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.

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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;

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