Strategies for Managing Marine Disease

Caroline K. Glidden[1a*], Laurel C. Field[1], Silke Bachhuber[1], Shannon M. Hennessey[1], Robyn Cates[2], Lesley Cohen[2], Elin Crockett[2], Michelle Degnin-Warner[2], Maya K. Feezell[1], Heather K. Fulton-Bennett[1], Devyn Pires[2], Brittany N. Poirson[1], Zachary H. Randell[1], Erick White[1], and Sarah A. Gravem[1]

[1] Department of Integrative Biology, Oregon State University, Corvallis, OR, USA

[2] College of Veterinary Medicine, Oregon State University, Corvallis, OR, USA

[a]*Corresponding author: ckglidden@gmail.com*

([*]Current address: Department of Biology, Stanford University, Stanford, CA, USA)

Open Research Statement: No data were collected for this study.

Abstract

The incidence of emerging infectious diseases (EIDs) has increased in wildlife populations in recent years and is expected to continue to increase with global change. Marine diseases in particular are relatively understudied compared to terrestrial disease, but they can disrupt ecosystem resilience, cause economic loss, or threaten human health. 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, often due to fundamental differences in marine and terrestrial systems. Here, we first illustrate how the marine environment and marine organism life history present challenges or opportunities for wildlife disease management. We then assess the application of common disease management strategies to marine versus terrestrial systems to identify those that may be most effective for marine disease outbreak prevention, response, and recovery. Finally, we recommend multiple actions that will enable more successful management of marine wildlife disease emergencies in the future. These include prioritizing marine disease research and understanding its links to climate change, preventatively increasing marine ecosystem health, forming better monitoring and response networks, developing marine veterinary medicine programs, and enacting policy that addresses marine and other wildlife disease. Overall, we encourage a more proactive rather than reactive approach to marine conservation in general and to marine wildlife disease in particular and emphasize that multi-disciplinary collaborations are key to managing marine wildlife health.

Key words: marine wildlife, disease ecology, marine conservation

Introduction

In the last 40 years, wildlife populations have experienced a pronounced increase in **emerging infectious diseases (EID)** occurrence across terrestrial (Daszak et al. 2000), freshwater (Reid et al. 2019), and marine environments (Tracy et al. 2019). When an EID disrupts ecosystems, causes economic loss, or threatens human health, it becomes a **disease emergency** (Groner et al. 2016). For marine wildlife in particular, mitigating disease emergencies is critical because of direct or indirect effects on fisheries, a $US400 billion dollar industry, with 10% of the global human population dependent upon fisheries for their livelihood (FAO 2020), and due to the vast potential for marine organisms to enable technological and biomedical advances (Blasiak et al. 2020).

Despite significant recent increases in marine wildlife disease (Harvell et al. 2004, Tracy et al. 2019), and the profound direct and indirect consequences of EIDs, there are few examples of large-scale wildlife management programs or mandates (see *Management Recommendations)*. Accordingly, identifying, developing, and implementing tractable management tools targeted to marine ecosystems is an urgent priority for scientists, managers, and policymakers alike. Interdisciplinary collaborations between human, animal, and ecosystem health professionals are essential to effectively understand and manage marine disease emergencies (Groner et al. 2016).

Terrestrial wildlife disease has been managed for many decades, and the successes and challenges in these systems serve as a jumping off point for developing successful management strategies in marine systems. Fundamental features of life in the marine environment can have profound consequences for disease dynamics, research, and management (Mccallum et al. 2004). Here, we: (1) briefly describe the relatively unique features of marine compared to terrestrial environments that are pertinent for applying or developing marine disease management strategies; (2) assess the application of terrestrial disease management strategies to the management of marine disease emergencies; and (3) make recommendations to improve marine disease management. While we focus on terrestrial and marine disease systems, we recognize that this dichotomy leaves out freshwater and estuarine habitats. The intent of this manuscript is not to provide a complete review of marine disease ecology (for a thorough investigation of this topic, see (Behringer et al. 2020). Rather, we highlight examples of relevant marine disease management strategies and give examples of systems in which they can be useful. Further, though some of our recommendations are focused on the US, many could be easily applied in any jurisdiction. We aim to identify useful management tools, aid in the development of novel strategies in marine systems and facilitate interdisciplinary collaboration between marine and terrestrial disease researchers and managers.

Disease Dynamics in the Marine Environment and Implications for Management

Pathogen dynamics, host susceptibility, and environmental conditions that affect host health and pathogen viability/transmission all contribute to an organism entering a disease state (Fig. 1, McNew 1960, Scholthof 2007, Thrusfield and Christley 2018). Each of these three variables make up the **disease triangle**, which can be modulated in turn to prevent or treat disease. We organize the relatively unique effects of life in the marine environment on disease dynamics into these vertices (for a more thorough review of marine versus terrestrial epidemiology, see Mccallum et al. 2004).

Pathogen dynamics

As marine disease systems are historically understudied, disease-causing agents are relatively uncatalogued (Harvell et al. 2004, Mccallum et al. 2004). First, pathogen transmission is different in water versus air. Airborne pathogens are typically viable for minutes to hours and are typically transported a few meters at most (e.g., Wells 1934, Olsen et al. 2003, Booth et al. 2005). In contrast, marine pathogens can remain viable in seawater from days to weeks (Hawley and Garver 2008, Oidtmann et al. 2018), moving hundreds of miles in ocean currents (McCallum et al. 2003). Together, these variables facilitate rapid transmission -- accordingly marine diseases have been documented to spread an order of magnitude faster than those on land (Cantrell et al. 2020). Extended viability, long-distance transport, and rapid transmission complicates the ability for managers to geographically contain marine pathogens.

In both water and air, diffusive spread dilutes pathogens and reduces exposure. Pathways that reduce dilution and increase transmission are common in terrestrial systems and include near direct contact between hosts, indirect contact with **fomites** like soil and vegetation, or **vectors** such as mosquitoes. On the other hand, the majority of marine pathogens documented to date are transmitted as free-living (Ben-Horin et al. 2015), despite the potential for dilution. Some marine pathogens use suspended particulate matter as fomites and zooplankton as vectors (Frada et al. 2014, Kough et al. 2014, Kramer et al. 2016, Certner et al. 2017) but few marine vectors have been identified (Harvell et al. 2004). Overall, there is still much to learn about pathogen biology and transmission in the ocean and, accordingly, how to modulate pathogen dynamics for marine disease management.

Host dynamics

A number of characteristics of marine hosts contribute to the complexity of understanding marine disease dynamics, including abundant colonial and sessile species, the importance of **pelagic larvae**, and different host immunity traits. Colonial and sessile life stages are more common in marine environments and many foundational species exhibit these traits (e.g., corals, sponges, and bivalves, Costello and Chaudhary 2017). Behavioral strategies used by more mobile species, such as avoiding sick individuals, are not employable by sessile organisms (Behringer et al. 2018), and the tendency of many species to grow in close proximity facilitates rapid pathogen transmission. However, if measures are taken before an outbreak causes infection of all hosts, these organisms are typically easier to capture, quarantine, or even breed in captivity. Many sessile and colonial animals are also filter feeders that can sequester rich assemblages of pathogenic microbes, offering a management tool unique to aquatic systems (Burge et al. 2016a).

Many marine taxa have pelagic larval phases, where propagules travel long distances before settling into adult habitat (Cowen and Sponaugle 2009). This **bipartite life history strategy** decouples local birth rates from death rates as young can be transported far from adult populations, creating complex population and disease dynamics that are challenging to predict (Williams and Hastings 2013). While similar long-distance propagule transport occurs in many terrestrial plants, this strategy is common among marina taxa, including fish, corals, crustaceans, mollusks, and echinoderms. This strategy often results in decoupled gamete production and larval settlement, creating complex population dynamics that are challenging to predict (Williams and Hastings 2013). Movement of highly mobile larvae between populations can have two potential outcomes for disease transmission: 1) Transport can allow offspring to escape infected hotspots or 2) larvae can in turn act as vectors, spreading pathogens to new communities (Kough et al. 2014). Larval export can also repopulate or establish new host populations (Carr et al. 2003) especially if the larvae acquire **trans-generational immunity** (Little et al. 2003). Pelagic larval strategies are often coupled with very high numbers of offspring, which increases the adaptation potential at the population level (e.g., Schiebelhut et al. 2018). On the other hand, if the pathogen remains in the population, the consistent arrival recruitment of larvae to an infected population may maintain a fuel outbreaks by repopulating pools of susceptible hosts (Behringer et al. 2020).

There are two branches of the host immune system, the presence and complexity of which vary among taxa. All organisms utilize **innate immunity,** which is a non-specific immune response that is widely activated upon detection of pathogen invasion (Mydlarz et al. 2006, Cooper 2018). Vertebrates also utilize **adaptive immunity,** where **antibodies** are created in response to **antigens,** creating pathogen-specific immunological memory (Pastoret et al. 1998). As the majority of terrestrial wildlife disease management has focused on vertebrates, some of the most effective and commonly used strategies capitalize on antibody responses for disease diagnostics (e.g., serological assays) and prevention (e.g., vaccination). Invertebrates make up the majority of animal taxa in the ocean (Mather 2013) requiring alternative and/or novel management strategies for many marine disease emergencies.

A Changing Environment: Climate Change and Disease Dynamics in the Sea

Organisms in marine and terrestrial environments are experiencing changing average temperatures and increased variability in local weather patterns, and marine organisms are additionally experiencing hypoxia and ocean acidification. Across systems, elevated temperatures increase virulence, growth rates, reproductive window, and overwintering success of many pathogens (Harvell et al. 2002, Shields 2019). Further, 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 and Baden 2018, Shields 2019, Schwaner et al. 2020). These stressors often occur simultaneously, with consequences ultimately compounded (Burge et al. 2014, Gobler and

Baumann 2016). These multiple stressors are especially threatening for sessile marine species that cannot escape their habitat when faced with rising temperatures, ocean acidification, or hypoxia. Thus, immediate study of the effects of climate change on marine disease dynamics is critical and ongoing. Disease forecasting is especially important for predicting and mitigating long-term disease impacts (see *Forecast Outbreaks* below and Cantrell et al. 2020).

Limited Access

Humans do not inhabit marine ecosystems and are always temporary visitors. Certainly, there are many terrestrial systems that are quite inaccessible (e.g., jungles, polar environments, deserts), but this is a nearly universal feature of marine environments. This has rendered marine disease systems relatively understudied compared to terrestrial systems (Harvell et al. 2004, Mccallum et al. 2004). Also, the feasibility of managing disease is diminished because disease emergencies are harder to detect and because accessing populations or individuals for disease management is generally quite limited or nigh impossible in some cases (e.g., the deep sea).

Management Strategies for Marine Disease Emergencies

In light of the fundamental differences in disease dynamics and the implications for management that we cover above, we now assess the application of myriad terrestrial disease management strategies to the management of marine disease emergencies. For each management strategy, we assigned a score between 1 and 4 based on potential utility (Fig. 2a). We group the strategies according to the timeframe during which they may be useful (surveillance, response and recovery) and the specificity to a given disease system (targeted or general) (Fig. 2b).

Outbreak Surveillance

Monitor Outbreaks (Score: 4)

Infectious disease surveillance in wild populations includes the ongoing systematic collection, analysis, and interpretation of data to detect and monitor the status of diseases (WHO 2006). In all systems, active surveillance programs (i.e. surveilling for a particular disease, Sleeman et al. 2012) are limited by high costs and complex logistics. This is especially true in marine systems where it is typically more expensive and more challenging to sample organisms directly than on land. Since pathogens in the ocean are relatively undescribed compared to those on land, surveillance is also limited by the availability of specific diagnostic tools (see *Diagnostics* below). However, there are several successful examples of active marine surveillance programs including: corals (Coral Reef Evaluation and Monitoring Project, (CREMP)) and abalone (California Department of Fish and Wildlife Shellfish Health Laboratory). Potential strategies for overcoming difficulties sampling focal species include sampling sentinel species (Halliday et al. 2007), filter feeders (Burge et al. 2016a), environmental DNA (Michaels et al. 2016, Sato et al. 2019). When pathogens have not been fully described, active surveillance could be accomplished via non-specific or broadly specific pathogen detection tools (e.g., biochemistry of innate immune markers (Glidden et al. 2018), high-throughput amplicon sequencing (Huang et al. 2019), and metagenomics (Gu et al. 2019).

Effective passive surveillance programs (i.e. studying animals found sick or dead, Sleeman et al. 2012) are contingent upon a network of observers (e.g., Rocky Mountain wildlife: Duncan et al. 2008), which again is likely more challenging in less-accessible marine systems. However, there are some excellent examples of these programs for marine taxa or habitats (e.g., West Coast Marine Mammal Stranding Network, Local Environmental Observer (LEO)

Network, Wildlife Health Information Sharing Partnership (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. Generally, passive and active disease surveillance is a key component of identifying and responding to marine disease outbreaks, and advances in sequencing and sampling technology continue to improve utility in all systems.

Forecast Outbreaks (Score: 3)

Disease forecasting relies on model-based early warning systems that combine environmental and epidemiological data to predict if, when, and where outbreaks may occur (Maynard et al. 2016). Long- and short-term forecasting has been particularly successful for human diseases when vector or **reservoir host** biology is linked to environmental conditions, as is the case for ectotherms (Chaves and Pascual 2007, Muñoz et al. 2020). Given that most marine wildlife are ectotherms and thus particularly sensitive to environmental variation, existing forecasting strategies for terrestrial systems have great potential to be applied in marine systems, with a few existing successful examples (coral disease outbreaks: Caldwell et al. 2016); lobster epizootic shell disease: (Maynard et al. 2015, 2016). Current applications in marine systems are limited by environmental monitoring capacity underwater. However, this is rapidly improving for key variables like temperature (Trevathan et al. 2012, Piermattei et al. 2018). Further, mechanistic models (see *Epidemiological Models*) describing environmental response curves (i.e., thermal response curves) have demonstrated the most promise at effectively predicting disease emergence (Kirk et al. 2020). Determining causal relationships between environmental variability, pathogen biology, and host physiology will continue to improve disease forecasts. In many marine systems, host, and even pathogen, thermal response has been explored in laboratory settings. Future work should aim to incorporate host and pathogen thermal and other environmental responses into mechanistic, predictive models. With more research and development of environmental monitoring systems, forecasting outbreaks is of great utility to marine systems, especially as the climate changes. Pairing forecasting with some of the outbreak prevention and response strategies we outline below could be especially effective.

Outbreak Response Strategies

Diagnostics (Score: 3)

Disease diagnostics characterize and identify the causative agent of disease in a host, and these diagnostics are critical for tracking and mitigating an outbreak. 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. 2016b). However, there is a comparative dearth of knowledge of marine disease agents (Harvell et al. 2004, Behringer et al. 2020), which makes diagnostics challenging. Further, in organisms that lack adaptive immune systems, diagnostics are limited to tools that directly identify the pathogen (e.g., histology, PCR) rather than an immune response. When pathogens are not quickly identified, many of the management strategies we cover elsewhere are hamstrung. For example, the cause of Sea Star Wasting Syndrome is still unclear (Hewson et al. 2018, 2019) and many proposed recovery efforts hinge on diagnosing the disease agent (Gravem et al. 2020). Overall, diagnostics must be an integral part of outbreak response, and techniques developed in terrestrial systems are a directly transferable and promising source of solutions in marine systems.

Isolation Strategies (Score: 2)

Isolation strategies include quarantine and geographic restriction. Although contentious, geographic restriction using fencing is widely employed in terrestrial systems for ungulates and other large species to prevent disease spread (Mysterud and Rolandsen 2019). However, geographic restriction is typically not possible in marine systems due to pathogen transmission through water and logistical challenges of limiting host movement in the water.

There are two primary quarantine strategies: isolating infected individuals until they are not infectious or isolating healthy animals until their reintroduction poses little risk of infection. Both can be employed quickly and without extensive knowledge of a disease process. Quarantine has had marginal success, but is generally restricted to wildlife that can be easily contained, are small, or do not migrate (e.g., frogs during chytridiomycosis outbreaks; Woodhams et al. 2011, isolation of fishes carrying viral hemorrhagic septicemia; Håstein et al. 1999). For marine species in particular, self-contained seawater facilities are needed. While these facilities do exist, (e.g., US Geological Survey field stations) they are primarily used for economically valuable species (e.g., fishes, corals). To make quarantine a viable option for marine wildlife disease outbreaks, infrastructure and expanded partnerships with existing institutions are necessary (e.g., zoos and aquariums: *Ocean Wise Research- Vancouver Aquarium*). Overall, quarantine only has utility for a limited range of marine taxa.

Antimicrobials (Score: 1)

Antimicrobial treatments are used extensively in human and veterinary medicine to combat disease (Schwarz et al. 2001, Rohayem et al. 2010, Woods and Knauer 2010, Foy and Trepanier 2010). Similar to terrestrial wildlife disease, the use of antimicrobials in marine disease 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, antimicrobials are being replaced by preventative measures, such as **probiotics** (see *Natural Therapeutics*), due to an increasing awareness of the importance of the microbiome and concerns of antibiotic resistance (Bachère 2003, Cabello et al. 2013). Antibiotic resistance has already been documented in marine mammal species (Schaefer et al. 2009, Wallace et al. 2013) and sea turtles (Foti et al. 2009). Antimicrobials have extremely limited utility in marine systems at this time.

Culling (Score: 2)

Targeted culling is the selected killing or removal of wildlife and is applicable to both outbreak response and prevention. Culling of infected hosts can prevent pathogen spread between populations and has historically been used in terrestrial systems to slow disease transmission (Daszak et al. 2000). Culling is commonly focused on **reservoir hosts** in terrestrial systems (e.g., African buffalo culled to control bovine tuberculosis; le Roex et al. 2016). In marine systems, culling has been employed to prevent spread of viral hemorrhagic septicemia (VHS) in hatchery salmon to wild populations (Amos et al. 1998) and proposed to reduce spread of withering syndrome in aquacultured red abalone (Ben-Horin et al. 2016). Culling reservoir hosts may be effective in marine systems, particularly if they are easy to access and capture (e.g., filter-feeding bivalves that accumulate pathogens; Burge et al. 2016a). However, culling should be exercised with caution since it can often have unintended consequences for disease transmission (e.g., Bolzoni and De Leo 2013, Bielby et al. 2014). Successful management requires mechanistic understanding of how host population and community ecology influences disease transmission as well as the ability to locate and cull diseased individuals and/or populations. Culling has been overshadowed by other more effective management strategies in terrestrial systems (Sokolow et al. 2019), and is likely not useful in marine systems under most circumstances.

Epidemiological Models (Score: 4)

Epidemiological models broadly refer to a wide range of mathematical tools used to track temporal and spatial distribution of infected hosts and disease-induced mortality. They are extensively used in terrestrial disease systems to understand disease dynamics, evaluate efficacy of intervention strategies, and predict outbreak outcomes (e.g., Beeton and McCallum 2011, Craig et al. 2014, Viana et al. 2015, Silk et al. 2019). While some techniques have been successful in marine systems, application of epidemiological models has been hindered by lack of understanding of pathogen transmission and host susceptibility (Powell and Hofmann 2015, Shore and Caldwell 2019). However, incorporating within-host processes (Bidegain et al. 2017), among host heterogeneity (intra- and inter- specific; Bidegain et al. 2016, 2017), environmental conditions (Zvuloni et al. 2015, Lu et al. 2020), and physics and oceanographic data to map pathogen spread (e.g., Ferreira et al. 2014, Pande et al. 2015, Aalto et al. 2020) has substantially advanced marine disease models. Epidemiological models are best used when output can be applied to surveillance (see *Forecasting Outbreaks*), prevention, and response. Overall, epidemiological models are a powerful tool and their application to marine disease management has great potential as new data streams and computational methods emerge.

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., Kawai'i thrush, Puaiohi; 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; Jameson et al. 1982, Lafferty and Tinker 2014). Further, careful maintenance of genetic diversity to minimize bottleneck effects in small populations is key (Willoughby et al. 2015). Additional considerations after an outbreak include avoiding disease reintroduction in the target area and avoiding moving healthy organisms to areas where disease is present (Stabili et al. 2010). These challenges make many translocations of terrestrial wildlife logistically and financially prohibitive, but they may be more 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 when conditions are met, 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 offspring that can be successfully reintroduced to the wild. 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. Captive breeding has been successful for many species in zoos, aquariums, and research and private facilities (Association of Zoos and Aquariums (AZA) Reintroduction Programs, Fraser 2008, Wasson et al. 2020). As with quarantine, implementation of this strategy for marine wildlife is contingent on increased availability of facilities. Additionally, captive breeding must be carefully employed to align with conservation goals, maintain genetic diversity and avoid disease introduction (Williams and Hoffman 2009, Albert et al. 2015, Grogan et al. 2017, Wacker et al. 2019). Well-designed programs can be utilized to 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** (Harris et al. 2009, Grant et al. 2016). 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 (*The IUCN policy statement on captive breeding* 1987, Snyder et al. 1996).

There are successful examples of reintroduction of captive bred animals in terrestrial and freshwater systems (e.g., California condor, Ohio river basin freshwater mussels, Oregon frog, AZA Reintroduction Programs), but their success in marine systems is highly variable and poorly understood (Fraser 2009). Reintroducing captive bred animals to the wild has many of the same limitations and considerations mentioned for translocations (i.e. high risk of failure, need to maintain genetic diversity, avoiding disease introduction, financial cost). The pelagic larval phase common to many marine species poses further challenges. However, the abundant reproductive capacity of many species, and partnerships with commercial aquaculture facilities may be two pathways to successful implementation. Ultimately, captive breeding and reintroduction is a key tool for marine wildlife managers, but more investment in infrastructure and research s 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 experiencing severe population declines, including Pacific salmonids in the Columbia River Basin (Barnas et al. 2015) and birds in woodlands of Victoria, Australia (Vesk et al. 2015). Targeted restoration benefits from strategically identifying optimal locations (Geist and Hawkins 2016) with access to a source population. 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 newly restored habitats. 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). However, many economically and ecologically important marine habitats have been successfully restored, including mangroves, seagrass meadows, and oyster reefs (Hashim et al.

2010, Orth et al. 2012, Lipcius and Burke 2018). As such, additional research and adequate resources are needed to ensure viability of marine habitat restoration for aiding species recovery following a disease outbreak.

Reduce Harvest (Score: 2)

Limiting harvest of organisms can speed species recovery from a disease outbreak and restrict transmission facilitated by harvesting (e.g., movement of individuals due to baiting or transport of infectious material). This method is used sporadically to recover populations in both marine and terrestrial systems and involves limits on fishing, hunting, or harvesting. In marine and terrestrial environments, reducing take is only useful if the species is harvested directly or as bycatch, and it does not ameliorate disease itself. Additionally, 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 et al. 2005, Wood et al. 2010). Overall, reducing harvest is a useful strategy if take is the primary factor inhibiting recovery but is not directly a disease management tool.

Endangered Species Lists (Score: 4)

Listing species as threatened or endangered offers direct protection for that species and facilitates restoration efforts by providing funding and resources for terrestrial and marine taxa alike. A major driver of listing is to increase visibility of a declining species. For example, the International Union for the Conservation of Nature (IUCN) Red List can increase public awareness, help generate funding, and facilitate effective management actions (e.g., Gravem et al. 2020). When tied to legislation (e.g., the United States Endangered Species Act), listing can criminalize harvest or other detrimental activities by humans (see *Reduce Harvest*). However, listing does not ameliorate disease outcomes. Further, it can be slow, politically fraught, and protections are dependent on enforcement. In some cases, listing can limit basic research and hinder recovery (Miller et al. 1994). Overall, endangered species listing is a useful strategy in situations where individual species are already recovering from disease and would further benefit from funding, attention, and policy action (e.g., black abalone; Balsiger 2009).

Targeted Outbreak Prevention Strategies

Vaccines (Score: 1)

Vaccination exposes organisms to a deactivated, live attenuated, or recombinant antigen that elicits an antibody response in the host's adaptive immune system and defends against subsequent infection (Sallusto et al. 2010). Vaccines are used in terrestrial wildlife (reviewed in Langwig et al. 2015), aquaculture of many fishes (reviewed in Sommerset et al. 2005), and marine mammals (Robinson et al. 2018). Three prerequisites must be met before vaccination is feasible. First, taxa must generally have an adaptive immune response. This is lacking in the majority of invertebrates, which comprise a huge portion of marine taxa (Roch 1999). There is some research to suggest that priming of the innate immune system may work as a partially effective, moderately specific vaccine, however, this has only been demonstrated for White Spot Syndrome Virus in shrimp (Syed Musthaq and Kwang 2014). Second, vaccines are often delivered via injections and bait, sometimes with multiple doses required (Sharma and Hinds 2012). For marine wildlife, lack of access to individuals and dispersal of bait reduces the feasibility of these methods. Third, vaccines are expensive to develop, and with the exception of charismatic megafauna, funding to develop vaccines for wildlife is limited. Ideal vaccination campaigns in wildlife confer **herd immunity** (Fine 1993). At this time, vaccines are primarily useful in marine systems for vertebrates that have small, easy to access populations (e.g., monk seals; Robinson et al. 2018).

Natural Therapeutics (Score: 2)

In wild systems, hosts are typically simultaneously infected with multiple commensal, symbiotic, and parasitic organisms that comprise the **microbiome** and **parasitome.** The composition and stability of these "omes" is inherent to disease resistance and tolerance across all taxa (Kueneman et al. 2016, Pollock et al. 2019, Hoyt et al. 2019, Carthey et al. 2020, Hoarau et al. 2020, Vega Thurber et al. 2020). Understanding the role of the microbiome and parasitome in preventing or causing disease may unlock a deeper understanding of disease dynamics as well as management strategies in all wildlife, including marine species.

The microbiome and parasitome can be manipulated to prevent or treat disease via three tools: **phage therapy**, probiotics, and **coinfection** (Inal 2003, Newaj-Fyzul et al. 2014, Rynkiewicz et al. 2015, Vaumourin et al. 2015). Phage therapy is a developing treatment for multidrug-resistant bacterial infections in humans, crops, and some animals (reviewed in Doss et al. 2017). In marine systems, phage coinfection has been documented to reduce withering foot syndrome in black abalone, and has been successfully used to experimentally treat several bacterial diseases in aquaculture (Friedman et al. 2014, Doss et al. 2017). While in its early stages, the characterization of marine phages is rapidly accelerating due to the development of new "omics" tools (reviewed in Thurber 2009). Probiotics are widely used to improve health and prevent disease in aquacultured organisms (reviewed by Martínez Cruz et al. 2012), and probiotic inoculation has successfully prevented disease in wild coral (Peixoto et al. 2017). Notably, disease may arise from complex microbiome shifts as opposed to infection by a single agent (Mera and Bourne 2018, Vega Thurber et al. 2020). As such, the microbiome should be studied to elucidate disease-causing assemblages without probiotic treatment. In a direct preventative management application, coinfection with flukes has been shown to reduce bacterial virulence in aquaculture salmonids (Karvonen et al. 2019). Altogether, coinfection is difficult to employ and has not been used as a preventative measure in marine wildlife. However, it does consistently affect the efficacy of surveillance and response tools in terrestrial and marine systems through a number of processes such as reducing sensitivity and specificity of diagnostic tools and influencing mortality and transmission rates (e.g., Stokes and Burreson 2001, Gibson et al. 2011, Ezenwa and Jolles 2015, Beechler et al. 2015, Figueroa et al. 2017), underscoring the importance of coinfection to disease management.

Due to similar administration challenges as antimicrobials and vaccines, natural therapeutics are only feasible in small, accessible populations at this time. 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 with the notable exception of a few intensively studied marine disease systems-- namely corals, abalone (Wang et al. 2017), and fishes in aquaculture (reviewed in Richards 2014). More research on this topic is necessary before natural therapeutics can be widely employed for marine disease management, especially in wildlife.

Biological Control (Score: 1)

Broadly, biological control is the introduction of novel organisms to the environment to suppress undesirable populations, including disease vectors and invasive species. To specifically manage disease, biological control has been studied in human disease systems to control vector abundance and competence (e.g., Wolbachia and mosquito-borne disease; Iturbe-Ormaetxe et al. 2011). In marine systems, biological control has been proposed to control bacterial pathogens in aquaculture but has not been applied to wildlife (Stabili et al. 2010). Biological control is likely less practical for marine wildlife because vectors are apparently less common (Harvell et al. 2004), fluid ecological boundaries make targeted control less feasible (Lafferty and Kuris 1996), and food web complexity challenges predicted outcomes (Simberloff and Stiling 1996). Further, biological control efforts for invasive species have resulted in unexpected and severe negative consequences to non-target populations or to the environment (Forrester et al. 2006, Saunders et al. 2009). Thus, the utility of biological control as a management strategy in marine systems is unclear, and any undertaking should be extremely well-vetted before implementation.

General Outbreak Prevention Strategies

Increase Biosecurity (Score: 3)

Movement of hosts and invasive species are commonly associated with novel disease introductions (Vilcinskas 2019), and biosecurity measures aim to prevent these occurrences. Many of the same biosecurity measures used in terrestrial and freshwater management can be implemented in marine ecosystems through policy, legislation, and informational campaigns (e.g., enforced border management of overseas goods in New Zealand, Champion 2018; firewood restrictions for fungal pathogens, Diss-Torrance et al. 2018). The aquarium trade and ballast water discharge are two major sources of anthropogenic pathogen movement in coastal systems. Movement of popularly-traded ornamental species is a common source of pathogen introduction even in systems with strict quarantine regulation (Whittington and Chong 2007).

Further challenges are posed by the overall fragmented nature of wildlife trade regulation and documentation among countries, and increased efforts in this area have high potential to reduce biosecurity risk globally (Smith et al. 2017). Release of ballast (water held in tanks and cargo ships and released in harbors) is a well-known point source of invasive species, novel pathogens, and pollutants (Aguirre-Macedo et al. 2008). Enforceable, international policy intervention is needed to ameliorate the multifaceted impacts of ballast water discharge on coastal ecosystems. We consider this to be a feasible, if challenging, goal with high potential to have widespread positive effects.

Reduce Spillover *(Score: 2)*

In marine systems, aquaculture and wastewater are sources of pathogen spillover to adjacent natural populations. In land-based aquaculture facilities, vaccination and sterilization of outflow water decrease spillover and are effective, feasible management tools (Sung et al. 2011). However, many aquaculture facilities are in open water or coastal systems (e.g., net pens) where uncontrolled water exchange occurs between facilities and the environment. This exchange can facilitate transmission of novel pathogens to native species, especially when non-native species are being cultured, and increase pathogen prevalence in the area around facilities (Lafferty and Hofmann 2016, Krkošek 2017, Klinger et al. 2017). As in terrestrial systems, preventative treatment like vaccination (which is only feasible for some species, like fishes), antimicrobials, natural therapeutics, or targeted culling may reduce spillover. Unique to marine systems is the potential to control pathogen abundance by co-culturing aquaculture species with filter feeders that can consume pathogens but do not serve as reservoirs (Burge et al. 2016a, see *Natural Ecosystem Filters*). Management and reduction of spillover is challenging in open marine systems, but successful large-scale aquaculture of many species is contingent upon improving understanding of and reducing spillover.

Additionally, waste-water runoff is a significant source of pathogen introduction from terrestrial to marine environments. For example, etiological agents of sea otter and coral diseases can originate from terrestrial effluent (Baskin 2006). Additionally, pollution can increase disease susceptibility and worsen infectious disease outcomes (Randhawa et al. 2015). Increased regulation of wastewater through local policy and informational campaigns are feasible strategies for improving biosecurity. Some ecosystems, including sea grasses, may also serve as natural filters for wastewater runoff, reducing prevalence (Lamb et al. 2017, see *Natural Ecosystem Filters*). Targeting these habitats for conservation and restoration will provide a number of ecosystem services including climate mitigation, storm surge protection, and disease resistance (see *Targeted Habitat Restoration* & *Biodiversity and Habitat Conservation*).

Natural Ecosystem Filters (Score: 3)

Natural filtering processes in aquatic ecosystems can reduce pathogen abundance (Stabili et al. 2010, Granada et al. 2016, Buck et al. 2018). Natural characteristics of aquatic biomes and the filter-feeding species that inhabit them have been used as a source of **biological filtration** in freshwater and marine systems, presenting unique opportunities for marine wildlife disease management (Yang et al. 2008, reviewed in Burge et al. 2016a, Wu et al. 2016). Mangroves, seagrass beds, and salt marshes act as passive filters by trapping microbes, changing water chemistry, and removing nutrients. Mangroves and seagrass beds have been shown to reduce levels of pathogenic bacteria in marine environments (Yang et al. 2008, Lamb et al. 2017). As a management strategy, utilization of passive filtering ecosystems has high potential to reduce disease risk, especially when the pathogen source is “upstream” of the affected host population (see *Reduce Spillover*).

Filter-feeding taxa, such as bivalves, sponges, and polychaetes, actively filter pathogens in the water column, accumulating them in their tissues or in sediment via pseudofeces (Burge et al. 2016a). Filter-feeders serve as a viable option for inactivating or eliminating harmful microbes from the environment. However, if pathogens are not inactivated, filter feeders can serve as reservoirs for pathogens, accumulating them from the water column and serving as a source of infection for the primary host. Although active filter-feeders have been used to treat aquaculture effluents (Vaughn and Hoellein 2018), they have not yet been widely implemented for mitigating marine disease transmission in open systems. However, use of active filter feeders is a useful and feasible option for preventing local disease transmission and as sentinel species when target hosts are challenging to sample (see *Monitoring Outbreaks*).

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. Biodiversity and habitat conservation may protect wildlife from anthropogenic disturbances that increase disease susceptibility and pathogen exposure even in degraded ecosystems (Shapiro et al. 2010, Lamb et al. 2017). They may also enable host populations to recover from disease more quickly by alleviating human-associated mortality (Groner et al. 2016, and see *Reduce Lethal Take)*. Further, they can provide a source population for nearby areas affected by disease (Carr et al. 2003). Reducing biodiversity loss can also decrease disease transmission, and the risk of EIDs, through a number of processes including increasing the relative abundance of **non-competent hosts** or increasing predation on vectors or reservoirs (Young et al. 2017, Rohr et al. 2020). However, in some cases, loss of biodiversity can lead to a reduction in disease transmission. As such, biodiversity conservation may buffer the spread of EIDs, but with the magnitude and direction of the relationship dependent upon pathogen biology (mode of transmission, host specificity), host composition, spatial scale, and context of the change in biodiversity (Halliday et al. 2020(Young et al. 2017, Rohr et al. 2020, Halliday et al. 2020).

Biodiversity and habitat conservation are already key components of marine conservation efforts (see the United Nations' Sustainable Development Goals & the UN Convention on Biological Diversity's '30 by 30' campaign). **Marine protected areas** (MPAs) and marine spatial planning are two key conservation tools that are used widely to achieve various conservation goals. In a disease context, there is a need for additional research into the relationship between biodiversity and disease transmission in marine biomes and how conservation areas may aid in species recovery after a disease outbreak (but see review by Davies 2020). Elucidating these relationships will facilitate the incorporation of disease management into existing conservation frameworks and infrastructure.

Recommendations

The nuance and complexity of the strategies we discuss above broadly emphasizes the challenges marine disease researchers and managers face. Below, we outline preliminary recommendations to guide scientists, managers, and funding bodies to prepare for the expected future increases in the frequency and severity of marine disease outbreaks.

Increase Basic Research on Marine Disease Systems

Terrestrial disease systems have historically received large amounts of research attention and funding, largely due to their use in elucidating general disease dynamics applicable to human disease, livestock, and agriculture. Despite the importance of marine wildlife for supporting human livelihoods and ecosystem services, there is less available funding which leads to a general dearth of knowledge with the possible exceptions of corals, eelgrasses and some aquacultured species. 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 on Marine Disease (Issue 371, 2015), the recent inclusion of marine systems in Ecology and Evolution of Infectious Diseases NSF grants (EEID), and the recent publication of a Marine Disease Ecology textbook (Behringer et al., 2020). To better monitor, manage, and ideally prevent or mitigate marine disease emergencies, we first need to better define variation in baseline distributions of pathogens across host species, environmental gradients, and time. Further, an improved mechanistic understanding of interactions between hosts, pathogens and the environment that form the disease triangle (Fig. 1) will facilitate a comprehensive and hopefully predictive understanding of major marine disease systems. Improved funding for basic marine disease ecology, advancement of molecular tools (Titcomb et al. 2019), and development of disease models (e.g., Ovaskainen et al. 2017) should enable scientists to more accurately construct this baseline, understand disease dynamics and subsequently utilize many of the management tools highlighted above.

Understand the Links Between Climate Change and Disease

Climate change is one of the greatest threats to both human and wildlife health and is expected to cause a marked increase in wildlife disease emergencies. Slowing climate change is a crucial component of improving marine wildlife health. While addressing climate change itself is well beyond the scope of most marine disease researchers and managers actionable management strategies, ameliorating it is one of the most important 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, we suggest incorporating long-term ecological studies on consequences of climate change on marine disease systems, at community and ecosystem scales, into programs that *Monitor Outbreaks*.

Improve Marine Ecosystem Health

Current funding for disease management at state and federal levels is typically dominated by mammals, birds, or those that have other economic value (e.g., fisheries). While this is logical, these “valuable” organisms do not exist in a vacuum, and they fundamentally depend on broader ecosystem health for survival. Furthermore, our own health as humans is tied to ecosystem health. Therefore, we recommend an increase in 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, 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 (see *Biodiversity and Habitat Conservation*). Additional management strategies that also increase ecosystem health include *Targeted Habitat Restoration*, *Increasing Biosecurity*, *Reducing Spillover*, and *Natural Ecosystem Filters*.

Form Marine Disease Monitoring and Response Networks

To enable timely detection and response to marine disease emergencies, infrastructure must be in place before an emergency begins (see *Monitor Outbreaks*). The excellent models of the West Coast Marine Mammal Stranding Network and the LEO Network , should be expanded to encompass more taxa over larger areas. For example, the recently formed PRIMED Network (Primary Responders in Marine Emergent Disease, https://www.primednetwork.org/) 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 these types of networks are crucial for effectively detecting and responding to marine disease outbreaks. However, clear long-term funding pathways for this and other potential networks are not clear. We recommend that state and federal agencies further incorporate marine wildlife disease monitoring and response initiatives into their priorities. Federal-level agency programs like the USGS National Wildlife Health Center or NOAA Fisheries are well-situated to sustain monitoring and response programs for a wider range of marine wildlife and to create the infrastructure necessary to employ marine disease management tools such as *Diagnostics*, *Isolation Strategies*, and *Captive Breeding.* For example, diagnostic approaches have already been developed for many marine diseases that affect aquacultured or fished species (e.g., World Organization for Animal Health 2016) and a similar approach could be undertaken for more marine wildlife disease systems.

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 Doctor of Veterinary Medicine (DVM) programs with a focus on aquatic and/or marine wildlife medicine. Programs that do incorporate marine wildlife are skewed toward marine mammals. Marine-focused internships and residency programs for veterinarians are few in number (but see programs associated with the International Association of Aquatic Animal Medicine and World Aquatic Veterinary Medical Association), and few funded positions for wildlife veterinarians exist. Legislation addressing these deficits has not received support (see the rejected Wildlife VET Act 2019 by Representative Alcee Hastings of Florida (Hastings et al. 2019)). Policy actions supporting experts are key to wildlife disease management and response, and it is critical that they explicitly include resources and support for marine wildlife veterinarians. This support will improve capacity for nearly all management strategies described in the *Outbreak Response Strategies* and *Targeted Outbreak Prevention Strategies*.

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, to the best of our knowledge, there is currently no enacted legislation in the US or globally that addresses wildlife disease emergencies. Wildlife population health is an underlying concern of multiple state and federal agencies and the time-sensitive nature of disease emergencies has inspired multiple federal-level 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 (Heck et al. 2015), the Wildlife Disease Emergency Act of 2018 introduced by Representative Carol Shea-Porter (Shea-Porter et al. 2018) and the Global Wildlife Health and Pandemic Prevention Act of 2020 introduced by Senator Christopher Coons of Delaware (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 benefits to the economy and human health. We recommend that continued efforts be undertaken to achieve the goals outlined in these pieces of legislation. That said, marine wildlife disease occurs worldwide and both hosts and pathogens disregard political boundaries. So, it is important that countries coordinate their monitoring and response programs whenever possible. At the international level, incorporating marine wildlife disease management into existing international agreements such as the United Nations' Sustainable Development Goals is recommended.

Conclusion

Active management of high value or charismatic megafauna, particularly terrestrial wildlife species, has been practiced for over a century (Leopold 1987, Bolen and Robinson 2003). In marine systems, the will to embrace these 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, active 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 rehabilitating wolves in Yellowstone or condors in California, are rarely considered for threatened marine species (exception: sea otter reintroduction, Jameson et al. 1982 and Southern Resident Orcas, Clevenger 2020). In the event of a marine wildlife species decline, the types of strategies outlined in this manuscript may become crucial in marine systems. 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).

Proactive rather than reactive approaches to marine disease management are needed to avoid catastrophic population loss. This approach will require a collaborative effort across academic institutions, federal agencies, and nonprofits. It will require people with expertise across disciplines spanning marine sciences, disease ecology, and veterinary medicine. We encourage broad collaboration, and for marine managers to follow the lead of their terrestrial counterparts to proactively manage marine systems.

Acknowledgements

We deeply thank Drs. Dede Olson of the US Forest Service, Brianna Beechler of the Carlson College of Veterinary Medicine and Anna Jolles of the OSU Carlson College of Veterinary Medicine & Integrative Biology Dept for their feedback and guidance as we crafted this manuscript. We also thank Drs. Ben Dalziel, Priya Nanjappa, and Drew Harvell, who helped

spark the idea for this project. This is a product of the ‘Challenges of Marine Disease’ seminar course taught by Dr. Gravem and taken by graduate students from the Integrative Biology Department and veterinary medicine students from the Carlson College of Veterinary Medicine at Oregon State University.

Works Cited

Aalto, E. A., K. D. Lafferty, S. H. Sokolow, R. E. Grewelle, T. Ben-Horin, C. A. Boch, P. T. Raimondi, S. J. Bograd, E. L. Hazen, M. G. Jacox, F. Micheli, and G. A. De Leo. 2020. Models with environmental drivers offer a plausible mechanism for the rapid spread of infectious disease outbreaks in marine organisms. Scientific Reports 10:1–10.

Aguirre-Macedo, M. L., V. M. Vidal-Martinez, J. A.Herrera-Silveira, D. S. Valdés-Lozano, M. Herrera-Rodríguez, and M. A. Olvera-Novoa. 2008. Ballast water as a vector of coral pathogens in the Gulf of Mexico: The case of the Cayo Arcas coral reef. Marine Pollution Bulletin 56:1570–1577.

Albert, E. M., S. Fernández-Beaskoetxea, J. A. Godoy, U. Tobler, B. R. Schmidt, and J. Bosch. 2015. Genetic management of an amphibian population after a chytridiomycosis outbreak. Conservation Genetics 16:103–111.

Altizer, S., R. S. Ostfeld, P. T. J. J. Johnson, S. Kutz, and C. D. Harvell. 2013. Climate change and infectious diseases: From evidence to a predictive framework. Science 341:514–519.

Amos, K., J. Thomas, and K. Hopper. 1998. A Case History of Adaptive Management Strategies for Viral Hemorrhagic Septicemia Virus (VHSV) in Washington State. Journal of Aquatic Animal Health 10:152–159.

Bachère, E. 2003. Anti-infectious immune effectors in marine invertebrates: Potential tools for disease control in larviculture. Pages 427–438 Aquaculture. Elsevier.

Balsiger, J. W. 2009. Endangered Status for Black Abalone. Federal Register 74:1937–1946.

Barbier, E. B., S. D. Hacker, C. Kennedy, E. W. Koch, A. C. Stier, and B. R. Silliman. 2011, May 1. The value of estuarine and coastal ecosystem services. John Wiley & Sons, Ltd.

Barnas, K. A., S. L. Katz, D. E. Hamm, M. C. Diaz, and C. E. Jordan. 2015. Is habitat restoration targeting relevant ecological needs for endangered species? Using Pacific Salmon as a case study. Ecosphere 6.

Baskin, Y. 2006. Feature Sewage and pathogen pollution. Page BioScience. Oxford Academic.

Beechler, B. R., C. A. Manore, B. Reininghaus, D. O’Neal, E. E. Gorsich, V. O. Ezenwa, and A. E. Jolles. 2015. Enemies and turncoats: bovine tuberculosis exposes pathogenic potential of Rift Valley fever virus in a common host, African buffalo (*Syncerus caffer*). Proceedings of the Royal Society B: Biological Sciences 282:20142942.

Beeton, N., and H. McCallum. 2011. Models predict that culling is not a feasible strategy to prevent extinction of Tasmanian devils from facial tumour disease. Journal of Applied Ecology 48:1315–1323.

Behringer, D. C., A. Karvonen, and J. Bojko. 2018, July 19. Parasite avoidance behaviours in aquatic environments. Royal Society Publishing.

Behringer, D., B. Silliman, and K. Lafferty, editors. 2020. Marine Disease Ecology. Oxford University Press.

Ben-Horin, T., G. Bidegain, L. Huey, D. A. Narvaez, and D. Bushek. 2015. Parasite transmission through suspension feeding. Journal of Invertebrate Pathology.

Ben-Horin, T., K. D. Lafferty, G. Bidegain, and H. S. Lenihan. 2016. Fishing diseased abalone to promote yield and conservation. Philosophical Transactions of the Royal Society B: Biological Sciences 371:20150211.

Bidegain, G., E. N. Powell, J. M. Klinck, T. Ben-Horin, E. E. Hofmann, T. Ben-Horin, and E. E. Hofmann. 2016. Marine infectious disease dynamics and outbreak thresholds: Contact transmission, pandemic infection, and the potential role of filter feeders. Ecosphere 7.

Bidegain, G., E. N. Powell, J. M. Klinck, E. E. Hofmann, T. Ben-Horin, D. Bushek, S. E. Ford,

D. M. Munroe, and X. Guo. 2017. Modeling the transmission of Perkinsus marinus in the Eastern oyster Crassostrea virginica. Fisheries Research 186:82–93.

Bielby, J., C. A. Donnelly, L. C. Pope, T. Burke, and R. Woodroffe. 2014. Badger responses to small-scale culling may compromise targeted control of bovine tuberculosis. Proceedings of the National Academy of Sciences of the United States of America 111:9193–9198.

Blasiak, R., R. Wynberg, K. Grorud-Colvert, S. Thambisetty, N. M. Bandarra, A. V. M. Canário, J. da Silva, C. M. Duarte, M. Jaspars, A. Rogers, K. Sink, and C. C. C. Wabnitz. 2020, August 1. The ocean genome and future prospects for conservation and equity. Nature Research.

Bolen, E., and W. Robinson. 2003. Wildlife Ecology and Management. Prentice Hall.

Bolzoni, L., and G. A. De Leo. 2013. Unexpected Consequences of Culling on the Eradication of Wildlife Diseases: The Role of Virulence Evolution. The American Naturalist 181:301–313.

Booth, T. F., B. Kournikakis, N. Bastien, J. Ho, D. Kobasa, L. Stadnyk, Y. Li, M. Spence, S. Paton, B. Henry, B. Mederski, D. White, D. E. Low, A. McGeer, A. Simor, M. Vearncombe, J. Downey, F. B. Jamieson, P. Tang, and F. Plummer. 2005. Detection of Airborne Severe Acute Respiratory Syndrome (SARS) Coronavirus and Environmental Contamination in SARS Outbreak Units. The Journal of Infectious Diseases 191:1472–1477.

Buck, B. H., M. F. Troell, G. Krause, D. L. Angel, B. Grote, and T. Chopin. 2018. State of the Art and Challenges for Offshore Integrated Multi-Trophic Aquaculture (IMTA). Frontiers in Marine Science 5.

Burge, C. A., C. J. Closek, C. S. Friedman, M. L. Groner, C. M. Jenkins, A. Shore-Maggio, and J. E. Welsh. 2016a. The Use of Filter-feeders to Manage Disease in a Changing World.

Integrative and Comparative Biology 56:573–587.

Burge, C. A., C. S. Friedman, R. Getchell, M. House, K. D. Lafferty, L. D. Mydlarz, K. C. Prager, K. P. Sutherland, T. Renault, I. Kiryu, R. Vega-thurber, and C. A. Burge. 2016b. Complementary approaches to diagnosing marine diseases : a union of the modern and the classic. Philosophical Transactions of the Royal Society B: Biological Sciences 371:20150207.

Burge, C. A., C. Mark Eakin, C. S. Friedman, B. Froelich, P. K. Hershberger, E. E. Hofmann, L. E. Petes, K. C. Prager, E. Weil, B. L. Willis, S. E. Ford, C. D. Harvell, C. M. Eakin, C. S. Friedman, B. Froelich, P. K. Hershberger, E. E. Hofmann, L. E. Petes, K. C. Prager, E. Weil, B. L. Willis, S. E. Ford, and C. D. Harvell. 2014. Climate change influences on marine infectious diseases : implications for management and society. Annual Review of Marine Science 6:249–279.

Cabello, F. C., H. P. Godfrey, A. Tomova, L. Ivanova, H. Dölz, A. Millanao, and A. H. Buschmann. 2013. Antimicrobial use in aquaculture re-examined: Its relevance to antimicrobial resistance and to animal and human health. Environmental Microbiology 15:1917–1942.

Caldwell, J., S. Heron, C. Eakin, and M. Donahue. 2016. Satellite SST-Based Coral Disease Outbreak Predictions for the Hawaiian Archipelago. Remote Sensing 8:93.

Cantrell, D. L., M. L. Groner, T. Ben-Horin, J. Grant, and C. W. Revie. 2020. Modeling Pathogen Dispersal in Marine Fish and Shellfish. Trends in Parasitology 36.

Carr, M. H., J. E. Neigel, J. A. Estes, S. Andelman, R. R. Warner, and J. L. Largier. 2003. Comparing Marine and Terrestrial Ecosystems : Implications for the Design of Coastal Marine Reserves. Ecological Applications 13:90–107.

Carthey, A. J. R., D. T. Blumstein, R. V. Gallagher, S. G. Tetu, and M. R. Gillings. 2020. Conserving the holobiont. Functional Ecology 34:764–776.

Certner, R. H., A. M. Dwyer, M. R. Patterson, and S. V. Vollmer. 2017. Zooplankton as a potential vector for white band disease transmission in the endangered coral, Acropora cervicornis. PeerJ 2017:1–11.

Champion, P. D. 2018. Knowledge to action on aquatic invasive species: Island biosecurity – the New Zealand and South Pacific story. Management of Biological Invasions 9:383–394.

Chaves, L. F., and M. Pascual. 2007. Comparing Models for Early Warning Systems of Neglected Tropical Diseases. PLoS Neglected Tropical Diseases 1.

Clevenger, G. 2020. Protecting Free Willy’s Legacy: Creating a Seaside Sanctuary To Rescue and Rehabilitate the Southern Resident Orca Population. SSRN Electronic Journal.

Coons, M., and M. Graham. 2020. S. 3759 Global Wildlife Health and Pandemic Prevention Act.

Cooper, E. L. 2018. Advances in Comparative Immunology. Springer International Publishing, Cham.

Costello, M. J., and C. Chaudhary. 2017. Marine Biodiversity, Biogeography, Deep-Sea Gradients, and Conservation. Current Biology 27:R511–R527.

Cowen, R. K., and S. Sponaugle. 2009. Larval dispersal and marine population connectivity. Annual Review of Marine Science 1.

Craig, A. P., J. Hanger, J. Loader, W. A. H. Ellis, J. Callaghan, C. Dexter, D. Jones, K. W. Beagley, P. Timms, and D. P. Wilson. 2014. A 5-year Chlamydia vaccination programme could reverse disease-related koala population decline: Predictions from a mathematical model using field data. Vaccine 32:4163–4170.

Daszak, P., A. A. Cunningham, and A. D. Hyatt. 2000. Emerging infectious diseases of wildlife -

Threats to biodiversity and human health. Science 287:443–449.

Davies, C. E. 2020. Invertebrate health in Marine Protected Areas (MPAs). Journal of Invertebrate Pathology:107524.

Day, J., N. Dudley, M. Hockings, G. Holmes, D. Laffoley, S. Stolton, and S. Wells. 2012. Developing capacity for a protected planet Guidelines for Applying the IUCN Protected Area Management Categories to Marine Protected Areas. Page IUCN. Gland, Switzerland.

Diss-Torrance, A., K. Peterson, and C. Robinson. 2018. Reducing Firewood Movement by the Public: Use of Survey Data to Assess and Improve Efficacy of a Regulatory and Educational Program, 2006–2015. Forests 9:90.

Doss, J., K. Culbertson, D. Hahn, J. Camacho, and N. Barekzi. 2017, March 18. A review of phage therapy against bacterial pathogens of aquatic and terrestrial organisms. MDPI AG.

Duncan, C., L. Backus, T. Lynn, B. Powers, and M. Salman. 2008. Passive, Opportunistic Wildlife Disease Surveillance in the Rocky Mountain Region, USA. Transboundary and Emerging Diseases 55:308–314.

Eger, A. M., A. Vergés, C. G. Choi, H. Christie, M. A. Coleman, C. W. Fagerli, D. Fujita, M. Hasegawa, J. H. Kim, M. Mayer-Pinto, D. C. Reed, P. D. Steinberg, and E. M. Marzinelli. 2020. Financial and Institutional Support Are Important for Large-Scale Kelp Forest Restoration. Frontiers in Marine Science 7.

Ezenwa, V. O., and A. E. Jolles. 2015. Opposite effects of anthelmintic treatment on microbial infection at individual versus population scales. Science 347:175–177.

FAO. 2020. The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome.

Ferreira, J. G., C. Saurel, J. D. Lencart e Silva, J. P. Nunes, and F. Vazquez. 2014. Modelling of interactions between inshore and offshore aquaculture. Aquaculture 426–427:154–164.

Figueroa, C., P. Bustos, D. Torrealba, B. Dixon, C. Soto, P. Conejeros, and J. A. Gallardo. 2017. Coinfection takes its toll: Sea lice override the protective effects of vaccination against a bacterial pathogen in Atlantic salmon. Scientific Reports 7:17817.

Fine, P. E. M. 1993. Herd Immunity: History, Theory, Practice. Epidemiologic Reviews 15:265–302.

Forrester, N. L., R. C. Trout, S. L. Turner, D. Kelly, B. Boag, S. Moss, and E. A. Gould. 2006. Unravelling the paradox of rabbit haemorrhagic disease virus emergence, using phylogenetic analysis; possible implications for rabbit conservation strategies.

Foti, M., C. Giacopello, T. Bottari, V. Fisichella, D. Rinaldo, and C. Mammina. 2009. Antibiotic Resistance of Gram Negatives isolates from loggerhead sea turtles (Caretta caretta) in the central Mediterranean Sea. Marine Pollution Bulletin 58:1363–1366.

Foy, D. S., and L. A. Trepanier. 2010. Antifungal Treatment of Small Animal Veterinary Patients. Veterinary Clinics of North America - Small Animal Practice 40:1171–1188.

Frada, M. J., D. Schatz, V. Farstey, J. E. Ossolinski, H. Sabanay, S. Ben-Dor, I. Koren, and A. Vardi. 2014. Zooplankton may serve as transmission vectors for viruses infecting algal blooms in the ocean. Current Biology 24:2592–2597.

Fraser, D. J. 2008. How well can captive breeding programs conserve biodiversity? A review of salmonids. Evolutionary Applications 0:080602014503553-???

Friedman, C. S., N. Wight, L. M. Crosson, G. R. VanBlaricom, and K. D. Lafferty. 2014. Reduced disease in black abalone following mass mortality: Phage therapy and natural selection. Frontiers in Microbiology 5:1–10.

Geist, J., and S. J. Hawkins. 2016. Habitat recovery and restoration in aquatic ecosystems: current progress and future challenges. Aquatic Conservation: Marine and Freshwater

Ecosystems 26:942–962.

Gibson, A. K., S. Raverty, D. M. Lambourn, J. Huggins, S. L. Magargal, and M. E. Grigg. 2011. Polyparasitism is associated with increased disease severity in Toxoplasma gondii-infected marine sentinel species. PLoS Neglected Tropical Diseases 5:14–16.

Glidden, C. K., B. Beechler, P. E. Buss, B. Charleston, L. M. de Klerk-Lorist, F. F. Maree, T. Muller, E. Pérez-Martin, K. A. Scott, O. L. van Schalkwyk, and A. Jolles. 2018. Detection of pathogen exposure in African buffalo using non-specific markers of inflammation. Frontiers in Immunology 8:1–12.

Gobler, C. J., and H. Baumann. 2016. Hypoxia and acidification in ocean ecosystems: coupled dynamics and effects on marine life. Biology Letters 12:20150976.

Granada, L., N. Sousa, S. Lopes, and M. F. L. Lemos. 2016, September 1. Is integrated multitrophic aquaculture the solution to the sectors' major challenges? – a review. Wiley-Blackwell.

Grant, E. H. C., E. L. Muths, R. A. Katz, S. Canessa, M. J. Adams, J. R. Ballard, L. Berger, C. J. Briggs, J. Coleman, M. J. Gray, M. C. Harris, R. N. Harris, B. R. Hossack, K. P. Huyvaert, J. E. Kolby, K. R. Lips, R. E. Lovich, H. I. McCallum, J. R. Mendelson, P. Nanjappa, D. H. Olson, J. G. Powers, K. L. D. Richgels, R. E. Russell, B. R. Schmidt, A. S. der Sluijs, M. K. Watry, D. C. Woodhams, and C. L. White. 2016. Salamander chytrid fungus (*Batrachochytrium salamandrivorans*) in the United States—Developing research, monitoring, and management strategies. Open-File Report.

Gravem, S. A., W. N. Heady, V. R. Saccomanno, K. F. Alvstad, A. L. M. Gehman, T. N. Frierson, and S. L. Hamilton. 2020. Pycnopodia helianthoides. IUCN Red List of Threatened Species.

Grogan, K. E., M. L. Sauther, F. P. Cuozzo, and C. M. Drea. 2017. Genetic wealth, population health: Major histocompatibility complex variation in captive and wild ring-tailed lemurs (*Lemur catta*). Ecology and Evolution 7:7638–7649.

Groner, M. L., J. Maynard, R. Breyta, R. B. Carnegie, A. Dobson, C. S. Friedman, B. Froelich, M. Garren, F. M. D. Gulland, S. F. Heron, R. T. Noble, C. W. Revie, J. D. Shields, R. Vanderstichel, E. Weil, S. Wyllie-Echeverria, and C. D. Harvell. 2016. Managing marine disease emergencies in an era of rapid change. Philosophical Transactions of the Royal Society B: Biological Sciences 371.

Gu, W., S. Miller, and C. Y. Chiu. 2019. Clinical Metagenomic Next-Generation Sequencing for Pathogen Detection. Annual Review of Pathology: Mechanisms of Disease 14:319–338.

Halliday, F. W., J. R. Rohr, and A. Laine. 2020. Biodiversity loss underlies the dilution effect of biodiversity. Ecology Letters 23:1611–1622.

Halliday, J. E. B., A. L. Meredith, D. L. Knobel, D. J. Shaw, B. M. D. C. Bronsvoort, and S. Cleaveland. 2007. A framework for evaluating animals as sentinels for infectious disease surveillance. Journal of the Royal Society Interface 4:973–984.

Harris, R. N., R. M. Brucker, J. B. Walke, M. H. Becker, C. R. Schwantes, D. C. Flaherty, B. A. Lam, D. C. Woodhams, C. J. Briggs, V. T. Vredenburg, and K. P. C. Minbiole. 2009. Skin microbes on frogs prevent morbidity and mortality caused by a lethal skin fungus. ISME Journal 3:818–824.

Harvell, C. D., C. E. Mitchell, J. R. Ward, S. Altizer, A. P. Dobson, R. S. Ostfeld, and M. D. Samuel. 2002. Climate warming and disease risks for terrestrial and marine biota. Science 296:2158–2162.

Harvell, D., R. Aronson, N. Baron, J. Connell, A. Dobson, S. Ellner, L. Gerber, K. Kim, A.

Kuris, H. McCallum, K. Lafferty, B. Mckay, J. Porter, M. Pascual, G. Smith, K. Sutherland, J. Ward, R. Aronsen, N. Baron, J. Connell, A. Dobson, S. Ellner, L. Gerber, K. Kim, A. Kuris, H. McCallum, K. Lafferty, B. Mckay, J. Porter, M. Pascual, G. Smith, K. Sutherland, and J. Ward. 2004. The rising tide of ocean diseases: unsolved problems and research priorities. Frontiers in Ecology and the Environment 2:375–382.

Hashim, R., B. Kamali, N. M. Tamin, and R. Zakaria. 2010. An integrated approach to coastal rehabilitation: Mangrove restoration in Sungai Haji Dorani, Malaysia. Estuarine, Coastal and Shelf Science 86.

Hastein, T., B. J. Hiil, and J. R. Winton. 1999. Successful aquatic animal disease emergency programmes. Revue Scientifique et Technique de l’OIE 18:214–227.

Hastings, M., M. Kaptur, M. Cicilline, M. Cohen, M. Schrader, M. Vela, M. Norton, M. Barragan, M. Soto, M. Lynch, M. Raskin, and M. Serrano. 2019. H.R. 2099 Wildlife Veterinarians Employment and Training Act. Pages 1–37.

Hawley, L. M., and K. A. Garver. 2008. Stability of viral hemorrhagic septicemia virus (VHSV) in freshwater and seawater at various temperatures. Diseases of Aquatic Organisms 82:171–178.

Heck, M., M. Huffman, M. Capps, M. Jolly, M. Murphy, M. Pallone, M. Blumenauer, M. Delbene, M. Larsen, M. Kilmer, M. Mcdermott, and M. Smith. 2015. H.R. 936 Marine Disease Emergency Act of 2015. Pages 1–16.

Hernroth, B. E., and S. P. Baden. 2018, February 1. Alteration of host-pathogen interactions in the wake of climate change – Increasing risk for shellfish associated infections? Academic Press Inc.

Hewson, I., K. S. I. Bistolas, E. M. Quijano Cardé, J. B. Button, P. J. Foster, J. M. Flanzenbaum,

J. Kocian, and C. K. Lewis. 2018. Investigating the complex association between viral ecology, environment, and Northeast Pacific sea star wasting. Frontiers in Marine Science 5:77.

Hewson, I., B. Sullivan, E. W. Jackson, Q. Xu, H. Long, C. Lin, E. M. Quijano Cardé, J. Seymour, N. Siboni, M. R. L. Jones, and M. A. Sewell. 2019. Perspective: Something Old, Something New? Review of Wasting and Other Mortality in Asteroidea (Echinodermata). Frontiers in Marine Science 6:406.

Hoarau, A. O. G., P. Mavingui, and C. Lebarbenchon. 2020. Coinfections in wildlife: Focus on a neglected aspect of infectious disease epidemiology. PLOS Pathogens 16:e1008790.

Hoyt, J. R., K. E. Langwig, J. P. White, H. M. Kaarakka, J. A. Redell, K. L. Parise, W. F. Frick, J. T. Foster, and A. M. Kilpatrick. 2019. Field trial of a probiotic bacteria to protect bats from white-nose syndrome. Scientific Reports 9:9158.

Huang, B., A. Jennison, D. Whiley, J. McMahon, G. Hewitson, R. Graham, A. De Jong, and D. Warrilow. 2019. Illumina sequencing of clinical samples for virus detection in a public health laboratory. Scientific Reports 9:5409.

Inal, J. M. 2003. Phage therapy: A reappraisal of bacteriophages as antibiotics.

Iturbe-Ormaetxe, I., T. Walker, and S. L. O’Neill. 2011, June. Wolbachia and the biological control of mosquito-borne disease.

Jameson, R. J., K. W. Kenyon, A. M. Johnson, and H. M. Wight. 1982. History and Status of Translocated Sea Otter Populations in North America. Wildlife Society Bulletin (1973-2006) 10:100–107.

Karvonen, A., A. Fenton, and L. R. Sundberg. 2019. Sequential infection can decrease virulence in a fish–bacterium–fluke interaction: Implications for aquaculture disease management.

Evolutionary Applications 12:1900–1911.

Kirk, D., P. Luijckx, N. Jones, L. Krichel, C. Pencer, P. Molnár, and M. Krkošek. 2020. Experimental evidence of warming-induced disease emergence and its prediction by a trait-based mechanistic model. Proceedings of the Royal Society B: Biological Sciences 287.

Klinger, D. H., S. A. Levin, and J. R. Watson. 2017. The growth of finfish in global open-ocean aquaculture under climate change. Proceedings of the Royal Society B: Biological Sciences 284:20170834.

Kough, A. S., C. B. Paris, D. C. Behringer, and M. J. Butler. 2014. pathogens : the case of PaV1 in the Caribbean. Ices Journal of Marine Science 72.

Kramer, A. M., J. E. Ward, F. C. Dobbs, M. L. Pierce, and J. M. Drake. 2016. The contribution of marine aggregate-associated bacteria to the accumulation of pathogenic bacteria in oysters: an agent-based model. Ecology and Evolution 6:7397–7408.

Krkošek, M. 2017. Population biology of infectious diseases shared by wild and farmed fish. Canadian Journal of Fisheries and Aquatic Sciences 74:620–628.

Kueneman, J. G., D. C. Woodhams, R. Harris, H. M. Archer, R. Knight, and V. J. McKenzie. 2016. Probiotic treatment restores protection against lethal fungal infection lost during amphibian captivity. Proceedings of the Royal Society B: Biological Sciences 283:20161553.

Lafferty, K. D., and E. E. Hofmann. 2016. Marine disease impacts, diagnosis, forecasting, management and policy. Philosophical Transactions of the Royal Society B: Biological Sciences 371.

Lafferty, K. D., and A. M. Kuris. 1996. Biological control of marine pests. Ecology 77:1989–2000.

Lafferty, K. D., and M. T. Tinker. 2014. Sea otters are recolonizing southern California in fits and starts. Ecosphere 5:art50.

Lamb, J. B., J. A. J. M. van de Water, D. G. Bourne, C. Altier, M. Y. Hein, E. A. Fiorenza, N. Abu, J. Jompa, and C. D. Harvell. 2017. Seagrass ecosystems reduce exposure to bacterial pathogens of humans, fishes, and invertebrates. Science 355:731–733.

Langwig, K. E., J. Voyles, M. Q. Wilber, W. F. Frick, K. A. Murray, B. M. Bolker, J. P. Collins, T. L. Cheng, M. C. Fisher, J. R. Hoyt, D. L. Lindner, H. I. McCallum, R. Puschendorf, E. B. Rosenblum, M. Toothman, C. K. R. Willis, C. J. Briggs, and A. M. Kilpatrick. 2015, May 1. Context-dependent conservation responses to emerging wildlife diseases. Ecological Society of America.

Leopold, A. 1987. Game Management. University of Wisconsin Press.

Lipcius, R. N., and R. P. Burke. 2018. Successful recruitment, survival and longterm persistence of eastern oyster and hooked mussel on a subtidal, artificial restoration reef system in Chesapeake Bay. PLoS ONE 13.

Little, T. J., B. O'Connor, N. Colegrave, K. Watt, and A. F. Read. 2003. Maternal transfer of strain-specific immunity in an invertebrate. Current Biology.

Lu, T., Y. Yang, C. Chen, W. Wang, and C. Liao. 2020. Quantifying the impact of temperature variation on birnavirus transmission dynamics in hard clams *Meretrix lusoria*. Journal of Fish Diseases 43:57–68.

Lubchenco, J., and K. Grorud-Colvert. 2015, October 23. Making waves: The science and politics of ocean protection. American Association for the Advancement of Science.

Martínez Cruz, P., A. L. Ibáñez, O. A. Monroy Hermosillo, and H. C. Ramírez Saad. 2012. Use of Probiotics in Aquaculture. ISRN Microbiology 2012:1–13.

Mather, J. 2013, June 10. Marine invertebrates: Communities at risk. MDPI AG.

Maynard, J., R. Van Hooidonk, C. M. Eakin, M. Puotinen, M. Garren, G. Williams, S. F. Heron, J. Lamb, E. Weil, B. Willis, and C. D. Harvell. 2015. Projections of climate conditions that increase coral disease susceptibility and pathogen abundance and virulence. Nature Climate Change 5:688–694.

Maynard, J., R. Van Hooidonk, C. D. Harvell, C. M. Eakin, G. Liu, B. L. Willis, G. J. Williams, M. L. Groner, A. Dobson, S. F. Heron, R. Glenn, K. Reardon, and J. D. Shields. 2016. Improving marine disease surveillance through sea temperature monitoring, outlooks and projections. Philosophical Transactions of the Royal Society B: Biological Sciences 371.

McCallum, H., L. Gerber, and A. Jani. 2005. Does infectious disease influence the efficacy of marine protected areas? A theoretical framework. Journal of Applied Ecology 42:688–698.

McCallum, H., D. Harvell, and A. Dobson. 2003. Rates of spread of marine pathogens. Ecology Letters 6:1062–1067.

Mccallum, H. I., A. Kuris, C. D. Harvell, K. D. Lafferty, G. W. Smith, and J. Porter. 2004. Does terrestrial epidemiology apply to marine systems? Trends in Ecology and Evolution 19:585–591.

McNew, G. 1960. The Nature, Origin, and Evolution of Parasitism. Pages 19–69 *in* J. Horsfall and A. Dimond, editors. Plant Pathology: an advanced treatise. Academic Press, New York, NY, USA.

Mera, H., and D. G. Bourne. 2018. Disentangling causation: complex roles of coral-associated microorganisms in disease. Environmental Microbiology 20:431–449.

Michaels, L., D. Rejmanek, B. Aguilar, P. Conrad, and K. Shapiro. 2016. California mussels (Mytilus californianus) as sentinels for marine contamination with Sarcocystis neurona.

Parasitology 143:762–769.

Miller, B., R. Reading, C. Conway, J. A. Jackson, M. Hutchins, N. Snyder, S. Forrest, J. Frazier, and S. Derrickson. 1994. A model for improving endangered species recovery programs. Environmental Management 18:637–645.

Muñoz, Á. G., X. Chourio, A. Rivière-Cinnamond, M. A. Diuk-Wasser, P. A. Kache, E. A. Mordecai, L. Harrington, and M. C. Thomson. 2020. AeDES: a next-generation monitoring and forecasting system for environmental suitability of Aedes-borne disease transmission. Scientific Reports 10.

Mydlarz, L. D., L. E. Jones, and C. D. Harvell. 2006. Innate Immunity, Environmental Drivers, and Disease Ecology of Marine and Freshwater Invertebrates. Annual Review of Ecology, Evolution, and Systematics 37:251–288.

Mysterud, A., and C. M. Rolandsen. 2019. Fencing for wildlife disease control. Journal of Applied Ecology 56.

Neely, K. L., K. A. Macaulay, E. K. Hower, and M. A. Dobler. 2019. Effectiveness of topical antibiotics in treating corals affected by Stony Coral Tissue Loss Disease. bioRxiv:870402.

Newaj-Fyzul, A., A. H. Al-Harbi, and B. Austin. 2014. Review: Developments in the use of probiotics for disease control in aquaculture. Aquaculture 431:1–11.

Oidtmann, B., P. Dixon, K. Way, C. Joiner, and A. E. Bayley. 2018. Risk of waterborne virus spread - review of survival of relevant fish and crustacean viruses in the aquatic environment and implications for control measures. Reviews in Aquaculture 10:641–669.

Olsen, S. J., H.-L. Chang, T. Y.-Y. Cheung, A. F.-Y. Tang, T. L. Fisk, S. P.-L. Ooi, H.-W. Kuo, D. D.-S. Jiang, K.-T. Chen, J. Lando, K.-H. Hsu, T.-J. Chen, and S. F. Dowell. 2003. Transmission of the Severe Acute Respiratory Syndrome on Aircraft. New England Journal of Medicine 349:2416–2422.

Orth, R., K. Moore, S. Marion, D. Wilcox, and D. Parrish. 2012. Seed addition facilitates eelgrass recovery in a coastal bay system. Marine Ecology Progress Series 448.

Ovaskainen, O., G. Tikhonov, A. Norberg, F. Guillaume Blanchet, L. Duan, D. Dunson, T. Roslin, and N. Abrego. 2017. How to make more out of community data? A conceptual framework and its implementation as models and software. Ecology Letters 20:561–576.

Pande, A., H. Acosta, N. A. Brangenberg, and S. E. Keeling. 2015. Design of a detection survey for Ostreid herpesvirus-1 using hydrodynamic dispersion models to determine epidemiological units. Preventive Veterinary Medicine 119:80–84.

Pastoret, P.-P., P. Griebel, H. Bazin, and A. Govaerts, editors. 1998. Handbook of Vertebrate Immunology. First Edit. Academic Press.

Peixoto, R. S., P. M. Rosado, D. C. de A. Leite, A. S. Rosado, and D. G. Bourne. 2017. Beneficial Microorganisms for Corals (BMC): Proposed Mechanisms for Coral Health and Resilience. Frontiers in Microbiology 8.

Piermattei, V., A. Madonia, S. Bonamano, R. Martellucci, G. Bruzzone, R. Ferretti, A. Odetti, M. Azzaro, G. Zappalà, and M. Marcelli. 2018. Cost-Effective Technologies to Study the Arctic Ocean Environment †. Sensors 18:2257.

Pollock, F. J., J. B. Lamb, J. A. J. M. van de Water, H. A. Smith, B. Schaffelke, B. L. Willis, and D. G. Bourne. 2019. Reduced diversity and stability of coral-associated bacterial communities and suppressed immune function precedes disease onset in corals. Royal Society Open Science 6:190355.

Powell, E. N., and E. E. Hofmann. 2015. Models of marine molluscan diseases: Trends and challenges. Journal of Invertebrate Pathology 131:212–225.

Randhawa, N., F. Gulland, G. M. Ylitalo, R. DeLong, and J. A. K. Mazet. 2015. Sentinel California sea lions provide insight into legacy organochlorine exposure trends and their association with cancer and infectious disease. One Health 1.

Reid, A. J., A. K. Carlson, I. F. Creed, E. J. Eliason, P. A. Gell, P. T. J. Johnson, K. A. Kidd, T. J. MacCormack, J. D. Olden, S. J. Ormerod, J. P. Smol, W. W. Taylor, K. Tockner, J. C. Vermaire, D. Dudgeon, and S. J. Cooke. 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biological Reviews 94:849–873.

Richards, G. P. 2014. Bacteriophage remediation of bacterial pathogens in aquaculture: a review of the technology. Bacteriophage 4.

Robinson, S. J., M. M. Barbieri, S. Murphy, J. D. Baker, A. L. Harting, M. E. Craft, and C. L. Littnan. 2018. Model recommendations meet management reality: Implementation and evaluation of a network-informed vaccination effort for endangered Hawaiian monk seals. Proceedings of the Royal Society B: Biological Sciences 285.

Roch, P. 1999, March 1. Defense mechanisms and disease prevention in farmed marine invertebrates. Elsevier.

le Roex, N., D. Cooper, P. D. van Helden, E. G. Hoal, and A. E. Jolles. 2016. Disease Control in Wildlife: Evaluating a Test and Cull Programme for Bovine Tuberculosis in African Buffalo. Transboundary and Emerging Diseases 63:647–657.

Rohayem, J., M. Bergmann, J. Gebhardt, E. Gould, P. Tucker, A. Mattevi, T. Unge, R. Hilgenfeld, and J. Neyts. 2010. Antiviral strategies to control calicivirus infections. Antiviral Research 87:162–178.

Rohr, J. R., D. J. Civitello, F. W. Halliday, P. J. Hudson, K. D. Lafferty, C. L. Wood, and E. A. Mordecai. 2020. Towards common ground in the biodiversity–disease debate. Nature

Ecology and Evolution 4:24–33.

Rynkiewicz, E. C., A. B. Pedersen, and A. Fenton. 2015. An ecosystem approach to understanding and managing within-host parasite community dynamics. Trends in Parasitology 31:212–221.

Sallusto, F., A. Lanzavecchia, K. Araki, and R. Ahmed. 2010, October 29. From vaccines to memory and back.

Sato, Y., M. Mizuyama, M. Sato, T. Minamoto, R. Kimura, and C. Toma. 2019. Environmental DNA metabarcoding to detect pathogenic Leptospira and associated organisms in leptospirosis-endemic areas of Japan. Scientific Reports 9.

Saunders, G., B. Cooke, K. Mccoll, R. Shine, and T. Peacock. 2009. Modern approaches for the biological control of vertebrate pests: An Australian perspective. Biological Control 52:288–295.

Schaefer, A. M., J. D. Goldstein, J. S. Reif, P. A. Fair, and G. D. Bossart. 2009. Antibiotic-resistant organisms cultured from atlantic bottlenose dolphins (tursiops truncatus) inhabiting estuarine waters of charleston, sc and Indian River Lagoon, FL. EcoHealth 6:33–41.

Schiebelhut, L. M., J. B. Puritz, and M. N. Dawson. 2018. Decimation by sea star wasting disease and rapid genetic change in a keystone species, Pisaster ochraceus. Proceedings of the National Academy of Sciences of the United States of America 115:7069–7074.

Scholthof, K. B. G. 2007. The disease triangle: Pathogens, the environment and society. Nature Reviews Microbiology 5:152–156.

Schwaner, C., M. Barbosa, P. Connors, T. J. Park, D. de Silva, A. Griffith, C. J. Gobler, E. Pales Espinosa, and B. Allam. 2020. Experimental acidification increases susceptibility of Mercenaria mercenaria to infection by Vibrio species. Marine Environmental Research

154:104872.

Schwarz, S., C. Kehrenberg, and T. R. Walsh. 2001. Use of antimicrobial agents in veterinary medicine and food animal production. International Journal of Antimicrobial Agents 17:431–437.

Shapiro, K., P. A. Conrad, J. A. K. Mazet, W. W. Wallender, W. A. Miller, and J. L. Largier. 2010. Effect of estuarine wetland degradation on transport of toxoplasma gondii surrogates from land to sea. Applied and Environmental Microbiology 76:6821–6828.

Sharma, S., and L. A. Hinds. 2012, October. Formulation and delivery of vaccines: Ongoing challenges for animal management. Wolters Kluwer -- Medknow Publications.

Shea-Porter, C., M. CARTWRIGHT, M. DEFAZIO, M. NOLAN, and M. THOMPSON. 2018. H.R. 7005 Wildlife Disease Emergency Act of 2018.

Shields, J. D. 2019. Climate change enhances disease processes in crustaceans: Case studies in lobsters, crabs, and shrimps. Journal of Crustacean Biology 39:673–683.

Shore, A., and J. M. Caldwell. 2019, April 1. Modes of coral disease transmission: how do diseases spread between individuals and among populations? Springer Verlag.

Silk, M. J., D. J. Hodgson, C. Rozins, D. P. Croft, R. J. Delahay, M. Boots, and R. A. McDonald. 2019. Integrating social behaviour, demography and disease dynamics in network models: applications to disease management in declining wildlife populations. Philosophical Transactions of the Royal Society B: Biological Sciences 374:20180211.

Simberloff, D., and P. Stiling. 1996. How Risky is Biological Control? Page Source: Ecology.

Sleeman, J., C. Brand, and S. Wright. 2012. Strategies for wildlife disease surveillance. Pages 539–551 *in* A. A, O. R, and D. P, editors. New Directions in Conservation Medicine. Oxford University Press, New York, NY, USA.

Smith, K. M., C. Zambrana-Torrelio, A. White, M. Asmussen, C. Machalaba, S. Kennedy, K. Lopez, T. M. Wolf, P. Daszak, D. A. Travis, and W. B. Karesh. 2017. Summarizing US Wildlife Trade with an Eye Toward Assessing the Risk of Infectious Disease Introduction. EcoHealth 14:29–39.

Snyder, N. F., S. R. Derrickson, S. R. Beissinger, J. W. Wiley, T. B. Smith, I. D. William Toone, and B. Miller. 1996. Limitations of Captive Breeding in Endangered Species Recovery Captive Breeding of Endangered Species. Page Conservation Biology.

Sokolow, S. H., N. Nova, K. M. Pepin, A. J. Peel, J. R. C. Pulliam, K. Manlove, P. C. Cross, D. J. Becker, R. K. Plowright, H. McCallum, and G. A. De Leo. 2019. Ecological interventions to prevent and manage zoonotic pathogen spillover. Philosophical Transactions of the Royal Society B: Biological Sciences 374.

Sommerset, I., B. Krossøy, E. Biering, and P. Frost. 2005, February. Vaccines for fish in aquaculture. Taylor & Francis.

Stabili, L., R. Schirosi, M. Licciano, E. Mola, and A. Giangrande. 2010. Bioremediation of bacteria in aquaculture waste using the polychaete Sabella spallanzanii. New Biotechnology 27:774–781.

Stokes, N., and E. Burreson. 2001. Differential Diagnosis Of Mixed Haplosporidium Costale And Haplosporidium Nelsoni Infections In The Eastern Oyster, Crassostrea Virginica, Using Dna Probes. Journal Of Shellfish Research 20.

Sung, Y. Y., T. H. MacRae, P. Sorgeloos, and P. Bossier. 2011. Stress response for disease control in aquaculture. Reviews in Aquaculture 3:120–137.

Syed Musthaq, S. K., and J. Kwang. 2014, October 1. Evolution of specific immunity in shrimp - A vaccination perspective against white spot syndrome virus. Elsevier Ltd.

The IUCN policy statement on captive breeding. 1987. . Gland, Switzerland.

Thorne, E. T., and E. S. Williams. 1988. The Black-footed Ferret as a Recent Example. Conservation Biology 2:66–74.

Thrusfield, M., and R. Christley. 2018. Veterinary Epidemiology. Fourth edition. Wiley-Blackwell.

Thurber, R. V. 2009. Current insights into phage biodiversity and biogeography. Current Opinion in Microbiology 12.

Titcomb, G. C., C. L. Jerde, and H. S. Young. 2019. High-throughput sequencing for understanding the ecology of emerging infectious diseases at the wildlife-human interface. Frontiers in Ecology and Evolution 7:1–7.

Tracy, A. M., M. L. Pielmeier, R. M. Yoshioka, S. F. Heron, and C. Drew Harvell. 2019. Increases and decreases in marine disease reports in an era of global change. Proceedings of the Royal Society B: Biological Sciences 286.

Trevathan, J., R. Johnstone, T. Chiffings, I. Atkinson, N. Bergmann, W. Read, S. Theiss, T. Myers, and T. Stevens. 2012. SEMAT — The Next Generation of Inexpensive Marine Environmental Monitoring and Measurement Systems. Sensors 12:9711–9748.

Vaughn, C. C., and T. J. Hoellein. 2018. Bivalve Impacts in Freshwater and Marine Ecosystems. Annual Review of Ecology, Evolution, and Systematics 49:183–208.

Vaumourin, E., G. Vourc’h, P. Gasqui, and M. Vayssier-Taussat. 2015. The importance of multiparasitism: examining the consequences of co-infections for human and animal health. Parasites & Vectors 8:545.

Vega Thurber, R., L. D. Mydlarz, M. Brandt, D. Harvell, E. Weil, L. Raymundo, B. L. Willis, S. Langevin, A. M. Tracy, R. Littman, K. M. Kemp, P. Dawkins, K. C. Prager, M. Garren, and

J. Lamb. 2020. Deciphering Coral Disease Dynamics: Integrating Host, Microbiome, and the Changing Environment. Frontiers in Ecology and Evolution 8.

Vesk, P. A., D. Robinson, R. van der Ree, C. M. Wilson, S. Saywell, and M. A. McCarthy. 2015. Demographic Effects of Habitat Restoration for the Grey-Crowned Babbler Pomatostomus temporalis, in Victoria, Australia. PLOS ONE 10.

Viana, M., S. Cleaveland, J. Matthiopoulos, J. Halliday, C. Packer, M. E. Craft, K. Hampson, A. Czupryna, A. P. Dobson, E. J. Dubovi, E. Ernest, R. Fyumagwa, R. Hoare, J. G. C. Hopcraft, D. L. Horton, M. T. Kaare, T. Kanellos, F. Lankester, C. Mentzel, T. Mlengeya, I. Mzimbiri, E. Takahashi, B. Willett, D. T. Haydon, and T. Lembo. 2015. Dynamics of a morbillivirus at the domestic–wildlife interface: Canine distemper virus in domestic dogs and lions. Proceedings of the National Academy of Sciences 112:1464–1469.

Vilcinskas, A. 2019. Pathogens associated with invasive or introduced insects threaten the health and diversity of native species. Current Opinion in Insect Science 33.

Wacker, S., B. M. Larsen, P. Jakobsen, and S. Karlsson. 2019. Multiple paternity promotes genetic diversity in captive breeding of a freshwater mussel. Global Ecology and Conservation 17:e00564.

Wallace, C. C., P. O. Yund, T. E. Ford, K. A. Matassa, and A. L. Bass. 2013. Increase in Antimicrobial Resistance in Bacteria Isolated from Stranded Marine Mammals of the Northwest Atlantic. EcoHealth 10:201–210.

Wang, Y., M. Barton, L. Elliott, X. Li, S. Abraham, M. O'Dea, and J. Munro. 2017. Bacteriophage therapy for the control of Vibrio harveyi in greenlip abalone (Haliotis laevigata). Aquaculture 473.

Wasson, K., D. J. Gossard, L. Gardner, P. R. Hain, C. J. Zabin, S. Fork, A. D. Ridlon, J. M.

Bible, A. K. Deck, and B. B. Hughes. 2020. A scientific framework for conservation aquaculture: A case study of oyster restoration in central California. Biological Conservation 250:108745.

Wells, W. F. 1934. On air-borne infection. American Journal of Epidemiology 20:611–618.

Whittington, R. J., and R. Chong. 2007. Global trade in ornamental fish from an Australian perspective: The case for revised import risk analysis and management strategies. Preventive Veterinary Medicine 81.

WHO. 2006. Communicable disease surveillance and response systems Guide to monitoring and evaluating.

Williams, P. D., and A. Hastings. 2013. Stochastic Dispersal and Population Persistence in Marine Organisms. The American Naturalist 182:271–282.

Williams, S. E., and E. A. Hoffman. 2009. Minimizing genetic adaptation in captive breeding programs: A review. Biological Conservation 142:2388–2400.

Willoughby, J. R., M. Sundaram, B. K. Wijayawardena, S. J. A. Kimble, Y. Ji, N. B. Fernandez, J. D. Antonides, M. C. Lamb, N. J. Marra, and J. A. DeWoody. 2015. The reduction of genetic diversity in threatened vertebrates and new recommendations regarding IUCN conservation rankings. Biological Conservation 191:495–503.

Wood, C. L., K. D. Lafferty, and F. Micheli. 2010. Fishing out marine parasites? Impacts of fishing on rates of parasitism in the ocean. Ecology Letters 13:761–775.

Woodhams, D. C., J. Bosch, C. J. Briggs, S. Cashins, L. R. Davis, A. Lauer, E. Muths, R. Puschendorf, B. R. Schmidt, B. Sheafor, and J. Voyles. 2011. Mitigating amphibian disease: Strategies to maintain wild populations and control chytridiomycosis. Frontiers in Zoology 8:8.

Woods, D. J., and C. S. Knauer. 2010. Discovery of veterinary antiparasitic agents in the 21st Century: A view from industry. International Journal for Parasitology 40:1177–1181.

World Organization for Animal Health. 2016. Aquatic Manual.

Wu, S., P. N. Carvalho, J. A. Müller, V. R. Manoj, and R. Dong. 2016, January 15. Sanitation in constructed wetlands: A review on the removal of human pathogens and fecal indicators. Elsevier.

Yang, Q., N. F. Y. Tam, Y. S. Wong, T. G. Luan, W. S. Su, C. Y. Lan, P. K. S. Shin, and S. G. Cheung. 2008. Potential use of mangroves as constructed wetland for municipal sewage treatment in Futian, Shenzhen, China. Marine Pollution Bulletin 57:735–743.

Young, H. S., C. L. Wood, A. M. Kilpatrick, K. D. Lafferty, C. L. Nunn, and J. R. Vincent. 2017. Conservation, biodiversity and infectious disease: scientific evidence and policy implications. Philosophical Transactions of the Royal Society B: Biological Sciences 372:20160124.

Zvuloni, A., Y. Artzy-Randrup, G. Katriel, Y. Loya, and L. Stone. 2015. Modeling the Impact of White-Plague Coral Disease in Climate Change Scenarios. PLoS Computational Biology 11:1–22.

Box 1. Definitions box

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: immune response developed in response to specific features of a pathogen. It 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 repeated pathogen exposure.

Antigen: a foreign substance that induces an immune response, especially the production of antibodies.

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

Bipartite life history: a life history strategy characterized by two disparate forms. Many marine invertebrates, including many shellfish, echinoderms, and worms, have a free-floating, planktonic, and pelagic larval stage and undergo metamorphosis into a sessile adult stage.

Coinfection: 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 parasitism (Hoarau et al. 2020).

Disease emergency: emerging infectious disease outbreak that disrupts ecosystem and/or ecological community resilience, causes economic loss, or threatens human health (Groner et al. 2016).

'Disease Triangle': 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).

Emerging infectious disease: disease associated with infectious agents that are newly identified, have 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: the 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: a clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values (Day et al. 2012).

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

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

Parasitome: the ubiquitous community of parasites - including micro- and macroparasites- found living in close conjunction with animals, plants, and fungi.

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

Pelagic larvae: planktonic larval stages that drift in the open ocean until they attain metamorphic competency.

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

Probiotics: live microorganisms which, when administered in adequate amounts, confer a health benefit to the host.

Reservoir hosts: Hosts that become infected by a pathogen and maintain infections in the ecosystem (with or without disease). They transmit the pathogen to susceptible hosts; often identified in reference to a defined target population.

Trans-generational immunity: inherited immune resistance of offspring due to exposure of parents to local pathogens.

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

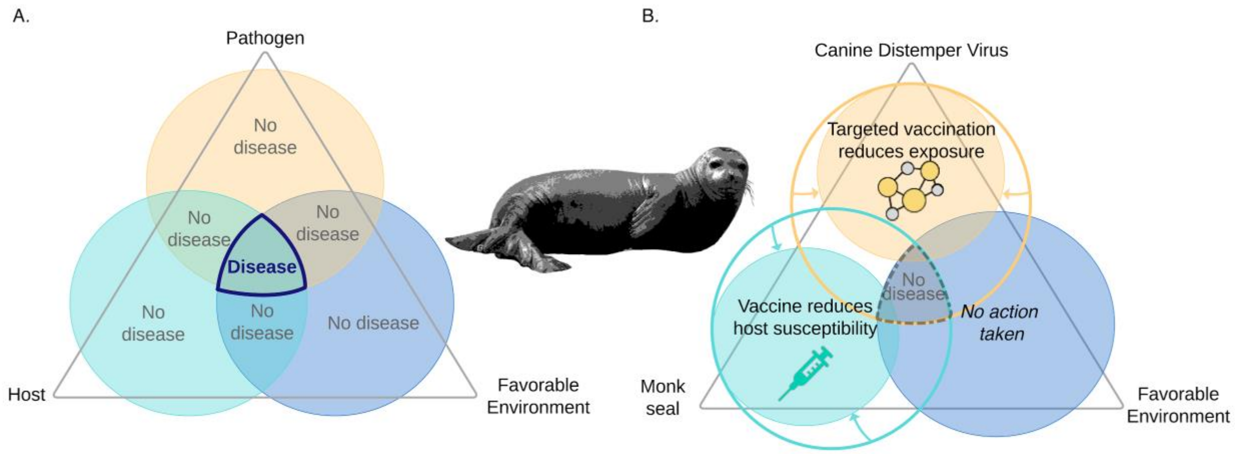

Figure 1. **(A) A conceptual disease triangle, where pathogen dynamics, host dynamics and favorable environments intersect to create disease and (B) management action reduce overlap of pathogen and host dynamics to reduce disease risk.** Robinson et al. 2018 vaccinated monk seals (host) against Canine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

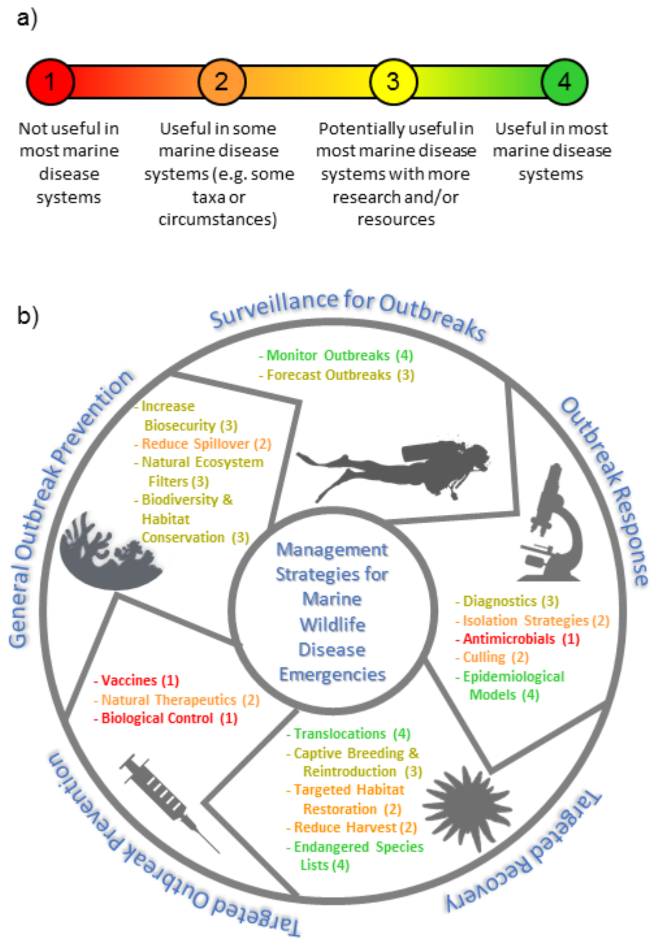

Figure 2. a) The scale used to classify a given management strategy according to its utility in managing marine disease emergencies. A high score of 4 (green) indicates that the strategy is useful in most marine disease systems. 3 (yellow) indicates the strategy is potentially useful in most marine disease systems with more research and/or resources. 2 (orange) indicates the strategy 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. b) Summary of management strategies and their utility score, according to color and scale in (a) in marine disease emergencies. Management strategies are grouped by the time frame during which they may be useful and the specificity to a given disease system in blue.