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The development of an integrated systems model for balancing coral reef health, land management and tourism risks on the Great Barrier Reef

Thomas, C.R. [1], **I.J. Gordon** [1], **S. Wooldridge** [2], **M. van Grieken** [1] **and P. Marshall** [3]

[1] *CSIRO Sustainable Ecosystems, Davies Laboratory, Townsville, Queensland, Australia;* [2] *Australian Institute for Marine Science, Townsville, Queensland, Australia;* [3] *Great Barrier Reef Marine Park Authority, Townsville, Queensland, Australia*
Email mailto:colette.thomas@csiro.au

Abstract: A prototype Bayesian belief network (BBN) is described that provides catchment-to-reef integration of previously unlinked components of the Great Barrier Reef (GBR) social-ecological system. The BBN is developed to help decision-makers understand the socio-economic trade-offs associated with managing for resilient reef communities given the threat posed by climate change. The probability of severe coral bleaching events increases with climate-driven increases in surface ocean temperatures, but this threat is synergistically linked to the water quality within the GBR lagoon. Improved inshore water quality requires the adoption of 'best practice' catchment management, which may incur considerable cost to the agricultural industry. However, this cost is countered by the associated benefit of safeguarding future reef tourism. The aim of this work is to develop a prototype model capable of investigating these key system linkages only.

The BBN formalises this socio-ecological cost-benefit analysis within a risk assessment framework. This aids the difficult task of prioritising alternative management actions. The complexity of the problem represents a challenging modelling task with a large envelope of solutions needing to be represented, each with its own scale and configuration of 'wins' and 'losses' across diverse system sectors. To simplify the modelling task, we specifically targeted key elements of the reef, agriculture, and tourism sectors and then focused on developing the most parsimonious set of cross-sector linkages to generate an integrated systems model. We focus here on the approach used, as results are not yet available. The diverse nature of the individual sectors presented a major challenge for model construction, not least because the causal (i.e. dependence) relationships *within* individual sectors exist at different levels of understanding and scientific development, as do the relationships *between* the separate sectors. Furthermore, the data that captures the functional behaviour of each sector (as well as cross-sector interactions) exists as an eclectic mix of simulated, empirical and subjectively-derived information. Fortunately, the adopted BBN approach is capable of resolving these system domain and data uncertainties in a transparent fashion, which includes the assigning of error estimates for the alternate system trade-off scenarios. By making these trade-off uncertainties explicit, the resultant framework provides decision-makers with a rational (i.e. quantitative) method to resolve catchment level questions such as;

- Which reef protection target provides the lowest risk and maximum benefit for the local community?
- How soon must reef protection targets be realised in order to maximise cross-sector benefits?
- Can win/win strategies be pursued with acceptable levels of certainty?
- For a given reef protection target, what are the costs to industry and how are they distributed across sectors?
- What are the risks and benefits of maximum and 'do nothing' reef protection targets, and how are these risks and benefits distributed?
- Are the economic benefits to tourism likely to be large enough to balance economic losses to agriculture?
- Are economic losses in any sector likely to exist at levels that substantially reduce community wellbeing?
- What are the most influential system components, and are they amenable to policy development?

The framework is currently under review by participants. Once the structure is verified, the prototype will be parameterised and evaluated.

Keywords: *decision support, water quality, Bayesian belief network, ecosystem services, risk trade-offs*

1. INTRODUCTION

The Great Barrier Reef (GBR) extends for 2 000 km along the Queensland coastline, from Bundaberg to Cape York (Figure 1). It covers roughly 348 000 km^2, and has been World Heritage-listed since 1982. GBR activities generate an estimated AU\$6.9 B/yr; tourism accounts for approximately 84 % of this, for example in 2006 alone, 1,831,609 visits were made to the GBR (Fenton et al. 2007).

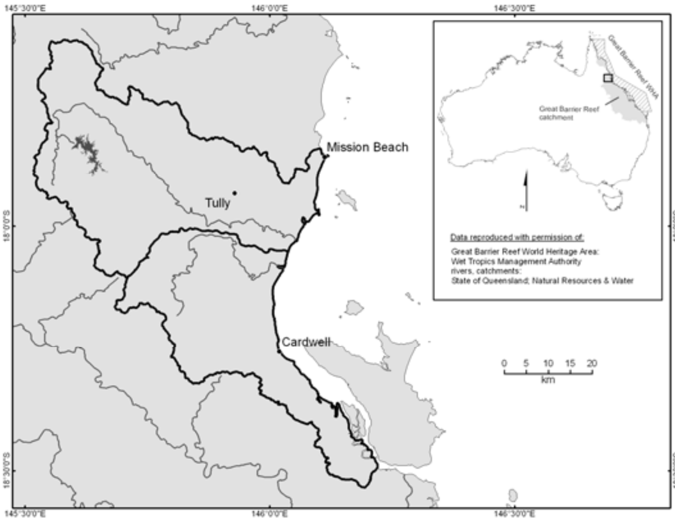

Figure 1. The Tully-Murray catchment, in the GBR region.

The health and resilience of coral reef communities on the GBR is shaped by 'global' and 'local' environmental drivers. Increasing sea surface temperatures (SSTs) due to global climate change is predicted to increase the incidence of coral bleaching, coral mortality and biodiversity depletion (Hoegh-Guldberg 1999). This emerging disturbance regime will have serious consequences for the Great Barrier Reef's biodiversity, ecology, amenity and dependent recreational use and economic activity (Done et al. 2003). Whilst little can be done at the local level to mitigate rising SSTs, there is evidence to suggest the overall risk profile for coral reefs due to thermal stress is synergistically linked to local water quality regimes on the GBR. For example, it has been demonstrated that corals which are regularly exposed to poor water quality are less resistant to thermal stress, such that upon exposure to sub-optimal temperatures (>28^{o}C) they display higher rates of bleaching and mortality (Wooldridge and Done 2009). Explanation for the negative impact of poor water quality has centred on the potential for elevated levels of dissolved inorganic nitrogen (DIN) to enhance the damaging cellular processes that underpin the thermal bleaching process (Wooldridge and Done 2009).

It has been estimated that the post-European development of the GBR catchment has resulted in an approximate 4-10 fold (average) increase in DIN loads entering the GBR lagoon (Furnas 2003). The identified linkage between water quality and thermal bleaching impacts suggests that a major water quality improvement program within the GBR catchment could reinforce corals' ability to resist the deleterious impacts of future SST warming. The majority of this DIN is sourced from intensely fertilised agricultural lands (viz. sugarcane, banana plantations) that tend to be located within close proximity of the coast (Furnas 2003). Since fertiliser application rates and associated land-use practices dominate the increasing DIN response, landscape nutrient budget models highlight the significant capacity for effective management initiatives to aid remediation; albeit with the risk of considerable social and economic costs to local farming communities (Roebeling et al. 2007).

Management interventions can have lasting repercussions to local communities. The risk of creating negative social outcomes needs to be assessed before management actions are implemented and trade-offs between ecological protection and human livelihoods take place. Preliminary risk analyses of the form proposed here can help policy makers decide whether effects of ecological protection measures to local livelihoods are likely to approach unacceptable levels. Information gained from such assessments can and should provide a critical first step in the policy planning process. To take a purely theoretical example, if interventions upon agricultural practice are unavoidable, but are known to have an unacceptable risk to the agricultural community, then additional work could be done to identify and strategically implement suitable socio-economic risk reduction measures. In summary, GBR policy-makers are tasked with determining the best course of action for reefs, agriculture and tourism under a future dominated by climate change. To do this well, they must understand;

- how the biological, physical and chemical components of both the catchment agro-system and the reef ecosystem are structured and function under different climate and human-use regimes,
- how these systems interact,
- the range of available alternatives,
- the risks and benefits of each alternative, and,
- how these risks and benefits are distributed across catchment sectors.

This is a complex, multidimensional problem characterised by substantial uncertainty in the form of incomplete knowledge and system stochasticity. By clarifying the climatic and land management conditions under which desirable/undesirable consequences of policy trade-offs might best be enabled/disabled, the prototype model described below supports development of intelligent policy interventions that are more likely to be effective in the long term.

The decision to use BBNs as the integrating platform enabled different disciplines, at different levels of scientific development, to be linked together. BBNs are tools for representing and reasoning about uncertainty in dependence relationships. BBNs are not the only choice for this type of modelling, but given the data availability and the ability of BBNs to use expert knowledge, the adopted approach provided a means of assembling fragmented knowledge for a complex system. This capacity is critical to the model's future success. BBNs also provide a flexible platform for anticipated future extensions to the integrated model, such as climate effects on land management consequences for water quality, and on tourism. We here report on development of the technical prototype structure; outcomes of this process are now being reviewed prior to data upload.

2. THE STUDY SYSTEM

The case study for this project is the Tully-Murray catchment, located on the north-eastern seaboard of Australia between Townsville and Cairns. The Tully and Murray Rivers drain directly to the GBR, as shown in Figure 1. The catchment covers 1 683 km^2, sustains a population of 5 585 and is one of the wettest catchments in Australia; the mean annual rainfall is 2 890 mm, 68 % of which leaves the basin as runoff (Productivity Commission 2003). The Tully-Murray has two or more major river discharge events every year and coral reef ecosystems within this zone are considered at high risk from plumes (Devlin et al. 2001). Tully land cover is mostly tropical rainforest (70 %), in cultivated areas production is dominated by sugarcane (Neil et al. 2002). Sugarcane accounts for most fertiliser use in the GBR and total use of fertiliser nitrogen on cane in Queensland has increased by over 35 % (1994-2000; Productivity Commission 2003).

3. THE PROBLEM: MULTIPLE-USE CONFLICTS

The problem addressed here is essentially about developing a prototype tool to guide the management of risks associated with multiple-use conflicts under climate change. The problem is similar to other multiple-use issues in that it deals with tensions between conservation and resource use in linked systems. Consequently, achievement of resource use objectives in the catchments can interfere with achievement of resource use and conservation objectives for the adjacent GBR lagoon.

Our problem is, therefore, is focussed on maximising gains across these disparate domains with minimum risk of loss. This is a challenging task, because as with most complex problems, there is no single correct answer but many alternative solutions, each with a different scale and configuration of 'wins' and 'losses' across system sectors. Here we describe the key components of a technical prototype tool to help decision-makers balance the risks and benefits of ecological protection across the system. The tool seeks to achieve this by identifying how the distribution of risks and benefits throughout the system change given different climate change and land management scenarios.

3.1. System connectivity

The tool is structured at a catchment level over three key system components; the local agricultural economy, the Great Barrier Reef, and the local tourism economy, with the rivers providing the 'glue' linking these components together (Figure 2). Rivers are a natural nutrient conduit from agricultural lands to coastal ecosystems. Most land uses can contribute DIN to rivers as runoff. Tool development uses

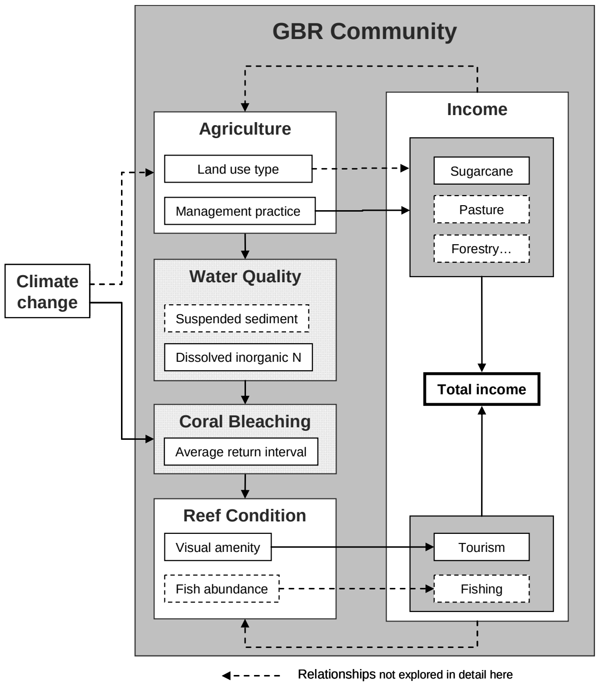

Figure 2. Conceptual model of the problem domain. Dashed lines will be examined in future project phases.

sugarcane as the focal agro-industry. In the Tully-Murray, sugarcane contributes the most DIN to runoff, largely due to its domination of the landscape (Mitchell et al. 2007). The quantities delivered might change under climate change; these relationships are slated for investigation in future project phases.

Enhanced exposure to DIN can increase the propensity for thermal bleaching impacts (Wooldridge 2009). Bleaching events can affect reef ecology (Done 1992) and visual amenity (Kragt et al. 2006). Severe bleaching can reduce coral reefs to barren 'rubble plains' devoid of fish or forests of fleshy macroalgae, and these conditions can last for extended periods of time (Done 1992). We focus here on degradation of visual amenity, which reduces reef tourist demand (Kragt et al. 2006), risking unwanted consequences for the local tourism economy. The effects of changes in reef condition to fish ecology will be investigated in future work.

4. DEVELOPMENT OF A RISK TRADE-OFF FRAMEWORK

This framework uses water quality outcomes to link reef condition with socio-economic attributes of the river and of the reef. Climate change is not manageable at the catchment level, but DIN can be reduced by implementing best management practices (BMPs) on agricultural land, reducing the risk of severe bleaching and reef degradation. If DIN from farm runoff can be minimised, reef condition will be improved or maintained. Implementation of some BMPs can benefit some growers (through decreased costs and higher productivity); however there is a risk that some land practice mixes achieving reduced DIN will also lower incomes (Roebeling et al. 2007). This raises the question of how much reef protection is likely to benefit or cost the agriculture industry. In contrast, the consequences of changes in management practice are likely to have generally positive effects upon the local tourism community. An analysis of risks and benefits to the catchment community of interventions in water quality management would, therefore, be incomplete without considering consequences to reef-based industries such as tourism.

This holistic view of the system raises additional questions, for example, about whether the risk-benefit trade-offs for any specific reef condition target are equally distributed across industries, or if these trade-offs produce a net benefit to the catchment community as a whole. The chances of developing effective and efficient policy are improved by addressing economic trade-offs for ecological outcomes at the whole-of-catchment, rather than an industry-by-industry, basis.

4.1. Approach

The prototype needed to demonstrate the capacity to functionally link agriculture with coral bleaching, and bleaching with tourism. Figure 3 shows how extant information and purpose-built models were used to develop these links, detail is given in alter sections. An agro-economic model estimates water quality at the river mouth and associated changes in agricultural income under a range of BMP scenarios. These outputs drive the coral bleaching and reef tourism BBNs. The bleaching BBN uses climate change and agro-economically driven estimates of future bleaching risk. This information is integrated by the reef tourism BBN to balance risks and benefits between the two industries as well as between income and ecology.

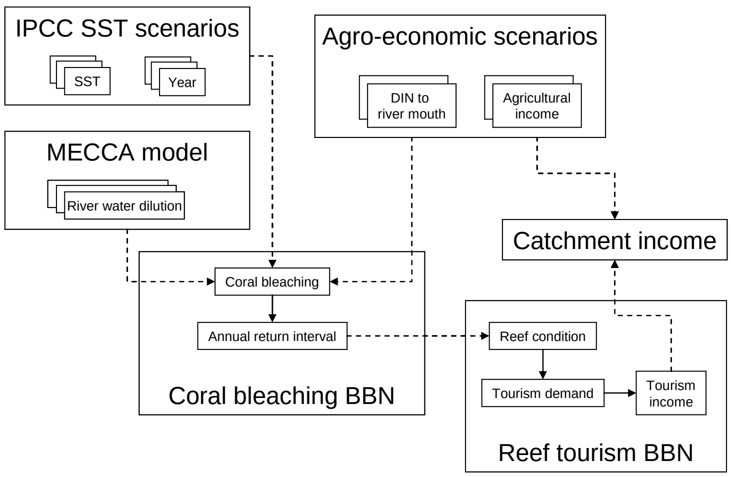

Figure 3. Schematic systems model. The prototype required integration of extant model outputs with new BBN models.

Relationships between agricultural land use practices and end-of-river water quality have been investigated in the GBR for many years, and reasonably robust models quantifying key processes have been developed (Roebeling et al. 2007). Links between coral survival and water quality have also been investigated for many years (Brodie 1992, Fabricius and Wolanski 2000), however direct relationships between bleaching risk and specific water quality components have been demonstrated only recently (Wooldridge et al. 2006, Anthony et al. 2007), and no suitable model for solving our question existed. Consequently, a coral bleaching model was purpose-built to predict the impact of future climate change and terrestrial DIN delivery on bleaching risk (Wooldridge 2009).

The final element of the systems model determines the influence of predicted coral bleaching outcomes on coral reef attributes that are valued by tourists. This allows exploration of how changes in these attributes might affect tourism demand (Kragt et al. 2006). A second model is being purpose-built to provide this element.

Linkages between the three elements of the system are at different stages of scientific development. The prototype, therefore, required integration of extant models as well as development of new models to develop the as-yet unexplored system linkages. BBNs provide a suitable platform for integrating data from the climate change and agricultural models, and being probabilistic, they facilitate a risk-based approach. BBNs are also useful for examining existing data in new ways, and filling key data gaps with expert knowledge, traits essential for developing the coral bleaching and reef tourism components.

4.2. EESIP model

To solve the first part of the problem (outlined in Section 3) we needed to establish a connection between the local agro-economy and the agro-ecosystem. An agro-economic model, EESIP (Environmental and Economic Spatial Investment Prioritisation; Roebeling et al. 2007), was available which estimates the contribution of a range of land management practices to DIN concentrations at the river mouth. EESIP is a spatially explicit model which evaluates the optimal mix of land management practices required to achieve a given level of DIN at the river mouth, and returns estimates of the economic return ($) associated with each mix (Roebeling et al. 2007, Figure 4).

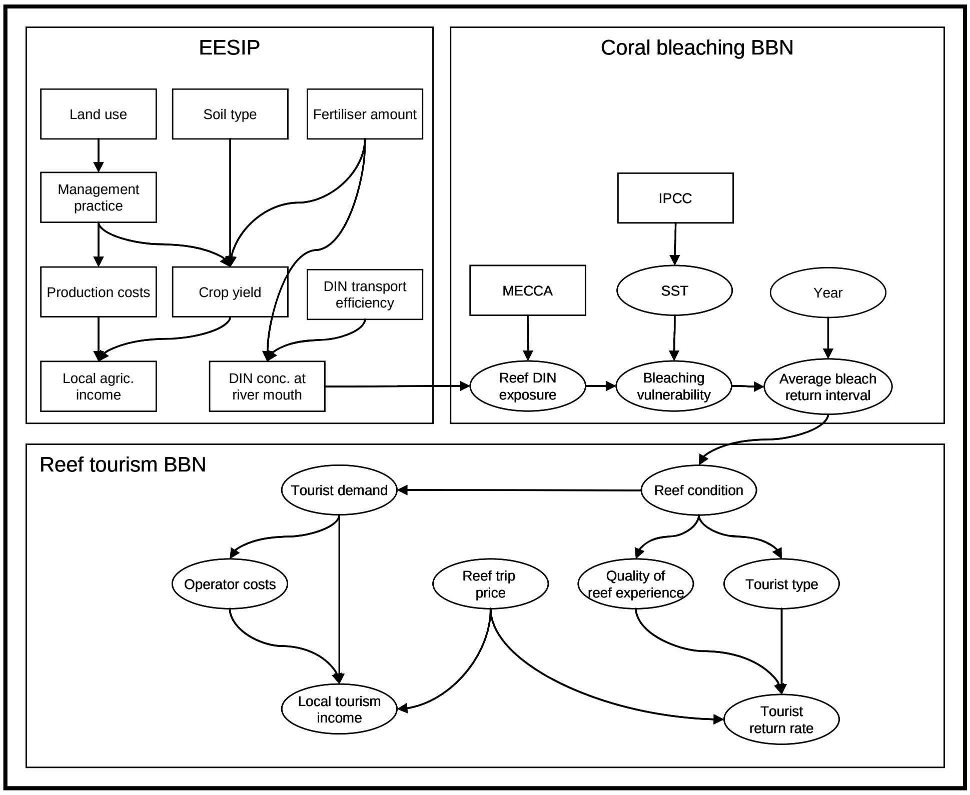

Figure 4. Some model details for trading-off economic and ecological risks and benefits under climate change in the GBR. Smaller boxes within each modelling component represent deterministic elements.

EESIP is deterministic and non-participatory but draws upon expert knowledge for some parameterisation tasks. EESIP integrates a production systems model (APSIM; Keating et al. 2003) and a hydrological model (SedNet/ANNEX; Hateley et al. 2006) with cost-benefit analysis, and can determine and map, for a given land use (e.g. sugarcane), the contribution of each land management practice, soil type, and fertiliser use to catchment nutrient generation, transport and delivery, as well as calculate the production costs, productivity, and profit generated by each land practice (Figure 4). Here, selected reduction targets (e.g. 0 %, 40 %, 80 %) for river mouth DIN will be used to estimate the associated economic return ($). These values will then be used to parameterise two scenario defining nodes in the bleaching BBN, *local agricultural income* and *river mouth DIN*.

4.3. Coral bleaching BBN

The second element of the problem was to establish a connection between climate change, the agro-ecosystem and the reef ecosystem. The coral bleaching BBN is a probabilistic, non-participatory model developed by the Australian Institute of Marine Science. It is driven by a hydrodynamic model of river flood plume distribution; Model for Estuarine and Coastal Circulation Assessment (MECCA; King et al. 2001), IPCC published projections of sea surface temperature under climate change (Nakicenovic and Swart 2000), predicted river mouth DIN concentrations from EESIP, and extant biological data. The MECCA information and the SST projections are adopted into the model structure as scenario defining (marginal) nodes, the MECCA node is parameterised by simulation outputs of probabilistic seawater dilution ratios. Collectively, output from the three donor models and the IPCC SST projections enables prediction of the likelihood that a coral bleaching event capable of killing 50 % of exposed coral will occur given a 75th percentile flood event (Figure 4). See Wooldridge (2009) for detail.

4.4. Reef tourism BBN

The final element of the problem was to establish a connection between the reef ecosystem and the local tourism economy. The reef tourism BBN draws upon results generated in EESIP and the coral bleaching BBN to create an integrated bio-economic risk assessment for reef condition, agriculture, and tourism at the catchment level (Figure 4). Outcomes generated by the coral bleaching BBN are used in the reef tourism BBN to link reef condition with industry components. Several studies have linked recreational welfare metrics with reef damage, see for example (Wielgus et al. 2003, Kragt et al. 2006), however, understanding of the quantitative relationship that exists explicitly between coral bleaching and tourism is in its infancy; indeed the only research we find on the topic is that of Wilkinson et al. (1999), who forecast but do not measure costs to tourism of a bleaching event in the Indian Ocean. Modelling relationships between bleaching and tourism is difficult because the mechanisms and sensitivities for several key relationships remain unclear, for example;

1. coral bleaching intensity and general reef condition,
2. reef condition and tourist demand, and,
3. tourist demand and the local tourism economy.

Given that understanding relationships between coral bleaching and tourism income is an active area of research, especially for Australian reefs, model development utilised expert judgment. The initial conceptual framework was developed in a workshop with experts in reef ecology and tourism. This highlighted the importance of tourists' perceptions and expectations on the quality of their experiences, and their intentions to return or to recommend the trip to others (Figure 4). Published information on these influences on tourism demand provided some additional detail. The framework is being reviewed prior to parameterisation and performance evaluation.

5. DISCUSSION AND CONCLUSIONS

This work integrates data and expert judgement across five domains; agronomics, tourism, hydrology, economics and coral reef ecology. Distillation of the problem into a minimal set of critical system linkages facilitated the use of extant models, and made modularisation of the framework more achievable. By adopting a modular approach to model development, differences between the three sectors could be managed efficiently without sacrificing faithfulness to the scientific mechanisms under investigation. The current prototype is sufficiently complex to enable cross-sector interactions to be represented over diverse components of the catchment at the systems level. These interactions are essential for viewing the risks of climate change-land management scenarios over multiple endpoints.

The decision to use BBNs as the integrating platform enabled different disciplines, at different levels of scientific development, to be linked together. This technology also provides a flexible platform for anticipated future extensions to the integrated model, such as climate effects on land management consequences to water quality and tourism. The framework is being reviewed prior to parameterisation. If approved for implementation, the proof-of-concept will first require a community consultation and approval.

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