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PROFILE

A Framework for Responding to Coral Disease Outbreaks that Facilitates Adaptive Management

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Abstract Predicted increases in coral disease outbreaks associated with climate change have implications for coral reef ecosystems and the people and industries that depend on them. It is critical that coral reef managers understand these implications and have the ability to assess and reduce risk, detect and contain outbreaks, and monitor and minimise impacts. Here, we present a coral disease response framework that has four core components: (1) an early warning system, (2) a tiered impact assessment program, (3) scaled management actions and (4) a communication plan. The early warning system combines predictive tools that monitor the risk of outbreaks of temperature-dependent coral diseases with in situ observations provided by a network of observers who regularly report on coral health and reef state. Verified reports of an increase in disease prevalence trigger a tiered response of more detailed impact assessment, targeted research and/or management actions. The response is scaled to the risk posed by the outbreak, which is a function of the severity and spatial extent of the impacts. We review potential management actions to mitigate coral disease impacts and facilitate recovery, considering emerging strategies unique to coral disease and more established strategies to support reef resilience. We also describe approaches to communicating about coral disease outbreaks that will address common misperceptions and raise awareness of the coral disease threat. By adopting this framework, managers and researchers can establish a community of practice and can develop response plans for the management of coral disease outbreaks based on local needs. The collaborations between managers and researchers we suggest will enable adaptive management of disease impacts following evaluating the cost-effectiveness of emerging response actions and incrementally improving our understanding of outbreak causation.

Keywords Climate change · Coral reefs · Coral disease · Management actions · Outbreaks · Response framework

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Introduction

Coral diseases can cause widespread coral mortality and have been a key factor in the degradation of important reef ecosystems, such as the Florida Keys (Porter and others 2001) and the wider Caribbean (Weil and Rosenberg 2004; Pandolfi and others 2005). Because coral diseases can progress rapidly, there is often only a brief window of opportunity for observations that can confidently attribute mortality to agents of disease (Harvell and others 2007). Some coral diseases are more prevalent in summer, like Black Band disease (BBD) (Sato and others 2009) and White Syndromes (WS) (Willis and others 2004). Summer provides a focal period for disease detection but even monitoring programs that visit sites repeatedly can underestimate disease-induced mortality if they are not undertaken when temperatures are at their peak. Therefore, the extent to which disease drives coral community structure—especially on Pacific and Indian Ocean reefs—is largely unknown (Sutherland and others 2004; Bruno and Selig 2007) and probably under-appreciated since it is likely that mortality caused by disease may be attributed to other disturbances (Osborne and others 2011).

There is an urgent need to better understand the implications of coral disease for coral reefs and their management (Raymundo 2010). Climate warming is projected to increase outbreaks of diseases in marine organisms like corals as well as in populations of humans, agricultural crops, and terrestrial wildlife (Harvell and others 2002). On coral reefs, rising temperatures are expected to increase the virulence of many of the pathogens that cause diseases (Harvell and others 2007; Rosenberg and others 2007). All of the following will also increase the susceptibility of corals to diseases: the frequency and severity of bleaching events (Hoegh-Guldberg and others 2007), increases in the frequency of severe storms (Abbs and others 2006), and the possibility of changes in rainfall patterns leading to more floods in some areas (Prudhomme and others 2002). The risk of more frequent coral disease outbreaks as the climate changes will be further exacerbated by regional and local-scale anthropogenic stressors (Bruno and others 2003; Marshall and Schuttenberg 2006), making it almost certain that coral disease will be an increasingly large contributor to coral reef decline in the changing climate of this century (Harvell and others 2007).

The potential for damage to coral reefs from coral disease has significant implications for the social systems that depend on goods and services from these rich ecosystems (general review in Adger and others 2005). More than 500 million people live in coral reef regions of the world (Burke and others 2004) and many rely heavily on these ecosystems for income, food and shoreline protection. In Australia alone, approximately $5.1 billion AUD is generated by tourism to the Great Barrier Reef (GBR) region annually and approximately $300 million is generated by fishing-related activities (Access 2007). The ability of reefs to meet these subsistence and cultural needs is undermined if disturbances like coral diseases cause extensive mortality. Even when mortality is localised it can substantially reduce economic flows to communities and industries that derive income from activities like fishing and tourism (Moberg 1999).

The ecological and social impacts of coral disease outbreaks can be severe, and a *Handbook* has been produced that provides a review of management options and aids managers in identifying diseases and assessing impacts when they occur (see Raymundo and others 2008). As yet though, there remains little guidance for coral reef managers faced with the need to operationally respond to coral disease outbreaks in a clearly defined, structured manner. From this point forward, ‘managers’ refers to anyone that has a responsibility to respond over any time scale to coral reef health impacts from the perspective of mitigating impacts, communications, or policymaking. Response actions for managers include: determining where outbreaks are likely to occur, effectively targeting response capacity and prioritising management investment, mitigating impacts at severely affected sites, trialing various emerging strategies, and communicating with other managers and stakeholders about outbreaks and their impacts. Guidance in all of these areas is critical given the prospect of increasingly frequent coral disease outbreaks and increasing expectations of a meaningful management response (Raymundo and others 2008). We have developed a framework for responding to coral disease outbreaks that helps meet these emerging challenges enabling a structured, adaptive response to this important, emerging risk.

The framework has four core objectives:

1. To increase our understanding of coral disease outbreak causation and help elucidate the relative importance of climate-related and anthropogenic stressors as drivers of outbreaks.
2. To enable rigorous assessments of outbreak severity so that the investment of management responses can relate directly to the severity and spatial extent of the impacts.
3. To facilitate prioritisation (based on cost-effectiveness and successful trials) of emerging responsive management actions that mitigate disease impacts or enhance recovery.
4. To ensure timely and credible information on coral disease outbreaks is made available to inform management responses and raise awareness of the coral disease threat amongst stakeholders.

The coral disease response framework is based on the widely adopted response framework for coral bleaching (see Maynard and others 2009), which has 4 components (see GBRMPA 2010): an early warning system, impact assessment and monitoring, management actions, and communication. Though the framework component names are shared, coral diseases and coral disease outbreaks warrant managers develop a response plan based on the framework that is distinct from bleaching because: (a) diseases affect corals year-round rather than seasonally, (b) diseases can be cryptic and can be difficult to identify rather than nearly always being visible at great distance, (c) there is greater scope for management action at a range of spatial scales, and (d) coral disease outbreaks pose unique challenges for communications given the misperceptions and lack of understanding of what coral disease outbreaks mean for human communities.

Each component of the framework forms a section of the paper and has been set up to be readily adapted by managers everywhere. Managers can prepare a tailored response plan based on the framework presented here by adapting the parts of the framework they find most applicable and relevant in their management area and given their organisation's structure and resources.

The early warning system section describes tools that predict the likelihood of outbreaks of temperature-dependent diseases. These tools are combined with a monitoring network that can both ground-truth predictions and report to managers when anomalous levels of disease are observed. Managers can either use the guidance here to develop their own predictive tools and monitoring networks or can use or tailor those already established. In the impact assessment and monitoring section, reports of outbreaks trigger site inspections that are used to determine whether further management investment is warranted in more detailed impact assessments. Managers can either undertake impact assessments themselves or collaborate with those implementing other monitoring programs and/or with researchers. If outbreaks are documented during impact assessment, management actions and communications efforts are triggered that vary from targeted research to temporary closures, reef restoration, trials of emerging strategies to mitigate the impacts of coral disease, and communication. A range of management actions and communications approaches are proposed such that all managers have at least some options and guidance is provided to help managers implement the framework.

Early Warning System

An effective response to coral disease outbreaks depends on knowledge of where they are likely to occur and/or timely receipt of in situ observations of an outbreak. Therefore, the early warning system has two parts: (1) predictive tools for assessing the risk of temperature-dependent disease outbreaks, and (2) a monitoring network (volunteer or otherwise) for in situ detection of all diseases that has the added benefit of strengthening relationships between managers, stakeholders and community members. More generic guidance on monitoring environmental conditions and assessing reef health should be sought from the many detailed publications available on these topics (Hill and Wilkinson 2004; Marshall and Schuttenberg 2006; Raymundo and others 2008).

Predictive Tools

Outbreaks of some coral diseases are caused by combinations of environmental and ecological conditions that can be used to assess outbreak likelihood. For example, researchers have shown that outbreaks of WS and BBD both appear to be seasonal with the greatest prevalence detected at the end of hot summers (Bruno and others 2007; Maynard and others 2011). Tools that assess bleaching risk can also be useful for determining the likelihood that outbreaks of temperature-dependent diseases will occur since bleaching increases disease susceptibility (Mydlarz and others 2009). For temperature-dependent diseases, there are four approaches to determining the likelihood that an outbreak will occur. Two are useful in the lead-up to summer: seasonal outlooks and forecasts of temperature anomalies. These help predict the likelihood of a spatially extensive bleaching event and are reviewed in Maynard and others (2009) so are not covered here. Two others are useful during the months when sea temperatures usually peak (summer or otherwise): near-real time monitoring of sea surface temperature (SST) and measures of temperature stress, and integrated risk prediction models. Tools that enable near-real time monitoring of SST and measures of temperature stress help to target surveys of bleaching impacts (Maynard and others 2009), and managers can then survey these sites in the months that follow for disease. Here, we focus on new integrated risk prediction models developed specifically for a group of coral diseases called WS.

Seasonal outlooks for temperature-dependent diseases can be produced in the lead-up to the known risk period for outbreaks of temperature-dependent diseases (i.e., summer). Research in Australia suggests the likelihood of outbreaks of WS in summer is increased when preceded by mild winter temperatures (Heron and others 2010, see Fig. 1a). The experimental seasonal outlook product produced by NOAA Coral Reef Watch is currently only available (at http://coralreefwatch.noaa.gov) for Australia's GBR and the Hawaiian archipelago but will become available for other reef regions as our understanding increases of the role of winter temperatures in causing coral disease outbreaks in other reef regions.

The abundance of (WS) on the GBR has been related to temperature stress and coral host density (Bruno and

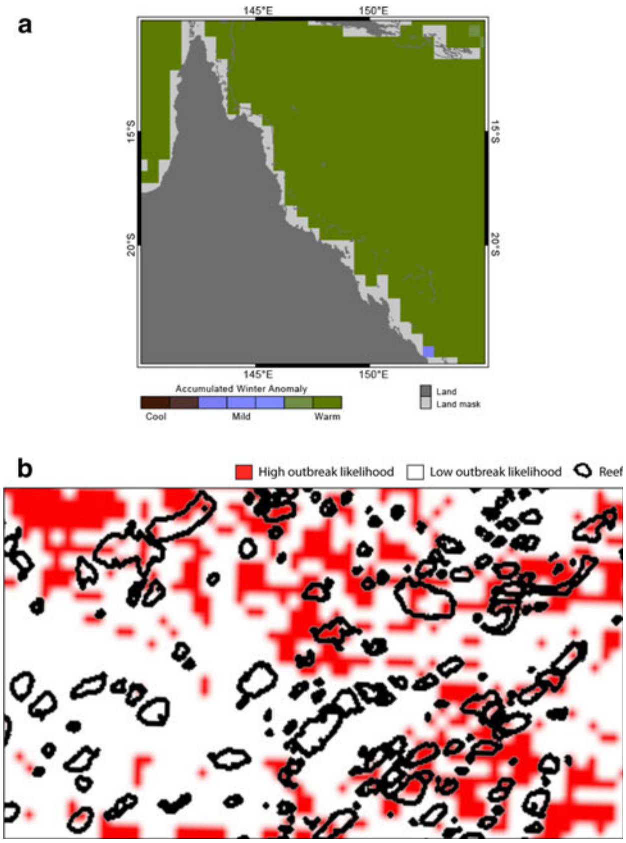

Fig. 1 Predictive tools specific to coral disease used in the early warning system. The experimental seasonal outlook of disease risk for the 2010/11 austral summer, issued October 2010, is shown in (**a**) and reflects that the 2010 winter was amongst the warmest on record for the area (Heron and others 2010). A tool enabling monitoring of the likelihood of outbreaks of WS is shown in (**b**) from the Swains reefs in the southern Great Barrier Reef in 2002. The image shown in (**b**) was produced in Google Earth™

others 2007), leading to the recent development of two *near real-time* tools for monitoring likelihood of outbreaks of WS. Using a decision-tree approach, one tool (Heron and others 2010) uses winter and summer sea temperature stress metrics at 50 km resolution to produce an outbreak risk assessment that has to be interpreted based on local knowledge of host density—i.e., risk is highest where coral cover is highest (http://coralreefwatch.noaa.gov). The complementary tool (Maynard and others 2011) provides advanced capacity to inform management decision-making in two ways: (1) it is based on the high-resolution ($\sim$1.5 km) temperature data used for the *Reef Temp* product suite (see Maynard and others 2008) so the tool enables the monitoring of disease risk at the scale of an individual reef; and (2) an overlay of historical coral cover is included, so outbreak likelihood is only shown to be high for locations where long-term monitoring suggests host density exceeds an empirically derived threshold. The integrated risk prediction tool (Fig. 1d) presented in Maynard and others (2011) is based on a multivariate regression model of disease abundance, temperature stress and coral cover conditioned on the values for each variable documented during an outbreak of WS on the GBR.

The value of the integrated risk prediction tool (Fig. 2b) was demonstrated in the north-central GBR in 2009 when the tool correctly identified locations where abundance levels of WS were anomalous. Targeted expert prevalence surveys in these locations (Fig. 3e) revealed more disease than was expected at sites with less than 50% coral cover (Maynard and others 2011). This result suggested that the density of coral hosts required for WS outbreaks on the GBR is likely to be lower than earlier research had suggested (Bruno and others 2007). The implication is that more reefs on the GBR are susceptible to WS outbreaks when temperature stress is severe than previously thought. This validation work has changed the way outbreak risk is calculated on the GBR enabling more targeted impact assessment and management responses.

Ground-truthing predictions made by predictive tools helps increase our understanding of the links between stressful temperatures and both the susceptibility of corals to diseases and the virulence of disease-causing pathogens. For now, these models are available for the GBR and Hawaii only and only for WS. However, the iterative approaches used to produce predictive models and tools can be applied to other diseases and/or reef regions. Models can be conditioned based on observations made at sites where disease outbreaks are known to have occurred in the past, then used to predict outbreaks, and validated and refined when stressful conditions suggest outbreaks will occur.

Monitoring Network

Detecting the early signs of a disease outbreak requires a network of observers since many reefs are visited by managers infrequently and because a disease outbreak can spread quickly (see Francini-Filho and others 2008). For temperature-dependent diseases, networks can ground-truth predictions made by tools that predict bleaching as well as the models described above and others like them when they become available. For all other coral diseases, networks can provide cost-effective reports on disease abundance from sites throughout a management area (see Mayfield and others 2001 for general review).

Through the *BleachWatch* program, monitoring networks have proven their merit by detecting the early signs of bleaching on the GBR and in Florida and helping to quantify the spatial extent and severity of bleaching events (Maynard and others 2009). Establishing and maintaining volunteer monitoring networks requires: (1) identifying potential participants, (2) training and knowledge/skill

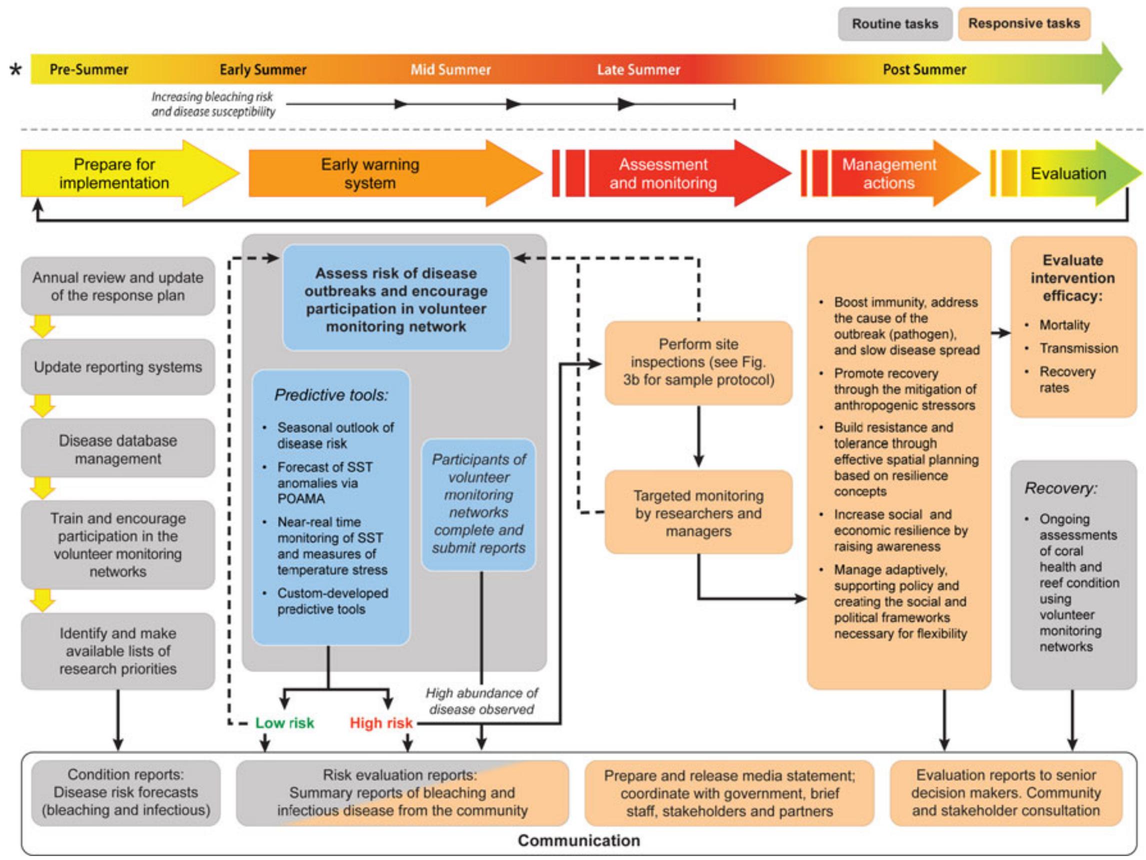

Fig. 2 Implementation of the response framework involves completing routine and responsive tasks through the course of a year. The coloured bar running along the top highlights that the risk of outbreaks of some coral diseases is highest in the summer, though managers could be at any stage of the response framework during any part of the year (*asterisk*), depending on when outbreaks are documented. Response framework implementation and the response framework itself are necessarily adaptive; evaluation informs preparing for implementation as the results of targeted monitoring and advances in research inform future management actions and future versions of this framework

testing, (3) data collection, and (4) facilitating communication between participants and managers (Musso and Inglis 1998). Several community-based monitoring programs have been established globally (e.g., ReefCheck, GCRMN). Managers may find benefit in strengthening links with these networks to increase participation or improve alignment of the objectives of monitoring programs with the information needs of managers (as in Pattengill-Semmens and Semmens 2003). New networks can be set up, or existing networks can be aligned with the information needs of managers, irrespective of local resource availability. How each of the four steps recommended above are carried out, the technologies used, and the extent to which existing training materials and datasheets are tailored for local use can all be adapted to local resource levels.

The training required will vary with different observers (i.e., some participants will not need to be trained) and needs to focus on the data collection protocol while also providing critical background and some insights as to how the information collected will be used. Ideally, the protocols used for monitoring networks will produce data that are comparable between reef regions (see Beeden and others 2008; Bruckner 2002). This suggests that protocols for collecting coral disease data should have the following characteristics: cover a defined area, produce estimates of the % of coral cover affected, list the number of colonies affected by the common types of coral diseases in a management area, describe the coral lifeforms affected by each of the common diseases, and be able to be completed in a timeframe (10–20 min) that does not interfere with the reason the observer is visiting the reef (see Fig. 3c). These are the characteristics of the data collection protocol used by the volunteer monitoring networks in Australia (Fig. 3b, c). A series (usually 3) of circular areas of reef with 5 m radii are surveyed at the same depth and the number of colonies within eight lifeform categories affected by common disease types are recorded, as is the coral cover, and percentage cover affected by disease (Fig. 3c). Notes regarding the prevalence of other diseases can also be taken

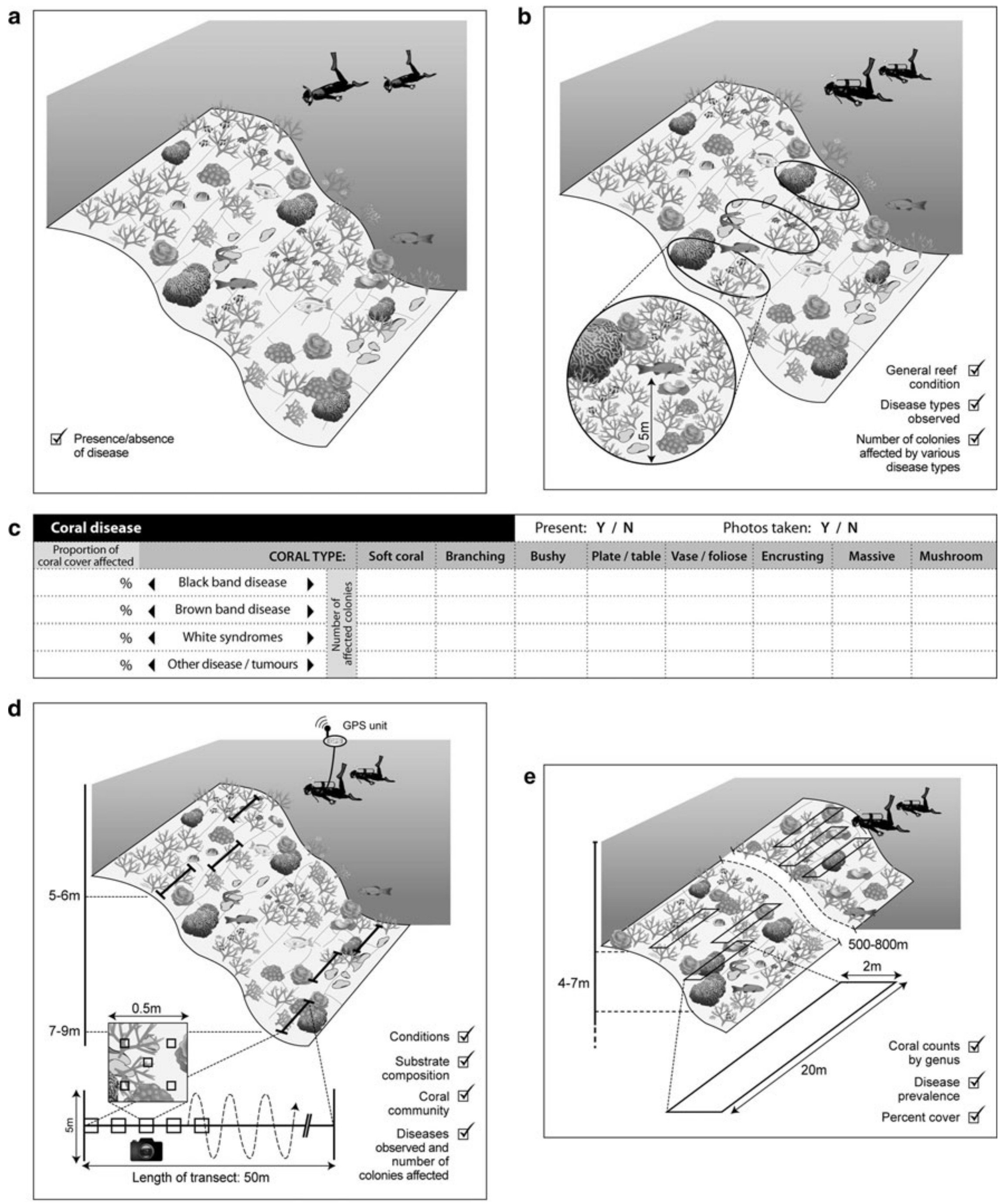

Fig. 3 Suggested impact assessment (**a–c**) and monitoring protocols (**d**) for the response framework. The simplest surveys conducted by participants in a monitoring network might only record presence/absence of disease (**a**). The monitoring networks on the Great Barrier Reef use the protocol shown in (**b**), as do managers when undertaking targeted impact assessments during site inspections, enabling completion of the table shown in (**c**). When outbreaks occur, surveying reefs using the protocol shown in (**d**) enables a rapid assessment of impacts and the creation of a longer-term record. Protocols forming **a**, **b**, and **d** are useful in determining 'status', measures of coral health and reef condition. Researchers can undertake (**e**) annually to determine trends in disease prevalence in an area

as can photos. More simply, managers can have participants collect data on presence/absence of diseases (Fig. 3a). In this way, even when resources are limited managers increase the chance that they will detect disease and can get in contact with collaborating NGO's, universities, or other management agencies to determine whether more detailed assessment and monitoring can be undertaken.

Observations of diseases from a monitoring network can ensure broad coverage that may help make clear whether coral diseases are more or less prevalent in areas of higher relative anthropogenic stress. In this way, having an early warning system helps ensure that targeted impact assessment, monitoring and research efforts help to elucidate the relative importance of climate-related and anthropogenic stressors in disease outbreak causation (objective 1 of the framework). Monitoring networks can also promote stewardship (Stepath 2000; Savan and others 2003) by encouraging members of reef-dependent industries (such as tourism and fishing), regular reef visitors, amateur naturalists and other enthusiasts to participate in monitoring while also tapping into the great wealth of their knowledge.

Monitoring seasonal outlooks of disease risk, sea temperature forecasts, measures of sea temperature stress in near-real time, custom-developed predictive tools (see Fig. 1) and reports sent in by observers all form routine tasks carried out every year regardless of conditions (see Fig. 2). 'Site inspections' will be conducted if conditions are highly conducive to disease outbreaks and/or reports of disease outbreaks are received from observers participating in a monitoring network. Site inspections form a responsive task and part of the impact assessment and monitoring component of the framework (Fig. 2) discussed in the next section.

Impact Assessment

The overarching objective of the assessment and monitoring component (objective 2 of the framework) is to assess the spatial extent and severity of outbreaks as a foundation for: communicating the status of coral health and reef condition at impacted sites, making management decisions, and taking account of likely social and economic impacts. Both assessment and monitoring and management actions are responsive tasks in the framework (see Fig. 2) and hence represent investment of management resources. We recommend a hierarchical approach whereby relatively small investments are made into site inspections first since they can determine whether larger investments are well founded. Site inspections are impact assessments at high risk sites. These surveys determine whether and where targeted research and monitoring should be undertaken, which, in turn, determines whether and where management actions should be taken, as well as what management actions are appropriate.

Locations may be classified as having a high risk of an outbreak due to conditions at the site being conducive to either bleaching or diseases. At these locations, site inspections will often be the first surveys conducted at the site since the onset of stressful conditions. Alternately, disease outbreak risk at a site may be classified as high due to the receipt of numerous reports of coral disease from participants in the monitoring network. In these cases, site inspections serve to validate observations made by observers participating in monitoring. In either case, the survey protocol could be that proposed for the monitoring networks (Fig. 3d) and completed by either managers or collaborating researchers. On the GBR, the severity of an outbreak is defined by a matrix of disease abundance (cases in a defined area) and the spatial extent of the outbreak—the number of reefs affected in the management area (see Fig. 4). The matrix helps to scale management responses and could be adapted for any management area. Managers can work with researchers to determine what level of disease abundance or prevalence should correspond to the low, medium and high categories. Spatial extent may not be a useful component of a measure of the severity of threat posed by a disease outbreak in small management areas. For larger areas, managers can set the spatial areas (or number of reefs) that define local, regional and widespread. Managers may also want to simplify the matrix to low and high, and local and regional. In these cases, the severity of the disease threat either triggers a management response or does not, rather than the scaled responses produced by the 3×3 matrix shown in Fig. 4.

In the matrix used in the Great Barrier Reef, expert site inspections are triggered if disease abundance is high and/or medium disease abundance (see Fig. 4) has been observed at reefs throughout the management area.

The approach to monitoring coral disease outbreaks on the GBR is similar to that used for bleaching for two reasons. Disease outbreaks require some of the same communication and engagement with the media and stakeholders (but see communications section below for more detail). Also, like bleaching events, disease outbreaks create opportunities for researchers and managers to collaborate to advance our understanding of outbreak causation and trial actions to mitigate impacts (see next section). Rapid assessments of outbreak severity are complemented with detailed surveys to meet communications and engagement requirements as well as take advantage of the research opportunities outbreaks present. The survey protocols used in the Great Barrier Reef for disease are shown in Fig. 3b, e). The rapid assessments are conducted using the same protocol employed by the monitoring networks whereby disease cases are counted within 76 m^2 circles using a radial belt sampling method (Fig. 3b). Detailed prevalence surveys involve counting all corals and disease cases on three 20×2 m^2 belt transects at two sites at each reef location (Fig. 3e). The detailed surveys are undertaken in collaboration with researchers that identify infected and healthy corals to genus to help determine whether spatial patterns in disease prevalence are correlated with climate and/or anthropogenic stressors.

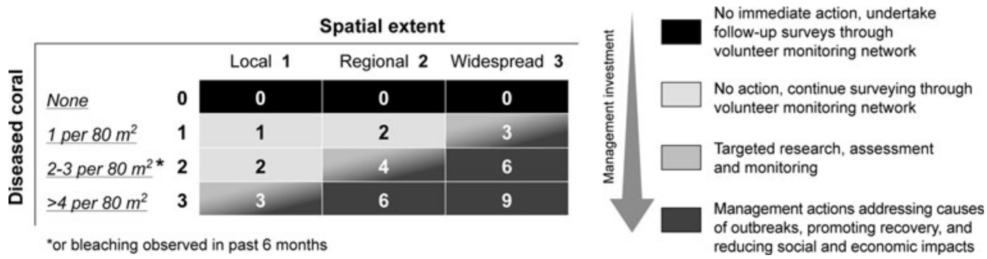

Fig. 4 Matrix used to inform hierarchical investment of management resources. The criteria for each level of coral disease impacts and spatial extent can be adapted to local knowledge of diseases and the size and number of reefs contained within a management area. Values shown for the levels of coral disease impacts refer to those used in the Great Barrier Reef

Given links between bleaching and disease, managers and their collaborators can look for disease when assessing the spatial extent and severity of bleaching impacts or when undertaking surveys to assess recovery from bleaching. Surveys of bleaching may work to target disease surveys to locations where bleaching was most severe. This highlights that managers will want to train staff to identify a range of reef health impacts. Protocols used to monitor impacts are useful in determining the status of coral health and reef condition but managers may also want to work with researchers to develop a long-term monitoring program that can detect trends in disease abundance and prevalence (see Beeden and others 2008; Page and others 2009).

Management Actions

The response framework we describe here is designed to facilitate the implementation of established management strategies to support reef resilience while enabling testing and evaluation of the effectiveness of emerging actions specific to restoring reefs and mitigating coral disease impacts (objective 3 of the framework). Both types of actions are described below. For restoring reefs and actions that can mitigate disease impacts we identify knowledge gaps that when filled will enable managers to prioritise the action options based on their effectiveness.

Mitigating Disease Impacts and Reef Restoration

The growing awareness of disease risk has resulted in an exponential increase in research efforts to identify and test ways to mitigate disease impacts (Bruckner 2002; Raymundo and others 2008). Preventing outbreaks or reducing their impact may be acheived by boosting immunity, or reducing pathogen abundance or rates of disease transmission (see overview in Raymundo 2010). Strategies include: stimulating coral immune systems (as in Little and Kraaijeveld 2004), removal of disease by physical means (Hudson 2000), aspirating the disease bands on corals affected by Black Band and Yellow Band and covering the affected area with clay or putty (reviewed in Raymundo 2010), phage therapy (Efrony and others 2007, 2009), using normal cell micro-biota as probiotics (Ritchie 2006), disruption of cell-cell communication in pathogenic bacterial communities (Teplitski and Ritchie 2009), and traditional strategies like quarantining, vaccination, and antibiotic treatment and culling (Wobeser 2006). Though these strategies have strong potential to be vital to managers in the future, all are currently highly experimental and likely to be prohibitively expensive on all but the smallest of spatial scales (10's–100's of m^2, but not km^2). As importantly, there are critical gaps in our understanding of how to implement these strategies. A list of the critical knowledge gaps is provided in Table 1, which can serve to inform future research and trials of these actions both in labs and at outbreak sites. Managers communicating the need for this research and targeting trials of the approaches at sites severely affected by disease can help ensure the most effective of the strategies listed above become operational in the future.

Sites severely impacted by disease can be restored through well documented approaches that are notoriously expensive and challenging to implement like transplantation, coral gardening and installing artificial reefs (Edwards and others 2007). These actions are like those described above to mitigate impacts in that they are likely to only be useful on small spatial scales but may be warranted at high priority sites (e.g., sites with high resilience, or special conservation significance).

There are critical gaps in our understanding of approaches to restoring reefs given the extent and nature of all of the potential downsides to these approaches (see Table 1 and review for coral transplantation in Edwards and others 2007). For that reason, continuing to fill those knowledge gaps should be complemented with other actions that managers can take to promote reef resilience.

Promoting Reef Resilience

Losses to macroalgae in the competition for space on the benthic substrate of reefs can reduce recovery rates either through limiting the growth of resident corals or by

Table 1 Critical knowledge gaps for management action options (1) specific to coral disease outbreaks and (2) for enhancing reef recovery once the outbreak abates or is controlled. This list is not intended to be an exhaustive list of the research that should or could be conducted in each of these areas but highlights the knowledge gaps that, if filled, would facilitate a re-assessment of the feasibility of implementing these strategies over any spatial scale

Category	Strategy	Critical knowledge gaps
(1) Mitigating disease impacts by boosting immunity, and reducing pathogen abundance and rates of disease transmission	Removal of disease by physical means	Extent to which known methods will be successful when suctioning disease agents from branching corals
		Procedures for safely implementing known methods in areas with high coral cover have yet to be developed
	Traditional strategies including quarantine, vaccination, antibiotic treatment, and culling.	Causative agents of many types of coral diseases
		The threshold number of affected colonies that have to be treated in an area (of any given size) for the strategy to significantly decrease either disease transmission rates or total mortality rates
	Phage therapy	Understanding the effects of phages on other closely related bacteria
		Threshold numbers of affected colonies that have to be treated to significantly decrease disease transmission rates and/or total mortality rates
	Normal coral micro-biota as probiotics	The precise roles of beneficial bacteria
		The cellular mechanisms underlying the anti-microbial activity, and conditions driving microbial activity
	Disruption of cell–cell communication in pathogenic bacterial communities	Whether cell–cell communication is an important virulence mechanism in coral diseases
		Whether strategies to disrupt cell–cell signaling and reduce pathogenicity will disrupt the production of antibiotics that contribute to natural mechanisms of disease resistance
	Stimulation of coral immune systems	Whether coral immune systems can be primed at all
		If the immune systems of corals can be primed, whether a process can be developed that prevents undesirable decreases in physiological resources that affect susceptibility to diseases or other disturbance and reduce reproductive output
(2) Promoting recovery	Coral transplantation/assisted colonization and coral gardening	The threshold number of colonies that need to be translocated to see significant increases in recovery rates
		The extent to which threshold numbers vary between species
	Mitigating anthropogenic stressors	Effectiveness when anthropogenic stress is low to moderate.

reducing substrate available to new recruits for settlement (review in Hughes and others 2007). Local stressors, like poor water quality (i.e., nutrient rich), the extraction of herbivorous fishes (Mumby and others 2006), and physical damage due to anchoring and/or divers and snorkelers (McManus and others 1997) all have the potential to increase the competitive advantage of macroalgae and hence reduce recovery rates. Aside from reducing recovery rates these anthropogenic stressors can increase pathogen virulence and coral susceptibility (Raymundo and others 2008, Willis and others 2004). As an example, increased dissolved nutrients, bacterial loads, and dissolved pollutants (i.e., poor water quality) have all been linked to some coral diseases and can increase the susceptibility of corals to disease-causing microbes (Raymundo 2010). Management actions that minimise human stressors therefore promote both of the key components of reef resilience; resistance and recovery.

Improving local water quality and temporary closures could be the most successful management actions in response to disease. Improving water quality is an action some local managers will have control over and can result in a number of positive consequences for coastal ecosystems (Raymundo and others 2009; Raymundo 2010). Managers with no or limited control over water quality can add increasing bleaching (Wooldridge 2009) and disease resistance to the list of benefits to come from improving water quality when engaging with the responsible managers and agencies. Local stressors can also be reactively mitigated by many coral reef managers following outbreaks through temporary closures (Day 2002), as was done following the severe bleaching in 2010 in Thailand. Some of the benefits of temporary closures will be realised immediately since preventing entry can reduce rates of disease spread directly (i.e., through disease transfer, though this requires more research) or indirectly (i.e., through injuring corals with fins or anchors) (Raymundo and others 2009). Other benefits could take years to manifest and the capacity of temporary closures to enhance recovery rates will depend on the severity of anthropogenic stress in the area, and whether the site is severely disturbed again in the near-term. The latter is largely out of management control. The former, however, requires managers to decide whether it is worth investing resources – temporary closures will have the greatest impact on recovery timeframes in areas where anthropogenic stress is high (but will also be the most controversial here), while closures may have no impact on recovery if anthropogenic stress is low or moderate (review in McClanahan and others 2009).

Identification of reefs (or reef sites) with greater relative resilience to climate change provides an opportunity to build minimising coral disease risk into long-term spatial management plans. Approaches to assessing coral reef resilience are available (see Obura and Grimsditch 2009; Maynard and others 2010) that focus mostly on resilience to thermal stress and bleaching. These approaches are also likely to be of use in identifying sites resilient to disease given links between bleaching and disease and between thermal stress and temperature-dependent diseases. The published resilience assessment protocols identify sites: (1) that are likely to have lower relative exposure or greater resistance to exposure, and/or (2) have features (like high coral diversity) that reduce the likelihood a coral bleaching event or disease outbreak will kill high proportions of the coral colonies at the sites.

Sites with lower relative exposure often have features (e.g., adjacent deep water or high mixing) that reduce exposure to stressful temperatures that can be identified, measured or estimated (see Grimsditch and Salm 2006). As for resistance when exposed to stressful temperatures, recent evidence suggests having highly variable temperatures can confer resistance to bleaching (McClanahan and others 2007, Oliver and Palumbi 2011). Managers can identify locations with features that reduce exposure and efforts are underway to produce high-resolution maps of locations where past temperature regimes are characterised by high variability (Guest and others in review). Identifying and protecting sites with low exposure or greater relative resistance can and should be complemented with protecting sites with high biodiversity when possible. Protecting and promoting diversity could offer some protection from loss of reef services and resilience (as shown for bleaching in Baskett and others 2010) given differences among coral taxa in their susceptibility to bleaching (Marshall and Baird 2000) and disease (Willis and others 2004).

Communication, discussed next, will be vital to the success of trials of emerging actions to mitigate disease impacts and to the implementation of the established actions discussed above to support reef resilience.

Communication

Communication is critical to an effective management response to coral disease outbreaks. Disease outbreaks can cause significant and rapid declines in reef condition, and therefore have the potential to attract interest from the public, media and fellow managers. Response plans produced by adapting this framework can ensure timely and credible information on coral disease outbreaks, enabling reef managers and reef users to be proactive in presenting information to the broader community (objective 3 of the framework). Some of the issues warranting strategic management of communications relating to coral disease include:

- Outbreaks of diseases can catch managers by surprise, highlighting the importance of raising awareness of the threat of coral disease amongst managers to facilitate allocation of resources to support outbreak responses.
- Injuries and other stressors have the potential to increase susceptibility of corals to diseases. Consequently, increased management of tourism activities at reef sites susceptible to disease outbreaks may be warranted. Appropriate communications can be used to minimise the frequency of touching, kicking and otherwise contacting corals by tourists visiting vulnerable sites.
- Managers need to train participants to identify coral diseases and motivate participants through a two-way exchange of information for monitoring networks to be effective as part of the early warning system.
- The term ‘disease’ may frighten the very stakeholders and community members that need to support actions managers take in response to coral disease. Managers can play an educational role and explain that: impacts from human activities can increase susceptibility of corals to diseases, humans cannot contract the common types of coral diseases, and that caution will need to be exercised if outbreaks of an unknown disease occur as the disease may pose a human health risk.
- Awareness also needs to be raised amongst stakeholders and community members that some management

responses to coral disease necessarily limit use. Heightened awareness is likely to raise support for and compliance with management actions when implemented. Through informing resource users, managers can raise their own awareness of stakeholder needs, ensuring future management strategies are as tailored to the needs of users as possible.

- Misinformation can affect reef-dependent industries like tourism operators who depend on clients whose perception of reef condition in an area can be easily influenced by the media. Timely reporting of the severity and extent of coral disease outbreaks can dispel misinformation in the media about an outbreak.
- Managers need to select sites and determine timeframes for trials of emerging strategies to mitigate coral disease impacts. This decision-making process should be transparent and participatory to raise further support for the implementation of management actions in response to coral disease.
- Researchers and managers need to share results following trialing various management strategies through inter-institutional collaboration and email and report exchange.

Implementation of the Response Framework

Response plans produced based on this framework would be in effect year-round since coral disease outbreaks can occur during any time of the year. However, research suggests corals become more susceptible to diseases following periods of anomalously warm sea temperatures (e.g., Bruno and others 2007; Heron and others 2010; Maynard and others 2011). Also, spatially extensive bleaching events, caused by anomalously warm temperatures, can greatly increase the susceptibility of corals to diseases, as can seasonal rainfall and runoff (Miller and others 2009; Mydlarz and others 2009; Haapkylä and others 2011). For these reasons, the schedule of implementation (shown in detail in Fig. 2) has been set up with 'Preparation' scheduled for pre-summer. This ensures that systems that monitor summer conditions as part of the early warning system are maintained, and also provides an opportunity to evaluate the response framework and revise/update it as necessary. Both preparation and evaluation are routine (shown in grey in Fig. 2) and hence ongoing tasks. Assessing impacts when disease outbreaks are documented and the implementation and trial of management actions both form responsive tasks. Re-prioritising various management actions once tested may need to become a routine task given the severity of the climate change threat and the need for adaptive management (Tompkins and Adger 2004).

Conclusion

This framework has been developed to meet a rapidly emerging need among coral reef managers. While initially developed for use on the Great Barrier Reef, it draws on studies and management experiences from coral reef regions around the world and makes operational the components of a structured adaptive disease response first reviewed by Raymundo and others (2008). The framework can be tailored to different regions and scaled to suit different levels of management resources and operational capabilities.

Widespread adoption of the framework presented here would help establish a community of practice. A community like this already exists for bleaching with more managers adopting the response framework presented in Marshall and Schuttenberg (2006, see also Maynard and others 2009) each year and sharing their experiences. A similar community of those managing coral disease could lead to vital advances in our understanding of how to manage coral disease outbreaks. This is due to knowledge transfer and experience sharing being critical to determining the cost-effectiveness of the emerging strategies to mitigate disease impacts we review here. For this reason, adding to the arsenal of strategies available to managers to respond to coral disease outbreaks requires management responses be implemented in collaboration with researchers. This framework is designed to encourage and facilitate such a collaborative approach, and thus can accelerate improvements in the management of coral disease impacts and risk globally.

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