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A Bayesian Belief Network to assess rate of changes in coral reef ecosystems

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ABSTRACT

It is crucial to identify sources of impacts and degradation to maintain functions and services that the physical structure of coral reef provides. Here, a Bayesian Network approach is used to evaluate effects that anthropogenic and climate change disturbances have on coral reef structure. The network was constructed on knowledge derived from the literature and elicited from experts, and parameterised on independent data.

Evaluation of the model was conducted through sensitivity analyses and data integration was fundamental to obtain a balanced dataset. Scenario analyses, conducted to assess the effects of stressors on the reef framework state, suggested that calcifying organisms and carbonate production, rather than bioerosion, had the largest influence on the reef carbonate budgetary state. Despite the overall budget remaining positive, anthropogenic pressures, particularly deterioration of water quality, affected reef carbonate production, representing a warning signal for potential changes in the reef state.

1. Introduction

Coral reefs are important ecosystems that support biodiversity and provide ecological, social and economic benefits for many communities (Moberg and Folke, 1999; Cesar et al., 2003; Burke et al., 2011).

The extent to which services (e.g. shore protection) and functions (e.g. biodiversity) are maintained by coral reef ecosystems is associated with the persistence of their three-dimensional structure (framework; Perry et al., 2008). Unfortunately, coral reefs have suffered, and continue to suffer, significant framework degradation and loss (Alvarez-Filip et al., 2009; Perry et al., 2013). Anthropogenic disturbances and pressures, such as urban and industrial developments, destructive fishing activities, catchment misuse and coastal and inland deforestation (Burke et al., 2002, 2011; Edinger et al., 2000), have increased the vulnerability of these systems to climate variability (Hoegh-Guldberg et al., 2007; Anthony et al., 2008; Baker et al., 2008; Eakin et al., 2010), overall threatening reefs' functionality (Kennedy et al., 2013).

Rate of changes of the reef framework have been largely investigated through carbonate budget assessments that estimate contribution from reef-building (e.g. hermatypic corals, crustose coralline algae) and bioerosive (e.g. sea urchins, sponges, parrotfish) organisms (Eakin, 1996, 2001; Edinger et al., 2000; Hubbard et al., 1990; Mallela and Perry, 2007; Perry et al., 2013; Stearn and Scoffin, 1977). Coral reef structural integrity is associated with positive budgets that occur when calcium carbonate production exceeds the rate of erosion, whereas negative budgets occur generally as a result of changes in the natural reef processes (Perry et al., 2008; Kennedy et al., 2013).

Despite carbonate budgets being valuable in determining the 'state' of a reef system, they do not always provide a full picture of disturbances and pressures responsible for changes in the framework state, and are therefore limited in their application for long-term management. In addition, varied and often incomplete datasets, as well as limited knowledge on the relationships between coral reef abiotic and biotic factors, can result in considerable uncertainty in the parameters of resulting models. In coral reef ecosystems uncertainty may be associated with ecological and biological processes (e.g. coral reef framework growth and erosion)

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and with changes triggered by climatic and anthropogenic disturbances and pressures (e.g. changes in ecosystem state due to extreme sea water temperatures, sedimentation, water pollution). This has the potential to limit the identification of management priorities and the definition of effective management actions (Olsson et al., 2004; Smith et al., 2011).

A comprehensive approach that integrates uncertainty, can aid sustainable coral reef management and prevent further decline. Although, it is impossible to predict with certainty the result of management decisions, it is important to provide decision-makers with models that consider the impacts of implementing management interventions or decision options in order to maximize their benefit (Uusitalo et al., 2015). Therefore, to evaluate the effects of anthropogenic and climatic disturbances on the reef framework, we propose a Bayesian Belief Network (BBN) approach, which offers a methodological framework to address uncertainty (Bennett et al., 2013; Kelly et al., 2013).

BBNs associate variables via conditional probability distributions and use inference algorithms to calculate posterior probabilities of the outcome states (Jensen and Nielsen, 2007). They consist of two structural components: (1) a direct acyclic graph (DAG), where each vertex represents one of the variables in the model; (2) conditional probability tables (CPTs), indicating the strengths of the links in the graph by denoting the likelihood of the state of a 'child' node given the states of its 'parent' nodes (those from which edges entering the node originated) (Renken and Mumby, 2009; Landuyt et al., 2013). The DAG consists of a set of variables or nodes that can take on a number of pre-defined discrete "states", which are mutually exclusive and exhaustive (Borsuk et al., 2004). The presence of an edge linking two variables indicates the existence of statistical dependence between them (Aguilera et al., 2011). Inference can be used to propagate conditional probabilities through the network (Aguilera et al., 2011), whilst accounting for uncertainty.

BBNs enable the integration of empirical data and expert knowledge (Uusitalo, 2007; Aguilera et al., 2011; Chen and Pollino, 2012), can operate in a data poor environment (Uusitalo, 2007), and can be readily updated with newly available data, by combining the new information with prior probabilities such that, the network posterior probabilities are updated in response to additional observational information (Marcot et al., 2001). Although BBNs are efficient in integrating variables presented at different scales (Wooldridge et al., 2005), they are constrained in describing explicit spatial and temporal dynamics and interactions, requiring the use of different nodes to represent and incorporate information on different locations or times (Marcot et al., 2001; Kelly et al., 2013). In addition, since they do not allow for feedback loops among variables, time steps to describe such effects are needed (Marcot et al., 2001; Kelly et al., 2013), adding complexity to the model and limiting their application to systems or processes described by feedback interactions (e.g. nutrient cycle; food webs). Due to the explicit handling of uncertainty (as well as their ability to integrate different type of data and knowledge) BBNs provide the opportunity to identify key knowledge gaps in our scientific understanding of complex systems, and hence inform future research priorities (Marcot et al., 2001; Uusitalo, 2007; Renken and Mumby, 2009).

The graphical structure of BBNs is particularly relevant in ecosystem management since it facilitates a participatory approach during the development of the model and provides a user-friendly framework to communicate the results (Marcot et al., 2001; Borsuk et al., 2004; Jakeman et al., 2006; Aguilera et al., 2011; Chen and Pollino, 2012; Vilizzi et al., 2013). Extensive reviews of the use of BBN for environmental modelling can be found in Aguilera et al. (2011) and Chen and Pollino (2012).

The Carbonate Budget BBN (CARBNET) was developed to evaluate coral reef carbonate balance under changing environmental conditions and across reef bioregions. The aim was to identify those disturbances and pressures that exert the greatest influence in modifying the reef framework $CaCO_3$ (carbonate) budgetary state.

2. Methods

2.1. Network development process

CARBNET construction followed a well-defined procedure through which i) variables affecting and describing the state of the '*Calcium carbonate budget*' output node were identified, ii) the relationships among these variables were identified, iii) the CPT tables were populated with data cases after discretisation of the data.

2.1.1. Identification of the variables composing CARBNET network

In CARBNET, variables contributing to coral reef framework growth and destruction were identified through a literature search with the key words 'carbonate budget + coral reef', '$CaCO_3$ budget + coral reef' and 'calcium carbonate budget + coral reef' conducted in *ISI Web of Science* (Reuters) and *Reefbase* (http://www.reefbase.org) between November 2010 and January 2011. The variables composing the network were selected among those that defined the quantitative contribution of the reef-building and bioerosive taxa to the reef carbonate budget (see Appendix A). Reef-building organisms were identified as calcifying organisms (i.e. hard corals, crustose coralline algae and epibionts) that contribute to biogenic carbonate production and deposition. Bioeroders were identified as organisms contributing to chemical or mechanical removal of carbonate from the reef framework while grazing on (i.e. sea urchins and parrotfish) or boring into (i.e. sponges, bivalves, sipunculans, polychaetes and euendoliths) the reef substrate.

Climatic and anthropogenic disturbances and pressures were also included in the network to determine the extent to which impacts affect reef preservation and carbonate balance. In this paper we refer to disturbances as 'actions' (e.g. logging) that can translate into increasing pressures (e.g. sedimentation and eutrophication) on the ecosystem, leading to likely changes in the state of the reef communities (response), that as a consequence, may impact reef framework functionality. Many of these disturbances included those arising from climate change, such as sea surface temperature rise, ocean acidification and increasing occurrence of hurricane or cyclones, as well as disturbances from human activities including destructive fishing practices, inland deforestation, coastal degradation and fish farming. In light of increasing regional and global anthropogenic and climate change disturbances, features giving information on the effects of disturbances on reef ecosystem and communities, allowed for '*what if*' analysis, providing the basis to underpin changes in the framework $CaCO_3$ budgetary state (Cooper et al., 2009; Burke et al., 2011), as well as illustrating the effects that implemented management interventions may have on preserving coral reef framework. Disturbance and pressure variables were identified among the carbonate budget studies that assessed changes in the $CaCO_3$ budgetary state, relative to climatic and anthropogenic impacts (Table A.2, Appendix A), as well as from the *Reefs at Risk* tool (Burke et al., 2002; Burke and Maidens, 2004; Burke et al., 2011, 2012) where threats to the world's coral reefs are described through map-based indicators (Table A.3, Appendix A).

As part of this review, the information was conceptualised in a diagram (not shown) in which dependencies were identified among variables including the '*Calcium carbonate budget*' response node.