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The Challenges of Managing Marine Disease

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Abstract

The incidence of emerging infectious diseases (EIDs) has increased in wildlife populations in recent years. Though relatively understudied, in the marine environment disease can disrupt ecosystem resilience, cause economic loss, or threaten human health, and these disease emergencies are expected to increase in frequency and severity in the future. While there are many existing tools to combat the direct and indirect consequences of EIDs, these management strategies are often insufficient or ineffective in marine habitats compared to their terrestrial counterparts due to fundamental differences in marine and terrestrial environments. In this paper, we first illustrate the organismal life history and marine system differences that challenge our traditional conceptualization of wildlife disease management. We then assess the application of disease management strategies routinely used in terrestrial systems to marine disease management, with the aim of identifying management tools that may be effective in the areas of disease outbreak prevention, response, and recovery in marine environments. Finally, we provide recommendations for actions that will enable more successful management of marine wildlife disease emergencies in the future. Our assessment of the challenges for managing marine disease identifies several ways forward, with many existing strategies for disease management showing promise for utility in marine systems. Overall, to have the ability to mitigate marine disease emergencies, we recommend multi-disciplinary collaboration and rapidly embracing active management of marine disease.

Introduction

The issue

Within the last 40 years, wildlife populations have experienced a pronounced increase in occurrence of **emerging infectious disease (EID)** in terrestrial (Daszak et al., 2000), freshwater (Reid et al., 2019), and marine environments (Tracy et al., 2019). When an EID disrupts ecosystem resilience, causes economic loss, or threatens human health, it becomes a **disease emergency** (Groner et al. 2016). For marine wildlife in particular, preventing disease emergencies is critical because fisheries are a 400 billion dollar worldwide industry (FAO 2020), with approximately 10% of the global population depending on fisheries for their livelihood (FAO 2020), and the potential for marine organisms to enable technological and biomedical advances is vast (Blasiak et al., 2020). In other words, preventing marine EIDs epitomizes the OneHealth concept defined as the collaboration of multiple disciplines working to optimize the interconnected health of people, animals and our environment (Centers for Disease Control and Prevention, 2020).

Despite significant increases in wildlife disease (Tracy et al. 2019), and the potentially profound direct and indirect consequences of EIDs, there are no federal mandates for responding to wildlife disease in the United States. Thus, identifying, developing, and implementing tractable management tools targeted to marine ecosystems is an urgent priority for scientists, managers, and policy-makers alike. As emphasized by the OneHealth concept, and highlighted throughout this synthesis, interdisciplinary collaborations between human, animal, and ecosystem health professionals are essential to effectively understand and manage marine disease emergencies (Groner et al., 2016).

The Disease Triangle

The “disease triangle” has historically provided a conceptual map for understanding and mitigating terrestrial disease dynamics. For a host organism to enter a disease state, host susceptibility, **pathogen** dynamics, and environmental conditions that affect host health and pathogen viability must all align (McNew 1960, Scholthof 2007, Thrusfield 2018). The co-occurrence of these three variables constitute the disease triangle, where vertices of the triangle are modulated to mitigate or prevent disease across a broad range of systems, including marine wildlife (Figure 1). While the disease triangle is a useful concept for marine disease management strategies, due to life history differences of organisms in the sea, many specific tools that adjust vertices in terrestrial wildlife systems are logistically impractical or need to be adapted for use in marine environments. We illustrate below the organismal life history and marine system differences that challenge a traditional modulation of the marine disease triangle vertices.

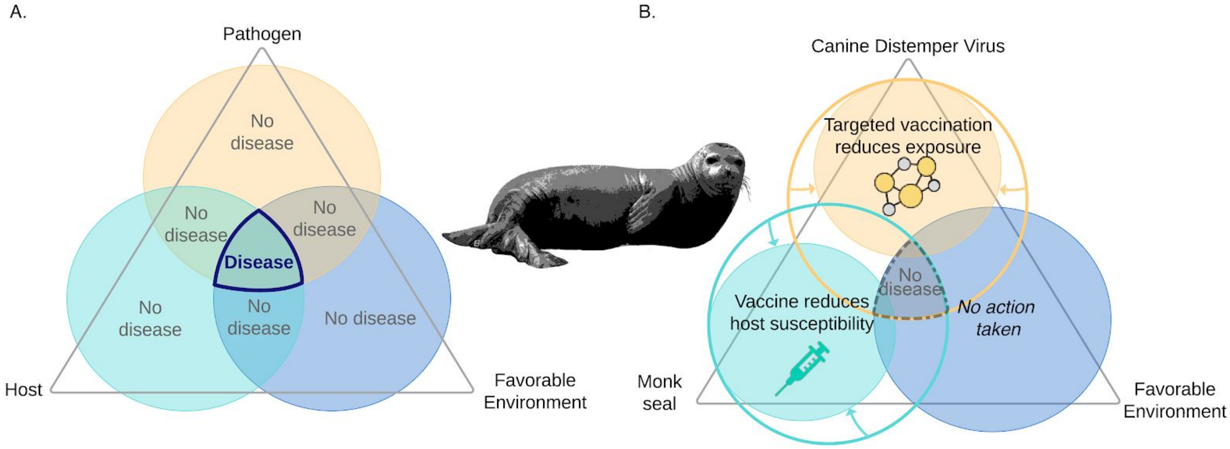

Figure 1. ***(A) A conceptual disease triangle, where pathogen dynamics, host dynamics and favorable environments intersect to create disease and (B) management action reduce overlap of pathogen and host dynamics to reduce disease risk.*** *Robinson et al. (2018) vaccinated monk seals against Canine Distemper Virus (host) and used network science to target vaccination at seals with the most contacts, ultimately reducing pathogen transmission and exposure (pathogen).*

Effects of Life in the Sea on Disease Dynamics and Implications for Research and Management

Limited Accessibility

A fundamental challenge to understanding any ocean process, including disease dynamics, is the limited accessibility humans have to marine compared to terrestrial and often aquatic environments. First, an understanding of what is a "normal" or "healthy" baseline for a marine disease system, a species, a population, or a community is harder to attain, simply because humans have been studying underwater systems for less time and because our visitation to the marine environment is always temporary. Second, detecting an abnormal event, like a disease outbreak, is also more challenging in the sea because fewer scientists and members of the public will encounter it by happenstance compared to terrestrial systems. Third, treating individual wild marine organisms for disease is very challenging and nigh impossible in many cases, simply because access to populations is limited. Thus, because of this limited accessibility, it is more useful to approach marine wildlife disease by managing host populations in various ways, rather than directly treating individuals.

Immune Systems of Marine Organisms

Host immunity consists of two branches, with the presence and complexity of each branch variable among taxa. The first branch, **innate immunity,** is a non-specific immune response that is widely activated upon pathogen invasion (Cooper 2018). Innate immunity typically consists of an inflammatory response that orchestrates immune cell recruitment to the site of infection and/or pathogen phagocytosis. In invertebrates, the innate immune response is typically the dominant immune response (Copper 2018, Mydlarz et al. 2006). In vertebrates, the innate immune response is the first line of defense and helps to initiate the adaptive immune response (Pastoret et al. 1998).

The second branch, **adaptive immunity**, found in vertebrates, develops in response to specific infections by creating immunological memory and **antibodies** to unique features of a pathogen known as **antigens** (Pastoret et al. 1998). This immune memory enables the host to swiftly and effectively mount an immune response when re-infected by the same pathogen -- disease management strategies for wild vertebrates capitalize on antibody responses for disease diagnostics (e.g., serological assays) and prevention (e.g., vaccination).

While management strategies that use the adaptive immune response may be applicable to marine vertebrates (i.e., mammals and fish), invertebrates make up the majority of species diversity in the sea (Mather 2013). The ubiquitous lack of complex adaptive immunity in marine taxa prohibits utilization of some of the most effective disease management strategies available (McCallum et al. 2004), requiring alternative and/or novel management strategies for many marine disease emergencies.

The Water Medium

Due to the water medium, pathogen transmission is vastly different in terrestrial versus marine environments. Airborne pathogens are typically viable for minutes to hours and, at most, transported a few meters (e.g. Wells 1934, Olsen et al 2003, Booth 2005). Thus, pathogen transmission on land typically occurs through near-direct contact between hosts, indirect contact with **fomites** like soil and vegetation, or **vectors** such as mosquitoes. In contrast, marine pathogens can be viable in seawater from days to weeks (Hawley & Garver 2008, Oidtmann et al. 2018). Further, ocean currents enable transport over hundreds of miles (McCallum et al. 2003). Extended viability and long-distance transport may significantly increase the probability of pathogen exposure and complicates the ability for managers to contain marine pathogens.

On the other hand, the three-dimensional ocean can dilute pathogens as they spread, which may reduce pathogen exposure (Miller 2001). To overcome this, it seems logical that marine pathogens should utilize behavior, fomites, or vectors to ensure they reach a suitable host, just like their terrestrial counterparts. However, marine pathogens are typically transmitted as free-living (Ben Horin et al. 2015). There is some evidence that marine pathogens use suspended particulate matter as fomites and zooplankton as vectors (Frada et al., 2014, Kough et al. 2015, Kramer et al., 2016, Certner et al., 2017) but, to date, few marine vectors have been identified (Harvell et al., 2004). Overall, there is still much to learn about pathogen transmission in the ocean and, accordingly, how to modulate pathogen dynamics for marine disease management.

Pelagic Larval Phases

The availability of a three-dimensional ocean habitat, often replete with food and serving as a convenient mode of transport, has led to the evolution of **pelagic larval phases** for the majority of marine taxa in all phyla (Cowen & Sponaugle 2009). Adult organisms release gametes or propagules into the water column, where larvae develop and grow while floating or swimming from hours to months before metamorphosing into adults (Strathmann 1987). This **bipartite life history** can decouple local birth rates of young from death rates of adults, which results in complex and somewhat unpredictable population dynamics and, subsequently, disease dynamics (Williams & Hastings 2013). While this bipartite strategy is common in marine and some freshwater systems, it is relatively rare in terrestrial taxa, except plants and some insects.

The transport of larvae to new populations can be a tool or a hindrance to marine disease management. On one hand, this transport could enable offspring to escape infection hotspots, particularly if larva acquire **maternal immunity** (Little et al. 2003). Further, most organisms that have larvae produce prolifically (Carr et al. 2003) (e.g., Atlantic bluefin tuna can produce millions of eggs throughout the reproductive season (Medina 2020)). Advantageously, high reproductive output enables a local population to be repopulated if a viable source population exists nearby (Carr et al 2003), as well as increases the potential for survivors to adapt to disease (e.g., Schiebelht et al. 2018). On the other hand, if the pathogen remains in the population, the consistent recruitment of larvae may fuel outbreaks via repopulating the pool of susceptible hosts (Behringer, Silliman, Lafferty 2020). Additionally, larval vectors could increase pathogen distribution and persistence (Kough et al. 2015). Ultimately, the ubiquity of larval phases and the high population connectivity of most marine species may be both helpful and challenging when managing disease.

Sessile and Colonial Life Strategies

Within the animal kingdom, colonial and sessile life stages tend to be more common in marine environments (e.g. corals, sponges, bivalves) than on land (Costello and Chaudhary, 2017), at times making them more similar to terrestrial plants and fungi than animals. Consequently, behavioral strategies used by more mobile species, such as avoidance of sick individuals, are not employable by sessile organisms (Behringer et al. 2018). Limited movement and close proximity of sessile/colonial marine animals also means that density-dependent transmission can occur very quickly once a population is exposed, making it very hard to isolate individuals in the wild. However, it can enable capture, quarantine, and even captive breeding of these animals. Many colonial and sessile animals are also filter feeders that can collect and harbor rich assemblages of pathogenic microbes, offering a management tool unique to aquatic systems (Burge et al. 2016). Generally, the prevalence of colonial and sessile animals present distinctive disease management challenges and opportunities.

Climate Change and Disease Dynamics in the Sea

While climate change is occurring in both terrestrial and marine environments, the emergent environmental consequences differ. Organisms in both environments are experiencing warmer average temperatures, but ocean organisms are experiencing the additional effects of increasing hypoxia and ocean acidification. Across systems, elevated temperatures increase virulence, growth rates, reproductive window, and overwintering success of many pathogens (Harvell et al. 2002, Mordecai et al., 2019, Shields 2019). Additionally, heat stress in host organisms increases the amount of energy devoted to metabolic demands and respiration, leaving fewer resources for immunological function (Shields 2019). In the sea, ocean acidification and hypoxia further deplete host energy reserves and damage tissue, ultimately increasing susceptibility to infection (Hernroth et al., 2018, Shields 2019, Schwaner 2020). Importantly, these stressors often occur simultaneously, with consequences ultimately compounded (Gobler & Baumann 2016). These multiple stressors are especially threatening for sessile marine species that cannot escape their habitat when heat waves, acidic waters, or hypoxia events occur. Thus, immediate study of the effects of climate change on marine disease dynamics is critical.

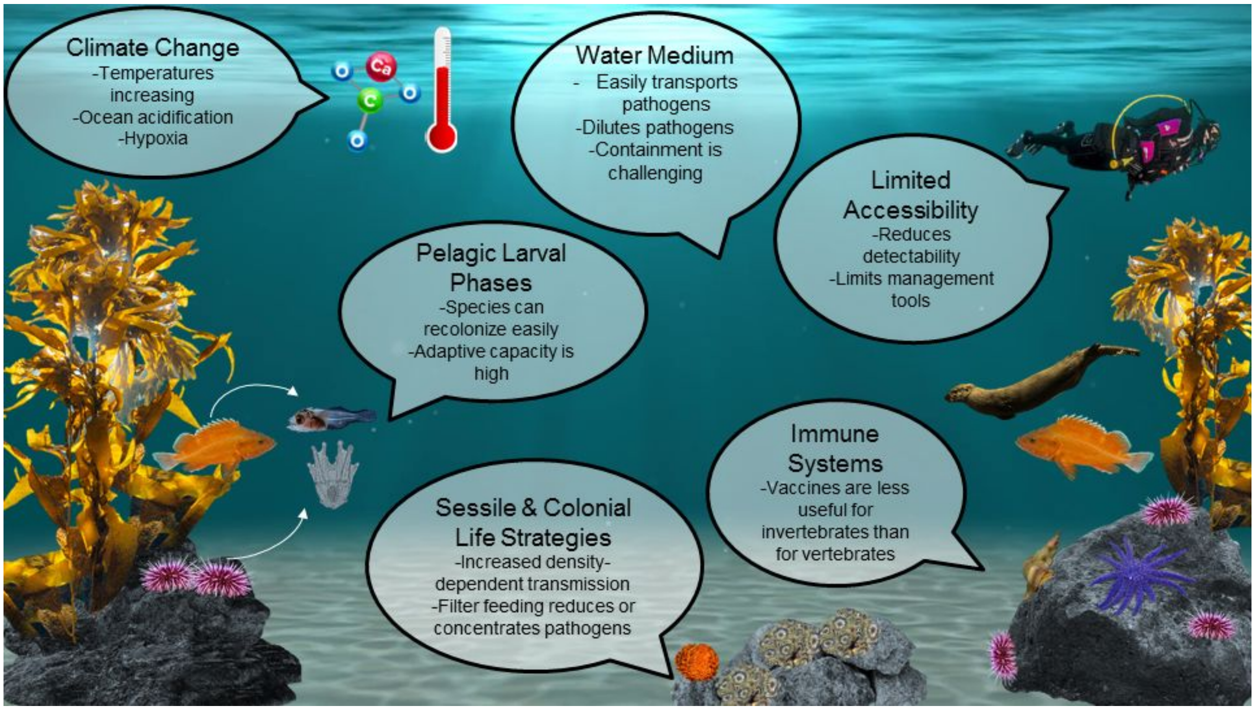

Figure 2. Various fundamental attributes of the marine environment and its inhabitants (as compared to terrestrial environments and its inhabitants) present both marine disease management challenges and opportunities.

Management Strategies for Marine Disease Emergencies

Intent and Scope of This Resource

The fundamental differences in life in the sea versus land have profound consequences for marine disease dynamics. As such, the utility of management strategies to mitigate marine wildlife diseases are often much different than they are on land. In this paper, we assess the application of disease management strategies routinely used in terrestrial systems to marine disease management. While we mainly focus on comparing terrestrial versus marine disease systems, we recognize that this dichotomy leaves out multiple important ecosystems, including freshwater and estuarine. Further, there are multiple taxa that can travel amongst ecosystems or inhabit transitional zones (e.g. salmon, sea birds). Thus, we utilize this dichotomy merely as an instructional tool. Our goal is not to detail a prescriptive manual for managing marine disease. Rather, we intend to identify which management tools are or are not typically useful in marine environments, to aid in the development of more successful marine management tools. For each management strategy, we assigned a score from 1 to 4, with 1 being not useful in most marine disease, 2 being useful in some marine disease systems (e.g. some taxa or circumstances), 3 being potentially useful in most marine systems with more research and/or resources, and 4 being useful in most marine disease systems (Figure 3). We group the strategies according to the timeframe during which they may be useful and the specificity to a given disease system, including: 1) Surveillance for Outbreaks, 2) Outbreak Response Strategies, 3) Targeted Recovery Strategies After a Host Decline, 4) Targeted Outbreak Prevention Strategies, and 5) General Outbreak Prevention Strategies (Figure 4). Since diseases can reoccur, these phases are inherently circular. In the final section, we make several recommendations for successful management of marine wildlife disease in the future.

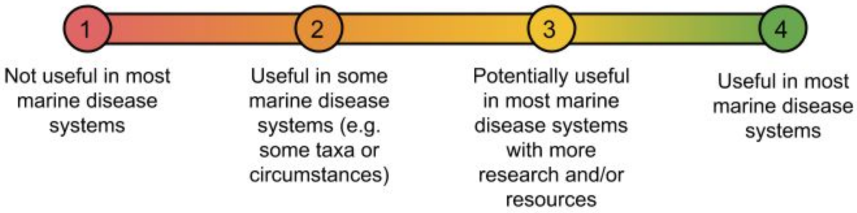

Figure 3. The scale used to classify a given management strategy according to its utility in managing marine disease emergencies. A high score of 4 (green) indicates that the strategy is useful in most marine disease systems, 3 (yellow) indicates it is potentially useful in most marine disease systems with more research and/or resources, 2 (orange) indicates it is useful in some marine disease systems depending on the taxon or circumstances, and 1 (red) indicates the strategy is not useful in most marine disease systems.

Figure 4. Summary of management strategies and their uses in marine disease emergencies. Management strategies are grouped by the broader management category in blue. The text color of a given strategy indicates its utility in managing marine disease emergencies. Green (score 4) indicates that the strategy is useful in most marine disease systems, yellow (score 3) indicates it is potentially useful in most marine disease systems with more research and/or resources, orange (score 2) indicates it is useful in some marine disease systems depending on the taxon or circumstances, and red (score 1) indicates the strategy is not useful in most marine disease systems.

Surveillance for Outbreaks

Monitor Host Populations (Score: 4)

Infectious disease surveillance in wild populations is the ongoing systematic collection, analysis, and interpretation of data to detect and monitor the status of diseases managed for mitigation (WHO 2006). Successful disease surveillance examples include: systems for detecting white-nose syndrome in bats, BSal in salamanders, bacterial and fungal disease in corals, white spot disease in crustaceans, multiple diseases in marine mammals, and many others (e.g., NABat 2018, Batrachochytrium salamandrivorans (Bsal) Surveillance, AIMS Long-term Monitoring, AQUAVETPLAN 2013, West Coast Marine Mammal Stranding Network 2020, Emergence 2020).

In all systems, **active surveillance** programs (i.e. surveilling for a particular disease, Sleeman, Brand and Wright 2012) are limited by high costs and complex logistics, and this is especially true in marine systems where it is typically more expensive and more challenging to take samples than on land. Tactics for overcoming these challenges includes sampling sentinel species (Halliday et al., 2007), filter feeders (Burge et al. 2016), or environmental DNA (Micheals et al., 2016, Sato et al. 2019). Further, since pathogens in the ocean are relatively undescribed compared to those on land, surveillance is limited by the availability of specific diagnostic tools (see below). Consequently, active surveillance requires using non-specific pathogen detection (e.g., biochemistry of innate immune markers (Glidden et al., 2018)) and discovery tools (e.g., high-throughput amplicon sequencing (Huang et al., 2019), metagenomics (Gu, Miller, & Chiu 2019)).

Universally, effective **passive surveillance** programs (i.e. studying animals found sick or dead, Sleeman, Brand and Wright 2012) are contingent upon a network of observers (e.g., Duncan et al., 2008), which again is likely more challenging in less-accessible marine systems. While there are some excellent examples of these programs for marine taxa or habitats (e.g. West Coast Marine Mammal Stranding Network 2020, LEO Network 2017, WHISPers), increasing connectivity among people or entities that study marine wildlife health, creating or augmenting reporting systems and databases to include marine organisms, and engaging public participation in surveillance would substantially increase the effectiveness of passive surveillance in marine systems.

Forecast Outbreaks (Score: 3)

Disease forecasting uses early warning systems that combine environmental and epidemiological data to predict if, when, and where outbreaks may occur (Maynard et. al 2016). Rapidly increasing marine environmental monitoring capacity (SeaTemperature.org, Trevathan et al., 2012, Piermattei et al., 2018) means that the utility of environmental indicators to predict disease has also increased. For example, temperature data have been used to predict coral epidemics and epizootic shell disease in lobsters (Caldwell et al., 2017, Maynard et al. 2015, 2016). However, for environmental indicators to be useful, a mechanistic understanding of how the environment influences disease dynamics is crucial (Dakos et al., 2015). Further, knowledge of an impending event does not immediately translate into tenable action. Thus, for both marine and terrestrial systems, early warning indicators are most effective when causal triggers are clear and when management responses include tools discussed elsewhere in this document.

Outbreak Response Strategies

Diagnostics (Score: 3)

Disease diagnostics is the procedure by which the causative agent of disease is characterized and identified in a host; developing diagnostics is well described in the Manual of Diagnostic Tests for Aquatic Animals by the World Organization for Animal Health (2017). Diagnostics are critical for tracking and mitigating a disease emergency, and the speed at which diagnostics are developed can result in a disease emergency being relatively containable (e.g. rapid diagnostic development for white-nose syndrome in bats (NABat 2018; Lorch et al. 2011)) or cause extreme population declines and even extinction (e.g. slow diagnostic development for chytridiomycosis in amphibians; Berger et al. 1998, Lips et al. 2016).

Many classic (gross observations, cell culture, microscopy, histopathology) and modern diagnostic tools (quantitative PCR, amplicon sequencing, metagenomics, analytical biochemistry) that are utilized in terrestrial settings are directly applicable to marine settings and have been used successfully (reviewed in Burge et al., 2016). For marine organisms that typically lack adaptive immunity, assays that detect the pathogen itself, rather than a specific host immune response, are especially useful for diagnostics. As stated previously, etiological agents of marine disease are relatively undocumented; as such, etoliogical agents are challenging to identify. For example, the 2013 North American West Coast sea star wasting syndrome outbreak is likely the largest marine epizootic on record (Hewson et al. 2014), but the cause is still unclear and no diagnostic test exists (Hewson et al. 2018, 2019), which may hinder management action (Gravem et al. 2020). If advancement in our ability to diagnose marine disease does not keep pace with the increasing frequency of EIDs in many marine taxa (Tracy et al. 2019), future marine disease emergencies will likely face similar management challenges.

Quarantine (Score: 2)

Quarantine involves isolating infected individuals for a period of time until they are not infectious or isolating healthy animals until their reintroduction poses little risk of infection. It can be employed quickly and without extensive knowledge of a disease process. For wildlife, it can be successful in terrestrial, freshwater, and marine disease outbreaks (e.g. frogs during chytridiomycosis outbreaks; (Woodhams et al. 2011) and isolation of fishes carrying viral hemorrhagic septicemia (Håstein et al., 1999)). However, quarantine is not usually a viable option for marine disease emergencies (Burge et al., 2014) because it requires immediately-available seawater facilities to house organisms, and this can be logistically difficult, prohibitively expensive, or impossible (e.g. for larger animals like sharks). Select government facilities can effectively and rapidly quarantine marine organisms, especially species with economic value (e.g. USGS National Wildlife Health Center Honolulu Field Station, USGS Marrowstone Marine Field Station). Zoos and aquariums also have facilities and actively research marine disease in wild and captive organisms (e.g. Ocean Wise Research at Vancouver Aquarium). To make quarantine a viable option for marine disease emergencies, further infrastructure and expanded partnerships with existing institutions are necessary. Even then, quarantine may not be a viable outbreak containment strategy, except for diseases that are restricted to select individuals, individuals that are easily captured and held in captivity, and species where the benefits of quarantine outweigh the costs.

Antimicrobials (Score: 1)

Antimicrobials are used extensively in human and veterinary medicine to combat disease (Schwarz et al. 2001; Woods and Knauer 2010; Rohayem et al. 2010; Foy and Trepanier 2010). Similar to terrestrial wildlife disease, the use of antimicrobials in the marine environment may be contraindicated because of challenges associated with drug distribution and delivery in large open water systems. Only localized distribution in small, accessible marine populations is likely to prove effective (e.g., Stony Coral Tissue Disease in small coral populations; Neely et al., 2019). Furthermore, antibiotics are being replaced by preventative measures, such as probiotics, due to an increasing awareness of the importance of the **microbiome** and concerns of antibiotic resistance (Cabello et al. 2013; Bachere 2003), which has already been documented in marine mammal species (Wallace et al. 2013; Schaefer et al. 2009) and sea turtles (Foti et al. 2009).

Epidemiological Models (Score: 4)

Epidemiological models typically use a suite of mathematical tools to track the temporal and spatial distribution of infected hosts and disease induced mortality. In response to disease emergencies, these models are generally used to understand and predict outbreak and/or epidemic outcomes as well as evaluate efficacy of intervention (e.g., Childs et al. 2020). Epidemiological models are one of the most widely used tools in terrestrial wildlife disease management (e.g., Beeton & McCallum 2011, Craig et al. 2014, Viana et al., 2015, Silk et al., 2019), and have also been developed for multiple marine organisms, including corals, bivalves, seals, and sea stars (e.g. Sokolow et al., 2009, Powell and Hofmann 2015, Robinson et al., 2018, Aalto et al. 2020; reviewed by Ben-Horin et al. 2020). In marine systems, application of epidemiological models has been hindered by lack of understanding of pathogen transmission and infection rate in the ocean medium, and therefore use of models in marine disease management is limited (Powell and Hofmann 2015, Shore & Caldwell 2019). However, similarly to terrestrial systems, the use of physics to map pathogen spread (e.g., Aalto et al., 2020, Pande et al., 2015, Ferreira et al., 2014) as well as incorporating within-host processes and among host heterogeneity (e.g., Bidegain et al. 2017), environmental conditions (e.g., Lu et al. 2020, Zvuloni et al., 2015), and host community composition (e.g., Bidegain et al., 2016, Bidegain et al. 2017) have substantially advanced marine disease models. Epidemiological models are best used when output can be applied to intervention. Overall, epidemiological models are a powerful tool and their application to marine disease management warrants significant attention.

Targeted Recovery Strategies After a Host Decline

Translocations (Score: 4)

Translocation involves taking individuals from larger or healthier populations and moving them to smaller populations that have been severely reduced by disease (e.g., the Puaiohi Soorare, Switzer et al. 2014). This strategy can be used successfully in marine systems, provided there is enough understanding of epidemiology and natural history to ensure the translocated animals will stay in the area, remain healthy, and increase the breeding pool. However, when organisms are highly mobile or live in groups with complex social structures, translocations can fail (e.g. sea otters; Lafferty & Tinker 2014, Jameson et al. 1982). Further, careful maintenance of genetic diversity to minimize bottleneck effects in small populations is key (Willoughby et al. 2015). Additional considerations after disease include avoiding introducing diseased organisms to the target area and avoiding moving healthy organisms to an area containing diseases (Young et al. 2017). Translocation may be especially tenable in marine systems because many invertebrates and fishes have high numbers of offspring and little or no maternal care, meaning that sufficient numbers may be rapidly obtained and that maintenance of social or family groups is less important. Overall, translocations are a useful tool for marine wildlife managers to bolster vulnerable populations, and can be especially effective when combined with other direct management strategies like captive breeding, diagnostics, and habitat restoration.

Captive Breeding and Reintroduction (Score: 3)

Captive breeding and reintroduction involves the maintenance of adult breeding populations in captivity, with the goal of producing healthy, genetically-diverse offspring that can eventually be successfully reintroduced to the wild. Similar to translocating organisms, this method can help recover populations that have been severely reduced by disease (e.g., blackfooted ferret; Thorne and Williams 1988), or are experiencing low genetic diversity after disease, provided that careful management styles are employed (i.e breeding different populations, introducing new individuals, and using multiple-paternity (Grogan et al. 2017, Williams and Hoffman 2009, Wacker et al. 2019, Albert et al. 2014)). Also, in cases where the population decline is so severe that few remain in the wild, captive breeding may be the only way to maintain the population (Snyder et al. 1996, *The ICUN policy statement on captive breeding, 1987*).

Captive breeding has been used successfully for marine mammals (Robeck et al. 2009) and fish (Fraser 2008), and has the potential to be used for marine invertebrates (e.g. native oysters; (Wasson et al. 2020)). However, like quarantine, captively breeding marine organisms requires substantial infrastructure, expertise, and may not be feasible for all organisms. The bipartite life history of many marine species complicates the expertise and resource needs, but abundant offspring common to marine organisms means that the initial investment can provide ample individuals for the reintroduction phase. While captive breeding of marine wildlife for reintroduction is not common, the substantial advances in commercial aquaculture mean partnerships with these groups is a strategy with very high potential for effective disease management.

Reintroducing captively bred animals to the wild has many of the same limitations and considerations mentioned for translocations (i.e. risk of failure, need to maintain genetic diversity, avoiding disease introduction). Captive breeding can also have deleterious effects on an organism's reproductive fitness in the wild, and can even harm wild populations through genetic mixing. But these detrimental effects can be minimized with proper procedures (Williams and Hoffman 2009). Further, captive breeding programs can be utilized to concertedly increase the **adaptive capacity** of a population, including selective breeding for resistance to pathogens, applying prophylactic treatments to help prevent disease spread (see natural therapeutics), and **bioaugmentation** (Grant et al. 2016; Harris et al. 2009). Ultimately, captive breeding and reintroduction is a key tool for marine wildlife managers, but more investment in infrastructure and research for captive breeding of marine organisms is needed before this is a scalable option for most species.

Targeted Habitat Restoration (Score: 2)

Targeted habitat restoration, which involves renewing or restoring degraded ecosystems, has been generally used to aid recovery of species that have suffered unnatural population declines (e.g. Pacific salmonids in the Columbia River Basin (Barnas et. al. 2015), birds in woodlands of Victoria, Australia (Vesk et al 2015)). Critical coastal marine ecosystems such as mangroves, seagrass meadows, oyster reefs, and kelp forests have been successfully restored (Hashim et al. 2010, Orth et al. 2012, Lipcius and Burke 2018, Layton et al. 2020). As such, restoring marine habitats could be a viable strategy for aiding species recovery following a disease outbreak.

Similar to terrestrial environments, targeted restoration in marine systems benefits from strategically identifying optimal locations (Giest and Hawkins, 2016) and must have a source population nearby to populate the restored habitat. Additionally, habitat restoration may protect a site from new outbreaks (Sokolow et al 2019), but does not typically protect a species from disease re-emergence if the pathogen has not been extirpated from the area. The ubiquity of larval stages in the marine environment may be either a challenge or an advantage for a successful habitat restoration project; recruitment of larvae is often sporadic and unpredictable, but high population connectivity means that larvae may easily settle in the newly restored habitat. One way to circumvent this uncertainty is to pair habitat restoration with translocation or captive breeding and reintroduction. Because of the relative inaccessibility of marine compared to terrestrial environments, marine habitat restoration can be logistically intensive and expensive, especially on a large scale (e.g., kelp forest restoration: Eger et al., 2020). Further, more research is needed to link restoration to effective disease management.

Reduce Lethal Take (Score: 2)

Reducing lethal take by limiting human harvest of organisms can speed species recovery from a disease. This method is used widely to recover populations in both marine and terrestrial systems and involves limits on activities like fishing, hunting, or harvesting. Having a legal licensing system can have the additional benefit of raising funds for further management actions and recruiting fishermen to help cull target species. In marine and terrestrial environments, reducing take is only useful if the species is harvested directly or as bycatch, and it does not usually ameliorate disease itself. Overall, reducing lethal take is a useful targeted recovery strategy if take is hindering population recovery from disease. However, in disease systems with high density-dependent transmission or overpopulation, allowing lethal take may slow parasite/pathogen transmission by decreasing host density (see *Culling*) (McCallum, Gerber, & Jani 2005, Wood, Lafferty, & Micheli 2010).

Endangered Species Lists (Score: 4)

Threatened or endangered species lists are used to protect or restore species and the ecosystems they depend upon. Listing has been used to help recover both marine and terrestrial taxa after disease has caused severe declines in populations, and a major driver of listing is to increase visibility of an issue (Smith et al. 2006). Lists like the International Union for the Conservation of Nature (IUCN) Red List can increase public awareness and help generate funding sources, and identify promising management actions (e.g. Gravem et al. 2020). When tied to legislation (e.g. the United States Endangered Species Act), listing can criminalize lethal take (see *Reduce Lethal Take*) so listing may be useful if lethal take or other direct human actions are a major threat to recovery. However, listing does not influence disease dynamics, is often a slow process, and is sometimes politically fraught. Listing can even hinder recovery because it can limit basic research done by scientists and conservationists (Miller et al. 1994). Overall, non-legally binding listing is useful for all species affected by disease (e.g. IUCN assessment for sunflower sea stars; Gravem et al. in press), and legally-binding listing is a useful “failsafe” option when humans and disease simultaneously threaten a species with extinction (e.g. ESA listing for Black abalone; Balsiger 2009).

Targeted Outbreak Prevention Strategies

Vaccines (Score: 1)

Vaccines expose organisms to a deactivated, live attenuated, or recombinant **antigen**, which elicits an antibody response in the host’s adaptive immune system, thus enabling a rapid and effective defense against subsequent infection or disease (Sallusto et al. 2010). Vaccines are used for terrestrial wildlife (reviewed in Langwig et al. 2015), in aquaculture of many fishes (reviewed in Sommerset et al. 2005), and in marine mammals (Robinson et al. 2018). However, crucial prerequisites must be met before vaccinations can be a viable option. First, invertebrates constitute a huge portion of sea life, and they lack an adaptive immune system, which typically makes vaccination unsuitable (Roch 1999; but see vaccines for White Spot Syndrome Virus in shrimp: Syed Musthaq and Kwang, 2014). Second, vaccines are often delivered using injections, sometimes with multiple doses required (Sharma and Hinds, 2012), making ease of access to organisms crucial. Third, vaccines are expensive to develop, and with the exception of charismatic megafauna, funding to develop vaccines for wildlife is limited. Finally, effective vaccination campaigns in wildlife confer **herd immunity** (Fine 1993) so, given the logistics of administration, vaccination is generally only effective in small populations (e.g. monk seals; Robinson et al. 2018). Collectively, vaccines are primarily useful in marine systems for vertebrates that have small, easy to access populations.

Natural Therapeutics (Score: 1)

In wild systems, hosts are typically simultaneously infected with multiple commensal and parasitic organisms that comprise the **microbiome** and **parasitome.** The composition and stability of these organisms is inherent to disease resistance and tolerance across all taxa (Kueneman et al., 2016, Hoyt et al., 2019, Pollock et al. 2019, Carthey et al 2020, Hoarau et al., 2020). Within-host communities can be manipulated to prevent or treat disease via three tools: **phage therapy**, **probiotics,** and **co-infection** (Inal et al. 2003, Newaj-Fyzul et al. 2014, Vaumourin et al., 2015, Rynkiewicz et al. 2015).

In marine systems, phage therapy (reviewed by Doss et al. 2017) has been used to reduce withering foot syndrome in black abalone (Friedman et al. 2014). Probiotics are widely used to improve health and prevent disease in aquacultured organisms (reviewed by Martinez Cruz et al., 2012), and probiotic inoculation has successfully prevented disease in wild coral (Peixoto et al. 2017). Importantly, disease may arise from a complex shift in the microbiome, as opposed to infection by a single agent (Mera & Bourne 2018); as such, in absence of applying probiotics, the microbiome should be studied to elucidate disease-causing assemblages. In a direct preventative management application, co-infection with flukes has been shown to reduce bacterial virulence in aquaculture salmonids (Karvonen, Fenton, Sunberg 2019). However, co-infection is difficult to employ and has not been used as a preventative measure in marine wildlife, co-infection commonly affects the efficacy and benefit of surveillance and response tools in terrestrial and marine systems (e.g., Stokes & Burreson 2001, Gibson et al. 2011, Beechler et al., 2015, Ezenwa & Jolles 2015, Figueroa et al 2017), thus considerations of co-infection in management remain important.

Due to similar administration challenges as antimicrobials and vaccines, natural therapeutics are more tenable for easy to access, small populations. Further, these tools necessitate specific knowledge of the infectious agent, the natural therapeutic that benefits the host, and the ability to produce the therapeutic (e.g., culturing a co-infecting parasite). On the other hand, developing some natural therapeutics, particularly probiotics, may be less costly and time consuming than developing vaccines or synthetic antimicrobials and can be effective in hosts that lack adaptive immunity. Overall, our understanding of healthy baseline microbiomes and parasitomes is rudimentary, and more research on this topic is necessary before natural therapeutics can be widely employed for marine disease management.

Culling (Score: 1)

Targeted culling of infected hosts can prevent spread of pathogens across populations and is commonly used in terrestrial systems to slow disease transmission (Daszak et al. 2000). In marine systems, culling has been employed to prevent spread of viral haemorrhagic septicaemia (VHS) in hatchery salmon to wild populations (Amos et al 1998) and been proposed to reduced spread of withering syndrome in aquacultured red abalone (Ben-Horin et al., 2016). Disease management can also be focused on culling of groups or species that act as **reservoir hosts** (e.g., African buffalo culled to control bovine tuberculosis; le Roex et al., 2016). Culling reservoir hosts may be effective in marine systems, particularly if they are easy to access and capture (e.g. filter-feeders bivalves that accumulate but don't deactivate pathogens; Meyers 1984; Molloy et al. 2013, Burge et al. 2016). Culling may alter eco-evolutionary trajectories by selecting for more persistent/less virulent strains if only highly-symptomatic individuals are culled (Bolzoni and Leo 2013), but should be exercised with caution, since it can often have unintended consequences (e.g., Biebly et al., 2014). To make culling of both infected individuals and reservoir hosts a useful management strategy, there must be substantial foundational knowledge of diagnostics, transmission, the ecological effects of a particular disease system, diagnostic testing must be available, and widespread removal of infected individuals or reservoir species must be economically and logistically feasible. As such, culling is likely a useful management tool in only a narrow set of circumstances.

Biological Control (Score: 1)

Biological control, a common practice in terrestrial and freshwater ecosystems, is the introduction of a new species to an environment for the purpose of suppressing another (e.g., Cuda et al. 2008, van Wilgen et al. 2012), including suppressing a pathogen, parasite, or vector that causes disease (Scholte et al. 2004, Hoddle 2004, Iturbe-Ormaetxe et al. 2011). However, many examples exist of biological control having surprising and severe negative consequences to non-target populations or to the environment (e.g. use of rabbit haemorrhagic disease to control rabbits has led to outbreaks elsewhere Forrester et al. 2006, Saunders et al. 2009). In marine systems, biological control is not commonly utilized (Lafferty and Kuris 1996, Atalah et al. 2015). There are several possible reasons, including that vectors are apparently less common in the sea making vector control less useful (Harvell et al., 2004), that marine ecosystems have fluid ecological boundaries making targeted control less feasible (Lafferty and Kuris 1996), and that marine food webs are typically very complex making predicted biological control outcomes uncertain (Simberloff and Stiling 1996). Thus, the utility of biological control as a management strategy is unclear, and any undertaking should be extremely well-vetted before implementation.

General Outbreak Prevention Strategies

Increase Biosecurity (Score: 3)

Biosecurity is a set of measures to prevent the spread and/or introductions of harmful organisms into an environment. Many of the same biosecurity measures used in terrestrial and freshwater management can be implemented in marine ecosystems through policy, legislation, and informational campaigns. Biosecurity has been a valuable tool in preventing the spread of invasive organisms and pathogens (e.g., enforced border management of overseas goods in New Zealand (Champion, 2018) and firewood restrictions for fungal pathogens (Diss-Torrance et al. 2018)). In marine systems, biosecurity measures may be useful to prevent disease spread through the aquarium trade (Whittington and Chong 2007), wastewater runoff (Miller et al. 2002), and ballast water (water held in tanks and cargo ships and released in harbors; Aguirre-Macedo et al. 2008). Although the role of the aquarium trade in disease spread is not clear, anthozoans (corals and sea anemones) show the third highest number of shipments in the CITES (Convention on International Trade in Endangered Species) Wild Fauna and Flora Database and have been severely impacted by infectious disease in the past decade, so there is high potential for spread. The trade of endangered species is regulated by CITES, which could incorporate provisions for reducing disease spread to regulate introduction of novel pathogens (Smith et al. 2017). Similarly, the role of ballast water in spreading disease is unclear, but multiple invasive species have been introduced in this manner (Carlton, 1985), so it is a likely route of disease introductions. Thus, restrictions on ballast water discharge are valuable in maintaining marine health and biosecurity, but they will require international cooperation and coordination (e.g., the US coast guard prohibiting dumping untreated ballast water in U.S. waters (Standards for Living Organisms in Ships' Ballast Water Discharged in US Waters)).

Reduce aquaculture spillover (Score: 2)

With increases in aquaculture production worldwide, there are connected increased instances of pathogens "spilling over" from aquaculture farms to adjacent natural populations (Krkošek 2017). To control this, aquaculturists have implemented measures to decrease transmission by vaccinating aquaculture organisms (e.g. salmon) and sterilizing outflow water with UV light, electrochlorination, or **biological filtering** (Sung & McRae 2011; See *Natural Ecosystem Filters*). These are effective tools that are feasible and can control disease spread in most land-based aquaculture. However, many aquaculture farms are in coastal or open water systems (e.g. netted pens in protected bays or estuaries) where there is uncontrolled exchange of water and pathogens between the natural environment and the facilities, which often house non-native organisms and novel pathogens (Naylor 2006, Klinger et al. 2017). Similarly to land-based systems, management actions that include preventative treatments like vaccination (primarily for fish), antimicrobials, natural therapeutics, or culling (see above) may be useful for preventing spillover from open water aquaculture facilities to wild systems. Additionally, co-culturing aquaculture species with filter-feeders (see *Natural Ecosystem Filters*) could reduce spillover (Stabili et al 2010, Granada et al 2016, Buck et al. 2018).

Natural Ecosystem Filters (Score: 3)

As particulates, and/or pathogens move within the water medium, there is potential for harnessing the natural filtering processes of ecosystems such as mangroves, seagrass beds, and bivalve reefs to reduce pathogen loads, a process termed **biological filtering**, or biofiltering (Burge et al 2016). Biofiltering is not a viable management tool in terrestrial ecosystems, but presents unique opportunities for freshwater and marine disease management. Biofiltering has been used extensively in freshwater ecosystems (reviewed by Faust et al 2009, Vaughn and Hoellein 2018) and to treat aquaculture effluents (Stabili et al 2010, Granada et al 2016, Buck et al. 2018). Biofiltering systems can be passive or active, and can involve protecting or restoring biofiltering habitats or species. The utility and scalability of biofiltering as a management strategy depends on the filtering ecosystem or species and the disease.

Passive filtering marine ecosystems include mangroves, seagrass beds, wetlands, and salt marshes. Mangroves have been shown to be effective biofilters for human sewage and other pollutants (Yang et al., 2008), and seagrass beds have been shown to reduce levels of pathogenic bacteria due via seagrass-associated biofilms, natural biocides, and associated filter-feeders (Lamb et al 2017). As a management strategy, passive filtering has low potential for harm and a high potential to reduce a diversity of diseases, especially when the pathogen source is “upstream” of the affected host population.

In marine ecosystems, active filter-feeding taxa such as bivalves, sponges, and polychaetes filter particles and pathogens of various sizes from the water column. Pathogens can accumulate in host tissues or the sediment (through pseudofeces), where the pathogen can either remain infectious or is deactivated (Burge et al 2016). Thus, filter-feeding of pathogens can result in either the spread, or the decline of disease. In cases where pathogens are deactivated, protection or restoration of active filter feeders is a broadly useful and feasible management strategy. This strategy has not yet been widely implemented for mitigating marine disease transmission in open systems, but shows promise (Faust et al 2009, reviewed in Burge et al 2016).

Biodiversity and Habitat Conservation (Score: 3)

Biodiversity conservation aims to preserve the variety of species necessary to maintain naturally functioning ecosystems, and habitat conservation accomplishes these goals by protecting the habitats in which those species live. Habitat conservation may also protect wildlife from anthropogenic disturbances that increase disease susceptibility and pathogen exposure (Shapiro et al 2010, Lamb et al. 2015, Lamb et al. 2017). When pathogens have the capacity to infect multiple host species, biodiversity conservation may increase the density of **non-competent host** species that prevent or slow disease transmission (Venesky et al. 2014, reviewed in Young et al. 2017, Rohr et al. 2020). Biodiversity conservation may slow disease transmission by supporting populations that consume pathogens (e.g., filter feeders (see *Natural Ecosystem Filters*)) and/or reservoir hosts and vectors. In marine systems, **Marine Protected Areas** (MPAs) are a major tool for preventing loss of biodiversity from fishing or habitat degradation. The relationship between biodiversity, habitat conservation and disease is underexplored in the ocean, but if there is a positive relationship between biodiversity, habitat health, and disease outcomes, then MPAs may be useful tools for marine disease management. However, biodiversity may amplify disease transmission (Young et al. 2017, Rohr et al. 2020) and parasite prevalence increased in some marine taxa in Chilean MPAs (Wood et al., 2010), so the marine biodiversity-disease relationship should be carefully considered. In addition to promoting biodiversity and providing protected habitat, MPAs may enable host populations to recover from disease more quickly by alleviating human-associated mortality (Groner et al. 2016) (see *Reduce Lethal Take)*, promoting genetic diversity (Blasiak et al. 2020), and providing a source population for nearby areas affected by disease (Carr et al 2003). Importantly, while MPAs may be a useful tool in reducing marine disease or aiding recovery, they cannot directly mitigate disease transmission nor the multiple anthropogenic stressors (warming, ocean acidification, pollution) that can trigger disease (Lamb et al. 2016).

Recommendations

Our evaluation of the challenges for managing marine disease emergencies reveals multiple pathways forward, and we outline our six major recommendations below. The recommendations are meant to provide guidance for scientists, managers, and funders to be better prepared for the expected increases in the frequency and severity of marine disease emergencies in the future.

Increase Research on Marine Disease Systems

Compared to terrestrial disease systems, the funding landscape for marine wildlife disease studies does not match the need, and an increase in basic and applied science research in these systems is critical. Consequently, there is a general dearth of knowledge of marine disease systems compared to terrestrial disease systems. Multiple initiatives have been undertaken in the last decade to increase this knowledge base, including an NSF-supported Research Coordination Network (RCN) on the Ecology and Evolution of Infectious Disease in Marine Systems, a resulting special issue in the Philosophical Transactions of the Royal Society B: Biological Sciences (Issue 371, 2015) on Marine Disease, the recent inclusion (Nov 2020) of marine systems Ecology and Evolution of Infectious Diseases (EEID) NSF grants, and the recent publication of a Marine Disease Ecology textbook (Behringer et. al 2020). To better monitor and manage emerging marine disease and ideally prevent or mitigate disease emergencies, we need to better define a baseline distribution of pathogens and microbes across host species, environmental gradients, and time. Improved funding for basic marine disease ecology, advancement of molecular tools (Titcomb et al. 2019), and development of user-friendly cutting edge models (e.g. Ovaskainen et al. 2017) should enable scientists to more accurately construct this baseline subsequently enabling use of the management tools included in *Surveillance for Outbreaks* (e.g. *monitor host populations*), *Outbreak Response Strategies* (e.g., *diagnostics*), and *Targeted Outbreak Prevention Strategies* (e.g., *natural therapeutics*) sections highlighted above.

Form Marine Disease Monitoring and Response Networks

When disease outbreaks occur in wild marine species, they are often first noticed by chance as scientists or members of the public report increasing abnormalities and deaths. As an emergency becomes apparent, academics, state, and federal managers must find time and resources in their already overburdened schedules and budgets to “squeeze in” an appropriate response. This can easily lead to missed detection of disease emergencies, insufficient response times, and lost opportunities to both understand and effectively respond to marine disease emergencies. For example, the recent sea star wasting epizootic was so rapid that the scientific community was unable to respond quickly enough to identify the disease agent (Hewson et al. 2018).

To enable timely detection and response to marine disease emergencies, infrastructure must be in place before an emergency begins. For example, the marine mammals Unusual Mortality Events (UME) working group was formed by NOAA Fisheries under the Marine Mammal Protection Act https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-unusual-mortality-events. Their Marine Mammal Stranding Network detects, responds to, and identifies the cause of mortalities -- an excellent model that should be expanded to more marine wildlife taxa. The recently formed the PRIMED Network (Primary Responders in Marine Emergent Disease, https://primed-osu.weebly.com/) covers a wide range of wildlife taxa with the goal of increased disease surveillance and responsiveness to marine disease emergencies on the North American West Coast. We believe this type of network is crucial for effectively detecting and responding to marine disease outbreaks. However, clear long-term funding pathways for this and other potential networks is not clear. We recommend that state and federal agencies incorporate marine wildlife disease monitoring and response initiatives into their purviews. Federal-level agency programs like the USGS National Wildlife Health Center or NOAA Fisheries are well-situated to sustain monitoring (e.g., *monitor host populations*: active, sentinel surveillance) and response programs for a wider range of marine wildlife and to create the infrastructure (e.g. quarantine, diagnostic, and captive rearing facilities) necessary to manage marine disease emergencies. For example, diagnostic approaches have already been developed for many marine diseases that affect aquacultured or fished species (*Manual of Diagnostic Tests for Aquatic Animals, 2017*) and a similar approach could be undertaken for marine wildlife.

Enact Policy that Addresses Marine Wildlife Disease

A major pathway to increased research on marine disease systems and toward forming monitoring and response networks is through legislation. However, there is currently no enacted legislation in the US that addresses wildlife disease emergencies for either terrestrial or marine organisms. Wildlife population health is an underlying concern of multiple state and federal agencies and the time-sensitive nature of disease emergencies has inspired multiple legislative proposals, but none have been successful. Examples include the Marine Disease Emergency Act of 2015 introduced in response to SSWS by Representative Dennis Heck of Washington (H.R. 936, Heck et al. 2015), the Wildlife Disease Emergency Act of 2018 introduced by Representative Carol Shea-Porter (H.R. 7005, Shea-Porter et al. 2018), and the Global Wildlife Health and Pandemic Prevention Act of 2020 introduced by Senator Christopher Coons of Delaware (S.3759, Coons and Graham 2020). This type of legislation would increase our capacity to identify and declare wildlife disease emergencies and to coordinate rapid responses, with potential benefits to the economy and human health. We recommend that continued efforts be undertaken to achieve the goals outlined in these pieces of legislation.

Develop Marine Veterinary Medicine Programs in the US

Another pathway to increased research on marine disease systems and toward forming monitoring and response networks is through an increase in marine wildlife veterinary experts.

However, there are currently no American Veterinary Medical Association-accredited veterinary colleges that have a Doctor of Veterinary Medicine (DVM) program with extensive training and specialization in aquatic and/or marine wildlife medicine, and programs with marine components focus primarily on marine mammals. Learning opportunities are sparse and students often have to search outside the program to gain training, often paying out of pocket. Marine-focused internships and residency programs for veterinarians are similarly few in number. Further, the US is facing a growing shortage of veterinarians, and we may not have the necessary veterinarian workforce to control pandemic and large-scale outbreaks of disease (USGAO 2009). Many of the issues above are outlined in the Wildlife VET Act 2019 by Representative Alcee Hastings of Florida (H.R. 2099, Hastings et al. 2019), which was not passed. The act recommends expanding programs and curricula for wildlife medicine, incentives to study and practice wildlife veterinary medicine and increased government positions for wildlife veterinarians. We recommend that these actions be adopted and stress that marine wildlife be explicitly included in these efforts. Adopting this recommendation would certainly lead to improved capacity for nearly all management strategies described in the *Outbreak Response Strategies* and *Targeted Outbreak Prevention Strategies* we outline above.

Improve Marine Ecosystem Health

Current funding for disease management at state and federal levels is typically dominated by only organisms that we fish, animals with feathers or fur, or those that have other economic value. While this is logical, these “valuable” organisms do not exist in a vacuum, and they fundamentally depend on broader ecosystem health for survival. Furthermore, as our own health as humans is tied to ecosystem health, we recommend holistic approaches to disease management that are focused on entire ecosystems rather than isolated target species. This is exemplified by the OneHealth Initiative for the Center for Disease Control (Centers for Disease Control and Prevention, 2020), which aims to achieve optimal health outcomes by recognizing the interconnection between people, animals, plants, and their shared environment. We emphasize that marine ecosystem health is similarly important to humans as terrestrial ecosystem health because a huge proportion of our global population relies on marine systems as their primary food source (FAO 2020). An increasingly popular and effective approach for increasing marine ecosystem health is to designate marine protected areas that preserve biodiversity and conserve habitat. Additional management strategies that also increase ecosystem health include *increasing biosecurity*, utilizing *natural ecosystem filters*, and *habitat restoration*.

Understand the Link Between Climate Change and Disease

Climate change is the greatest threat to both human and wildlife health and is expected to cause a marked increase in wildlife disease emergencies. While addressing climate change itself is well beyond the scope of actionable management strategies it is one of the most prominent threats, and ameliorating it is one of the most long term goals for improving marine wildlife health. Over the short term, we recommend prioritizing research that improves the understanding of the effects of climate on host-pathogen relationships in marine ecosystems.

For example, explicitly incorporating climate change-related stressors in epidemiological models of disease transmission or in models that forecast outbreaks is of high importance. Further, long-term ecological studies on consequences of climate change on marine disease systems, at community and ecosystem scales, are critical. These approaches are useful for understanding the interplay between climate change and disease (Altizer et al. 2013).

Conclusion

The emerging conclusion of our synthesis is that we should move towards active management of marine wildlife. Active management of terrestrial wildlife species has been practiced for over a century (Leopold 1987, Bolen and Robinson 2003). In marine systems, the will to embrace these active management practices is more modest and is typically focused on managing commercial and recreational fisheries. For other wildlife, we have been more inclined to adopt geographically specific, ecosystem level management such as the creation of Marine Protected Areas (Lubchenco and Grorud-Colvert 2015). Recently, traditionally terrestrial targeted management and rehabilitation efforts have been slowly “moving seaward” into estuarine ecosystems, mangroves and coral reefs (Barbier et al. 2011). But the considerable efforts that managers regularly undertake for terrestrial wildlife, such as wolves in Yellowstone or condors in California, are rarely considered for threatened marine species (exception: sea otter reintroduction, Jameson 1982). In the event of a marine wildlife species declines, the types of strategies we outline above like *translocations*, *captive breeding and reintroductions*, and *targeted habitat restoration* may become crucial in marine systems, regardless of whether the declines are caused by disease. Adopting active management may be especially pressing as we are witnessing the collapse of entire coral reefs ecosystems (Hughes et al. 2018) and the outbreaks of marine epizootics on a global scale (Groner et al. 2016, Gravem et al. 2020).

We recommend that marine scientists and managers begin considering a more proactive rather than reactive approach to marine disease management to avoid situations where species are critically endangered before we begin to act. This approach will require a collaborative effort across academic institutions, federal agencies, and nonprofits and require people with expertise across marine sciences, disease ecology, and veterinary medicine. We encourage broad collaboration, including people who have successfully mitigated wildlife disease in terrestrial and aquatic systems. We look forward to a future where we have addressed the basic knowledge gaps of marine disease ecology and have employed multiple strategies listed throughout this synthesis.

Box 1.
Draft of definitions box- all words in bold in text.

Active Surveillance: A proactive process of surveying for a particular disease, usually ongoing (Sleeman, Brand and Wright 2012).

Adaptive Capacity: The capacity of a species or its populations to cope with or respond to a given change through genetic diversity and potential for evolutionary adaptation via natural selection.

Adaptive Immunity: Develops in response to specific features of the pathogen, creates immunological "memory" in case of future exposure to the same pathogen.

Antibodies: Proteins produced in response to and counteracting an antigen by directly or indirectly neutralizing their target; antibodies form a critical part of immunological memory and can rapidly increase in concentration upon a host's second exposure to a pathogen.

Antigen: A foreign substance which induces an immune response, especially the production of antibodies.

Antimicrobials: Drugs used to treat infection: antibiotics, antiparasitics, antivirals, and antifungals.

Bioaugmentation: Bioaugmentation is the inoculation of cultured microbial organisms into a host to increase adaptive capacity.

Biological Filtering: Use of filtering species or ecosystems to remove particulate or pathogens from the water column.

Bipartite Life History: Organisms that have two distinct forms in their life cycle. For marine invertebrates there is the pelagic larval stage and the sessile adult stage.

Co-infection: The occurrence of at least two genetically different infectious agents in the same host, can be defined as simultaneous infection, mixed infection, multiple infections, concomitant infection, concurrent infection, poly infection, polyparasitism, and multiple parasitisms (Hoarau et al. 2020)

Disease Emergency: EID that disrupts ecosystem and/or ecological community resilience, causes economic loss, or threatens human health [Groner *et al.* 2016]

Emerging Infectious Disease (EID): Disease associated with infectious agents that are newly identified, spread to a new population or whose incidence or geographic range is rapidly increasing.

Fomites: Object or material that carries an infectious agent.

Herd Immunity: Protection of populations from infection by the presence of immune individuals (Fine 1993).

Innate Immunity: Systems of immune response that are not pathogen-specific and do not require extensive development within the host prior to employment.

Marine Protected Area (MPA): A clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values (IUCN 2012).

Maternal Immunity: Inherited immune resistance of offspring due to exposure of parents to local and relevant pathogen risks.

Microbiome: The collection of microbes - bacteria, fungi, protozoa and viruses - that live on and inside animals and plants.

Non-competent Host: Hosts that, even after pathogen exposure, cannot generate new infections in other susceptible hosts.

Parisitome: The community of parasites - here, inducing micro- and macro- that live in animals and plants.

Passive Surveillance: Involves data collected from disease observations on an *ad hoc* basis (Sleeman, Brand and Wright 2012)

Pathogen: Broadly defined as disease causing micro- and macro- organisms.

Pelagic Larval Stages: Planktonic larval stages of marine organisms in the open-ocean water column.

Phage Therapy: Phage therapy is the use of bacteriophages, or bacteria-specific viruses (not harmful to the host), to fight off pathogenic bacteria).

Probiotics: Live microorganisms which when administered in adequate amounts confer a health benefit on the host

Reservoir Hosts: Hosts (environments or populations) that become infected by a pathogen and maintain infections (with or without disease) and serve to transmit the pathogen to susceptible hosts; often in reference to a defined target population (Groner et al. 2016; sensu Haydon et al. 2002).

Vectors: Living organisms that transmit pathogens between their animal or plant host.