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## Review

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## Managing marine disease emergencies in an era of rapid change

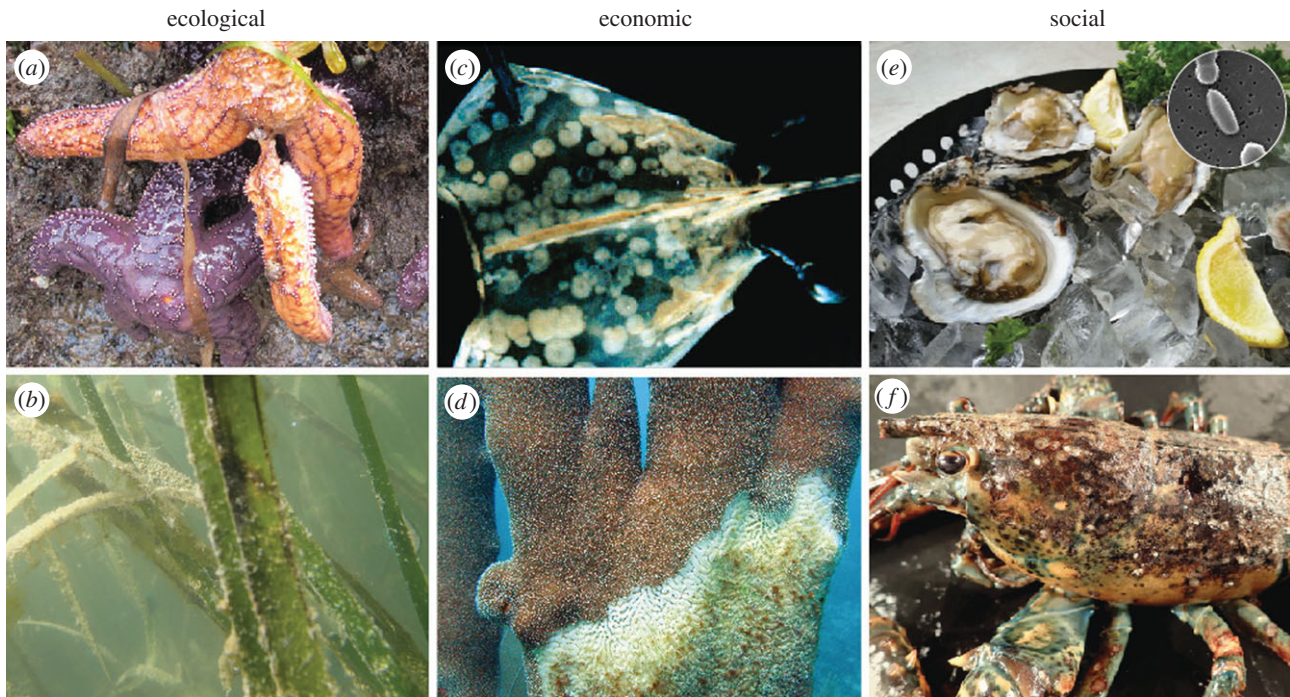
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Infectious marine diseases can decimate populations and are increasing among some taxa due to global change and our increasing reliance on marine environments. Marine diseases become emergencies when significant ecological, economic or social impacts occur. We can prepare for and manage these emergencies through improved surveillance, and the development and iterative refinement of approaches to mitigate disease and its impacts. Improving surveillance requires fast, accurate diagnoses, forecasting disease risk and real-time monitoring of disease-promoting environmental conditions. Diversifying impact mitigation involves increasing host resilience to disease, reducing pathogen abundance and managing environmental factors that facilitate disease. Disease surveillance and mitigation can be adaptive if informed by research advances and catalysed by communication among observers, researchers and decision-makers using information-sharing platforms. Recent increases in the awareness of the threats posed by marine diseases may lead to policy frameworks that facilitate the responses and management that marine disease emergencies require.

## 1. Introduction

Frequent and severe disease outbreaks are hypothesized to be a consequence of cumulative natural and anthropogenic stressors and could affect many marine species [1–3]. Most recently, a wasting disease outbreak decimated populations of sea stars (*Asteroidea*) in intertidal and sub-tidal regions of eastern and western North America [4]. In addition to uncounted deaths in the east, millions of individuals died in California, Oregon and Washington in 2013 and 2014 and more are dying now in Alaska [5]. The high mortality rate, unprecedented geographical scope and multi-species scale of impacts caught the scientific and resource



**Figure 1.** Marine diseases classifiable as emergencies due to the scope and scale of ecological, economic and social impacts. (a) Sea star wasting disease, (b) eelgrass wasting disease, (c) shrimp white spot disease, (d) white plague disease in the Caribbean coral *Dendrogyra cylindrus*, (e) *Vibrio parahaemolyticus* and *V. vulnificus* infections in oysters and (f) epizootic shell disease in lobsters. Most of these as well as many other marine disease emergencies cause significant impacts in more than one category. (Online version in colour.)

management community by surprise, emphasizing that we lack an effective framework for the detection and management of marine diseases.

The recent experience with the sea star wasting disease (SSWD) outbreak suggests early detection and diagnosis is the key to response and management. Fortunately, as reports of marine disease impacts are increasing, so is interest in creating policy to manage marine diseases. Such policy needs to address several basic questions including: (i) which marine disease outbreaks warrant management responses? And, (ii) how can we prepare for and manage marine disease emergencies? To answer these questions, we describe how coordinated research and management of marine diseases can reduce disease and its impacts for a variety of marine organisms. We provide examples of ongoing marine disease surveillance and response and discuss some of the inconsistencies in the coordination of these efforts. In the USA and Canada, governmental, non-profit and academic agencies often coordinate management responses. However, many recent marine disease outbreaks constitute emergencies not covered under current policies. Managing emerging outbreaks is essential and viable with strategic investment in research and response.

## 2. Which marine disease outbreaks are emergencies that warrant management responses?

Every disease is not an emergency. Parasites and pathogens are common in seaweeds and fishes. The typical fish caught by any marine angler often contains several parasite species, yet may still appear healthy. Most infectious agents do not

cause noticeable disease and, even when they do, the resulting population impacts may be beneficial to the marine community by returning host abundances to carrying capacity [6]. Even mass mortalities may not constitute an emergency if the die-off is localized, the outbreak is self-limiting, the system is resilient to the loss of the host, the species' existence is not under other threats, or the infectious agent does not put human communities at risk. However, when a disease causes large declines in the host population resulting in endangerment of that taxa or precipitating lasting ecological, economic or social impacts (figure 1), it becomes an emergency [2,3,7].

We define marine diseases as emergencies for their disruption of ecosystem functioning if they remove keystone predators or foundational species. For instance, the recent SSWD outbreak described in the introduction remains an emergency (figure 1a). Resultant ecological impacts are still unfolding and include a reduction in long-term ecological integrity through shifts in populations of foundation species such as mussels and ecosystem engineers like sea urchins. Seagrass wasting disease is a historical example (figure 1b) [8]. In the 1930s, a seagrass wasting disease epidemic in the North Atlantic extirpated an entire coastal ecosystem that had provided food for migratory birds and valuable habitat for commercially important fish and shellfish [9]. A range of ecosystem services deteriorated as a result, including sediment retention, filtration of waste nutrients and carbon sequestration [8,10]. While some ecological effects may be expected from most marine diseases, they are of higher concern when they reduce ecosystem services, biodiversity or ecosystem-level resilience to additional stresses.

The most costly epidemics are those affecting commercial species. The annual global value of wild and farmed fisheries is estimated in the 100s of billions of US dollars [11]. At least



67 infectious diseases have been identified as negatively impacting the economy of marine-based industries [12]. For example, billions of dollars were lost in the early 1990s as a result of a global pandemic of white spot syndrome in penaeid shrimp [12] (figure 1c). The pandemic was exacerbated by the high susceptibility of hosts to this viral pathogen and the movement of infected product among farms [12]. Subsequent management and mitigation of white spot has resulted in a return to profitable shrimp farming [13]. Economic losses associated with reduced ecotourism following disease outbreaks can also be substantial. Coral diseases have led to widespread mass mortality of acroporid corals throughout their geographical distribution [14]. In the early 1980s, white band disease changed the structure and composition of Caribbean coral reefs and affected reef-dependent fisheries and tourism industries (figure 1d) [14]. These examples demonstrate that marine diseases can cause emergencies if the economic costs are substantial.

Marine disease emergencies can also have significant social impacts capable of disrupting public safety, threatening human health or decreasing the resilience of local human communities. Along with our reliance on ocean resources, the probability of humans acquiring infections from marine organisms is also increasing [15]. These include brucellosis, leptospirosis and trichinellosis from marine mammals, avian influenza from marine birds and cryptosporidiosis and vibriosis from shellfish [16]. The most common infection route is ingestion through seafood, such as oysters. For example, transmission of pathogenic *Vibrio parahaemolyticus* and *V. vulnificus* through shellfish or other means can cause human gastrointestinal illness, septicaemia, cellulitis and, in some cases, death (figure 1e) [17]. Both *V. parahaemolyticus* and the more lethal *V. vulnificus* have increased recently as a direct response to ocean warming [18]. The emergence of epizootic shell disease in lobsters also demonstrates how marine diseases can impact human communities. Shell disease has severely damaged the historic southern New England stock, reducing an important resource for lobster fishermen in Long Island Sound and Cape Cod [19,20]. In turn, these losses have downstream impacts on the livelihood and economic vitality of these fishing communities. Collectively, these examples demonstrate how disease outbreaks that constitute emergencies can have ecological, economic and social impacts.

### 3. How can we systematically prepare for and manage marine disease emergencies?

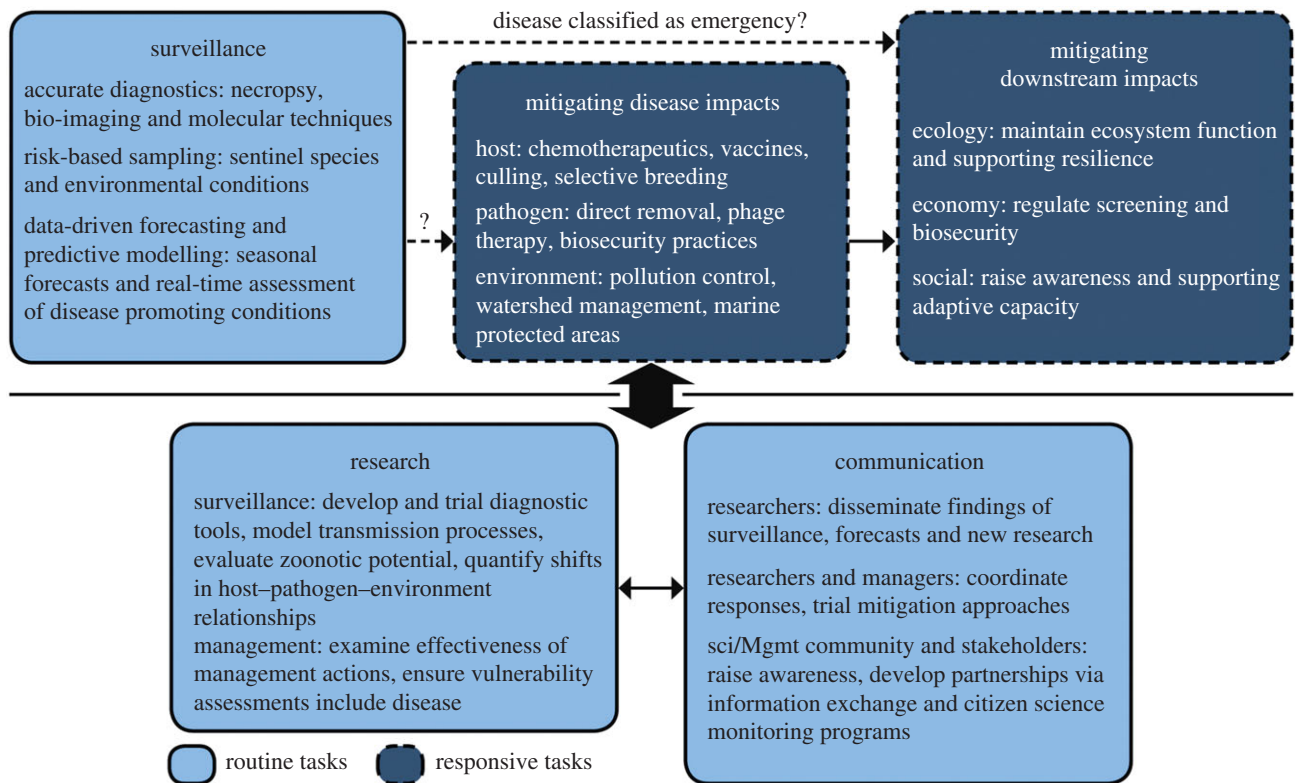
Preparing for and managing marine diseases requires surveillance and responsive mitigation (figure 2). Filling key information and capacity gaps through research, outreach and education informs management programmes for disease surveillance and mitigation. Consequently, the process used to prepare for and manage a disease emergency is adaptive; one refines diagnostic methods, initiates surveillance programmes and tailors impact mitigation as research advances and capacity among the community builds (figure 2). The response framework we recommend below highlights how effective disease surveillance creates opportunities to proactively mitigate disease and its impacts.

#### (a) Pathogen and disease surveillance: the key to proactive impact mitigation

Disease surveillance requires the use of fast and accurate diagnostic tools to identify causative agents within clinically unhealthy individuals or to determine the presence of certain pathogens in a host or environment. Some governmental, non-profit and academic organizations do on-going marine disease surveillance for numerous diseases (electronic supplementary material, table S1). Federal agencies such as the National Oceanic and Atmospheric Administration and the National Institutes of Health monitor diseases of marine mammals in the USA, universities and state agencies monitor diseases in many crustaceans and shellfish in the USA and Canada, and a variety of organizations including academic institutions, international non-governmental organizations and federal and state agencies monitor diseases of corals around the globe. Diagnostic tools are critical for early detection in the absence of visible or clinical signs or when the causative agent is unknown or multifactorial (e.g. dual infections or a combination of infection and temperature). Such tools have to be paired with strategic spatio-temporal sampling designed to detect new or emerging pathogens close to their onset. This risk-based surveillance is important because knowledge gaps in how infectious agents propagate and disperse in the ocean constrain predictive modelling. Nonetheless, when possible, data-driven forecasting of disease-promoting conditions or modelling of disease dynamics can inform sampling programmes. This can result in the application of mitigation strategies before, or at the onset of an outbreak. Delaying diagnoses will be likely to make the problem more difficult to manage.

Fortunately, new diagnostic techniques are under development [21]. Recent advances in diagnostic tools such as quantitative PCR, flow cytometry and immunocapture techniques improve the ability to quantify specific pathogens at low cost. For example, in a single run with the commercially available platform Fluidigm BioMark®, it is possible to simultaneously perform 96 unique diagnostic tests on 96 samples while maintaining high analytical sensitivity [22]. The Department of Fisheries and Oceans Canada is using this platform to monitor wild and farmed salmonids for a multitude of infections [23]. In total, 47 assays for 46 microbes suspected or known to cause disease worldwide, including four viruses that are listed by the World Organisation for Animal Health (OIE), are in development for simultaneous assessment using this platform [23,24]. The utility of such diagnostic tools will continue to improve as we focus on their application to marine disease.

Although powerful, diagnostic methods have their limitations [25]. For example, qPCR recognizes and quantifies DNA of the target species (assuming high specificity of the assay), but does not imply viability or infection [26]. These assays, when fully validated, can be used as proxies for parasite or disease presence, especially in locations where the disease (agent) has been confirmed. Validation of diagnostic tools is a critical, non-trivial step. The OIE Manual of Diagnostic Tests for Aquatic Animals describes assay validation as a four-stage pathway to assess a test's 'fitness-for-purpose' (e.g. screening versus confirmatory assay) in a designated target population/species: stage 1, analytical characteristics; stage 2, diagnostic sensitivity and specificity; stage 3, reproducibility among laboratories; and stage 4, programme implementation [24].



**Figure 2.** A framework for adaptively managing marine disease emergencies. Routine disease surveillance enables early detection of more diseases. A working group then determines whether the disease is an emergency, triggering responsive efforts to mitigate disease and downstream impacts. Surveillance tools and mitigation approaches are informed by research and catalysed by effective communication among researchers, managers and stakeholders. (Online version in colour.)

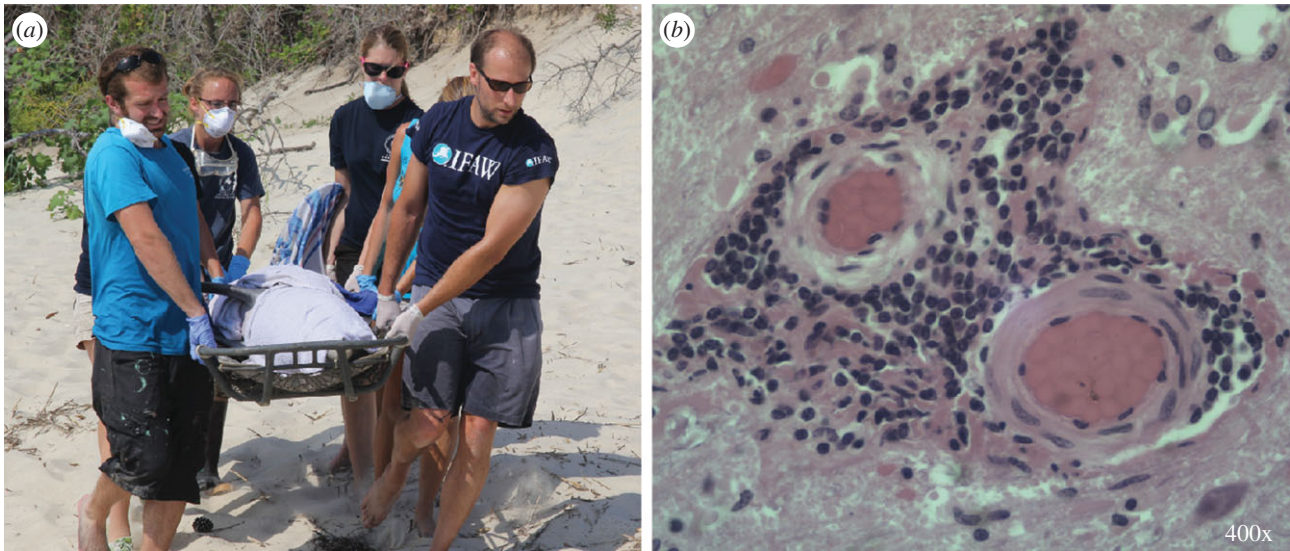
Completion of stages 1, 2 and 3 is interpreted as being fit for the originally intended purpose, usually at a national level, and would be expected for tests used in a diagnostic laboratory setting. Without validation, interpretation of diagnostic test results becomes challenging with unknown false positive and negative rates. Development of validated diagnostic tools for pathogens in non-commercial species, such as seastars, sea urchins and many species of crabs or lobsters, is needed and may shed light on the ecological role of the pathogen, whether it is obligate, facultative or opportunist, a generalist or a specialist, and if it is newly introduced to an area.

The advantages of rapid diagnostic tools are only realized with strategic spatio-temporal sampling, which can be informed through identification of risk factors using epidemiological models, risk analysis and disease simulations. Risk factors can relate to the host (e.g. species, demographic stage and sex), pathogen (e.g. range expansions or changes in virulence) or environment (e.g. temperature or salinity). Filter-feeding shellfish that act as bioaggregators of microbes in the water column can help monitor for the presence of human pathogens. For instance, mussels in the northeast coast of the USA have the highest disease prevalence and parasite burdens in the USA mussel watch programme, suggesting that this may be an area to target future surveillance [27]. Similarly, marine mammals are monitored as sentinel species for zoonotic pathogens, due to their phylogenetic and dietary similarity to humans, long-life and high-level of exposure to pathogens [16]. In both cases, diagnostic tools and strategic sampling have been paired to detect and respond to diseases as well as understand their ultimate causes (figure 3).

For some diseases affecting tropical corals, web-accessible seasonal forecasts and near real-time assessments of outbreak

likelihoods exist. White syndrome outbreaks in Australia's Great Barrier Reef occurred with greater severity following mild winters and when summer conditions were warm [28,29]. These empirical findings were made possible by strategic monitoring programmes that assessed disease presence and severity for 10 years. The forecasting tools developed from such observations can visualize outbreak likelihoods as high, medium or low based on data-driven mathematical algorithms that query remotely sensed sea surface temperature datasets (figure 4). Assessments showing high outbreak likelihoods trigger managers to target monitoring efforts and, if disease is severe, implement actions to reduce impacts or support recovery. Essentially, forecasting disease-promoting conditions increases support for and the vigilance of those engaged in disease surveillance, which can result in earlier and more robust disease detection.

Forecasting tools can be developed for other diseases if two criteria are met: (i) the major environmental risk factors for disease are known; and (ii) the relevant environmental data are available regularly and at a sufficiently high quality and spatial and temporal resolutions to represent conditions the organisms experience [30]. Candidate diseases for the development of forecasting tools include seagrass wasting disease and abalone withering syndrome because field and experimental data exist to calibrate and validate models. Recent advances allow such forecasts and real-time assessments of environmental conditions to be paired with models of disease transmission and spread. For example, three-dimensional oceanographic models that enable hydrodynamic modelling of environmentally sensitive pathogens has proved useful for predicting transmission probabilities of salmon pathogens, thereby influencing aquaculture strategies in Norway [31]. Monitoring of environmental



**Figure 3.** Cetacean morbillivirus (CeMV) causes dolphin stranding and mortality. Identifying CeMV as the cause of a mortality event depends on: fresh tissues, trained responders (a), and available, equipped diagnostic laboratories. In 2013/2014 CeMV was detected by PCR, virus isolation and histology, which stains intensely brown where the virus is present (b). This rapid response effort was made possible under the US Marine Mammal Health and Stranding Program. Under future legislation, similar coordinated responses could be possible for diseases in other marine taxa. Photos courtesy of Virginia Aquarium & Marine Science Center (both) and David Rotstein (b). (Online version in colour.)

conditions conducive to marine disease outbreaks will be increasingly important as the climate changes. As with diagnostics and sampling, developing data-driven forecasting tools and predictive modelling for marine diseases will require new investments in research that could be facilitated by policy changes.

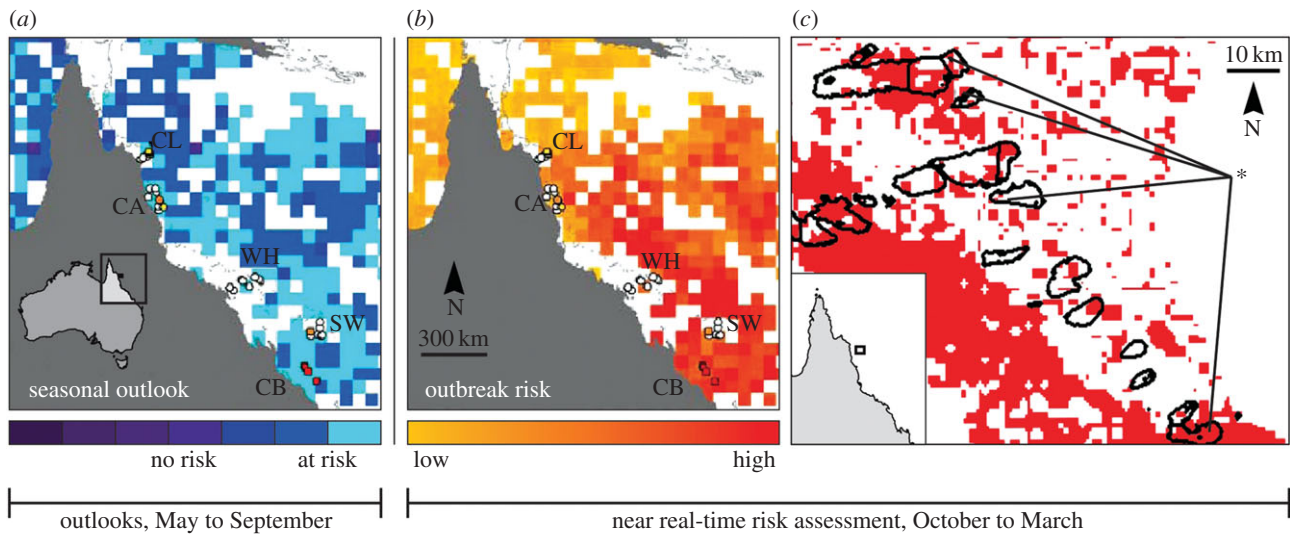
### (b) Shifting host–pathogen–environment relationships to mitigate disease

Management interventions *can* reduce the extent or severity of the outbreak itself, dispelling the notion among some that nothing can be done to reduce marine diseases [12]. Mitigation options include targeting the host or the infectious agent, ameliorating disease-promoting environmental conditions, or some combination (figure 5). The majority of mitigation efforts undertaken to date have been for diseases related to aquaculture and for marine mammals in wildlife hospitals. Nonetheless, there are some examples of disease mitigation in wild populations (table 1). These programmes often target the host by reducing the pool of infectious or susceptible individuals. This includes vaccination (e.g. on fish farms [39] or, for marine mammals [40]), application of chemical treatments to lower pathogen intensity [39], culling of diseased individuals or even whole populations (e.g. sabelid worms in abalone and various pathogens in farmed salmon [12]), and proper disposal of sick individuals that incorporates biosecurity measurements (e.g. crabs with bitter crab syndrome, bycatch or offal from processing plants) [41,42]. Host populations can also be manipulated by promoting increased resistance to disease. Frequencies of resistant genotypes may be increased in wild populations through the designation of marine protected areas (MPAs) or sanctuaries, or in aquaculture populations through selective breeding. Both of these methods are being used to increase resistance in oysters affected by MSX and dermo diseases [33]. Managers are not forced to watch in despair as a marine disease emergency unfolds.

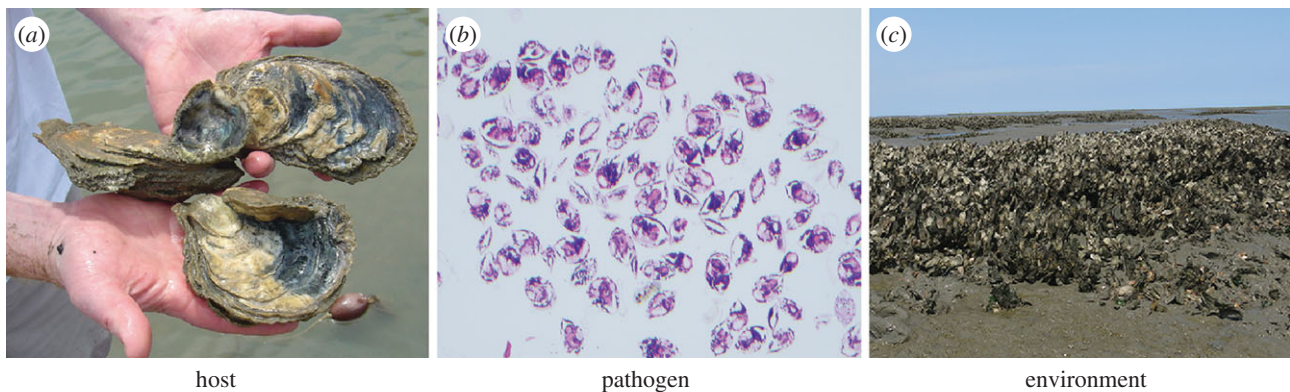
Interventions that directly target marine pathogens are effective by either direct removal of pathogens or manipulation of microbial communities to reduce pathogen virulence. Methods for direct removal of sea lice on salmon farms include biological control by co-stocking with endemic cleaner fish that are sea louse predators [43]. In another approach, mussels (*Mytilus edulis*) are placed near salmon farms to filter larval sea lice and pathogenic *Vibrio* bacteria species from the water column [44,45]. These multi-trophic approaches are promising for sustainable management of various types of infections in aquaculture and warrant continued development. Phage therapy also has potential. In this approach, pathogenic bacteria are targeted with specific viruses that lyse the cells [46] or, in the case of the rickettsia-like organisms that cause withering syndrome in abalone, reduce the virulence of the infected cells [47]. Interventions like these require creative problem-solving based on research.

Altering the environmental conditions where marine diseases occur can also be effective at reducing impacts. Many natural marine habitats provide ecosystem services in the form of disease reduction. For example, shrimp aquaculture benefits from nearby mangrove forests, through filtering of water-borne pollutants and supply of larval broodstock [48]. Mangroves restoration could improve water quality and reduce nutrients that trigger disease and reduce the need to import shrimp larvae (which might introduce disease). Similarly, because seagrasses have been shown to filter and detoxify human pathogens and other pollutants [8,49], protecting or restoring seagrasses that harbour valuable bacteria with algicidal properties against harmful algal blooms could have beneficial effects [50]. While environmental manipulations are most feasible on smaller scales, such as those relevant to aquaculture, they can also occur at larger scales. For example, *Vibrio* sp. are known to increase with nutrient-driven increases in estuarine plankton [51]. Watershed-based reductions of nutrient loading to estuarine systems can retain the natural abundance and diversity of





**Figure 4.** Predictive tools developed for the coral disease white syndromes (WS) in Australia's Great Barrier Reef. Statistical analyses were used to relate sea surface temperature patterns in the winter (seasonal forecast (a)) and summer (near real-time risk assessment (b,c)) to WS prevalence during outbreak and non-outbreak years [28,29]. These web-accessible tools are monitored by managers and scientists and used to target response efforts. Forecasting and near real-time monitoring of disease-promoting conditions can increase vigilance and support for surveillance efforts, resulting in earlier disease detection. (Online version in colour.)



**Figure 5.** Management of oysters in the eastern US to reduce the impacts of *Perkinsus marinus* (dermo) and *Haplosporidium nelsoni* (MSX) can target the host, the pathogen or the environment. Disease-resistant hosts are protected in sanctuaries from harvest to promote an increase in the frequency of resistant genotypes (a). Biosecurity management focuses on pathogen screening in aquacultured seed (viewed histologically here) to prevent disease introduction into new areas and exacerbation of disease where it occurs (b). Conserving and restoring three-dimensional reef habitat enhances growth, reproduction and recruitment of healthy oyster metapopulations (c). (Online version in colour.)

bacterial and phytoplankton species in the receiving waters, thereby reducing risks to human health [52]. Another effective strategy is to reduce the impacts of other stressors on diseased species. For example, designation of MPAs can decrease the amount of damage resulting from boats, abandoned fishing gear and human impacts [53]. Such areas have lower coral disease prevalence than adjacent areas that are frequently visited and fished [54].

### (c) Mitigating downstream impacts of marine diseases

Mitigating marine disease itself reduces downstream ecological, economic and social impacts; however, in many cases the impacts themselves require mitigation. The local context and constraints, including whether the affected populations and communities can benefit from changes in human activities or habitat restoration, will dictate what types of restoration are possible. A recent meta-analysis suggests that, while often slow, restoration of impacted ecosystems can be successful [55]. These actions may help to mitigate economic and social impacts, though there are also more direct options.

Direct mitigation of economic impacts of diseases can include revising stock-recruitment fishery models to explicitly account for disease [56] and ensuring biosecurity practices reduce or eliminate transport of infected individuals and product. Both the Pacific herring and Tanner crab industries have used stock assessment models that include disease and adjust allowable catch to account for disease-induced mortality [32,38]. Changes to those fisheries models were implemented after disease outbreaks occurred, but such model adjustments can be made more proactively in the future for other marine diseases through increased monitoring of risk factors.

The billions of dollars lost due to white spot disease among penaeid shrimp in the 1990s demonstrates the role that biosecurity practices play in reducing economic impacts (figure 1c). Biosecurity is also critically important for reducing the most alarming of social impacts: human illness and death. Concerns about spillover of marine diseases into humans usually involve food or water-borne contact. Such contact can often be reduced through public health messaging. For example, when a *V. parahaemolyticus* outbreak occurs in a particular

**Table 1.** Marine disease mitigation in wild North American populations. Included are the disease mitigated, host and pathogen species, the agencies that have conducted the mitigation, the strategies implemented and the project goal.

disease	host	pathogen	mitigation approach	agency <sup>a</sup>	goal
bitter crab disease	snow crabs	<i>Hematodinium</i> sp.	dispose of infected animals in landfills; no culling of diseased animals at sea [19]	DFO	control
bitter crab disease	Tanner crab	<i>Hematodinium</i> sp.	include disease in fisheries models [32]	NOAA	control
epizootic shell disease	American lobster	bacterial dysbiosis	moratorium on being considered on mid-Atlantic fishery [20]	ASMFC	recovery
MSX, dermo	oysters	<i>Haplosporidium nelsoni</i> , <i>Perkinsus marinus</i>	promotion of resistant populations through sanctuaries from harvest, rotational harvest programs [33,34]	VMRC, MDNR	recovery
sabellid infestation	abalone, black turban snails	sabellid polychaete <i>Terebrassabella heterouncinata</i>	culling of highly susceptible and preferred hosts (black turban snails), installing screens at abalone mariculture facility [35]	CDFG	eradication
black band disease	12 coral species	bacterial colonies	vacuuming bacterial mat from affected area and then sealing with underwater epoxy [36]	NOAA, universities	control disease
disease outbreak	corals	various	close the reef to any human activities [36]	NOAA	prevent transmission
viral haemorrhagic septicaemia (VHS)	salmonids	viral haemorrhagic septicaemia virus (VHSV)	quarantine and cull hatchery salmon testing positive [37]	WDFW	control
ichthyophoniiasis, VHS	Pacific herring	<i>Ichthyophonus hoferi</i> , VHSV	include disease in fisheries models [38]	NOAA	control

<sup>a</sup>WDFW, Washington Department of Fish and Game; CDFG, California Department of Fish and Game; DFO, Department of Fisheries and Oceans Canada; ASMFC, Atlantic States Marine Fisheries Commission; VMRC, Virginia Marine Resources Commission; MDNR, Maryland Department of Natural Resources.

area, the Interstate Shellfish Sanitation Conference requires the Shellfish Control Authority to immediately close the affected area, issue an advisory and initiate a recall of oyster and other shellfish products [57]. These examples can be tailored for use with other marine diseases.

Disease management must be adaptive and involve information exchange. Importantly, timely implementation and trial of mitigation actions hinges entirely on disease surveillance. For some types of marine disease management decisions, competing interests will have to be balanced and many groups will need to be involved. Resolving contentious issues that may involve public health or industry viability will require clear policy and coordinated efforts. This attests to the value of future policy for bringing increased attention and resource mobilization to marine disease responses.

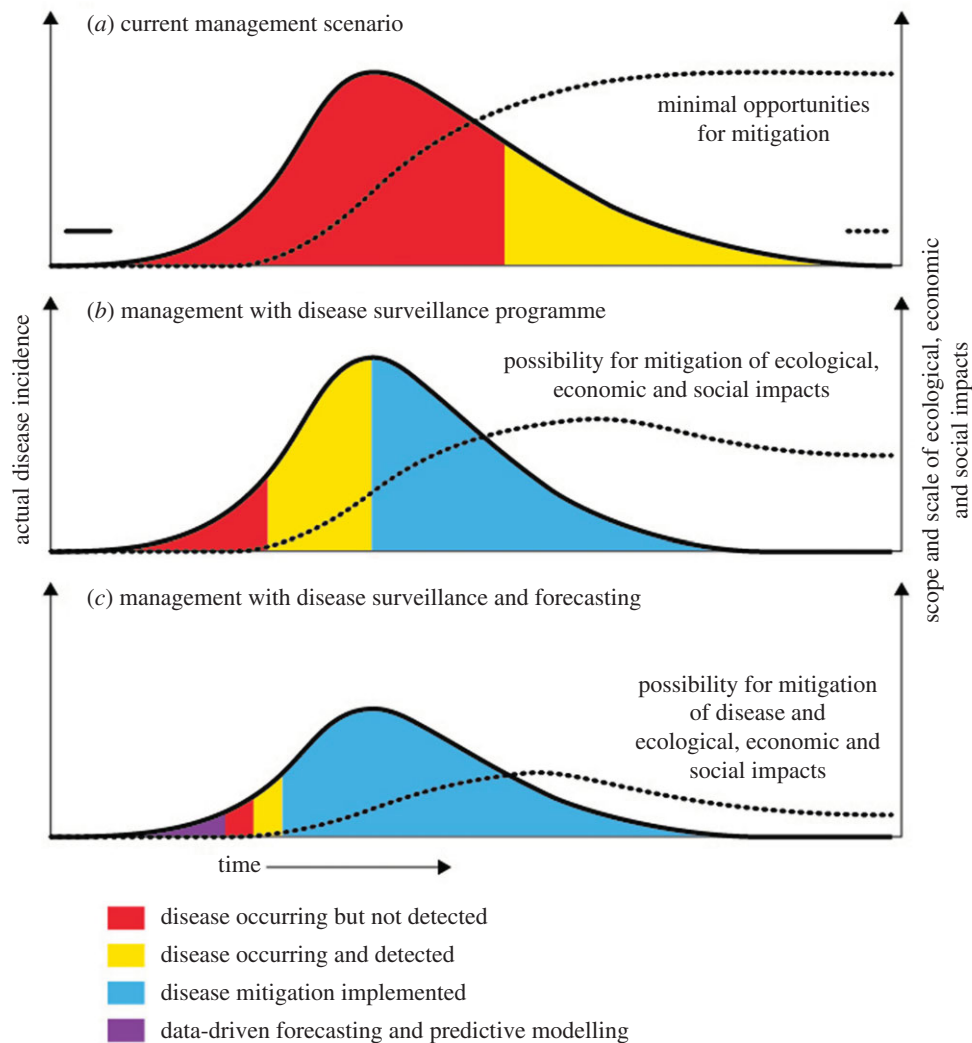
## 4. Future directions and conclusion

Some marine disease outbreaks that qualify as emergencies are ongoing (e.g. sea star wasting in Alaska and morbillivirus in

dolphins along the eastern seaboard of the USA) and new outbreaks are certain to occur in the coming years. The framework we used to summarize marine disease management can maximize opportunities to mitigate the impacts of future disease emergencies. For the framework we recommend to be adaptive, both surveillance and responsive impact mitigation need to be informed by research and catalysed by effective communication among research, management and stakeholder groups. Key areas for investment of research effort include as follows.

### (a) Surveillance

- Developing and evaluating more diagnostic tools and increasing capacity among the science and management communities to use these tools.
- Developing hydrodynamic models of pathogen propagation and dispersal.
- Quantifying the nature of shifts in host, pathogen and environment relationships under climate and anthropogenic change and using these data to develop monitoring and forecasting tools.



**Figure 6.** How the proposed disease management framework improves the timing of disease detection and extent of impact mitigation. Currently, marine diseases are detected near or after their epidemic peak (a) and there is limited management of the disease outbreak or downstream ecological, economic or social and cultural impact. Diseases could be detected earlier with greater disease surveillance, which increases management opportunities, especially for mitigating downstream impacts (b). Diseases are best managed when surveillance programmes can include data-driven forecasting and predictive modelling, ensuring mitigation starts before the epidemic peak (c) (see also figure 4). (Online version in colour.)

- Developing data-sharing and disease-mapping tools to transfer information among scientists, managers and the public.

### (b) Impact mitigation

- Trialling and evaluating management actions implemented to mitigate disease and its downstream impacts.
- Supporting the adaptive capacity of human communities dependent on fisheries.
- Ensuring that vulnerability assessments of fisheries include disease.
- Developing models and monitoring programmes to assess disease impacts and mitigation plans.

### (c) Development of marine disease adaptive management policies

How might changes to policy help us diagnose and manage marine diseases? One limitation is the lack of a coordinated response or timely funding. For instance, investigation of

the sea star wasting disease depended on interested parties donating time and resources. The need for policy that supports marine disease emergency responses and management is starting to be recognized by some governing bodies. In response to the ongoing SSWD outbreak, Washington state representative Dennis Heck of the US Congress introduced a bill that, if passed, will become the Marine Disease Emergency Act (MDE Act, HR936). This bill would increase capacity for timely and coordinated responses to future marine disease outbreaks and would: (i) ensure marine disease outbreaks are considered for classification as 'emergencies'; (ii) appoint a working group in the US National Oceanic and Atmospheric Administration to advise on assessing, declaring and responding to emergencies; (iii) form a data repository to disseminate and facilitate research to manage disease impacts; and (iv) designate financial resources for research and response coordination. A similar programme, the US Unusual Mortality Event (UME) programme, coordinates responses to marine mammal mortality events. After unprecedented mortalities of dolphins along the eastern seaboard of the USA in 1987 and 1988 [58], this programme was established under the Marine Mammal Protection Act (MMPA) amendments in



1992. The value of the MMPA for marine mammals was demonstrated during the rapid response to increasing dolphin mortalities following the Deepwater Horizon oil spill in the Gulf of Mexico [59]. However, the MMPA does not cover either fish or invertebrates, hence the need for the proposed MDE Act.

Disseminating surveillance data and research findings through open access data repositories will facilitate research and uptake of findings among decision-makers. The recent proliferation of information-sharing platforms is a positive part of this era of rapid change within which we have to manage marine disease. Indeed, linked open data that enables sophisticated data queries is already revolutionizing human disease diagnosis and care management (e.g. [60]). Such communication platforms can connect marine disease researchers with decision-makers. Consequently, management and responses coordinated under the MDE Act or future similar legislation can be adaptive and effective (figure 6). Research advances can be incorporated into

management strategy and responses can be coordinated when disease is detected or anticipated, warranting these marine emergencies the attention they require.

**Authors' contributions.** All authors contributed to the conception of the article and figure content and design. M.L.G., J.M. and C.D.H. led drafting of the manuscript with substantial input from all other authors.

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