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Interpreting coral reef monitoring data: A guide for improved management decisions

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ABSTRACT

Coral reef monitoring programmes exist in all regions of the world, recording reef attributes such as coral cover, fish biomass and macroalgal cover. Given the cost of such monitoring programs, and the degraded state of many of the world's reefs, understanding how reef monitoring data can be used to shape management decisions for coral reefs is a high priority. However, there is no general guide to understanding the ecological implications of the data in a format that can trigger a management response. We attempt to provide such a guide for interpreting the temporal trends in 41 coral reef monitoring attributes, recorded by seven of the largest reef monitoring programmes. We show that only a small subset of these attributes is required to identify the stressors that have impacted a reef (i.e. provide a diagnosis), as well as to estimate the likely recovery potential (prognosis). Two of the most useful indicators, turf algal canopy height and coral colony growth rate are not commonly measured, and we strongly recommend their inclusion in reef monitoring. The diagnosis and prognosis system that we have developed may help guide management actions and provides a foundation for further development as biological and ecological insights continue to grow.

1. Introduction

Monitoring is a fundamental part of resource management, providing information on the state of the system which can be used to detect the impacts of natural and anthropogenic stressors, assess the potential recovery of the system, and measure the success of management interventions (Day, 2008; English et al., 1997; Legg and Nagy, 2006). Ecological monitoring of coral reefs, defined as repeated surveys collecting data on attributes such as abundance of fish and coral, has been conducted since reef survey techniques were first described in the 1970s (Jackson et al., 2014; Risk, 1999, 1972). While all regions of the world have some form of reef monitoring, the regional comprehensiveness, level of replication, and depth of detail captured is highly variable globally (Wilkinson, 2008). With the increasing level of stress that reefs are being subjected to (Wolff et al., 2015), including the recent global bleaching event, it is more important than ever that reef monitoring data can be used to guide management action.

The dynamic nature of coral reefs and local differences in environmental conditions make interpreting changes in reef monitoring data difficult. For monitoring data to provide feedback to management, managers need a framework not only for collecting data but also for understanding and interpreting it (Houk and van Woesik, 2013; Renken and Mumby, 2009). Standard methods exist for surveying reefs (e.g. English et al., 1997; Hill and Wilkinson, 2004), with many programmes having developed regional variants, such as the Atlantic and Gulf Rapid Reef Assessment (AGRRA; Lang et al., 2010), the Caribbean Coastal Marine Productivity Program (CARICOMP, 2001), the Great Barrier Reef long-term monitoring program (Sweatman et al., 2008), and Reef Check (Hodgson et al., 2006). Survey methods have been subjected to extensive testing for accuracy and precision (Bohnsack and Bannerot, 1986; Brown et al., 2004; Carleton and Done, 1995; Leujak and Ormond, 2007;

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Ohlhorst et al., 1988), but the methods for interpreting the resulting data have not received so much attention.

Much work has been done on biological assessments of ecosystem health and the identification and testing of biological indicators (bioindicators) in freshwater and estuarine ecosystems (Borja and Dauer, 2008; Karr and Chu, 1999). Development of bioindicators for coral reefs has lagged behind in part due to a lack of consistent, long-term datasets, differing sample methods, and the relative complexity of coral reef ecosystems (Jameson et al., 1998; McField and Kramer, 2006). Over the past decade there has been considerable work on developing and testing indicators for coral reefs (Bradley et al., 2008; Chabanet et al., 2005; Fisher et al., 2008; McField and Kramer, 2007) and a recent focus on indicators of resilience (McClanahan et al., 2012; Obura and Grimsditch, 2009). Some programmes at the regional level have developed indicators and thresholds that are used to interpret reef monitoring data and inform management. For example, the Healthy Reefs Initiative (HRI) for the Mesoamerican Barrier Reef was the first programme to develop specific target values for a variety of coral reef indicators (Kramer et al., 2015; McField and Kramer, 2007), several countries in the Eastern Caribbean have developed a reporting system modelled on the HRI indicators (CaribNode, 2016), and Bonaire, in the Southern Caribbean, has a monitoring program that uses a set of indicators to inform management (Steneck et al., 2016, 2005). However, there are still no general rules or guides for the interpretation of trends and patterns in reef monitoring data, to help answer questions such as: what are the likely causes of a given change in reef state? What sort of change should be considered potentially problematic?

To improve the use of coral reef monitoring data in management decisions a diagnostic approach has been suggested (Downs et al., 2005). The paradigm is similar to that used in medicine: a clinical examination of the subject (reef), which includes a review of the subject's history and an examination of the current state of health to identify the cause of the illness (Downs et al., 2005). So far, diagnostics of reef health have mainly employed indices of biotic integrity such as foraminiferan composition (Jameson et al., 2001, 1998) or used indicators at the sub-organism level, such as cellular changes (Downs et al., 2012, 2005; Hédouin and Berteaux-Lecellier, 2014). Since many of these indicators are not routinely collected by monitoring programmes, a diagnostic approach that focuses on making the best use of commonly collected, or easy to collect, reef monitoring data is needed for better integration of monitoring data with management actions.

To help close the adaptive management loop between monitoring data collection and management action, we first provide a guide to interpreting trends in reef attributes collected by major coral reef monitoring programmes. We then build on this information, selecting key indicators and combining their interpretation to provide a method for identifying the most likely stressors on the reef (i.e. a diagnosis). Taking the clinical approach one step further, we integrate the diagnostic results with indicators linked to reef recovery processes to provide a relative prognosis of reef health, which might help a reef manager target interventions. By reviewing reef attributes that are needed for diagnosis and prognosis, we were able to identify a minimum set of attributes to guide targeted management action, which might help increase the cost-effectiveness of reef monitoring worldwide.

2. Methods

2.1. Interpreting changes in reef monitoring data

A list of the reef attributes that are used for coral reef assessment was collated from the seven internationally recognised coral reef assessment programmes with published protocols. Four of the assessment programmes included are monitoring programmes and three (AGRRA, CARICOMP and Reef Check) are reef assessment programmes that are often used for monitoring purposes.

For each attribute we provide an interpretation of its trend assuming that an observed trend would exceed two years to guard against – although not necessarily eradicate – measurement error or stochastic variability. We focus on trends that will negatively impact reef health, such as a decrease in coral cover or an increase in macroalgal cover. For coral, dead coral, macroalgal and turf algal cover, we included interpretation of both acute and chronic trends because they involve distinctly different ecological interpretations. We use a threshold of a 10% change in cover to define an acute change as smaller changes may constitute normal inter-annual variation (Graham et al., 2011).

For each trend in an attribute we considered: (1) main possible drivers of the trend; (2) other attributes to cross-reference to help confirm drivers of the trend; (3) the impact of the trend on reef ecological processes. Cross-referencing other attribute trends can narrow down the list of potential drivers and therefore help determine where management efforts could be focused.

Our list of ecosystem processes is drawn from a conceptual model of ecological feedback processes (Fig. 1). The model does not attempt to incorporate all components of a reef ecosystem, but includes processes that are fundamental to the balance between a coral or algal-dominated reef, namely those that effect coral recruitment, growth and mortality (Hughes and Tanner, 2000).

2.2. Diagnosing the main stressors affecting a reef

We used an elimination approach to diagnose a stressor that has impacted or is impacting a reef. The approach uses a series of closed Yes/No questions, involving knowledge of trends of indicators, to reach a diagnosis. The indicators were selected from the list of coral reef monitoring attributes (Supplementary Material Table A1 Appendix A), local knowledge or information from open access internet databases. We selected indicators that are most strongly associated with a particular stressor or that could split groups of stressors (Table 1). For example, a recent thermal anomaly is a strong indicator of coral bleaching (a stressor). The indicators were arranged hierarchically into a decision tree, with each level either confirming or rejecting diagnoses. Decision trees have been used extensively in management guides, with several examples within the context of coral reefs (Edwards and Gomez, 2007; Marshall and Schuttenberg, 2006). They provide a simple way of presenting choices in a structured manner, without overwhelming the user with information.

For many of the indicators, it is necessary to provide a threshold that distinguishes between a 'Yes' or 'No' answer. The thresholds presented here (Table 1) should be treated as approximates that can be replaced by more precise information if available in the region of study. For example, a heavily degraded reef may not cross the 10% coral cover loss threshold used to indicate an acute stressor even when there is one because coral cover was low prior to the stressor and only resilient corals remain. This situation is particularly likely in the Caribbean where many reefs already have low coral cover, high macroalgal biomass and low herbivore biomass (Jackson et al., 2014). In these cases, lower threshold values may have to be used, which could be approximated by using data on the impact of stressors on comparable reefs within the region.

The chronic stressors of climate change (i.e. ocean acidification and the effects of increasing water temperatures on coral growth rates and fecundity) are not included as diagnosable stressors, as they are problematic to detect using common reef monitoring data

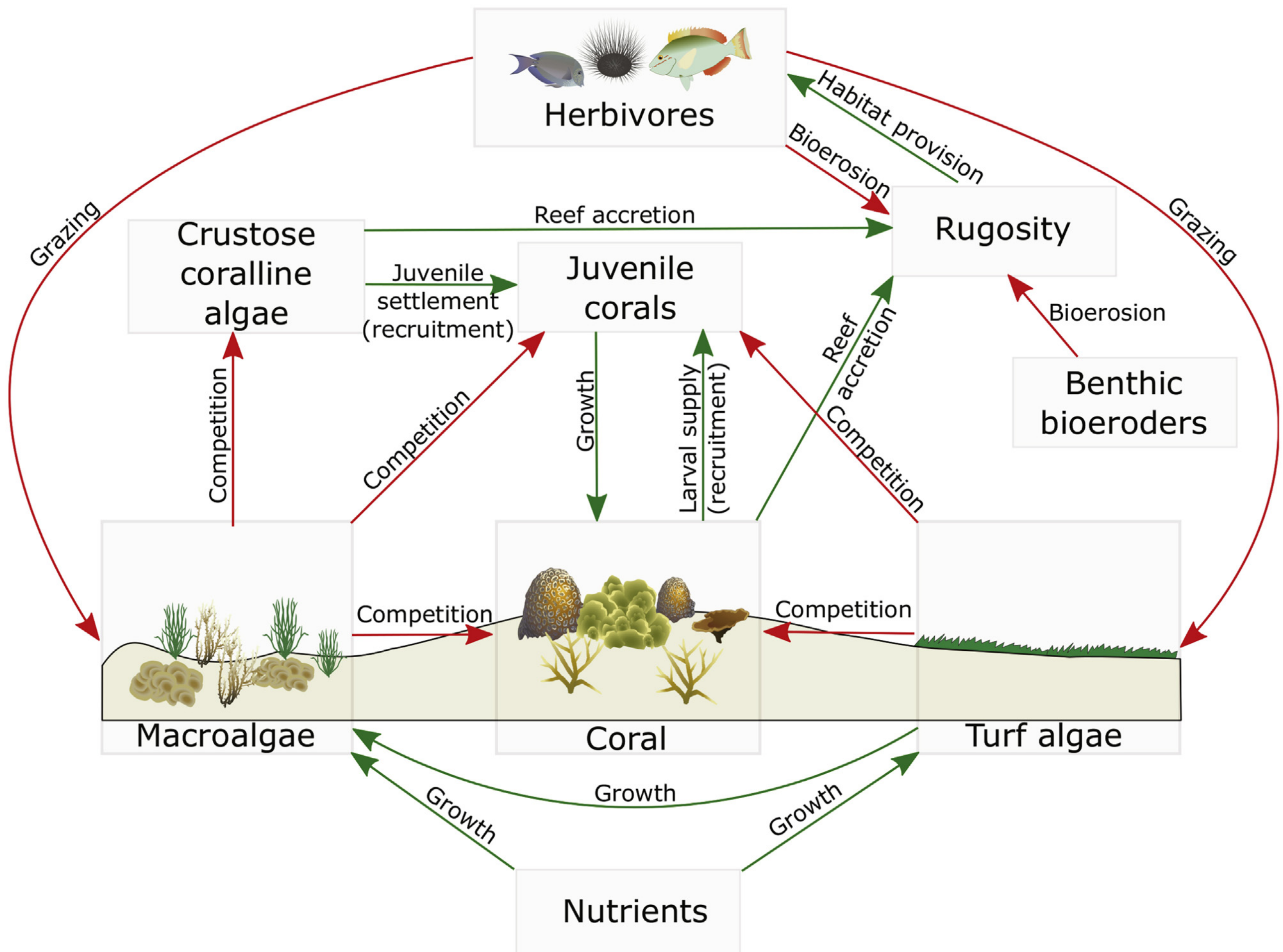

Fig. 1. Main reef ecological feedback processes. Boxes show reef attributes, arrows show processes. Green arrows indicate a positive effect on the attribute; red arrows indicate a negative effect. Although not indicated, corals can also settle on short turf algae. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Indicators for diagnosis of stressors affecting a reef. Thresholds identified are general guidelines to indicate magnitude of change required for a 'Yes' response to the indicator.

Indicator	Diagnostic use (indicator of)	Thresholds and information sources (if not reef monitoring data)	Supporting references
Sudden decrease in coral cover?	Acute stressor	≥10% coral cover loss between consecutive data points	Graham et al. (2011)
Sudden decrease in rugosity?	Physical damage to reef	≥8% decrease in rugosity between consecutive data points	Alvarez-Filip et al. (2011)
Recent storm?	Storm	Information from either local knowledge or online via: http://www.wmo.int/pages/prog/www/tcp/Advisories-RSMCs.html	N/A
Recent thermal anomaly?	Coral bleaching	Information from local observations or NOAAs Coral Reef Watch programme: http://coralreefwatch.noaa.gov/	Liu et al. (2014)
Crown-of-thorns starfish outbreak?[a]	Crown-of-thorns starfish outbreak	Threshold density for outbreak ≥ 1500 adult starfish km^{-2}	Moran and De'ath (1992)
Species specific coral loss?	Disease outbreak	≥10% coral cover loss (Graham et al., 2011) of coral species particularly affected by coral diseases	Raymundo et al. (2008)
Proximal flooding or landslide?	Sedimentation	Information obtained from local knowledge	N/A
Increase in macroalgae?	Large nutrient increase	≥10% increase in macroalgal cover (to eliminate seasonal variability as cause) between two consecutive data points	Smith et al. (1981)
Increase in turf height?	Increased algal growth or algal grazing has decreased	Increase in average height may be 1 or 2 mm per year	Mumby et al. (2013), Russ (2003)
Decrease in herbivores?	Ecosystem overfishing of herbivores (fish and/or urchins)	Decrease in herbivorous fish biomass. Decrease in *Diadema* urchin density where they are significant grazers	Heenan and Williams (2013), Mumby et al. (2006)
Reduced coral growth rate?	Sedimentation stress (when used in combination with next question)	Coral growth rate is at or below minimum observed for that species. For Caribbean coral growth rates see: http://geography.exeter.ac.uk/reefbudget/datasets/ For Indo-Pacific growth rates see collated data and references in (Kubicek et al., 2012; Ortiz et al., 2014a suppl. info.)	Carricart-Ganivet and Merino (2001), Torres (2001)
Increased partial mortality of massive corals?	Sedimentation stress (when used in combination with previous question)	Partial mortality incidence in massive corals is above 50%	Nugues and Roberts (2003)
Slow decline in coral cover?	Unknown chronic stressor	< 10% but >1% coral cover loss per annum	Graham et al. (2011)

[a] Indo-Pacific reefs only.

and are also difficult to disentangle from other stressors (Mumby and van Woesik, 2014).

2.3. Relative prognosis of reef health

2.3.1. Selection of indicators

To assess the prognosis for a reef, we first had to identify a set of indicators that provide the most information on the potential of the reef to recover. Since the process of coral recovery is fundamentally driven by recruitment, growth and mortality of corals, we focused on identifying suitable indicators of change in these processes. Indicators were identified using the same conceptual model of a coral reef used for diagnosis (Fig. 1). Crustose coralline algae (CCA) were excluded at this point because of their rarity in much of the Caribbean (Newman et al., 2006 suppl.), but they could be added for Indo-Pacific analyses. The indicators identified as relevant to assess the prognosis for a reef were turf, macroalgae, herbivores, juvenile corals and coral growth. Where multiple metrics are available for measuring an indicator, we used that which provided the clearest signal of the ability of the reef to recover (Table 2). For cases where the stressor to the reef has already been diagnosed as sedimentation, a coral disease outbreak or a crown-of-thorns starfish outbreak, there are specific prognosis indicators that help determine how severe the continuing impact on the reef will be (Table 2).

2.3.2. Scoring system

To place a reef on a relative prognosis scale from 'best potential future outcome' to 'worst potential future outcome' we provided a score for each indicator based on evidence from the published literature. As with the diagnosis, the indicators are assessed via closed questions with simple 'Yes' or 'No' answers. A score of either 1 or 2 is given for a 'Yes' answer to an indicator question, reflecting a negative impact on reef recovery. A score of 2 is given where there is strong evidence from the literature that two indicators will interact synergistically, with the emergent outcome of their combined impact likely to be worse than the simple addition of the two individual effects (Table 2). Working through each indica-

Table 2
Prognosis indicators, their scores and reasons for inclusion in prognosis. Addition scores results in a 'prognosis score' for a reef, with the highest value representing the worst possible prognosis.

Indicator	Conditions for inclusion in prognosis	Score for Yes answer (No = 0)	Justification for inclusion in prognosis and scoring
Turf canopy height increasing?	None	1	Coral recruitment decreases with increases in turf canopy height (Arnold et al., 2010; Birrell et al., 2008; Vermeij et al., 2010)
Juvenile coral density decreasing?	None	1	Indicates reduced recruitment – recovery of reef impaired (Hughes and Tanner, 2000) and possible reduction of genetic diversity (Knowlton, 2001)
Coral community dominated by sediment sensitive corals? (for heavy sedimentation, e.g. due to beach nourishment or proximate construction, always answer "Yes" regardless of coral community)	only for stressor = sedimentation	1	Recovery will be impaired due to coral mortality, slow growth and reduced fecundity and recruitment (Fabricius, 2005; Rogers, 1990)
Coral disease incidence increasing?	only for stressor = disease	1	Recovery will be impaired due to coral mortality, slow growth and reduced fecundity (Weil and Rogers, 2011)
COTS density higher than threshold?	only for stressor = COTS outbreak Threshold density for COTS outbreak ≥ 1500 COTS km^{-2} (Moran and De'ath, 1992).	1	Coral mortality exceeds rate of recovery (Moran and De'ath, 1992; Pratchett et al., 2014)
Coral community dominated by slow growing corals?	Acute stressor diagnosed?	2	Recovery impaired as corals will tend to be outcompeted for space by macroalgae (Mumby et al., 2007; Ortiz et al., 2014b)
	Chronic stressor diagnosed?	1	As above, but less severe as reduction in coral cover is less than in acute stressor case
Macroalgal cover increasing?	If community dominated by slow growing corals	2	Corals will tend to be outcompeted for space by macroalgae (Nugues and Bak, 2006; Rasher and Hay, 2010). Macroalgae reduce space available for recruitment and increase mortality of juvenile corals (Box and Mumby, 2007).
	If not	1	As above, but faster growing corals are more competitive for space.
Decrease in herbivores? (Decrease in herbivorous fish biomass and/or *Diadema* urchin density where they are significant grazers)	If community dominated by slow growing corals	2	Herbivory is important for control of algae (Burkepile and Hay, 2009; Williams and Polunin, 2001). Slower growing corals will struggle to outcompete algae for space (Ortiz et al., 2014a; Roff and Mumby, 2012).
	If not	1	As above, but faster growing corals are more competitive for space
Coral growth rate decreasing?	If community dominated by slow growing corals	2	Slower growing corals will struggle to outcompete algae for space (Ortiz et al., 2014a; Roff and Mumby, 2012).
	If not	1	As above, but faster growing corals are more competitive for space

tor for which the user has data available and summing the scores obtained provides a prognosis score, with the lowest score indicating the best prognosis. The more indicators that the user has data for, the broader the spectrum of possible prognoses; for example, with data for only turf canopy height, only scores of 0 or 1 are possible, but if data for coral growth rate are also available, scores from 0 to 3 are possible. Using more indicators will also give the user more assurance that the prognosis is likely to be correct. To reduce redundancy, indicators that have already been used in the diagnosis should not be used to calculate the prognosis, as this would simply increase all potential prognosis scores by 0, 1 or 2 (depending on the indicator) rather than increase the difference between the prognoses. For example, if the chronic stressor 'nutrient increase' is diagnosed for a reef, the user must have used the indicators turf height and herbivore biomass to get to this diagnosis. Using these indicators again for the prognosis does not provide new information, it only adds a constant to all the possible prognosis scores.

3. Results and discussion

3.1. Interpreting changes in reef monitoring data

A total of 41 reef attributes were collated from the monitoring programmes assessed. We grouped the attributes into four categories: Scleractinian coral, algae, other benthic attributes and fish (Supplementary Material Table A1 in Appendix A). The benthic cover attributes of coral, macroalgae, sponge, sediment, bare substrate and other sessile organisms were included in all programmes. Coral size distribution, coral growth and sponge height and abundance were each included in only one programme. One monitoring programme (Coral Reef Evaluation and Monitoring Project, South Florida) does not include fish in their monitoring, and of the remaining six, two (Reef Check and AIMS LTMP) only include abundance and length for a small number of fish indicator species.

For each reef monitoring attribute, there are often multiple possible drivers of a trend which are not mutually exclusive; for

Table 3
Interpretation of coral reef monitoring attributes.

Attribute	What is the trend?	Main possible drivers of trend	Other attributes to cross reference to confirm driver	Supporting references	Direct impact of trend on ecological processes
Scleractinian coral:					
Coral juvenile density	Decrease	Decrease in substrate suitable for recruitment, e.g. due to thick algal turfs, fleshy macroalgae or cyanobacteria	Macroalgal cover, turf canopy height, cyanobacteria cover, herbivorous fish biomass, *Diadema* density	(Box and Mumby, 2007; Kuffner et al., 2006)	
		Acute stressor[a] caused juvenile mortality	Coral cover, rugosity, coral bleaching prevalence/incidence	(Mumby, 1999)	
		Decrease in coral larval supply	Coral cover by genus/species, coral cover of nearby reefs	(Gilmour et al., 2013; Jones et al., 2009; Vermeij and Sandin, 2008)	
		Decreased water quality (including sedimentation)	Water quality data, sediment trap data	(Cortés and Risk, 1985; Ritson-Williams et al., 2009)	
Coral cover	Acute decrease	Acute stressor[a] caused high coral mortality	Rugosity, coral bleaching and disease incidence, crown-of-thorns starfish density, macroalgal cover, local knowledge of recent storms, blasting or shipwrecks (acute stressors)	(Graham et al., 2011)	Reef accretion ↓ Coral recruitment ↓
	Chronic decrease	Reduced coral recruitment	Coral juvenile density, turf algal height, macroalgal cover	(Hughes and Connell, 1999; Hughes and Tanner, 2000)	Reef accretion↓ Coral recruitment ↓
		Continuous, low-level coral mortality. Possibly caused by:			
		• disease at low incidence	Coral cover by genus/species, disease prevalence/incidence	(Couch et al., 2014; Osborne et al., 2011; Ruiz-Moreno et al., 2012)	
		• chronic water quality issues (sediments and/or nutrients)	Water quality data, turf canopy height macroalgal cover	(Fabricius, 2005; Nugues and Roberts, 2003)	
Coral cover by growth form & Coral cover by genus/species (following 4 groupings used for purposes of useful ecological interpretation):					
• Slow growing (mainly massive corals)	Decrease in relative abundance (for reefs with high relative abundance of group)	Bleaching	Coral bleaching prevalence/incidence	(Marshall and Baird, 2000)	Reef accretion ↓
		Disease	Coral disease prevalence/incidence	(Raymundo et al., 2008; Ruiz-Moreno et al., 2012)	Reef accretion ↓
		Sedimentation	Sediment trap data, coral partial mortality, coral growth rate	(Fabricius, 2005; Nugues and Roberts, 2003)	Reef accretion ↓
• Fast growing (mainly branching and plating corals)	Decrease in relative abundance (for reefs with high relative abundance of group)	Bleaching	Coral bleaching prevalence/incidence	(McClanahan et al., 2007)	Habitat provision↓ Reef accretion ↓
		Disease (for acroporids in Atlantic)	Coral disease prevalence/incidence	(Aronson and Precht, 2001)	
		Storm	Rugosity	(Madin, 2005)	
• Disease sensitive corals	Decrease in relative abundance (for reefs with high relative abundance of group)	Disease	Coral disease prevalence/incidence	(Raymundo et al., 2008; Ruiz-Moreno et al., 2012)	Reef accretion ↓
• Sediment sensitive corals	Decrease in relative abundance (for reefs with high relative abundance of group)	Increased sediment on reef e.g. due to deforestation of surrounding land	Sediment trap data, coral partial mortality, coral growth rate	(Fabricius, 2005; Nugues and Roberts, 2003)	Reef accretion ↓

Table 3 (*Continued*)

Attribute	What is the trend?	Main possible drivers of trend	Other attributes to cross reference to confirm driver	Supporting references	Direct impact of trend on ecological processes
Coral size distribution	Decrease in abundance of large corals	Coral colony mortality (partial or whole) due to stressor	Coral cover, rugosity, coral bleaching and disease prevalence/incidence	(Alvarado-Chacón and Acosta, 2009; Hughes and Jackson, 1980)	Reef accretion ↓
		If coral mortality only partial, may result in increase in abundance of small corals	Coral partial mortality, abundance of small corals (see below)		
	Decrease in abundance of small corals	Decrease in coral recruitment	Coral juvenile density	(Alvarado-Chacón and Acosta, 2009; Hughes and Jackson, 1980)	Reef accretion ↓
	Increase in abundance of small corals	Increased partial mortality of large corals (fission of colonies)	Coral partial mortality, abundance of large corals (see above)	(Gilmour et al., 2013; Hughes and Jackson, 1980; Lewis, 1997)	
		Increased coral recruitment	Coral juvenile density		
Coral growth	Decrease	Increased sedimentation on reef	Sedimentation and/or water quality data, coral cover by species	(Carricart-Ganivet and Merino, 2001; Torres, 2001)	Reef accretion ↓
		Current or past presence of disease or bleaching	Disease/bleaching prevalence/incidence, coral cover by species	(Gladfelter, 1982; Goreau and Macfarlane, 1990)	
		Increased algal competition	Coral cover, macroalgal cover, turf cover, turf canopy height	(Box and Mumby, 2007; Tanner, 1995)	
Coral predation (abundance of predators or tissue scars)	Increase	Increased abundance of predators and/or coral predation rates	Coral cover by genus/species, abundance of coral predators	(Rotjan and Lewis, 2008)	Reef accretion ↓ Bioerosion ↑
Coral partial mortality	Increase	Chronic stressor[b] causing partial coral mortality. Most likely sources:			Reef accretion ↓ Coral colony growth ↓
		• Sediment	Coral growth rate, coral size distribution, sediment/water quality data	(Fabricius, 2005; Nugues and Roberts, 2003)	
		• Coral disease	Coral disease prevalence/incidence	(Jones et al., 2004)	
		• Coral bleaching	Coral bleaching incidence	(Baird and Marshall, 2002)	
		• Predation	Coral predation	(Garzón-Ferreira et al., 2005)	
Coral disease prevalence	Increase	Favourable environmental conditions, possibly:			
		• extreme temperatures (frequently disease following coral bleaching)	Thermal anomaly data, coral bleaching prevalence/incidence	(Harvell et al., 2007; Randall and van Woesik, 2015; Ruiz-Moreno et al., 2012)	Reef accretion ↓ Coral colony growth ↓
		• reduced water quality	Sediment/water quality data, coral growth rate, coral partial mortality	(Haapkylä et al., 2011; Harvell et al., 2007; Thurber et al., 2013)	

Table 3 (*Continued*)

Attribute	What is the trend?	Main possible drivers of trend	Other attributes to cross reference to confirm driver	Supporting references	Direct impact of trend on ecological processes
Coral bleaching prevalence	Increase	Coral bleaching due to elevated water temperatures (may be linked to weakening of resilience by chronic stressors such as increased nutrient levels) Other possible causal stressors: • decreased water temperature • solar radiation • reduced salinity • bacterial infection	Thermal anomaly data, water quality data, coral disease prevalence/incidence (may increase following bleaching)	(Brown, 1997; Eakin et al., 2010; Hoegh-Guldberg, 1999; Lesser, 2011)	Reef accretion ↓ Coral colony growth ↓
Algae:					
Macroalgal cover (fleshy macroalgae)	Acute increase	Acute stressor resulting in increase in substrate available for macroalgal colonization due to coral mortality	Coral cover, rugosity, coral bleaching and disease incidence, crown-of-thorns starfish density, local knowledge of recent storms, blasting or shipwrecks (acute stressors)	(Diaz-Pulido et al., 2009; Hatcher, 1984; Mumby et al., 2005)	Coral-algal competition↑ Coral growth ↓ Coral recruitment ↓
		Large increase in nutrients	Water quality data	(Smith et al., 1981)	
	Chronic Increase	Decrease in herbivores	Herbivore biomass, fisheries data	(Williams and Polunin, 2001)	
		Increase in nutrients	Nutrient levels	(Burkepile and Hay, 2006; Cooper et al., 2009)	
Macroalgal canopy height	Increase	Decrease in herbivores	Herbivore biomass, fisheries data	(Williams and Polunin, 2001)	Coral-algal competition↑ Coral growth ↓ Coral recruitment ↓
		Increase in nutrients	Nutrient levels	(Burkepile and Hay, 2006; Cooper et al., 2009)	
Macroalgal cover by species/genus (see main algal functional groups – fleshy macroalgae, calcareous macroalgae, CCA and turf)					
Turf cover	Acute Increase	Acute stressor[a] resulting in increase in substrate available for turf algal colonization due to coral mortality	Coral cover, rugosity, coral bleaching and disease incidence, crown-of-thorns starfish density, local knowledge of recent storms, blasting or shipwrecks (acute stressors)	(Diaz-Pulido and McCook, 2002; Williams et al., 2001)	Coral-algal competition↑ Coral recruitment ↓
		Large increase in nutrients due to increased terrestrial run-off, e.g. from storms	Water quality data	(Russ and McCook, 1999)	
	Chronic Increase	Decrease in herbivores	Herbivores biomass, fisheries data	(Arnold et al., 2010; Mumby et al., 2013)	Coral-algal competition↑ Coral recruitment ↓

Table 3 (*Continued*)

Attribute	What is the trend?	Main possible drivers of trend	Other attributes to cross reference to confirm driver	Supporting references	Direct impact of trend on ecological processes
		Increase in nutrients	Water quality data	(McClanahan et al., 2002; Vermeij et al., 2010)	
Turf canopy height	Increase	Decrease in herbivores	Herbivore biomass, fisheries data	(Arnold et al., 2010; Mumby et al., 2013; Vermeij et al., 2010)	Coral recruitment ↓
		Increase in nutrients	Water quality data	(McClanahan et al., 2002; Vermeij et al., 2010)	Coral recruitment ↓
		Increase in dead coral (substrate available for grazing)	Coral cover, dead coral cover, turf cover	(Diaz-Pulido and McCook, 2002; Williams et al., 2001)	
Crustose coralline algae (CCA) cover	Decrease	Increased sediment or pollutants	Sediment trap data, coral partial mortality, coral growth rate	(Fabricius and De'ath, 2001; Harrington et al., 2005; Steneck, 1997)	Coral recruitment ↓ Reef accretion ↓
		Reduction in herbivores CCA disease, possibly linked to increased water temperature	Herbivore biomass CCA disease incidence, water quality, sea surface temperature data	(Burkepile and Hay, 2009, 2006) (Miller et al., 2013; Quéré et al., 2015)	
Calcareous algal cover	Increase	Reduction in herbivores	Herbivore biomass	(Ferrari et al., 2012)	Coral-algal competition ↑
Cyanobacteria cover	Increase	Increased terrestrial run-off, particularly nutrients	Water quality data	(Albert et al., 2005; Brocke et al., 2015; Kuffner et al., 2006)	Coral recruitment ↓
Other benthic attributes: *Diadema* density	Decrease	Disease outbreak	*Diadema* disease prevalence	(Feehan and Scheibling, 2014; Lessios, 1988)	Bioerosion ↓ Grazing ↓
		Increase in predators	Predator biomass (principally species of families Balistidae, Diodontidae and Haemulidae)	(Harborne et al., 2009; McClanahan and Shafir, 1990)	
	Increase	Reduction in predator population	Predator biomass (principally species of families Balistidae, Diodontidae and Haemulidae)	(Harborne et al., 2009; McClanahan and Shafir, 1990)	Bioerosion ↑ Grazing ↑
		Increased recruitment	Juvenile *Diadema* density	(Carpenter and Edmunds, 2006)	
Clionid sponge cover	Increase	Decrease in water quality	Water quality data, macroalgal cover, turf canopy height, cover of other benthic heterotrophic feeders (e.g. zoanthids)	(Holmes, 2000; Rose and Risk, 1985; Ward-Paige et al., 2005)	Bioerosion ↑
		Recent bleaching event	Thermal anomaly data, coral bleaching incidence, coral partial mortality	(Carballo et al., 2013; Schönberg and Ortiz, 2009)	Bioerosion ↑
Sponge cover, Sponge cover by growth form,	Decrease	Sponge disease	Sponge disease incidence	(Webster, 2007)	Habitat provision↓ (especially for massive and erect branching species)

Table 3 (*Continued*)

Attribute	What is the trend?	Main possible drivers of trend	Other attributes to cross reference to confirm driver	Supporting references	Direct impact of trend on ecological processes
Sponge height, Sponge abundance (excluding Clionids – see separate attribute above)		Increased predation	Abundance of predators (principally angelfishes)	(Loh and Pawlik, 2014; Pawlik et al., 2013)	
Octocoral cover, Octocoral cover by growth form[c], Octocoral abundance	Decrease Decrease in phototrophic octocorals and/or increase in autotrophic octocorals	Octocoral disease Increased water turbidity and nutrients	Octocoral disease incidence Water quality data, sediment trap data	(Harvell et al., 2007) (De'ath and Fabricius, 2010; Fabricius and De'ath, 2001)	Habitat provision ↓ Habitat provision ↓
Cover of other sessile organisms (e.g. Corallimorphs, Zoanthids)	Increase	Decreased water quality	Water quality data, macroalgal cover, turf height, cover of other benthic heterotrophic feeders	(Cruz et al., 2014; Kuguru et al., 2004; Muhando et al., 2002; Norström et al., 2009)	Coral recruitment ↓
Dead coral cover	Acute increase	Acute stressor[a] causing high coral mortality – most be very recent as no algal overgrowth of dead coral	Coral cover, rugosity, coral bleaching incidence	(Kramer, 2003)	Coral recruitment ↓ Reef accretion ↓
	Chronic increase	Chronic stressor[b] causing persistent coral mortality	Coral cover by genus/species, disease/bleaching prevalence/incidence, coral growth rate, macroalgal cover, water quality data	(Chadwick and Morrow, 2011)	Coral recruitment ↓ Carbonate production ↓
Sediment cover (includes sand, mud, silt and other fine sediments)	Increase	Storm redistributed sediments on the reef	Water quality data, sediment trap data, coral cover, rugosity	(Mah and Stearn, 1986; Risk and Edinger, 2011; Scoffin, 1993)	Coral recruitment ↓ Coral growth ↓
		Flooding event or increased terrestrial run-off smothered reef with silt and other sediment	Water quality data, sediment trap data, coral partial mortality	(Bartley et al., 2013; Fabricius, 2005; Risk and Edinger, 2011)	
Rubble cover	Increase	Major mechanical stressor (e.g. cyclones, ship groundings, coral blasting) fragmentation in situ or on neighbouring reefs. Bioerosion may assist process	Coral cover, rugosity, clinoid sponge (and other bioeroder) cover	(Fox and Caldwell, 2006; Rasser and Riegl, 2002; Scoffin, 1993)	Bioerosion ↑ Coral recruitment ↓
Bare substrate (rock, pavement) cover	Increase	Abrasion and erosion of surfaces due to storm Increased grazing intensity by substrate excavators/scrapers (Urchins and herbivores)	Rubble cover, sediment cover Herbivore biomass (herbivorous fish excavators/scrapers and *Diadema*)	(Mah and Stearn, 1986; Woodley et al., 1981) (Williams et al., 2001)	Coral recruitment ↑
Rugosity	Decrease	Major mechanical stressor (e.g. cyclones, ship groundings, coral blasting) damaged reef structure	Coral cover, local knowledge of recent blasting/ship groundings and storms.	(Alvarez-Filip et al., 2011; Bozec et al., 2015; Fox and Caldwell, 2006)	Coral recruitment ↓ Habitat provision ↓

Table 3 (*Continued*)

Attribute	What is the trend?	Main possible drivers of trend	Other attributes to cross reference to confirm driver	Supporting references	Direct impact of trend on ecological processes
		Increased bioerosion (most likely driver if decrease in rugosity is slow)	Herbivore biomass, cover of heterotrophic feeders (e.g. clinoid sponge cover), rubble cover	(Alvarez-Filip et al., 2011; Glynn, 1997)	
Lobster (principally *Panulirus argus)* density	Decrease	Increasing fishing pressure	Fisheries records and size data (largest sizes targeted by fishing)	(Ehrhardt et al., 2011; Wynne and Côté, 2007)	
		Loss of habitat	Coral cover, rugosity	(Ehrhardt et al., 2011; Wynne and Côté, 2007)	
		Decrease in larval recruitment	Lobster size-frequency data	(Ehrhardt et al., 2011)	
		Disease outbreak	Disease incidence in population	(Behringer et al., 2009)	
Conch (principally *Strombus gigas*) density	Decrease	Increasing fishing pressure	Fisheries record and size data (largest sizes targeted by fishing)	(Appeldoorn et al., 2011; Stoner et al., 2012)	
		Loss of habitat	Seagrass and mangrove survey data (key conch habitats)		
Crown-of-thorns starfish density, Indo-Pacific reefs only	Increase	Decreased water quality	Water quality data, macroalgal cover, turf height, cover of other benthic heterotrophic feeders	(Brodie et al., 2005; Fabricius et al., 2010)	Bioerosion ↑
Fish:					
Abundance by species & Total fish abundance	Decrease	Potential overfishing	Fisheries data, species level biomass data	(Newman et al., 2006; Wilson et al., 2008)	
		Loss of habitat	Rugosity, coral cover	(Gratwicke and Speight, 2005; Wilson et al., 2008)	
Length by species	Decrease	Potential overfishing	Fisheries data, slope of size-spectra	(Dulvy et al., 2004; Graham et al., 2005)	
Biomass[d] by species (see family groups below for details)	Decrease	Potential overfishing	Fisheries data, species level biomass data	(Newman et al., 2006; Wilson et al., 2008)	
		Loss of habitat	Rugosity, coral cover	(Gratwicke and Speight, 2005; Wilson et al., 2008)	
Biomass by family[e]:					
• Chaetodontidae (Butterflyfishes)	Decrease	Reduction in coral cover (food and habitat)	Cover cover, coral cover by species, rugosity	(Chong-Seng et al., 2012; Cole et al., 2008)	
		Collection for aquarium trade	Fisheries data	(Tissot and Hallacher, 2003; Wabnitz et al., 2003)	
• Haemulidae (Grunts)	Decrease	Overfishing	Fisheries data, abundance and length data	(Ault et al., 1998; McClenachan and Kittinger, 2013)	

Table 3 (*Continued*)

Attribute	What is the trend?	Main possible drivers of trend	Other attributes to cross reference to confirm driver	Supporting references	Direct impact of trend on ecological processes
		Loss of nursery habitat (mangroves and seagrass) and/or foraging grounds	Habitat survey data	(Burke, 1995; Mumby et al., 2004; Nagelkerken et al., 2000)	
• Lutjanidae (Snapper) & • Serranidae (Groupers, Sea bass)	Decrease	Overfishing	Fisheries data, abundance and length data	(Hawkins and Roberts, 2004; Mumby et al., 2012)	
		Loss of reef complexity	Rugosity, coral cover	(Gratwicke and Speight, 2005; Wilson et al., 2008)	
		Loss of nursery grounds (mangroves, seagrasses and coral reef)	Cora cover, rugosity, seagrass and mangrove survey data	(Dorenbosch et al., 2005; Igulu et al., 2014; Mumby et al., 2004)	
• Muraenidae (Moray eels)	Decrease	Overfishing	Fisheries data	(Gilbert et al., 2005; Johnson, 2010)	
		Loss of habitat	Rugosity, coral cover	(Gilbert et al., 2005)	
Herbivorous fishes functional groups[e] biomass:					
• Scrapers/excavators	Decrease	Overfishing (fishing down the food web)	Fisheries data, turf canopy height	(Edwards et al., 2014; Mumby et al., 2012)	Grazing↓ Bioerosion ↓
		Loss of habitat	Rugosity, coral cover	(Bozec et al., 2013; Wilson et al., 2008)	
	Increase	Unless fishing pressure recently declined, an increase is usually attributed to a large loss of coral and increase in algal food	Coral cover, fisheries data, turf canopy height	(Adam et al., 2011; Gilmour et al., 2013)	Grazing ↑ Bioerosion ↑
• Grazers/detritivores	Decrease	Overfishing (fishing down the food web)	Fisheries data, turf canopy height	(Edwards et al., 2014; Mumby et al., 2012)	Grazing ↓
		Loss of habitat	Rugosity, coral cover	(Bozec and Mumby, 2015; Wilson et al., 2008)	
• Browsers	Decrease	Overfishing (fishing down the food web)	Fisheries data, macroalgal cover	(Edwards et al., 2014; Mumby et al., 2012)	Grazing ↓
		Loss of habitat	Rugosity, coral cover	(Bozec and Mumby, 2015; Wilson et al., 2008)	
• Territorial damselfish	Increase	Decrease in abundance of their predators (mainly mesopredators)	Damselfish predator (mesopredators) biomass, turf algae cover	(Arnold et al., 2010; Hoey and Bellwood, 2009; Mumby et al., 2012)	
Lionfish abundance, Caribbean/Western Atlantic reefs only (where lionfish are invasive)	Increase	Lionfish population has not reached maximum density	Biomass of prey species	(Green et al., 2012; Morris and Akins, 2009)	
	Decrease	Removal efforts reducing numbers	Lionfish removal data	(Frazer et al., 2012; León et al., 2013)	

[a] Acute stressors: Storms (cyclones), coral blasting, shipwreck, mass bleaching event, major disease outbreak, Crown-of-thorns starfish outbreak, flooding or landslide resulting in heavy sedimentation, massive nutrient increase.

[b] Chronic stressors: Continuous or repeated nutrient flow onto reef (e.g. from sewage leakage), continuous or repeated sediment flow onto reef (e.g. due to deforestation combined with rainfall), overfishing of herbivores (herbivorous fish and/or Diadema).

[c] Classified as autotrophic and heterotrophic for ecological interpretation.

[d] Biomass is used rather than length or abundance because biomass can be interpreted more usefully and can be easily calculated from length and abundance values (Bohnsack and Harper, 1988).

[e] Biomass by family – family groups are those included in more than one monitoring programme. Herbivorous fishes (family groups Scaridae, Acanthuridae and Pomacanthidae) are broken into four functional groups (as per Edwards et al., 2014) so that ecologically meaningful interpretation can be provided.

example, a decrease in coral juvenile density could be driven by a decrease in substrate suitable for recruitment, an acute stressor causing juvenile mortality, a decrease in coral larval supply, and/or decreased water quality (Table 3 column 3). By cross-referencing those attributes suggested in Table 3 column 4, a user should be able to confirm which is the most likely driver of a trend.

3.2. Diagnosis of reef stressors

The diagnostic decision tree is a representation of an elimination process for determining the most likely stressor(s) affecting a reef (Fig. 2). It is a graphical summary of select indicators from Table 3, and allows the path between reef health and possible stressors to be followed. Although all major reef stressors are included, the list of stressors is not exhaustive, so it is possible to make an incorrect diagnosis, just as with any diagnostic process.

A total of 14 indicators were used to construct the decision tree. Nine of these indicators stem from monitoring data: coral cover (used twice), coral cover by species, coral partial mortality, coral growth rate, macroalgal cover, turf algae height, rugosity, crown-of-thorns starfish density and herbivore biomass (used twice). Data for the other three indicators (recent storm, recent thermal anomaly, and proximal flooding or landslide) can be obtained through local knowledge or freely available internet databases (Table 1).

The diagnostic decision tree is split into two major branches: acute and chronic stressors. When an acute stressor has been diagnosed the diagnostic process is repeated, starting with the first indicator on the chronic stressor branch of the decision tree ("Increase in turf height?"), as an additional underlying, undiagnosed chronic stressor may also exist. Ideally, all indicators on the chronic stressor side of the diagnostic decision tree should be assessed to ensure no stressors are missed in the diagnosis, however this will depend on the data available to the user. In two cases an 'unknown' diagnosis may be reached. On the acute stressor branch of the tree, alternative explanations for this 'unknown' diagnosis include an unobserved coral predator outbreak or coral disease that caused coral loss across multiple species. Monitoring data on coral predator scars could be examined in the former case and adjacent reefs could be surveyed for disease in the latter case. For the 'unknown' diagnosis on the chronic stressor branch of the tree, coral predators or disease could also be the underlying cause, and appropriate monitoring data should be consulted.

If a diagnosis of 'Potential for future impact on reef' is reached, continued monitoring of herbivores and turf algal height is particularly important as declines in density or biomass of herbivores may lead to an increase in algal turf height or macroalgal cover, which could reduce coral recovery rates (Mumby et al., 2015) or even precede recruitment failure (Arnold and Steneck, 2011; Fig. 1).

3.3. Relative prognosis of reef health

Several prognosis decision trees can be constructed depending on the stressors that were diagnosed. Two decision trees are presented here for the situations where the chronic stressors 'ecosystem overfishing of herbivores' or 'nutrient increase' have been diagnosed (Fig. 3), and the acute stressors 'storms', 'coral blasting/ship grounding' or 'mass bleaching' have been diagnosed (Fig. 4). Further decision trees are presented in the Supplementary data (Figs. A1–A5 in Appendix A). For situations where both acute and chronic stressors have been diagnosed, the prognosis decision tree for the chronic stressor should be used as it is this stressor that will, by definition, have continuing impact on the reef and be more likely to affect the long-term prognosis.

By working through the indicators in the prognosis decision trees in turn, a prognosis score is obtained for a reef, with the lowest score representing the best prognosis. A reef's prognosis score places the reef on a scale from 'worst future scenario' to 'best future scenario'. These scores are not comparable between different decision trees and they do not represent absolute magnitudes of recovery potential.

In addition to being an accessible graphical representation of the prognosis scoring system, the decision trees also enable the user to identify the potential levers for management action in terms of improving the prognosis for a given reef. For example, in Fig. 3, if a reef had a score of 6 (worst prognosis), management actions that could reduce macroalgal cover, such as increasing herbivore populations, would reduce that score to 4, thus improving the relative prognosis outcome. Further information on the use of the prognosis decision trees is provided in Supplementary Material Appendix B.

3.4. Informing management decisions

Once a stressor has been diagnosed, it allows management actions to focus on the driver of that stressor where possible. For example, if the diagnosis reveals sedimentation as the stressor, management can focus on controlling sources of sediment, possibly through watershed management or control of coastal development. However, for many of the acute stressors, such as storms or mass bleaching, it will not be possible to manage the immediate drivers of the stressor. In these cases management actions can focus on improving preparedness for mitigating future stressors, work to reduce any chronic stressors to the reef, and, in some cases, assist recovery through restoration efforts (Table 4).

3.5. Potential improvements to monitoring programmes

The indicators used in diagnosis and prognosis can form a minimal set to be included in reef monitoring programmes (Table 5). Two of these indicators are not commonly included in monitoring programmes: turf canopy height is measured in only two of the programmes we collated data from, and coral growth rate in only one. Their inclusion in all programmes might increase the management usefulness of monitoring results. Turf canopy height is a rapid indicator of a shift in the relative importance of bottom-up and top-down controls of algae, thereby indicating either a strengthening of nutrification or a reduction in herbivory. Experimental and observational studies have found that an increase in turf canopy height can reduce coral recruitment directly (Arnold et al., 2010; Mumby et al., 2013) and the situation is compounded if turfs also trap sediments (Birrell et al., 2008). Measuring algal turf height is a quick and simple process requiring only a ruler, and is therefore easy to include in reef monitoring programmes. Coral colony growth rate can reflect the impacts of multiple stressors including sediments, temperature, and algal competition (Box and Mumby, 2007; Carricart-Carricart-Ganivet and Merino, 2001; Carricart-Ganivet et al., 2012) and strongly influences the ability of a reef to recover after an impact (Ortiz et al., 2014a). Growth rate can be measured using permanent quadrats (van Woesik et al., 2009) or tagging individual colonies (English et al., 1997). Tags can be attached using plastic cable ties for branching corals or nails for massive colonies (Hill and Wilkinson, 2004), though the use of nails may be prohibited in some protected areas and can be damaging to the coral.

Disease prevalence was measured by all except one of the reef monitoring programmes, but none of them measured disease incidence which we have used in the prognosis. Prevalence is the proportion of diseased corals at a single point in time, whereas incidence is the number of new cases of disease over time. Prevalence data are easier to collect on a snapshot survey but have limited value for monitoring. For example, the coral population might have

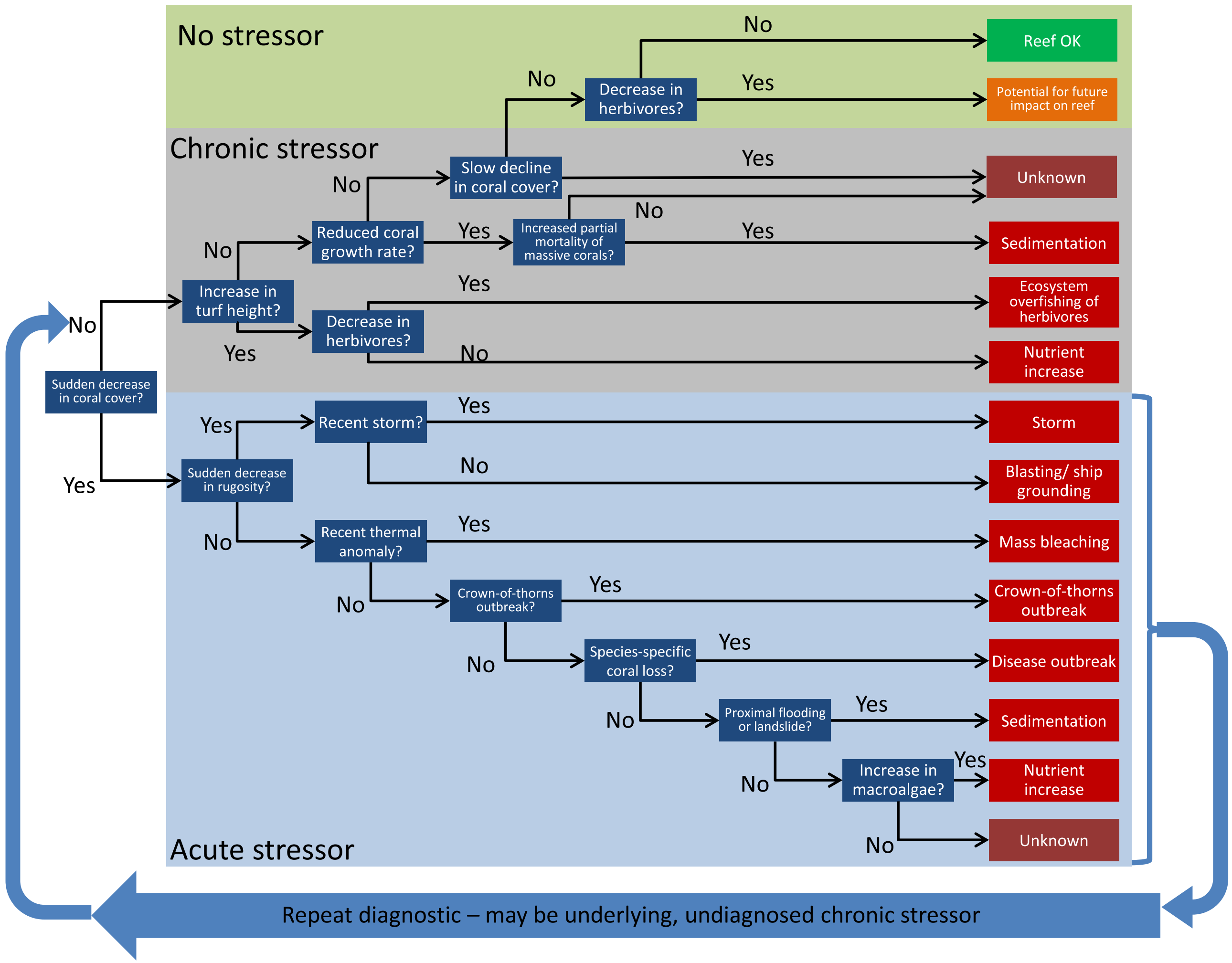

Fig. 2. Diagnostic decision tree for main reef stressors. Stressors are shown in red boxes and indicators in blue boxes. When an acute stressor is diagnosed, the diagnostic processes should be repeated, starting with the "Increase in turf height?" indicator, to check for chronic stressors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

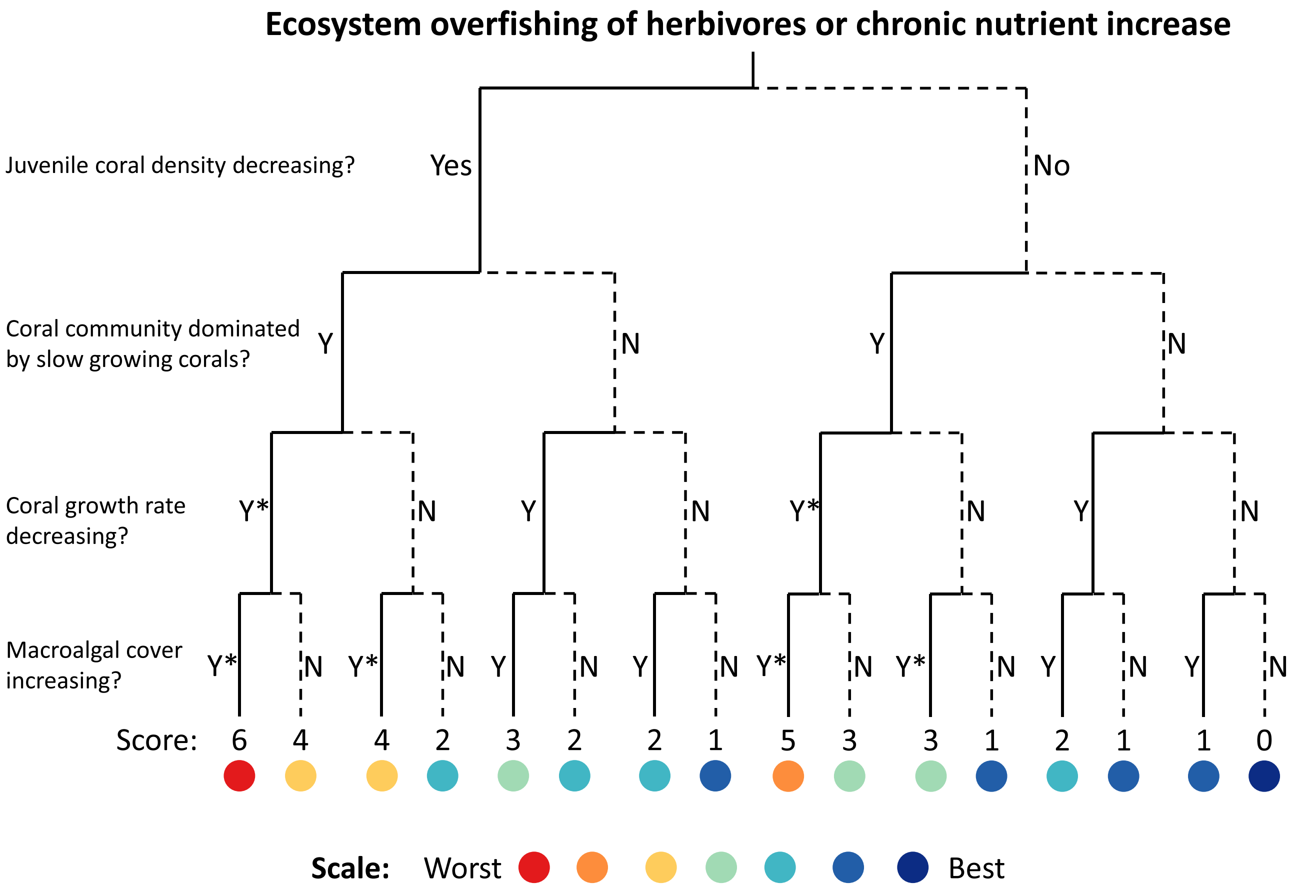

Fig. 3. Prognosis decision tree for chronic stressors 'ecosystem overfishing of herbivores' or 'nutrient increase'. Dashed branches are for 'No' answer to indicators, solid branches for 'Yes' answers. Scores at the bottom of each branch are summation of scores obtained by working through each branch. Each 'Yes' answer ('Yes'/'Y') scores 1, each 'No' answer ('No'/'N') scores 0, and each Yes answer with asterisk ('Y*') scores 2 to account for expected synergistic impacts.

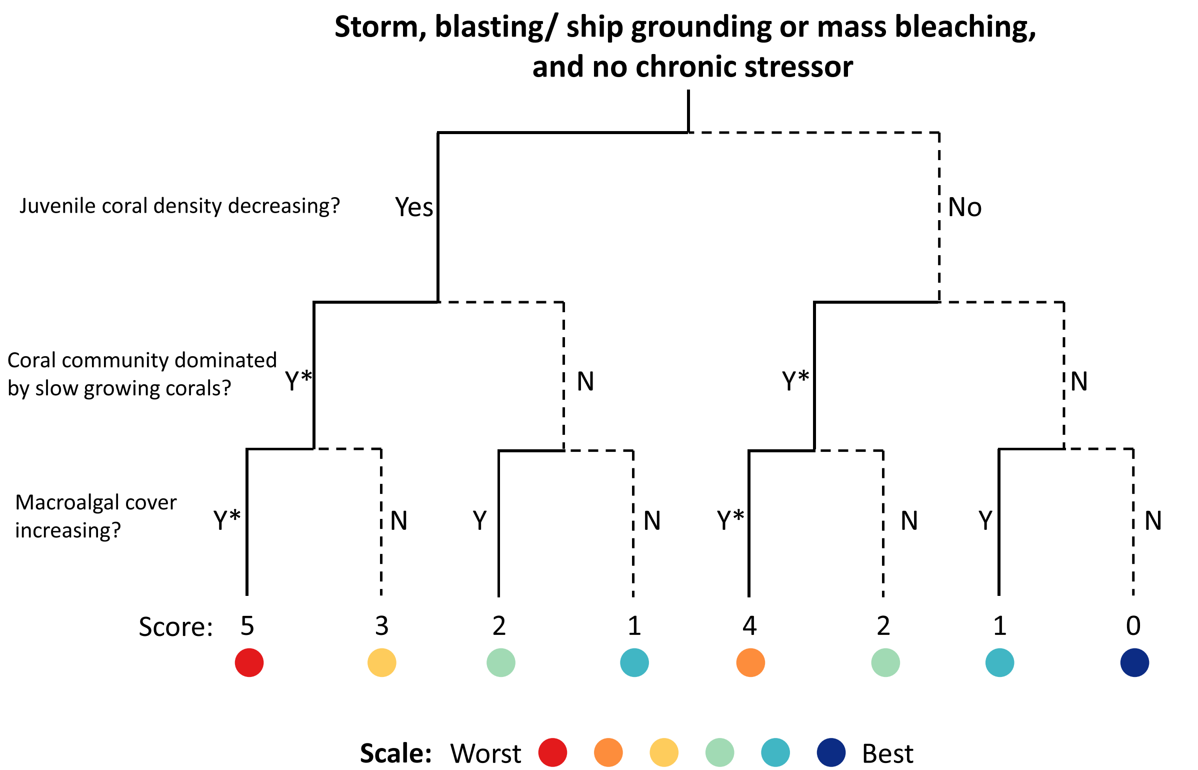

Fig. 4. Prognosis decision tree for acute stressors 'storm', 'blasting/ship grounding' or 'mass bleaching', and where no chronic stressor has been diagnosed. Dashed branches are for 'No' answer to indicators, solid branches for 'Yes' answers. Scores at the bottom of each branch are summation of scores obtained by working through each branch. Each 'Yes' answer ('Yes'/'Y') scores 1, each 'No' answer ('No'/'N') scores 0, and each Yes answer with asterisk ('Y*') scores 2 to account for expected synergistic impacts.

Table 4
Potential management actions for reef stressors.

Stressor	Acute/Chronic	Potential management actions (partially adapted from Anthony et al., 2014)
Sedimentation	Both	Improve management of watershed through education, regulation, incentives and penalties. Re-vegetation of surrounding land. Control coastal development activities
Ecosystem overfishing of herbivores	Chronic	Improve fisheries management through education, regulation, incentives and penalties. For example: ban trap fishing and/or herbivore harvesting, implement no-take zones
Nutrient increase	Both	Improve management of urban, agricultural and shipping activities through education, regulation, incentives and penalties
Storm	Acute	Preparedness and recovery planning locally. Reduce any local chronic stressors
Coral blasting	Acute	Increase incentives for non-destructive harvest of resource through education, regulation and enforcement. Improve recovery through substrate stabilisation and reef restoration measures
Ship grounding	Acute	Reduce likelihood of groundings through education, regulation, incentives and penalties. Use compensation payments to aid recovery through substrate stabilisation and reef restoration measures
Mass coral bleaching	Acute	Reduce any local chronic stressors. Identify sites that may have lower vulnerability as possible refugia for protection
Crown-of-thorns starfish outbreak	Acute	Improve management of watershed through education, regulation, incentives and penalties. Protection of CoTS predators, surveillance to detect early signs of CoTS build up with tactical CoTS control
Disease outbreak	Acute	Reduce stressors that can increase incidence and severity of diseases such as increased nutrient levels and other land-based runoff (see sedimentation and nutrient increase above)

a constant 10% prevalence of diseased colonies but the implications are dramatically different if this 10% constitutes the same colonies from year to year (i.e. corals that tolerate the disease) versus a new set of infected colonies each year which likely implies that coral populations will decline markedly over time. Resolving the latter requires tagging of colonies (both infected and uninfected) and monitoring changes in the incidence as well as the response of corals to disease. Although not included in diagnosis or prognosis, bleaching incidence can also be a useful indicator.

Monitoring needs to be done at appropriate time intervals to detect trends with sufficient early warning to affect useful management interventions. Due to economic and logistic factors, there is a trade-off between the frequency of monitoring and the number of sites that can be sampled. For example, frequent sampling at a small number of sites may not give a true picture of overall reef health in an area, but could still be time consuming and expensive (Hill and Wilkinson, 2004). For many reefs, annual or even biennial monitoring is sufficient to detect change, as many changes are slow, e.g. the Great Barrier Reef Long –term Monitoring Program uses both broad-scale annual surveys and biennial intensive surveys to balance the need for detail and spatial and temporal coverage (Sweatman et al., 2008). However, monitoring should also be adaptive so that following an acute stressor, such as a bleaching event, more frequent monitoring, possibly including more sites, can be initiated to track reef recovery or decline.

3.6. Limitations of methods and future directions

The methods presented here are a first attempt at providing a general framework for interpreting reef monitoring data. However, the relative importance of ecological processes varies geographically; therefore the framework would benefit from careful tailoring to specific regions. For example, herbivory in the Caribbean is currently dominated by parrotfishes (Mumby et al., 2006) whereas surgeonfishes likely dominate this function in many Pacific locations (Marshell and Mumby, 2015; Russ, 1984). Furthermore, as work continues on finding ecosystem thresholds (e.g. Karr et al., 2015), these can be incorporated into the methods. In other words, the principles embodied in the framework are likely to hold generically although the specific details and thresholds will differ from region to region.

Table 5
Key indicators used in diagnosis and prognosis.

Indicator	Used in: Diagnosis?	Prognosis?
Coral cover	√	
Coral cover by species	√	√
Juvenile coral density		√
Coral growth rate	√	√
Coral partial mortality	√	
Coral disease incidence		√
Macroalgae cover	√	√
Turf canopy height	√	√
Crown-of-thorns starfish density	√	√
Herbivore biomass (fish and *Diadema* where they are significant grazers)	√	√
Rugosity	√	

As many reefs are currently impacted by more than one stressor (Ban et al., 2014), an improvement to the methods developed here would be to evaluate whether multiple stressors act additively, synergistically, or even as an antagonism. While both empirical (Darling et al., 2010) and modelling studies (Bozec and Mumby, 2015) have looked at the impacts of multiple stressors, more work will be needed before a general framework for understanding and quantifying these impacts can be provided. Long-term monitoring of reefs will help in this process, providing the opportunity to study multiple stressors, which more reefs will be exposed to as the impacts of climate change increase in frequency and intensity (Côté et al., 2016).

4. Conclusion

Reef monitoring is expensive and there have been previous criticisms of the lack of focus on useful indicators (Downs et al., 2005; Risk, 1999). Calls to change the suite of attributes recorded on surveys have generally gone unheeded, most likely because of difficulty prioritizing attributes given the great complexity of the reef ecosystem, historical inertia of programmes, and confusion and disagreement as to the best indicators. Our attempt to build a framework for the interpretation of monitoring data draws on a diverse ecological literature and we hope that continued advances in reef science can be incorporated to improve such frameworks in future. While our framework should not surprise reef ecologists, we hope that it will help practitioners interpret monitoring data and identify appropriate management actions in the field.

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Appendix A. Supplementary data

Appendix B. Supplementary data can also be found online.

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2016.09.003.

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