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Brace for the wave: planning for and responding to marine disease emergencies

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Marine diseases are increasing globally, posing significant threats to both marine and human populations. Establishing ecosystem health baselines, detecting emerging diseases in marine wildlife and responding in time to manage an outbreak require a plan to be in place *before* a disease emergency unfolds. This enables monitoring and response networks to immediately begin to identify the etiologic agent, track disease progression, assess the ecological or economic risks, and prioritize the most appropriate and effective management strategies. Here, we present a marine disease outbreak contingency plan where a suspected infectious disease has caused a sudden increase in mortality of a generic marine wildlife host species, and much of the plan is also relevant for non-pathogenic mortality events and protected or economically valuable host species. The contingency plan has three sections: *Diagnostics and Disease Dynamics*, *Ecology and Environment*, and *Mitigation and Remediation*. Each section describes major goals and action items at different phases of an outbreak and highlights actions taken during the sea star wasting disease outbreak as a case study in disease response. We recommend strategies for increasing the overall preparedness for disease emergencies. Given our collective dependence on coastal ocean resources and the expected increase in marine disease outbreaks with climate change, we emphasize the importance of infrastructure and a network of human communities to address disease emergencies.

This article is part of the theme issue 'Managing infectious marine diseases in wild populations'.

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1. Introduction

Coastal marine ecosystems are intricately linked to human health and well-being. They provide valuable services including food from fisheries and aquaculture, protection of adjacent land from storms and tourism [1,2]. Marine disease outbreaks can permanently alter ecosystems and imperil these services, especially if the host is a strong interactor like a top predator or a foundation species [3–6]. While disease is a natural component of any ecosystem, the frequency of marine disease outbreaks is increasing globally [3,7–12].

Marine disease is increasing through a range of mechanisms. Humans can directly affect disease dynamics by moving diseases around the globe through the aquarium trade, aquaculture, shipping or accidentally through conservation actions [13–16]. Anthropogenically caused climate change can alter disease dynamics by changing the environment to favour pathogens. For example, warming temperatures can increase pathogen virulence [17,18], decrease host immunity [17–20] and cause dysbiosis or microbiome imbalance [21–23]. Ocean acidification may weaken host immune function [24–26]. Increasing frequency or severity of storms may cause increased physical damage to hosts or transport pathogens [6,20,24,27–29]. Lower dissolved oxygen and altered salinity, though less studied, can have important impacts on marine disease dynamics [8,30]. Finally, climate change is driving range expansions of host species and pathogens, bringing pathogens into contact with naive populations [17,31].

Novel disease outbreaks in the ocean provide a uniquely challenging set of conditions for response and management [32,33]. In particular, marine environments are generally relatively harder to access than other environments, so detecting an outbreak is challenging and, in many cases, there is limited baseline understanding of the host's natural history or population levels before a disease outbreak [34–36]. Also, pathogens in marine environments can often be easily transported by currents, allowing rapid spread and making containment challenging [37–39]. Furthermore, most marine organisms are invertebrates that do not have adaptive immune systems, rendering management interventions like vaccination less useful [20]. Finally, the ubiquity of pelagic larval phases has profound consequences for both disease and population dynamics [32,33].

Within the context of increasing disease frequency and the challenges of disease management in the marine environment, it is crucial that scientists and managers become proactive about detecting, understanding and addressing disease emergencies [32,34,40]. A '*disease emergency*' [34] occurs when an infectious disease causes large declines in the host population that results in endangerment of the host or precipitates lasting ecological, economic or societal impacts. Therefore, not every disease outbreak constitutes a disease emergency. While the exact conditions and timing of disease outbreaks are difficult to predict, creating response plans for disease emergency scenarios will enable scientists and managers to effectively respond to an emerging outbreak [41].

Contingency plans have been created for emerging diseases such as *Batrachochytrium salamandrivorans* (Bsal) in salamanders, white-nose syndrome in bats and several coral diseases [42–46], among others. Those contingency plans address responses to specific taxa or emerging diseases with a known aetiologic agent for which scientists have often developed diagnostic tools. The contingency plan described here is informed and inspired by these predecessors, but unique in its wider breadth: it covers marine disease outbreaks in no pre-identified host, for which we may not have diagnostic tools, and which may have unknown aetiologies. As a result, information about the timeframe, species affected and disease progression may not be known, and surveillance methods for the disease may not be developed.

2. Approach

(a) Contingency plan contributors

The need for a contingency plan that could provide general guidance for disease emergency response across a wide variety of taxa and systems was the subject of a Marine Disease Outbreaks workshop held in November 2018 in Portland, Oregon and sponsored by the BAND Foundation. The workshop was hosted by Oregon State University, and many attendees were active participants in the Sea Star Wasting Disease Task Force at the time, so the challenges presented by that particular marine disease emergency were top of mind. The >30 participants included academics, aquarists, private and government scientists, resource managers, veterinarians, science outreach coordinators and students with expertise in disease pathology, epidemiology, ecology, environmental monitoring, conservation, aquaculture and veterinary medicine. During the 2-day meeting, goals and actions for this plan were identified and a skeleton framework was constructed.

(b) Sea star wasting disease as a test case for marine disease monitoring and response

The 2013–2015 outbreak of sea star wasting disease (SSWD, figure 1) affected 12–20 species of Asteroids from Baja California to Alaska [47,48]. Some species were well-studied before the outbreak (e.g. *Pisaster ochraceus*, *Pycnopodia helianthoides*), so a rapid response by ecologists allowed fairly good estimates of extent and severity [4,49–52]. However, gaps in our understanding of the decline remain for these species, and the effects on many other species (e.g. *Pisaster brevispinus*, *Solaster dawsoni*, *Orthasterias koehleri*, *Leptasterias* spp.) remain less understood (but see [47]). Several epidemiological and modelling studies performed shortly after the outbreak [22,37,53,54] pointed to various potential causes or exacerbating factors including a virus, microbes limiting oxygen diffusion, dysbiosis, warm temperatures and other environmental drivers. However, a decade of effort has allowed scientists to just recently identify the pathogen as the bacteria *Vibrio pectenicida* [55].

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Figure 1. (a) The sunflower sea star *Pycnopodia helianthoides* exhibiting symptoms of sea star wasting disease. Photo by Jan Kocian from Reef Check. (b) Sampling the microbiome of a symptomatic *Pisaster ochraceus* for sea star wasting disease. Photo by Grant Callegari at the Hakai Institute.

In the decade after SSWD, this contingency plan served as a roadmap for many of the actions that members of the SSWD Task Force and later the *Pycnopodia* Recovery Working Group have undertaken, continue to undertake or would have undertaken in hindsight (for SSWD-specific action plans, see [56,57]). The response to SSWD was substantial, yet, we believe that many of the scientists and managers (including many of the co-authors) could have been much more prepared. Should a similar marine disease emergency occur, we assert that cohesive monitoring and response networks would enable scientists to avoid some of the missed opportunities that occurred in this case.

(c) Intent and scope

Here, we share the product of the collaborative workshop outlined above: a marine disease contingency plan that can be used to guide coordinated efforts to prepare for, document, investigate and mitigate future marine disease emergencies. Though this plan was developed with sea star wasting disease in mind, we constructed it to be widely applicable to any marine disease outbreak scenario, and many of the actions may also be applied to non-marine systems. Below, we describe the goals and action items that could be undertaken in any marine disease outbreak. Throughout, we illustrate how SSWD scientists have carried out those actions as callouts labelled with a sea star icon, ✹.

This plan was primarily developed for a basic scenario where: (i) a sudden increase in sick or dying individuals of one or more marine species is observed, (ii) the severity, expanse and time course of the event is unknown, and (iii) the cause is unknown but is suspected to be a pathogen-driven disease. In this basic scenario, the affected host species was assumed to be unprotected by federal, state or local law for approaching or handling, and not commercially or recreationally harvested. This final stipulation was chosen, so we might focus on a scenario applicable to a generic host. However, most of our action items are applicable to a protected or harvested host species but may be either less challenging (e.g. baseline population health status) or more challenging (e.g. human impacts). Where appropriate, we added brief further considerations for protected or harvested species such as obtaining permits prior to handling or sampling animals, but did not attempt to include an exhaustive set of considerations. Also, many actions in the *Ecology and Environment* and *Mitigation and Remediation* sections are also relevant for a non-disease driven mortality event.

Because organizational roles, jurisdictions and mandates will vary with the location, scale and species involved in each disease emergency, no attempt was made to link recommended actions to specific agencies. We instead focus on the actions that should be done and the expertise necessary to elicit these actions. Note that this plan is based on the collective expertise of the

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authors and contributors, and it is not an exhaustive review of the possible actions in a marine disease response. We intend for this plan to be a useful roadmap for groups of scientists, managers or conservation practitioners preparing for or responding to a marine disease emergency, and particularly emphasize that embracing collaborations is key to an effective response.

(d) Structure of the contingency plan

(i) Disease phases

A visual outline of the contingency plan and its relevant goals, actions, decision-points and products at different stages of a disease emergency is shown as a path diagram in figure 2. Throughout, we delineate four phases of a disease emergency. The first is before any outbreak has begun, which we term the *baseline* phase. The baseline phase is broad, and all species and populations are conceivably in a baseline phase unless they are in any of the other three phases. The three following phases occur during or after a disease outbreak and include an *emerging outbreak*, *mid-outbreak* and *post-outbreak*. The transition between each of the four disease phases is aligned with transition decision points (purple diamonds in figure 2) that we consider to be critical collective yes/no decisions that should be made by experts before moving response plans to the next phase. For example, when a population decline or increase in mortality is putatively caused by a disease, a transition from *baseline* to *emerging outbreak* occurs. When an outbreak is deemed a 'disease emergency' [34], a transition from *emerging-* to *mid-outbreak* occurs, and when the threat of the disease to the host population abates, a transition to a *post-outbreak* phase occurs. These transition points will not be precise and phases may overlap in time, but they are split here since each action item below is associated with one or more disease phases.

(ii) Monitoring network

During a suspected disease emergency, there is a need for rapid mobilization to allow effective data collection and mitigation. Thus, infrastructure to launch an adequate response must be in place *before* a disease emergency takes place [32,40]. *Having a disease Monitoring Network is critical for (i) assessing background population densities of affected species and their community members, (ii) cataloguing the physical signs that might indicate infected and healthy organisms, (iii) documenting background levels of disease and genetic diversity, and (iv) employing strategic time-series sampling to track the rate of disease spread or host decline*. Monitoring Network members can and should be drawn from existing research and monitoring programmes to track marine communities. Members of the Monitoring Network should be populated by academic scientists, agency scientists, community science groups, fishermen, local naturalists and others with 'eyes' on the target marine environment.

(iii) Response network

Once a marine disease emergency is suspected, the *Monitoring Network* would then notify and activate the *Response Network*. *Having a pre-identified disease Response Network enables (i) determination of response urgency, (ii) rapid collection of tissue and environmental samples to establish the cause and signs of the disease, (iii) prompt deployment of more intensive population health and ecological surveys, and (iv) identification of feasible measures for preventing or mitigating disease spread*. The Response Network should convene and ideally grow in response to the disease emergency. This Response Network could include natural resource and wildlife managers, disease modellers, epidemiologists, geneticists, conservationists, disease ecologists and others with expertise in disease dynamics, the host species or the target marine system. These networks are not mutually exclusive, and it is likely that network members would participate in both monitoring and response, with the Monitoring Network relatively more targeted to baseline to mid-outbreak phases and Response Network more targeted to the emerging and to post-outbreak phases.

(iv) Scientific expert groups

The contingency plan is divided into three main scientific areas (blue lanes in figure 2): *Diagnostics and Disease Dynamics (DD)*, *Ecology and Environment (EE)* and *Mitigation and Remediation (MR)*, which we describe in more detail below. While there is often overlap between these areas, we found that they aligned well with the types of training and expertise of our co-authors and contributors and that actions broadly align with one or two of these *Expert Groups*. Ideally, Monitoring and Response Network members should sort themselves into these Expert Groups to collectively pursue the goals and action items that are outlined in the contingency plan below.

3. Contingency plan for monitoring and responding to marine disease emergencies

(a) Diagnostics and disease dynamics

(i) Overview

The Diagnostics and Disease Dynamics Group focuses on establishing baseline health indices before an outbreak, tracking health during an outbreak, identifying the causative agent and transmission dynamics and understanding the symptoms of and response by the host species after exposure. In this section, we focus on the goals of: (i) assessing the health of individuals and

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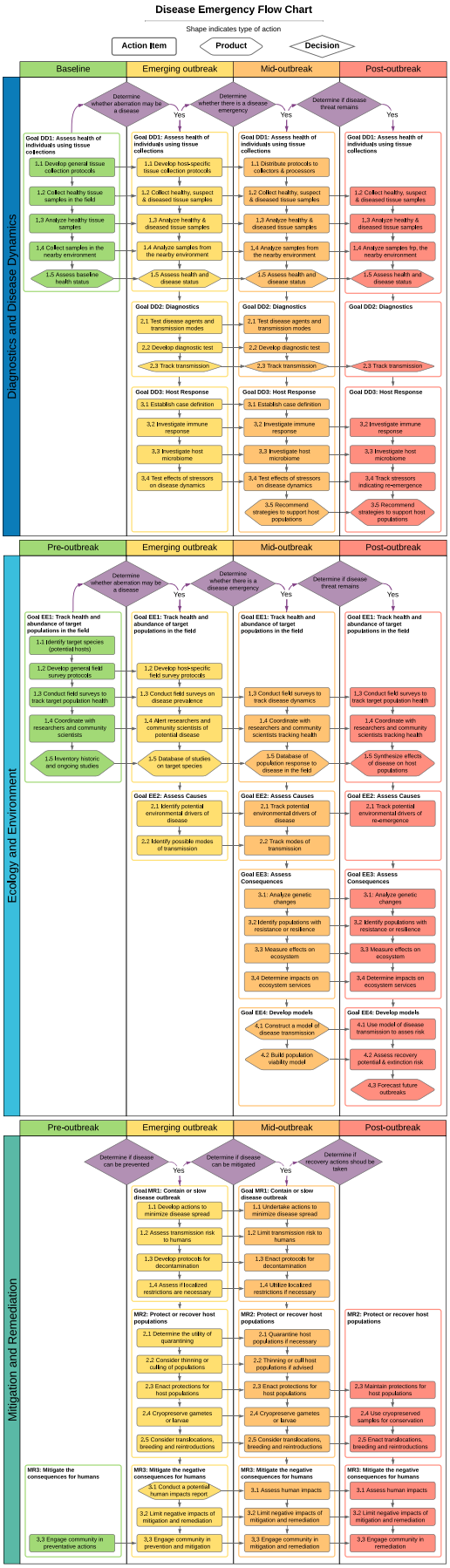

Figure 2. A visual outline of the contingency plan. The three main scientific expert groups are listed as panels and include (top) Diagnostics and Disease Dynamics, (middle) Ecology and Environment, and (bottom) Mitigation and Remediation. Vertical lanes/columns divide the four temporal phases of a disease emergency: Baseline, Emerging outbreak, Mid-outbreak and Post-outbreak (green, yellow, orange and pink). Shape and fill indicate decision points (purple diamonds), goals (unfilled boxes), action items (filled boxes coloured by phase) and products (filled hexagons coloured by phase). Horizontal arrows connect related actions over time, and vertical arrows depict actions that inform one another.

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populations using tissue and sample collections, (ii) conducting laboratory experiments to identify the causal agent of disease and its transmission dynamics, and (iii) identifying the signs of the disease and the immune responses of the host species. Achieving these goals requires substantial time, resources and infrastructure. This becomes especially challenging when the pathogen is unknown, the disease has no case definition, or when the host species is generally not well-studied.

(ii) Goals and action items: diagnostics and disease dynamics (DD)

Goal DD1: assess health of individuals and populations using tissue collections

Action Item DD1.1: develop tissue collection protocols to track the health of target host marine species (see Goal EE1.1 for identifying target species). These protocols would be employed before outbreaks to establish health baselines in diverse taxa, then refined during an emerging outbreak for a given host species. The protocol should enable well-coordinated collection techniques in the field for subsequent laboratory analyses, be widely utilized during an outbreak to track disease progression over time and space and be crucial for establishing tissue health baselines before outbreaks (DD1.2–1.5; e.g. [58]). The protocol should also address logistical issues like obtaining permits for sample collection and shipping (e.g. CITES guidelines, https://www.fws.gov/international-affairs/cites). Approaches to tissue collection include (i) collecting whole organisms (live or dead) for dissection, (ii) nonlethal collection from live organisms (e.g. blood draws, tissue samples, fin clips), or (iii) collecting samples associated with those organisms (e.g. faeces). The type of information needed determines the best approach for sampling, handling and storage techniques (for more guidance, see [59,60]) and includes (i) collecting live animals to track disease progression or perform aetiological experiments, (ii) freezing samples for DNA and RNA extraction, histology or necropsy, (iii) preserving samples in ethanol for DNA or pathogen analysis, and (iv) fixing samples in reagents that allow transcriptomic analyses (e.g. RNALater). Collection of multiple tissue types is recommended, to account for potential tissue tropism (*baseline to mid-outbreak*).

✸*For SSWD, much of the tissue collection methods had to be rapidly developed or adapted from other marine animal collection methods* [61]. *SSWD scientists developed a guide for tissue preservation and sample storage depending on the pathogen and/or desired test* [59]. *In P. helianthoides, the tissue type determines how clearly V. pectenicida stands out as differentially abundant—i.e. tissue tropism* [55].

Action Item DD1.2: collect healthy, suspect and diseased tissue samples in the field using the protocols established in DD1.1, to track the health of target marine species. Collecting before an outbreak helps establish a health baseline (DD1.5). During outbreak emergence and mid-outbreak, sampling teams should rapidly mobilize to sample areas within and outside of the geographic extent of the outbreak and continue sampling and monitoring for changes after an outbreak. These collections are time-sensitive and critical for diagnostics (Goal DD2). For increased efficiency, these collections should be done in coordination with field surveys to track population density and health (Goal EE1) (*baseline to post-outbreak*).

✸*Sharing sampling kits has enabled broad-geographic sampling across a wide range of analysis types in SSWD, including disease detection* [55], *host genomics* [62] *and host immune response*.

Action Item DD1.3: analyse healthy, suspect and diseased tissue samples that were collected in Action DD1.2. Because of high cost, it may be more efficient to delay analysing baseline health samples until an outbreak is emerging or a given target species faces a significant disease threat. Once a disease is emerging or in the outbreak phase, rapid activation of this step will be necessary (*emerging to post-outbreak*).

Action Item DD1.4: collect and analyse samples in the nearby environment that could harbour or transmit the pathogen. This includes abiotic samples (e.g. water and sediment), closely related species that could act as reservoir hosts or potential vectors (e.g. parasites, predators, herbivores, prey species, humans, vehicles or infrastructure). If found, communicate this to the Mitigation and Remediation Group to institute measures that reduce transmission (Goal MR1). While this targeted inquiry of the environment is more feasible once a disease outbreak is underway, it is possible that ongoing monitoring programmes (e.g. ongoing testing for water quality) may retroactively enable testing for pathogens present during earlier phases (*baseline to mid-outbreak*).

Action Item DD1.5: assess the health status of the population using the protocols, collections and analyses in Actions DD1.1–1.4 as well as any information gathered in goals DD2, DD3 and EE1 (diagnostics, host responses and health and abundance in the wild). Collecting samples of healthy target species can be an invaluable asset when assessing both the cause and consequences of disease outbreaks, so are ideally performed before an outbreak occurs. When an outbreak is emerging, it may be necessary to find unexposed individuals or populations to acquire these baseline samples. A lack of understanding of baseline health can hinder determination of the causal agent of disease or its transmission dynamics (Goal DD2). Once a disease emergency is underway, continuously re-assessing health status is crucial for determining the scope of the disease and to determine which other action items are necessary (*baseline to post outbreak*).

✸*This was a particular issue for SSWD—early work suggested a viral pathogen that later was found to be generally common among sea stars and not the disease agent. This shows the power of baseline data to change inference* [48,63].

Goal DD2: diagnostics—conduct laboratory experiments to identify the causal agent of disease and its transmission dynamics

Action Item DD2.1: test disease agents and transmission modes by conducting challenge experiments in the laboratory. These disease challenge trials should be guided by updated Koch's postulates where possible [64], which includes infection experiments that identify the causal pathogen. It is crucial to individually isolate and quarantine all animals used in experiments to prevent spurious inferences from animals exposed to the disease in the wild. While straightforward, this work can take years to complete [55], so undertaking these experiments quickly once an outbreak is identified can be vital. Of particular importance is marine quarantine facilities with seawater systems where pathogens may be filtered from the system. Understanding the disease agent, together with diagnostics (DD2.2), is key for tracking transmission (DD2.3) (*emerging to mid-outbreak*).

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✸*For disease challenge experiments, lessons from SSWD suggest to keep a broad sweep of potential pathogens in early experimental work (e.g. metatranscriptomic analysis) and to evaluate across disease signs and tissue types* [55].

Action Item DD2.2: develop a diagnostic test for identifying and quantifying the disease agent to indicate whether an organism is infected or uninfected. Create disease-specific sampling and storage protocols by refining protocols in DD1.1, which may include new information on target tissues, infrastructure requirements for administering the test. Ideally, sampling kits should be distributed to members of the Monitoring and Response Networks and others for consistent collection of samples (DD1.2, DD1.4, EE1.3). Together with knowledge of the disease agent and transmission modes (DD2.3), diagnostics is a crucial component for tracking transmission (*emerging to mid-outbreak*).

Action DD2.3: track disease transmission dynamics by synthesizing the information collected from analysed tissue samples (DD1.3), environmental samples (DD1.4), transmission experiments (DD2.1), diagnostics (DD2.2) and field surveys of organisms (Goal EE1). This information should be shared with the Ecology and Environment Group as they assess the cause and spread of the outbreak (Goal EE2) and with the Mitigation and Remediation Group as they manage disease transmission (Goal MR1). Since pathogens or hosts may be transported by currents, this is especially challenging and often urgent for fast-moving marine diseases (*emerging to post-outbreak*).

✸*In SSWD, the Multi-Agency Rocky Intertidal Network (MARINe) quickly created an online portal (seastarwasting.org) where scientists and members of the public could submit observations of wasting and healthy sea stars. This enabled geographically broad tracking of the disease spread* [47,49].

Goal DD3: host responses—identify the signs of the disease and the immune responses of the host species

Action Item DD3.1: establish a case definition of the disease based on the most common susceptible species, prevalent clinical signs and disease progression. Determine a simple scale of severity based on visible signs and share this scale with the Monitoring and Response Networks so that health can be tracked consistently during field surveys (EE1.2–1.3). The scale should be simple enough that members of the public and other scientists can participate in community-based tracking of the disease progression, if such involvement is possible and safe (EE1.4) (*emerging to mid-outbreak*).

✸*A formal case definition can take a long time to develop, and one does not exist for SSWD yet. Early work to create a severity-index based on visible signs was imperative for the tracking of SSWD across geographies and time* [51,65,66].

Action Item DD3.2: investigate the immune response of the host to infection using laboratory trials. Areas of interest include histopathology, host transcriptomic response, microbiome composition and proteomic immune response to experimental infection. These trials should occur swiftly once a disease emergency has been identified and can be done in coordination with disease challenge trials (DD2.1) (*emerging to post-outbreak*).

✸*Coordinated immune response work with pathogen discovery work can provide insight into which pathogens to evaluate and supporting evidence for putative pathogens* [67].

Action Item DD3.3: investigate the response of the host microbiome to infection using field collections and laboratory trials on healthy, diseased, exposed and unexposed individuals. Pairing host microbiome studies with controlled disease challenge trials (DD2.1) will increase their utility. If possible, compare these with pre-outbreak baseline health samples as a control (DD1.5) (*emerging to post-outbreak*).

✸*The microbiome of sea stars in response to SSWD suggested dysbiosis, which now is hypothesized to be a secondary infection in a later stage of disease following initial V. pectenicida infection* [22,55,68].

Action Item DD3.4: experimentally test the influence of important potential stressors on disease dynamics in laboratory trials and communicate this to the Ecology and Environment Group. This is an important step for identifying which stressors may trigger or exacerbate an outbreak (Goal EE2), and the information acquired will be essential for developing disease transmission and population viability models (EE4.1–4.2) (*emerging to post-outbreak*).

✸*Field observations and lab experiments suggested that warm temperatures exacerbate SSWD* [4,49,50,69,70]. *Further work looking at interactions between pathogen and host and temperature are in the works following the identification of V. pectenicida as a causative agent of SSWD* [55].

Action Item DD3.5: recommend strategies to test for and support successful disease resistance, immune response or recovery of host to infection and communicate this to the Mitigation and Remediation Group. Considerations include the nature of the pathogen (e.g. bacterial, viral or protist) (DD2.1), the importance of stressors in triggering the disease (e.g. temperature, pollutants) (DD3.4, EE2.1) and the transmission mode (e.g. via a vector or due to human activity) (DD2.1, EE2.2) (*mid- to post-outbreak*).

(b) Ecology and environment

(i) Overview

Disease outbreaks can have devastating impacts on host species and can result in significant and lasting impacts to an entire ecosystem, particularly when the host is a keystone or foundation species [71–73]. In this section, our goals focus on: (i) tracking health and abundance of target wild populations in the field, (ii) assessing the causes of the disease emergency, (iii) assessing the consequences of the disease emergency for the host population, the ecological community and humans, and (iv) developing models that describe disease dynamics and forecast disease outbreaks. We recognize that establishing a marine disease monitoring network for many taxa over a large geographic area would be a monumental undertaking. So, instead of attempting to build such a network from scratch, it is more effective to leverage already-existing research and monitoring programmes targeting metrics like population dynamics and biodiversity in the region by inviting the programme leaders to

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become involved and contribute to targeted disease monitoring. Importantly, many of the actions recommended for the baseline phase would contribute greatly to our overall knowledge of the target species and/or ecosystem, regardless of whether a disease emergency should occur.

(ii) Goals and action items: ecology and environment (EE)

Goal EE1: track health and abundance of target wild populations in the field

Action Item EE1.1: identify target species (potential hosts) that are key candidates for outbreak monitoring before an outbreak occurs. Candidate species include those with an established history of disease, or for which a major disease event would be catastrophic in terms of ecosystem function or economic, cultural or social value [34]. These species include keystone species, foundation species and those that perform critical ecosystem services. Descriptions of signs of already known diseases in target species should be developed. Inclusion of traditional knowledge holders as experts is essential, including Tribal and First Nations entities (*baseline phase*).

Action Item EE1.2: develop field survey protocols to visually track population metrics and general health metrics for target species. Before an outbreak, protocols should be general enough to capture an unknown event in multiple species. As an outbreak emerges or occurs, protocols should be refined to the target species and disease. Protocols should be tiered in their complexity, from data that can be collected easily by the general public at a larger spatiotemporal scale, to rigorous scientific protocols that require training and expertise to track more precise dynamics. Where possible, all field surveys should capture: (i) health metrics that would establish baseline health for target species and help characterize the dynamics of an emerging disease (e.g. timing of emergence, prevalence, severity, signs of disease) and (ii) target species population metrics important for assessing the impact of and recovery from an outbreak (e.g. density, sizes, reproduction, recruitment, survivorship). The signs of disease and field protocols should be updated using observed disease responses from challenge trials (DD2.1). These protocols should be designed for integration into existing monitoring programmes and developed with the scientists, managers and community groups who will carry them out. Leveraging established monitoring programmes reduces the logistical and resource demands required to conduct field surveys and establish baseline health (*baseline to emerging outbreak*).

✸*Reporting for SSWD varied from community-facing reporting systems to detect disease and recovery* [47,49], *to more intensive survey methods used by ecologists to quantify severity and measure effects on host populations* [51,66,74]. *Having a tiered approach that includes both a depth of information and wide breadth of observations is crucial*.

Action Item EE1.3: conduct field surveys to track population abundance and general health metrics of target marine species using the protocols established in EE1.2. This should occur before, during and after an outbreak. During an outbreak, survey teams should be rapidly mobilized to areas both within and outside of the geographic extent of the outbreak to track the abundance of host populations and disease status. The success of these surveys depend on adequate training and timely coordination and response. Augmenting existing monitoring programmes and tissue collection efforts (Goal DD1, Action EE1.2) can make this more feasible (*baseline to post-outbreak*).

Action Item EE1.4: coordinate with scientists, managers, educational outreach groups, harvesters and community scientist groups to track population and disease metrics (using the protocols developed in DD1.1 and EE1.2). For public-facing coordination, platforms like iNaturalist.org where members of the general public can report any sightings of unhealthy organisms are useful resources (e.g. https://www.inaturalist.org/projects/primed-network). During and after an outbreak, a more rigorous reporting platform should be developed to gather contact information for participants, background information, sampling protocols, data and training materials, similar to the platform employed by the Multi-Agency Rocky Intertidal Network (MARINe) group for SSWD (https://marine.ucsc.edu/data-products/sea-star-wasting/index.html) (*baseline to post-outbreak*).

Action Item EE1.5: create a database to record the population and disease dynamics of the host species and its ecological community. As baseline monitoring occurs and an outbreak develops, collating information from various data streams (DD1.2–1.5, EE1.3) into a centralized database is essential for understanding the scope and consequences of a disease emergency. An excellent guide for developing this type of database is the IUCN (International Union for the Conservation of Nature) Red List Assessment Guide [75]. However, maintaining such a database requires management and resources that may not be available (e.g. data QA/QC, funding) (*baseline to post-outbreak*).

✸*See Gravem et al*. [49] *for an example database and assessment developed after the SSWD outbreak that incorporated data from several datasets with varying data collection methods*.

Goal EE2: assess causes of the disease emergency

Action Item EE2.1: identify and track the environmental factors that may influence disease dynamics. Candidate environmental conditions may include water and air temperature, salinity, dissolved oxygen, ocean acidification, turbidity, nutrient concentrations, harmful algal blooms and physical damage from factors like storms or sea ice. It may be important to consider how each factor varies in space and time. This work should be done in tandem with the Diagnostics and Disease Dynamics Group to test the effects of the environmental factors on disease dynamics in the laboratory and through modelling (DD2.3, EE4.1–4.2) (*emerging- to mid-outbreak*).

✸*Warm temperature is associated with exacerbating SSWD in several locations and in the lab and field* [4,50,69,70], *but warm temperatures may not have triggered the initial outbreak* [66].

Action Item EE2.2: identify possible modes of transmission many of which are unique to marine systems, including ocean currents, humans, ballast water in ships, river plumes, aquaculture, vectors, etc. [76–79]. Disease transmission models may be

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particularly helpful for this step (EE4.1). This work should be in coordination with the Diagnostics and Disease Ecology Group (Goals DD1 and DD2) (*emerging- to mid-outbreak*).

Goal EE3: assess consequences of the disease emergency for the host population, the ecological community and humans

Action Item EE3.1: analyse genetic data for changes in host populations associated with the outbreak using samples collected in DD1.3. Comparisons among exposure groups should be made, including unexposed, suspected exposed, diseased and recovered individuals as well as surviving offspring. Allele frequency changes may indicate adaptation, resilience or selection resulting from the disease event. This, combined with differential gene expression analyses can aid with understanding host symptoms or immune response (Goal DD3). Repeat sampling across multiple geographic locations is important to demonstrate how underlying genetics might impact disease outcomes and how the disease or population declines might negatively impact genetic diversity (*mid- to post-outbreak*).

✸*Comparing populations sampled before and after major wasting-associated mortality identified allele frequency changes consistent with natural selection* [80,81] *and comparing wasting versus non-wasting individuals highlighted differentially expressed genes associated with wasting* [82].

Action Item EE3.2: identify exposed populations that exhibit increased resistance or resilience to the disease through either lower infection rates or higher recovery rates, respectively. This can be at the individual or population level. If possible, identify variables associated with areas or populations of resistance or resilience (Goal EE1). This information may be particularly important for decision-making regarding protective measures or captive breeding (Goals MR1 and MR2) (*mid- to post-outbreak*).

✸*A comparative analysis of life history, ecological and other attributes illuminated traits of sea stars that may increase (or decrease) susceptibility or vulnerability to SSWD* [83]. *Remnant populations for* P. helianthoides *were identified in British Columbia, and further work indicated that cooler water locations within fjords were providing a refuge that reduced the mortality of SSWD outbreaks on* P. helianthoides *populations* [69].

Action Item EE3.3: measure the effects of disease-induced host decline on the surrounding ecosystem. Host decline could result in changes in the abundance, density, location or behaviour of other species in the host's ecological community not directly affected by the disease. Approaches could include quantifying changes in predators, prey, competitors, mutualists, symbionts and parasites as well as ecosystem-level processes like primary productivity, carbon sequestration or habitat formation (*mid- to post-outbreak*).

✸*In the case of SSWD, the loss of ochre stars had profound effects on the predation rates of sea stars on mussels in the rocky intertidal region* [66,84–86]. *The loss of sunflower sea stars from kelp forests likely triggered a trophic cascade where populations of their urchin prey expanded and overgrazed kelp forests in their absence* [87–89].

Action Item EE3.4: determine the realized or potential impacts of host decline on ecosystem services such as fisheries, aquaculture, tourism and culture. If appropriate, the economic or cultural impacts of the disease should be calculated (*mid- to post-outbreak*).

✸*Kelp forest losses tied to SSWD have impacted fisheries, endangered species and coastal communities and are estimated to have cost $47 million USD yr^{-1} in northern California and $23 million USD yr^{-1} or more in Oregon in lost economic value* [90,91].

Goal EE4: develop models that describe disease dynamics and forecast disease outbreaks

Action Item EE4.1: construct a model of disease transmission by integrating the findings of Goals DD1 (assess health of individuals using tissue collections), DD2 (diagnostics), EE1 (track health and abundance of target wild populations) and EE2 (assess causes of the disease emergency). Models should be directed towards answering questions that can aid in management, such as likely transmission modes given disease spread (EE2.2), or testing multiple intervention outcomes given what is known about the system. These types of models are generally underdeveloped for diseases in marine systems [32]. For a waterborne disease, models that can incorporate water currents and transport of hosts and pathogens by currents, combined with traditional epidemic models (Susceptible-Infectious Recovered, or SIR models), are a useful approach (e.g. [37,92]) (*mid to post-outbreak*).

✸*Models of SSWD have provided insight on a plausible mechanism of disease spread* [37], *the influence of refuge populations* [93] *and the effect of managed reintroductions* [94].

Action Item EE4.2: build population viability model to assess recovery potential and extinction risk of a severely affected host population across spatial scales to identify whether the species is a candidate for international, federal and/or state sensitive, threatened or endangered species lists. This analysis should include data on population declines among locales, rates of continued decline or recovery, remaining population demographics, reproductive output, dispersal potential, population connectivity and/or growth rates (informed by Goals DD1, EE1 and EE2). A useful guide for this process is the IUCN criteria for assessing extinction risk [75]. If recovery potential is low, management actions should be identified with the Mitigation and Remediation Group (Goal MR2) (*mid- to post-outbreak*).

Action Item EE4.3: forecast the likelihood of future disease outbreaks by building on the findings in EE4.1 and 4.2 and considering future risk factors such as host population densities, population size structure, the presence of disease in the past, the presence of the disease in closely related species or future environmental regimes. This is particularly important if disease severity or transmission is altered by environmental conditions like increasing temperatures, increased pollutants or other anthropogenic disruptions (*post-outbreak*).

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(c) Mitigation and remediation

(i) Overview

Mitigation and remediation are often situated at the interface of human communities and ecological systems. Choosing appropriate management actions requires knowledge of the disease and its impacts, but success also requires understanding unique cultural, social, spiritual and economic ties that human communities have with affected species and ecosystems. Ultimately, every disease outbreak will differ in which containment, mitigation, remediation and recovery actions are most appropriate. Broadly, the goals of the Mitigation and Remediation Group are to provide an overarching template for management that includes general and reasonably comprehensive potential actions. In this section, the goals are to: (i) contain or slow a disease outbreak with local and regional actions, (ii) pursue management actions to protect or recover host populations, and (iii) mitigate the economic, social and cultural consequences of disease for human communities. Not all potential actions will be relevant or appropriate for any given marine disease outbreak, but our goal is to provide a reasonable formula to aid in the construction and implementation of effective mitigation and remediation plans.

(ii) Goals and action items: mitigation and remediation (MR)

Goal MR1: contain or slow a disease outbreak with local and regional actions

Action Item MR1.1: develop actions to minimize disease spread. Important considerations for this action should be to first evaluate the utility (or futility) of this action, followed by the feasibility and any legal and regulatory constraints. The potential actions will depend on the causal agent of disease, transmission dynamics, causes of the disease emergency and findings from disease dynamics models (Goals DD2, EE2 and EE4). For example, if ballast water is a potential vector, special (and temporary) limitations on the uptake or discharge of ballast water may be recommended. Alternatively, if pollutants are a key driver, minimizing pollutant exposure would be advised. Finally, it is important to consult with stakeholders on potential management actions to minimize negative economic, social and cultural impacts (*emerging to mid-outbreak*).

Action Item MR1.2: assess transmission risk of the disease to humans. If human health is or could be affected, particularly if consequences may be severe, strategies to reduce public contact with the disease agent should be identified and shared with the local department of health and any personnel involved in monitoring. Local health departments have access to testing resources, disease transmission expertise and broad human health data. If transmission to humans is suspected or confirmed, they may be able to help with data and tissue collection and sample testing. Additionally, they have established protocols related to disease transmission; personal protective equipment such as gloves may need to be worn by individuals entering an area with known or likely disease presence (Goals DD1 and EE1, MR1.3) (*emerging to mid-outbreak*).

Action Item MR1.3: if human activity is involved in disease transmission (e.g. as a fomite), develop protocols for decontamination of equipment and people (DD1.1 and EE1.2). This could include limiting access to an area with known or suspected disease presence and developing guidelines for cleaning lab and field equipment and footwear such as rubber boots and other surfaces that could function as fomites. Protocols for commercial or recreational activities may also be necessary, such as a decontamination protocol for watersport gear [95,96] (*emerging to mid-outbreak*).

Action Item MR1.4: assess if localized fishery closures, harvest restrictions or temporary closures of public beach access may be necessary to control further spread of the disease outbreak or to limit consequences for the host or ecosystem. Stakeholders should be consulted to minimize negative economic, social and cultural impacts of proposed actions (supports Goal MR3). The necessity of potential area closures or restrictions should be clearly communicated to the public (*emerging to mid-outbreak*).

Goal MR2: pursue management actions to protect or recover host populations

Action Item MR2.1: determine the advisability of quarantining individuals of the affected species. Proper quarantine facilities and requirements for housing quarantined individuals should be identified suitable for marine hosts. Pathogen and species-specific protocols to maximize disease containment must be developed. Quarantined individuals can then be utilized to gather additional information about disease and to explore potential treatments. When an affected species is rare or the disease event is severe, consider isolating uninfected/unexposed individuals until the outbreak has subsided. To obtain requisite permits for quarantine activities, work with appropriate federal and state agencies (*emerging to mid-outbreak*).

✸*For SSW, captively held individuals have served as an important resource to fill gaps in knowledge about the host's life history and reproductive patterns* [97], *potential pathogens* [55], *pathophysiology* [98] *and genetic diversity and were key for developing treatments* [99].

Action Item MR2.1: evaluate the utility of thinning or culling affected populations if the spread of the disease is strongly linked to host density or if individual disease carriers can be identified. Note that a demonstrated link is essential before taking this action, as marine disease spread and severity is not always coupled with host density. Disease-specific protocols should be developed to minimize the loss of life, and appropriate federal and state agencies should be consulted for obtaining requisite permits. Prior to engaging in thinning or culling activities, Tribal/First Nation entities should be consulted to ensure proper handling/disposal with respect to legal and cultural sensitivities (supports Goal MR3) (*emerging to mid-outbreak*).

✸*Miner et al.* [51] *investigated any link between host density and the severity of SSWD and found no evidence of density-dependent disease severity in ochre stars*.

Action Item MR2.3: enact protections for resilient and/or surviving host populations by protecting habitat or limiting commercial or recreational take. The spatial and temporal scope of these protections should consider the local environmental stressors at the

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locale or genetic characteristics of the resilient populations (Goals DD3, EE2, EE3). The populations in these areas should be monitored, using similar protocols to other locales (DD1.1, EE1.2). Stakeholders should be consulted to minimize negative economic, social and cultural impacts of proposed actions (supports Goal MR3) (*emerging to post-outbreak*).

✸*For SSWD, the scientific community did not pursue take limitations for sunflower sea stars because humans do not generally fish sea stars, bycatch is minimal and because protections would have impeded scientific pursuits and caused unnecessary issues with fishermen* [49]. *They are likely to become listed under the US Endangered Species Act as 'threatened'* [100] *but no legal protections are currently in place.*

Action Item MR2.4: cryopreserve gametes or larvae to catalogue and protect genetic diversity for future conservation actions. Disease outbreaks can lead to rapid population declines and with that potential loss of genetic diversity. Preserving this diversity early in an outbreak generates a 'biobank' resource that becomes more important should host populations continue to decline and can serve to rescue a population in dire circumstances. Maintaining genetic diversity is important for adaptive potential to future and intensifying marine threats (*emerging to post-outbreak*).

✸*Aquarists and SSWD scientists have teamed up to form an AZA SAFE programme (Saving Animals from Extinction) for the sunflower sea star and a top priority is preserving gametes, embryos and larvae to document and preserve genetic diversity and to enable captive rearing research and reintroduction efforts* [101].

Action Item MR2.5: consider feasibility of translocation-based and/or captive breeding-based reintroduction programs. Translocation (i.e. moving individuals from source populations to a restoration area) should primarily be considered when source populations exist, the disease agent is known, and the potential for asymptomatic transmission is low. Captive breeding and reintroductions should be considered when local source populations are scarce, are genetically disadvantaged or could potentially transmit disease. For captive breeding, candidate donor populations (or captive individuals) that exhibit resistance and/or retain desired genetic diversity or suitability are desirable (EE3.2). Any reintroduction plan should consider impacts to candidate source and target populations and locations, ideal seasons and conditions, potential for long-term survival and disturbance/benefits to the ecosystem. Communication with stakeholders and the public about translocation, captive breeding and reintroduction efforts is essential (supports Goal MR3). After translocations or reintroductions, working with community-based monitoring programmes to collect population data to evaluate the success of the programme is crucial and can be leveraged by Goals DD1 and EE1 (*emerging to post-outbreak*).

✸*At the start of SSWD, no US West Coast sea stars with pelagic larvae had ever been reared past the early juvenile stage. Hodin* et al. [97] *developed the protocols for rearing* P. helianthoides*, and as of 2025, three research groups have experimentally returned cohorts of either captively bred (University of Washington Friday Harbor Labs, Sunflower Star Laboratory) or cohorts of wild-caught and translocated (Oregon Kelp Alliance) sunflower stars back to the wild. Little to no mortality has been observed during these translocations.*

Goal MR3: mitigate the economic, social and cultural consequences of disease for human communities

Action Item MR3.1: evaluate the economic, social and cultural impacts of the disease due to changes in the host species or host communities. A publicly available report and synthesized estimates of these impacts should be created and shared with managers and local communities to better inform management decisions and mitigate effects on human user-groups. To assess these impacts, convene community knowledge-holders including Tribal/First Nations governments, local governments, industries, community organizations, public health entities, resource economists, sociologists, recreationalists and experts on the disease outbreak. As part of this effort, management projects that could ameliorate some of the long-term societal impacts of the disease should be identified (*emerging to post-outbreak*).

✸*The Oregon Kelp Alliance is focused on restoring kelp forests on the Oregon coast, with contributions and partnerships from many of the diverse stakeholders outlined above. They recently published a public-facing report on kelp declines and its link to SSWD* [90].

Action Item MR3.2: assess potential economic, social and cultural impacts of enacted or proposed mitigation and remediation efforts. Convene community members (listed in MR3.1) to assess the potential long-term economic, social and cultural impacts of the recommended mitigation and remediation actions (*emerging to post-outbreak*).

Action Item MR3.3: engage affected community members in monitoring, data collection, mitigation, remediation and adaptation projects These projects can often be integrated into other community-based monitoring and response efforts (Goals DD1, EE1, MR1, MR2). When feasible, these efforts should prioritize employing affected community members (*baseline to post-outbreak*).

✸*SSWD scientists have teamed with the volunteer-based SCUBA diving organization Reef Check to monitor kelp forests, remove sea urchins and track sunflower sea star recovery in Oregon and California* [90,102].

4. Discussion

This contingency plan provides an essential framework for preparing for future marine disease outbreaks or emergencies. A collaborative network of participants with expertise in each of three specialty areas (Diagnostics and Disease Dynamics, Ecology and Environment, and Mitigation and Remediation) is an ideal format for approaching a marine disease management plan. Participants should be drawn from various disciplines and backgrounds, including researchers, policymakers, fishers, Tribal and First Nation members, natural resource managers and community scientists. Since the different goals and actions should be undertaken before, during and after a disease emergency, we recommend organizing network participants into Monitoring and Response Networks, with both teams ideally formed before a disease emergency occurs since several action items above must occur very quickly thereafter. Ultimately, effective disease response in a changing ocean hinges on our preparedness for marine disease emergencies. We advocate for infrastructure and support, including dedicated public funding, to build and maintain marine disease monitoring and response networks.

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The formation of this contingency plan was motivated by a marine disease event with specific parameters (see §2c, 'Intent and Scope'). Alternate scenarios would require additional considerations and likely different prioritization of particular goals or actions. For example, if the disease occurs in an endangered or protected species, additional oversight and permitting may be necessary to ensure that no harm is caused by monitoring or response efforts. The urgency of every mid- and post-outbreak action item would be heightened, and management efforts for mitigation and remediation would likely need to be pursued quickly. Alternatively, if the disease occurs in a commercially or recreationally harvested species, the knowledge base for species might already be well established; actions like identifying the symptoms and immune response or developing tissue sampling and field survey protocols may be unnecessary. The dynamics of transmission may also be much more complicated, especially if the pathogen is being exchanged between wild and captive populations or influenced by harvesting practices. Furthermore, many of the other goals would become more urgent, including identifying the cause, determining the consequences of decline, modelling disease dynamics, slowing the outbreak and mitigating the economic, social and cultural consequences of host decline. Finally, if a mortality event is not caused by an infectious disease (e.g. algal blooms, low oxygen events, marine heat waves), action items regarding diagnostics would be irrelevant, but several actions recommended for assessing the consequences for the host or the ecosystem or steps for mitigation and remediation actions would be easily transferable.

The generalized contingency plan we describe here explicitly addresses a strategy for improving surveillance, detection, response and mitigation of unpredictable and inevitable disease emergencies. This plan is meant as a basic starting point and guide, and the utility and sufficiency of this plan in a given disease emergency scenario should be evaluated by the relevant scientific expert groups. In particular, different actions may be given more urgency, weight or occur in a different order in a given case. For example, quarantining (MR2.1) or cryopreservation (MR2.4) may be most important for small, marginalized populations. Modelling transmission (EE4.1) or decontamination regulations may be important if humans are a fomite (MR1.3). Measuring the effects of host decline on the surrounding ecosystem (EE3.3) may be unimportant if the host is rare or a weak interactor. Ultimately, practitioners should evaluate and adapt this plan to their scenario and modify it continually as needed.

We stress that disease monitoring and response is only one part of a larger effort to improve global ocean health. Areas of interest for preventing disease outbreaks include preserving habitats that serve as natural ecosystem filters (e.g. mangroves, seagrasses and bivalve reefs), changes in biosecurity protocols to reduce pathogen movement, conserving habitats and biodiversity using Marine Protected Areas (MPAs), and identifying and reducing sources of point pollution [32]. Ultimately, anthropogenic impacts, particularly climate change and pollution, are major drivers of increasing marine disease in the changing ocean and proactive reduction of these threats is urgently needed.

We conclude with the hope that this contingency plan provides an effective framework and model for scientific communities to quickly and effectively respond to marine disease emergencies. The importance of ecosystem services provided to coastal communities, and the threats posed to them by marine diseases, cannot be overstated. Because these impacts are expected to worsen with climate change and ever-increasing demands on the ocean for use by people, building and supporting monitoring and response networks is crucial.

Ethics. This work did not require ethical approval from a human subject or animal welfare committee.

Data accessibility. This article has no additional data.

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. S.A.G.: conceptualization, funding acquisition, investigation, project administration, supervision, visualization, writing—original draft, writing—review and editing; L.C.F.: conceptualization, investigation, visualization, writing—original draft, writing—review and editing; S.B.: conceptualization, investigation, writing—original draft; J.L.B.: investigation, writing—review and editing; K.G.: investigation, writing—review and editing; S.L.H.: investigation, writing—original draft; L.L.M.: investigation, writing—original draft, writing—review and editing; C.M.M.: conceptualization, investigation, writing—review and editing; L.M.S.: investigation, writing—review and editing; K.J.T.: investigation, writing—original draft; A.-L.M.G.: conceptualization, investigation, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

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