Sundarbans mangrove forest of Bangladesh which support populations of Ganges river dolphins *Platanista gangetica* and Irrawaddy dolphins *Orcaella brevirostris* (Smith et al. 2006), both considered Endangered on the IUCN Red List (Minton et al. 2017, Braulik & Smith 2019). Between January and September 2018, the Bangladesh Forest Department conducted 63 SMART patrols lasting 10–12 d each and covering more than 68 000 km. A total of 322 offenders were arrested, more than half for illegal fishing that threatened dolphins. In addition, 292 vessels and 312 illegal fishing gears were seized, and 962 georeferenced sightings were made of Ganges river dolphins and 296 of Irrawaddy dolphins.

SMART is also being deployed in the Mekong River, which supports a genetically distinct Irrawaddy dolphin population (Krützen et al. 2018) considered Critically Endangered on the IUCN Red List (Smith & Beasley 2004). Sixty-eight river guards were recruited from local communities and stationed at 16 outposts throughout the 190 km long distribution of Irrawaddy dolphins in the Mekong. SMART patrols resulted in a dramatic increase, from 998 in 2014 to 2596 in 2016, in confiscation of illegal gillnets that bycatch Irrawaddy dolphins and certainly contributed to a reduction in mortality and an increase in dolphin abundance (Thomas & Gulland 2017).

As SMART is adaptable to use in different situations in different environments, it is ideal for guiding effective conservation management and promoting accountability using both top-down (e.g. government led) and bottom-up (e.g. community led) approaches. Information collected on marine mammals during SMART patrols, including geo-referenced sightings and mortalities, can be especially valuable in areas where dedicated studies and local capacity for conducting marine mammal research is lacking. A key factor in the success of SMART is intensive training and mentoring for field-level practitioners and data managers.

4.2. Molecular techniques

The rapid advancement and decreasing cost of DNA sequencing technology provides an ever-expanding suite of tools to assist in marine mammal conservation (Cammen et al. 2016). For example, the investigation of genetic data can highlight vulnerabilities from reduced genetic diversity, examine resilience and plasticity, assess susceptibilities to environmental and anthropogenic stressors, develop necessary management strategies associated with population differentiation and cryptic species, and help to understand the mechanisms that determine these factors.

Marine mammal distributions vary from local endemics to global species inhabiting all major ocean basins (Kaschner et al. 2006). Many species with large ranges are sub-divided among insular regional populations that are genetically differentiated (Hoelzel 2009, Vianna et al. 2010). The identification of these groups can help effective management by defining populations to protect and therefore conserving the evolutionary potential for the species as a whole (Barlow et al. 2018). It is also useful to compare patterns of genetic diversity and demography within and between distinct populations, as local adaptation and differing levels of diversity may reflect different sensitivities to exploitation and disturbance. For example, low genetic diversity in small populations or species increases the risk of inbreeding depression, a loss of evolutionary potential in a changing environment and increased risk of disease (Hoffman et al. 2014, Leroy et al. 2018).

One of the earliest, and still widely used, applications of genetics in marine mammal conservation is the forensic identification of animals to species, and sometimes population, of origin (Ogden & Linacre 2015, Baker & Steel 2018). Sequence data (such as the control region of mitochondrial DNA) from the sample in question is compared to a database of validated species (e.g. Ross et al. 2003), and can reveal illegal harvest and trade (Baker et al. 1996), and quantify the prevalence of a particular species in bycatch (Henshaw et al. 1997) or strandings (Alfonsi et al. 2013). They can even result in the discovery of new species when the samples have no database match (Dalebout et al. 2002). Advancements of these methods have allowed for the identification of specific individuals in genetic monitoring programmes, a particularly useful method to estimate vital life history parameters and connectivity when the recapture of individuals is possible (Carroll et al. 2018).

Future directions in conservation genetics will involve improving new sequencing technologies (Amarasinghe et al. 2020), expanding the use of '-omics' technologies in non-model species, refining methods to extract genomic material from minimally invasive material (i.e. seawater, faeces, exhaled breath, ancient samples; Carroll et al. 2018), combining genetic data with those of other monitoring techniques (e.g. telemetry or demographic) to inform meta-population dynamics (Carroll et al. 2020) and developing tools for storing and analysing vast quantities of genetic data for Big Data analyses (Siepel 2019).

Harnessing the power of advanced gene editing technology may also become an option in the wildlife conservation toolkit, with methods such as clustered regularly interspaced short palindromic repeats (CRISPR/Cas; Cong et al. 2013) and gene drives (Esvelt et al. 2014) opening the doors to de-extinction, more effective and/or humane eradication of pests/invasive species/pathogens, vaccine development and fitness improvements by increasing genetic diversity in the face of accelerating pathogen and climate change threats (Shapiro 2015, Novak et al. 2018).

4.3. Societal engagement

'Citizen science' can be defined as the collection or collation and processing of data by members of the public who may not necessarily have scientific credentials, but whose contribution can aid in ongoing scientific research (Bonney et al. 2014, Wood et al. 2015). The ever-increasing popularity of portable electronic devices gives users online accessibility to websites and social media platforms, and enables them to contribute data on subjects such as species occurrence and distribution (Wood et al. 2015) as well as incidents of injury or mortality (e.g. entanglement in plastic pollution; Donnelly-Greenan et al. 2019).

With quality checks, citizen science can be especially useful in gathering information on data-deficient, elusive and difficult to study marine mammal species, particularly in regions of the world where carrying out extensive surveys is logistically and financially challenging (Stafford & Baumgartner 2014, Olson et al. 2018). Information from social media posts can be a source of data where no other data exist and can be mined retrospectively, after citizens have shared their observations (Parton et al. 2019).

In India, a marine mammal data-deficient country, an increase in the number of annual marine mammal sighting/stranding records appeared after 2012 (www.marinemammals.in), when this open access database was first advertised widely, resulting in greater participation from the public and increased information. In Vietnam, another marine mammal data-deficient country, species occurrence and diversity were investigated by data mining social media and other online entries for sightings and stranding events along the entire coastline of the country over a 14 yr period. This yielded 166 events with at least 15 species of cetaceans, including 1 new species record (Vu & Ponnampalam 2018). Citizen science has also been used for more complex investigations. For example, in Australia, data collected by non-specialist volunteers has contributed to understanding local habitat use by migrating humpback whales (Bruce et al. 2014) and enabled scientists to monitor their rate of recovery (Pirotta et al. 2019). Similarly, in New Caledonia, Derville et al. (2018) found that citizen science data were a valuable tool in describing cetacean habitat in a study of humpback whale distribution.

The development of mobile applications, or 'apps', has led to the creation of various marine mammal reporting apps that are locality specific, such as Whale Alert, Dolphin and Whale 911, Beach Track, SEAFARI, Whale Track, Happywhale and SIREN. These enable the public to easily report any marine mammal sighting or stranding in a standardised manner that provides researchers with key information. Apps are also an opportunity for the public to become more informed, interested and involved in marine conservation issues (Edwards 2015). Investigating the effectiveness and limitations of mobile apps, as well as citizen science programmes, can improve those platforms and so ensure the quality of the data and enhance the sustenance of these programmes (Thiel et al. 2014, Hann et al. 2018). One caveat, however, is that citizen science programmes are not a panacea and are most valuable when a scientifically robust design is implemented at the outset (Bird et al. 2014, Embling et al. 2015).

5. PARTICULAR TAXA/ POPULATIONS THAT ARE IN URGENT NEED OF FOCUS

Despite the great strides made by researchers and conservationists towards finding ways to monitor and protect marine mammals and their habitats, species and populations continue to be lost. The baiji was declared likely extinct in 2006 (Turvey et al. 2007), and the vaquita is close behind. Here, we highlight selected examples of species for which additional focus might yet turn the tide of their fortunes. The North Pacific and the North Atlantic right whales (*Eubalaena* spp.) were driven to near-extinction by whaling by the early 20th century (nearly 30 000 were taken in the North Pacific during 1840–1849 alone; Scarff 2001, Reeves et al. 2007), and the populations have languished since then, even in the absence of whaling (Cooke & Clapham 2018). Right whales remain extremely rare throughout their historical range in the North Pacific, with few recent signs of successful reproduction and recruitment. The main threats to both species are ship strikes and entanglement in fishing gear (Harcourt et al. 2019a). However, climate change may be exacerbating problems by pushing whales further north. Every individual lost lessens the chances of recovery, and research effort focussing on solutions to mitigate these threats is urgently needed.

Similar to the plight of baleen whales, all monk seal species (genera *Monachus* and *Neomonachus*) experienced overhunting by sealers. Of the 3 species, the Caribbean monk seal is extinct, while the Hawaiian and Mediterranean monk seals are IUCN Red-listed as Endangered. After a long history of decline, Hawaiian monk seals managed to stabilize at around 1300 individuals in 2013–2015 (Baker et al. 2016). However, they have particularly low genetic diversity (following a population bottleneck) and have one of the highest documented rates of entanglement of any pinniped (Antonelis et al. 2006). For the Mediterranean monk seal, strong conservation efforts, in Madeira (Portugal), Greece and Mauritania, have enabled seals to persist in a few parts of their now highly fragmented range, but the entire meta-population comprises less than 500 mature individuals (Karamanlidis & Dendrinos 2015). Habitat loss, entanglement in fishing gear, deliberate persecution by fishermen, reduced genetic diversity and a litany of other stressors continue to threaten these seals.

All 4 sirenian species (genera *Dugong* and *Trichechus*) are classified as Vulnerable (Marsh et al. 2011). However, some populations (e.g. West Indian manatees *T. manatus*) are likely to be secure given their location in highly developed countries with advanced conservation practices. In contrast, the future of African manatees *T. senegalensis* is particularly concerning because of the high levels of poverty throughout most of their range, an issue that will be exacerbated by climate change. Similarly, local extinctions of very small, isolated populations of dugongs are likely in East Africa, the South Asian sub-continent, Palau and Japan (Marsh & Sobtzick 2017).

The Critically Endangered Atlantic humpback dolphin *Sousa teuszii*, endemic to nearshore waters between Western Sahara and Angola (Weir & Collins 2015), has a discontinuous distribution, with small remnant populations (typically 10s to low 100s) isolated by hundreds of kilometres. This likely reflects the distribution and relative intensity of several anthropogenic stressors, for example, habitat loss, gillnet fisheries and local consumption as marine bush meat (Collins et al. 2017). Although the conservation prospects in some areas appear 'intractable' (Ayissi et al. 2014), with stringent measures, the species' status could yet improve. An urgent focus is required on known strongholds with explicit measures to reduce bycatch, protect habitat (e.g. through MPA designation) and prevent hunting. To date, however, conservation has been limited by an absence of resources and capacity to conduct much-needed work (Van Waerebeek et al. 2004, Weir et al. 2011, Ayissi et al. 2014).

In southern Asia, small coastal, lagoonal and riverine populations of river dolphins (*Platanista*), Irrawaddy dolphins (*Orcaella* spp.), Indo-Pacific humpback dolphins (*Sousa* spp.) and finless porpoises (*Neophocaena* spp.) are threatened primarily by entanglement in gillnets and other fishing gear, and secondarily by chemical and noise pollution, loss and degradation of habitat as a result of water management policies and structures, competition with fisheries, inland shipping and low levels of hunting (Sutaria 2009, Sutaria et al. 2015, Khanal et al. 2016, Minton et al. 2017, Sule et al. 2017, Braulik & Smith 2019, Dey et al. 2019). The risk of losing local populations rises as their numbers become smaller over time in a region that is under immense development pressure, with ever-increasing human population densities and little or no evident political will to protect biodiversity and natural habitat.

The maritime fur trade of the 18th and 19th centuries caused a significant decline in sea otter populations, reducing their numbers from approximately ~300 000 to less than ~2000 individuals (Davis et al. 2019). Although some populations are now recovering due to the implementation of multi-national management measures, the pre-exploitation range of this species is highly fragmented, and some populations remain in decline due to issues such as habitat degradation and loss, oil spills, potential fisheries interactions, predation and disease events (Doroff & Burdin 2015).

Although some sub-populations of polar bears may initially benefit from the effects of climate change on sea-ice thickness (Laidre et al. 2020b), rising temperatures pose severe risks to the species as a whole. A reduction in sea-ice leads to diminished access to prey and lower reproductive success (Laidre et al. 2020a), as well as increased disturbance from humans due to the opening up of new shipping routes (Gross 2018). Accurate population estimates for polar bears are limited, and the current population trend for the species is unknown. Large reductions in the global polar bear population are predicted, however, if sea-ice loss continues as forecasted by climate models (Wiig et al. 2015).

6. CONCLUSION

Marine mammals are a diverse group, inhabiting marine, estuarine and many riverine environments globally. While very few marine mammal species have been driven to extinction in modern times, continued increases in anthropogenic pressures on our marine and freshwater ecosystems are placing new and powerful stressors on many species and populations. As we begin the Decade of Ocean Science for Sustainable Development, we have taken a renewed synthetic view of these key threats, discussed existing and future conservation mechanisms and outlined emerging research and monitoring techniques that can be engaged to help safeguard marine mammals over the horizon.

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