Exploring management scenarios for the Great Barrier Reef (GBR) using Bayesian Belief and Decision Networks

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ABSTRACT

Coral reefs globally face a variety of threats, both natural and anthropogenic, that may act synergistically in ways that are complex and currently not well understood. Bayesian belief networks present an ideal tool for modeling the range of uncertainties that exist in the interface between social and ecological systems. In this study, empirical evidence of stressor effects is combined with expert opinion from coral reef ecologists and managers to construct a Bayesian belief network (BBN) and Bayesian decision network (BDN) that will be used to explore different possible ecosystem outcomes in the context of uncertainty about feasibility and efficacy of different management strategies. In addition, different climate change scenarios that are associated with a range of possible sea surface temperature and acidification levels will be examined in conjunction with the range of available management strategies to explore the possibility of mitigating against deleterious effects of climate change on the GBR. The results of this study may assist coral reef managers when deciding which management actions and strategies are the most cost-effective in dealing with the effects of climate change.

INTRODUCTION

Interactions of multiple stressors, and the resulting cumulative impacts, have been identified as a research priority for coral reefs (GBRMPA 2009). Multiple stressors can generally be considered to be independent, antagonistic, or synergistic. Antagonistic stressors inhibit the adverse effects of one or more of the other stressors, whereas synergistic stressors exacerbate the adverse effects of one or more of the others. The importance of stressor interactions on ecological systems was identified over a decade ago (Breitburg, et al. 1999), but only recently have such interactions been quantified, especially from an ecosystem management perspective (Halpern, et al. 2008, Halpern, et al. 2008).

Coral reefs have persisted over evolutionary time despite five major extinction events, at least some of which have been associated with high atmospheric carbon dioxide concentrations and/or greenhouse conditions (Veron 2008). However, carbon dioxide levels are on a trajectory to values not seen since the mid-Eocene epoch, and increasing at a rate that is faster than any seen in at least the past 420,000 years (Hoegh-Guldberg, et al. 2007). Furthermore, the slow exchange of CO_2 between the atmosphere and the oceans means that further acidification and warming is inevitable, even with an immediate reduction in CO_2 emissions.

Climate change stressors will likely include increased ocean temperatures (Graham, et al. 2008, Reaser, et al. 2000) and possibly increased ocean acidification (Feely, et al. 2004). Different management regimes and development scenarios may also result in changes in nutrient loading and sedimentation onto reefs. If environmental managers wish to forestall and/or reduce climate change impacts on coral reefs, they must therefore consider factors that are either contributing to, or mitigating against, the inevitable adverse effects of warming and acidification. Obura (Obura 2005) identified four levels at which management intervention can act to mitigate coral bleaching, which also apply to acidification:

1) Protect resistance through both environmental (*e.g.*, heat stress) and intrinsic (genetic) factors, such as taking advantage of current patterns that minimize exposure to warm stagnant water and by protecting areas with a history of thermal acclimation;
2) Build tolerance through healthy coral organisms, minimizing exposure to harm (such as prolonged bleaching events), and capitalizing on intrinsic factors;
3) Promote recovery by enhancing connectivity, herbivory, water quality, and recruitment, and;

4) Support human adaptive capacity through economic diversity, supporting policies, capital and technology, and human resources.

Some of these factors, such as intrinsic resistance and exposure to certain deleterious conditions, are difficult to directly address through management actions. However, knowledge about these factors can contribute to more effective policy decisions in other areas, such as protected area design. For example, there is a potential linkage between thermal bleaching thresholds and nutrient enrichment (DIN loading) in the GBR (Wooldridge and Done 2009, Wooldridge, et al. 2006, Wooldridge 2009), and decreased bleaching resilience has been linked to chronic stress in Mesoamerican reefs (Carilli, et al. 2010, Carilli, et al. 2009), although the optimal protection strategies associated with these findings are not yet clear (Game, et al. 2008). For example, the selection of protected areas can represent prevailing currents (*e.g.*, areas that tend to entrain cooler waters) and manage local stressors to ensure the protection of more resilient areas as sources of larval replenishment. The first governance steps towards this management approach were taken with the Reef Water Quality Protection Plan initiated in 2003, and further improvements are underway in the form of planning reform initiatives (GBRMPA 2009). The logical next step is to consider how changes in protected area design can incorporate these types of stressor management plans.

From a management perspective, it is important to identify which (controllable) stressors on coral reefs may play a role in minimizing and/or mitigating deleterious anthropogenic effects on coral reefs. Given the strong governance structure and tradition of adaptive management, the Great Barrier Reef provides an ideal context for exploring different possible future management scenarios. Models of coral bleaching and anthropogenic effects on corals seldom include prescriptions for management actions to mitigate these effects. Thus, not only do models need to incorporate anthropogenic effects other than those directly associated with climate change, and natural variability in factors such as tidal height and

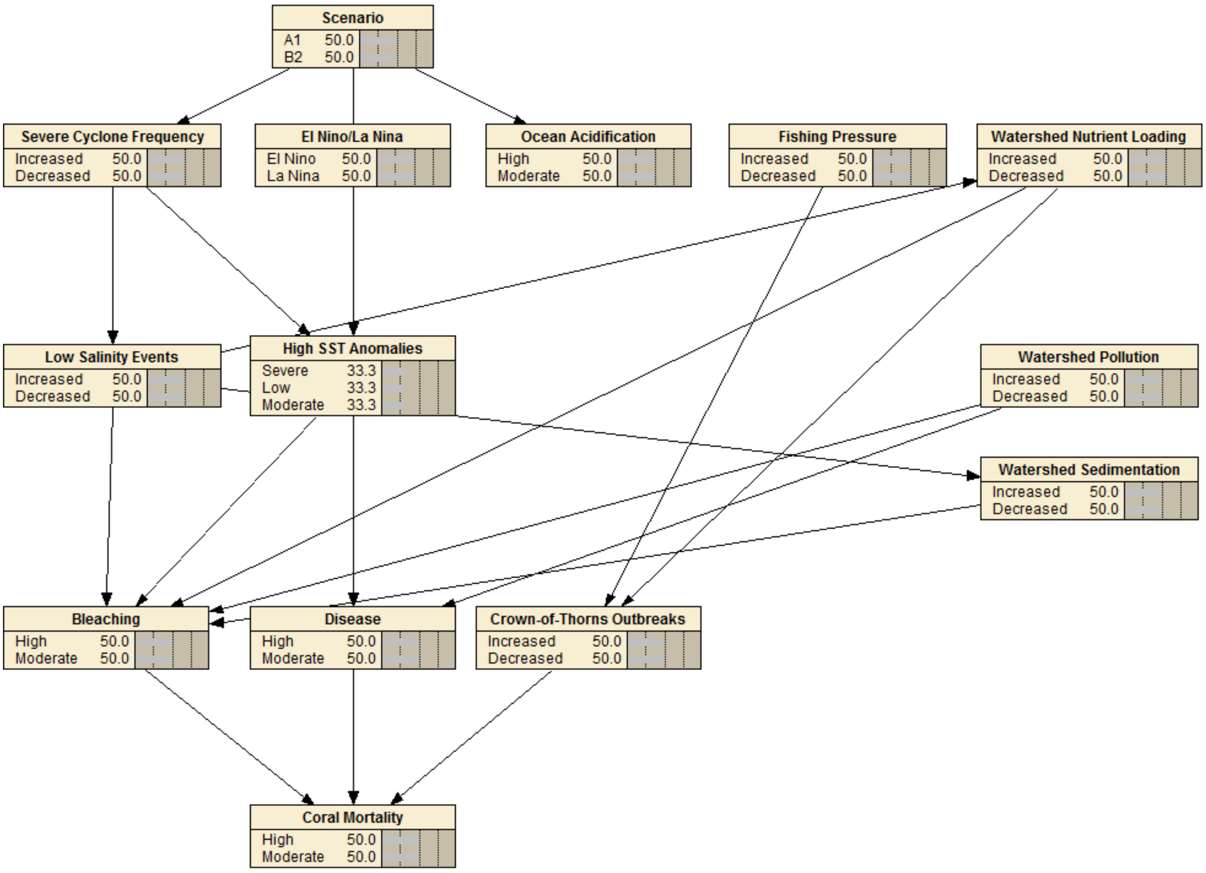

Figure 1. Hypothetical Bayesian belief network of natural and anthropogenic stressors contributing to coral bleaching, disease – and ultimately, mortality. Actions under the potential control of managers are at right.

ocean upwelling, they also need to include the effect(s) of actual or potential management actions on the intensity of stressors.

PROPOSED METHODS

To examine the possible effects of different management strategies, we will use a Bayesian belief network model. Bayes Rule states that the conditional (or posterior) probability of event A given event B, P(A|B) can be calculated by multiplying a prior belief P(A) by the likelihood that B will occur if A is true (P(B|A):

$$(1)\quad P(A|B) = \frac{P(B|A)*P(A)}{P(B)}$$

Bayesian belief networks (BBNs) allow for straightforward parameterization of the interactions between components (in the form of prior probabilities) while also allowing for explicit inclusion of uncertainty in parameter estimates through the use of probability distributions and likelihoods in lieu of a single number for a prior probability. The top level of a BBN consists of externally determined "parent nodes" whose variables or predictors whose values are not dependent (*i.e.*, conditional) on other components of the network. All nodes (variables) whose values are dependent on another part of the network are called "child nodes", but these may in turn be parent nodes to other nodes. Conditional probability is the probability that a certain variable in a node will take on a specific value (or range of values) given a particular value (or range of values) from a node or nodes with which it is connected. The full set of probabilities associated with a node is a conditional probability table. Nodes that are not directly connected within the network are considered to be "conditionally independent" - their values are not dependent on each other.

BBNs allow empirical data to be combined with expert opinion not only for model structure, but also to establish conditional probability tables for each node. One advantage of a Bayesian approach is that there is no distinction between parameters and data (MacNeil and Graham 2010), thus allowing conditional probability tables to be developed heuristically. Model training and validation will include cross-validation with major GBR bleaching events (*e.g.*, 1998 and 2002).

There is mounting evidence (mainly from the Caribbean thus far) of a bidirectional (bleaching affects susceptibility to disease, and vice-versa) interaction between thermal bleaching and disease (Muller, et al. 2008, Ben-Haim, et al. 2003, Brandt and McManus 2009, Harvell, et al. 2001). The first step of overall model development will be to create and refine a Bayesian network model of coral mortality focusing on coral disease and bleaching events as drivers of mortality (Figure 1).

A review of the literature indicates that there is insufficient information to fully inform all of the conditional probability tables in the network (Table 1). For example, the influence of temperature and irradiance (and to a lesser extent, nutrient loading) on bleaching probability is reasonably well-characterized (Berkelmans and Oliver 1999, Middlebrook, et al. 2008, Anthony, et al. 2007), as is the influence of temperature on the probability of disease outbreaks (Riegl 2002, Mydlarz, et al. 2010, Heron, et al. 2010, Bruno, et al. 2007). Thus, conditional probabilities (*i.e.*, the likelihood of a certain outcome in a child node given the state of a parent node) will be determined through a combination of literature review and expert opinion.

This model will focus on the interaction of two significant drivers of coral mortality (disease and bleaching), and the fast-changing (intra-annual to annual timescales) environmental variables influencing these events. Initial models will have a minimal set of putative predictors, and only aim to predict overall mortality probabilities for certain hard corals in a context-independent way (*i.e.*, ignoring the effect of other ecosystem components on this mortality).

As this model will be GBR-focused, white syndrome (WS) and black-band disease (BBD) will be the two main infections of interest. Both BBD (Green and Bruckner 2000, Boyett, et al. 2007) and WS (Heron, Willis, Skirving, Eakin, Page and Miller 2010, Bruno, Selig, Casey, Page, Willis, Harvell, Sweatman and Melendy 2007) are known to increase during periods of high water temperatures, and conversely may be inhibited by unusually cold winter periods (Heron, Willis, Skirving, Eakin, Page and Miller 2010). However, warmer winter temperatures also corresponded with fewer WS outbreaks in subsequent months, implying a subtle and complex overall effect of an increase in mean temperature. Furthermore, the incidence and prevalence of disease in general may also be exacerbated by high nutrient and sediment loading (Richardson 1998), although this has yet to be demonstrated conclusively on the GBR.

Inputs to the model will come from several sources:

- published literature to establish initial prior probabilities and model structure
- expert opinion for conditional probabilities that cannot be empirically derived or otherwise precisely determined, if necessary

- archived satellite data; specifically, AVHRR for sea surface temperatures, SeaWiFS for irradiance and water quality proxies (*e.g.*, K_d490)
- historical and modeled extent of flood plumes
- The AIMS Long-term Monitoring Program (LTMP) and Representative Areas Program (RAP) data

The software Netica (http://www.norsys.com/netica) will be used to develop and test these Bayesian belief networks. Once generated, the resulting models will then be implemented spatially on a cell-by-cell basis within a GIS.

RESEARCH SIGNIFICANCE

There are several objectives of this Bayesian belief model:

1) To translate available data into a quantitative model of bleaching and disease likelihoods
2) To determine whether models that incorporate additional predictors demonstrate improved predictive performance, and;
3) To examine the interaction effect of disease and bleaching events on coral mortality.

This approach differs from previous approaches (e.g., Wooldridge and Done 2004) in considering not only multiple possible sources of mortality (disease and bleaching), but also how environmental factors and stressor events themselves might interact to influence the frequency of these mortality events. This approach thus offers two useful outcomes: first, improving existing predictive models of bleaching and disease outbreaks; and secondly, offering an integrated bleaching and disease model that may be superior at predicting overall coral mortality than

Table 1. Asymmetric table of stressors affecting *incidence of* or *susceptibility to* other stressors. Color codes: Green - well supported, across many species/environments *or* a necessary physical-chemical relationship; yellow – evidence is contradictory; red - plausible/speculative, but not yet adequately supported with experimental evidence; grey - insufficient information to determine the nature of the interaction, or existence of the interaction is implausible.

Top row: stressor affecting → Left column: Stressor being affected ↓	(Increased) Acidification	(Thermal) Bleaching	CoTS	(Increased) Cyclones	Disease	(Over) Fishing	(Increased) Irradiance	(Increased) Nutrient loading	(Increased) Pollution	(Decreased) Salinity	(Increased) Sedimentation	(Increased) Sea level	(Increased) Temperature	(Increased) UV Exposure
(Increased) Acidification/ Decreased calcification	-	↑	-	-	?	-	↓	↑/ -/ ↓	?	?	?	-	↑/↓	?
(Thermal) Bleaching	↑	-	?	-	↑	-/↓	↑↓	↑/-/ ↓	↑	↑	↑/↓	↓/?	↑	↑/-/↓
CoTS outbreaks	-	?	↑	↑	-	↑	-	↑	↑	↑	↑	-	↑	?
(Increased) Cyclones	↑	-	-	-	-	-	-	↑	-	-	-	-	↑/↓	↑
Disease	↑	↑	↑	↑	↑	↑/↓	↑	↑	↑/-	-	↑	↑	↑/-	↑/↓
(Over)Fishing	↑	-	?	-	-	-	-	↓	?	-	-	-	-	-
(Increased) Irradiance	?	↑	-	-	?	-	-	↓	↑	-	↓	↓	↑	-
(Increased) Nutrient loading	↑	↑	-	↑	?	?	-	-	?	↑	↑	-	↑	-
(Increased) Pollution	?	?	-	↑	-	-	-	?	?	-	↑	-	?	-
(Decreased) Salinity	?	?	-	↑	?	-	↓	↑	-	-	↑	-	-	↑/?
(Increased) Sedimentation	?	?	-	↑/↓	-	-	-	↑	?	↑	-	↑	↓	↓
(Increased) Sea level	-	-	-	-	-	-	-	-	-	-	↑	-	↑	-
(Increased) Temperature	↑	↑	-	↓	?	-	↑/↓	↑	?	↑	-	?	-	↑/↓
UV exposure	-	↑	-	↓	-	-	↑/-	-	-	↑/?	↓	↓	↑/↓	-

models looking at these events in isolation.

The objective of this research is to examine implications of uncertainty for management actions in both stressor (forcing) conditions and ecosystem sensitivities to these stressors. This research will investigate whether any management strategies might be effective in mitigating or delaying climate change impacts on the Great Barrier Reef and determine what adaptive management responses are appropriate given the outcomes of the different modeling scenarios.

This research will explore uncertainties through explicit modeling of hypothetical management scenarios, and/or different uncertainty ranges in model parameters. In terms of management strategies, Game et al (Game, McDonald-Madden, Puotinen and Possingham 2008) showed that the optimal protected area strategy differed not only according to conservation objective (*i.e.*, maximizing chances of protecting a healthy site vs. maximizing the expected number of healthy sites), but also the likelihood of areas being in a generally degraded or generally healthy state. Furthermore, evidence that marine reserves provide protection or insurance against either bleaching (Graham, et al. 2007) or disease (Page, et al. 2009) is equivocal at best. New zoning or re-zoning of existing areas will need to consider the benefits and limitations of marine reserves, and will need to take into account factors such as the location and extent of existing and predicted stressor effects to maximize protection of resilient areas that could serve as refugia (Graham, McClanahan, MacNeil, Wilson, Polunin, Jennings, Chabanet, Clark, Spalding, Letourneur, Bigot, Galzin, Ã–hman, Garpe, Edwards and Sheppard 2008), and the incorporation of additional "insurance factors" (Allison, et al. 2003) against major disturbances. Zoning could take into account the location and extent of existing and predicted stressor effects to maximize protection of resilient areas that could serve as refugia.

This research will explore the effect of different management strategies and uncertainties in ecosystem responses through two means: first, by changing model parameters to reflect different interaction strengths between stressors or adaptive mechanisms, and second by altering the value or range of values associated with putative management actions. For example, the magnitude or certainty of the effect that nutrient loading has on bleaching susceptibility could be altered, or the range of possible nutrient loading values could be changed to reflect a change in watershed management.

Ultimately, the outcomes of this research could be used to aid managers in exploring the implications of different management decisions in the face of uncertainty about climate change impacts and the internal interactions of a complex ecosystem.

REFERENCES

GBRMPA (2009). Great barrier reef outlook report 2009, Great Barrier Reef Marine Park Authority.

D. Breitburg, et al. (1999). The effects of multiple stressors on freshwater and marine ecosystems: Preface. *Limnology and Oceanography* 44(3 II): 737-738.

B. S. Halpern, et al. (2008). Managing for cumulative impacts in ecosystem-based management through ocean zoning. *Ocean & Coastal Management* 51: 203-211.

B. S. Halpern, et al. (2008). A global map of human impact on marine ecosystems. *Science* 319(5865): 948-952.

J. E. N. Veron (2008). Mass extinctions and ocean acidification: Biological constraints on geological dilemmas. *Coral Reefs* 27(3): 459-472.

O. Hoegh-Guldberg, et al. (2007). Coral reefs under rapid climate change and ocean acidification. *Science* 318: 1737.

N. A. J. Graham, et al. (2008). Climate warming, marine protected areas and the ocean-scale integrity of coral reef ecosystems. *PLoS ONE* 3(8): e3039.

J. K. Reaser, et al. (2000). Coral bleaching and global climate change: Scientific findings and policy recommendations. *Conservation Biology* 14: 1500-1511.

R. A. Feely, et al. (2004). Impact of anthropogenic co2 on the caco3 system in the oceans. *Science* 305: 362-366.

D. O. Obura (2005). Resilience and climate change: Lessons from coral reefs and bleaching in the western indian ocean. *Estuarine, Coastal and Shelf Science* 63(3): 353-372.

S. A. Wooldridge and T. J. Done (2009). Improved water quality can ameliorate effects of climate change on corals. *Ecological Applications* 19(6): 1492-1499.

S. Wooldridge, et al. (2006). Exposure of inner-shelf reefs to nutrient enriched runoff entering the great barrier reef lagoon: Post-european changes and the design of water quality targets. *Marine Pollution Bulletin* 52(11): 1467-1479.

S. A. Wooldridge (2009). Water quality and coral bleaching thresholds: Formalising the linkage for the inshore reefs of the great barrier reef, australia. *Marine Pollution Bulletin* 58(5): 745-751.

J. E. Carilli, et al. (2010). Century-scale records of coral growth rates indicate that local stressors reduce coral thermal tolerance threshold. *Global Change Biology* 16(4): 1247-1257.

J. E. Carilli, et al. (2009). Local stressors reduce coral resilience to bleaching. *PLoS ONE* 4(7).

E. T. Game, et al. (2008). Should we protect the strong or the weak? Risk, resilience, and the selection of marine protected areas. *Conservation Biology* 22(6): 1619-1629.

M. A. MacNeil and N. A. J. Graham (2010). Enabling regional management in a changing climate through bayesian meta-analysis of a large-scale disturbance. *Global Ecology and Biogeography* 19(3): 412-421.

E. Muller, et al. (2008). Bleaching increases likelihood of disease on acropora palmata (lamarck) in hawksnest bay, st john, us virgin islands. *Coral Reefs* 27(1): 191-195.

Y. Ben-Haim, et al. (2003). Temperature-regulated bleaching and lysis of the coral pocillopora damicornis by the novel pathogen vibrio coralliilyticus. *Applied and Environmental Microbiology* 69(7): 4236-4242.

M. E. Brandt and J. W. McManus (2009). Disease incidence is related to bleaching extent in reef-building corals. *Ecology* 90(10): 2859-2867.

D. Harvell, et al. (2001). Coral bleaching and disease: Contributors to 1998 mass mortality in briareum asbestinum (octocorallia, gorgonacea). *Hydrobiologia* 460: 97-104.

R. Berkelmans and J. K. Oliver (1999). Large-scale bleaching of corals on the great barrier reef. *Coral Reefs* 18(1): 55-60.

R. Middlebrook, et al. (2008). The effect of thermal history on the susceptibility of reef-building corals to thermal stress. *Journal of Experimental Biology* 211(7): 1050-1056.

K. R. N. Anthony, et al. (2007). Bleaching, energetics, and coral mortality risk: Effects of temperature, light, and sediment regime. *Limnology and Oceanography* 52(2): 716-726.

B. Riegl (2002). Effects of the 1996 and 1998 positive sea-surface temperature anomalies on corals, coral diseases and fish in the arabian gulf (dubai, uae). *Marine Biology* 140(1): 29-40.

L. D. Mydlarz, et al. (2010). What are the physiological and immunological responses of coral to climate warming and disease? *Journal of Experimental Biology* 213(6): 934-945.

S. F. Heron, et al. (2010). Summer hot snaps and winter conditions: Modelling white syndrome outbreaks on great barrier reef corals. *PLoS ONE* 5(8): e12210.

J. F. Bruno, et al. (2007). Thermal stress and coral cover as drivers of coral disease outbreaks. *PLoS Biology* 5(6): 1-8.

E. P. Green and A. W. Bruckner (2000). The significance of coral disease epizootiology for coral reef conservation. *Biological Conservation* 96(3): 347-361.

H. V. Boyett, et al. (2007). Elevated temperature and light enhance progression and spread of black band disease on staghorn corals of the great barrier reef. *Marine Biology* 151(5): 1711-1720.

L. L. Richardson (1998). Coral diseases: What is really known? *Trends in Ecology & Evolution* 13(11): 438-443.

S. Wooldridge and T. Done (2004). Learning to predict large-scale coral bleaching from past events: A bayesian approach using remotely sensed data, in-situ data, and environmental proxies. *Coral Reefs* 23(1): 96-108.

N. A. J. Graham, et al. (2007). Lag effects in the impacts of mass coral bleaching on coral reef fish, fisheries, and ecosystems. *Conservation Biology* 21(5): 1291-1300.

C. A. Page, et al. (2009). Influence of marine reserves on coral disease prevalence. *Diseases of Aquatic Organisms* 87(1-2): 135-150.

G. W. Allison, et al. (2003). Ensuring persistence of marine reserves: Catastrophes require adopting an insurance factor. *Ecological Applications* 13(1): S8-S24.