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A Bayesian network model linking nutrient management actions in the Tully catchment (northern Queensland) with Great Barrier Reef condition

Will Shenton[A], *Barry T. Hart*[A,C] *and Jon Brodie*[B]

[A]Water Studies Centre, Monash University, Melbourne, Vic. 3800, Australia.
[B]Australian Centre for Tropical Freshwater Research, James Cook University, Townsville, Qld 4811, Australia.
[C]Corresponding author. Email: barry.hart@waterscience.com.au

Abstract. Correlating catchment management actions with improvements in the ecological condition of downstream coastal regions is challenging. We describe a Bayesian network (BN) model that predicts the effects of nitrogen-fertiliser management strategies in the Tully River catchment (northern Queensland) on the condition of inshore reefs of the Great Barrier Reef (GBR). The model consists of three linked submodels that relate sugarcane nitrogen management with runoff into the Tully River and nitrate concentration in the GBR lagoon, predicts phytoplankton biomass in the GBR lagoon from the nitrate inputs, and links the phytoplankton biomass with three marine influences to predict the probability of the reefs being dominated by coral (good) or macro-algae (bad). Four scenarios were modelled – current and the 'six easy steps' nitrogen management, and active and depleted algal grazing (herbivory) of the reef. The model predicts an increased probability of the reef being coral-dominated with current fertiliser practice and with active reef herbivory, with increased algal-dominance if reef herbivory is decreased. Introduction of a better nitrogen-fertiliser management with active herbivory resulted in an increased probability of coral dominance. This comparative-scenario analysis highlights the importance of both agricultural nutrient management practices and marine processes in predicting reef condition.

Additional keywords: decision support, fertiliser, nitrogen.

Introduction

The Great Barrier Reef (GBR) in north-eastern Australia is an iconic ecosystem of global significance that is threatened by climate change, the impacts of fisheries, and contaminants from the catchment (Hughes *et al.* 2007). The main water-quality issues are elevated concentrations of suspended sediment, nutrients and pesticides from diffuse agricultural sources, including rangeland grazing and intensive agricultural cropping systems (Baker 2003; Brodie *et al.* 2008).

The Reef Water Quality Partnership was a collaborative structure formed in response to uncertainty in the science supporting the reef plan and regional water-quality management plans (including water-quality improvement plans (WQIPs)), and the need for institutional collaboration across Queensland and Australian Governments and the regional natural resource management (NRM) bodies of the GBR to address these needs (Reef Plan 2003). The Reef Water Quality Partnership provided a linkage between the GBR and catchment-scale policy and planning processes, and focussed on improved target-setting, monitoring and reporting at both these scales.

A good example of these WQIPs is provided by that developed by the Mackay–Whitsunday Natural Resources Management Group (Drewry *et al.* 2008) and the Tully WQIP (Kroon 2008). These WQIPs are all intended to be adaptive management plans, with the capacity to change with time as more information becomes available. Eberhard *et al.* (2009) developed a protocol to guide the practical application of an adaptive approach in the coastal catchments of the Great Barrier Reef, and tested this protocol using the Tully WQIP.

A major problem faced by each of these WQIPs is the difficulty in relating catchment management actions with potential improvement in the condition of the GBR. Currently, several models are available to estimate the loads of suspended sediment and nutrients exported from each of the catchments (Drewry *et al.* 2007; Armour *et al.* 2009). Models have been developed to predict what happens to these contaminants once they enter the GBR lagoon, and their effects on the biota (e.g. coral reefs, seagrasses, phytoplankton, fish) (e.g. Wolanski *et al.* 2004); however, these models do not include a robust link to catchment land-use practices. Within WQIPs, targets for land-use management linked to marine ecosystem targets have been set using a variety of models strung together from the paddock to the reef (Kroon 2008, 2009). Problems can arise when the outputs of one model (e.g. at a paddock scale) are used as an input into the next model downstream (e.g. a catchment model) (Brodie *et al.* 2009).

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The present paper reports the development of a Bayesian network (BN) model that links the effects of nitrogen-fertiliser management strategies used in the sugarcane fields of the Tully catchment on the associated nutrient runoff into the Tully River, and then the ecological effects on the coral and algal communities located on the inshore reefs of the GBR lagoon. The potential for such BN models to assist in natural-resources decision-making is illustrated by considering four scenarios in which two different fertiliser management practices were combined with high and low grazing pressure by reef herbivores to predict the probability that the reefs would be coral-dominated (good) or algal-dominated (bad).

The system

The Tully catchment

The Tully River (18°1′S, 146°3′E, catchment area = 2850 km^2) is one of 31 river catchments that drain directly into the GBR. The Tully River originates in the Cardwell Range, 65% of which is in the Wet Tropics World Heritage Area. Wet-season flow in the Tully River is characterised by multiple flood events of short duration and varying magnitude (Mitchell and Furnas 2001). Mean annual rainfall within the catchment is 2855 mm, with the mean annual runoff being 1954 mm m^{-2} and the mean annual discharge being 3.3×10^6 ML. There has been a significant alteration to the hydrological regime in the floodplain, and pesticides and high nutrient loads (particularly nitrate) are evident in the lower reaches of the catchment (Brodie *et al.* 2001*b*; Mitchell *et al.* 2001).

Sugarcane agriculture dominates the nutrient-input regime of the Tully floodplain. This floodplain has been extensively cleared, with ~15% of the total catchment under sugarcane agriculture, 2% under horticulture (of which the largest component is banana farming) and 19% grazing land (Brodie *et al.* 2001*a*). The use of nitrogen fertiliser in the Tully region doubled in the 10-year period 1989–1999, from ~2090 t year^{-1} in 1989 to 4750 t year^{-1} in 1999, and has changed little since 1999 (Mitchell *et al.* 2001; Wrigley 2005). Moody *et al.* (1996) reported that of the 180 kg ha^{-1} of fertiliser applied to sugarcane fields each year, less than half (~70 kg ha^{-1}) is taken up by the crop.

Great Barrier Reef

The GBR extends along the Queensland coast for 2000 km, and encompasses an area of ~343 500 km^3 on the continental shelf (Brodie *et al.* 2001*a*; Kroon 2009). Increased loads of nutrients are considered a major factor responsible for deteriorating water quality on coral reefs (Koop *et al.* 2001; Fabricius 2005). Declining water quality as a result of nutrient pollution is considered by Wachenfeld *et al.* (1998) to be a 'principal issue' facing the long-term ecological functioning of the GBR. It has been estimated that the fluxes of nitrogen and phosphorus to the GBR lagoon have increased four-fold since European settlement (Neil *et al.* 2002), whereas the long-term abundance of phytoplankton, measured as Chlorophyll *a* (Chl-*a*), in waters off the catchments with elevated nitrogen delivery has more than doubled (Brodie *et al.* 2007). Fabricius (2005, 2007) has reviewed the impacts of catchment runoff on corals and coral reefs of the GBR.

The present study is focussed on the effects of nutrients on inner shelf coral reefs out to a depth of 20 m. This spatial extent was chosen to reflect the fact that flood waters are known to extend regularly to the inner shelf of the GBR, and less frequently to the mid- or outer shelf (Brodie and Furnas 1996; Devlin and Brodie 2005). Here, we consider only high flows because these will be the conditions when most contaminants are delivered to the GBR lagoon.

Sugarcane farming practice in Queensland

Sugarcane farming extends over 400 000 ha from northern New South Wales to northern Queensland (Brodie and Mitchell 2005), and is currently the major user of nitrogenous fertiliser in northern Australia. The environmental impacts of cane farming differ during the three recognised stages – crop growing, harvesting and post-crop fallow. Losses of nitrogen can occur during all three stages, and particularly during crop growing and harvesting. The present study is focussed on the use and losses of fertilisers, particularly nitrogenous fertilisers, because nitrogen is the limiting nutrient in the GBR lagoon (Wooldridge *et al.* 2006).

The sugar industry has been active in recent years in attempting to change fertiliser management and harvesting and tillage practice to reduce the amounts of sediment, nutrients and pesticides lost from their activities and subsequently contaminating the GBR. Under conventional sugarcane harvesting and tillage practices, annual soil loss from cane lands can be quite high. For example, Prove and Hicks (1991) reported losses up to 500 t ha^{-1} year^{-1} in the Johnstone River catchment. With the advent of new techniques in tillage and harvesting, this figure has been reduced to <15 t ha^{-1} year^{-1} (Rayment 2003).

Fertiliser management

Four nitrogen-fertiliser management practices are currently available (or should be soon) in the Tully region, and are as follows: (*1*) *current practice* is to apply nitrogen at a rate of ~170 kg ha^{-1} year^{-1}; (*2*) *six easy steps practice* is an integrated nutrient-management tool that enables the adoption of best-practice nutrient management on-farm (Schroeder *et al.* 2007), where the average nitrogen-fertiliser application rate may be reduced to 140 kg ha^{-1} year^{-1}; (*3*) *nitrogen replacement* takes into account nitrogen that is stored in soil and litter, which allows farmers to adjust the required nitrogen rate to ~110 kg ha^{-1} year^{-1} (Thorburn 2004); and (*4*) *nitrogen fixation* is an experimental strategy (John Reghenzani, pers. comm.) that seeks to produce a variety of sugarcane that has a good ability to associate with nitrogen-fixing bacteria, and may reduce the fertiliser rate to 10 kg ha^{-1} year^{-1}.

Tillage

The model allows for the following two forms of tillage: (*1*) conventional ploughing and (*2*) minimum (or sometimes zero) tillage where little ploughing is undertaken and weeds are suppressed by using herbicides (Bakker 1999; Cheesman 2004).

Green-cane harvesting/trash blanketing

In 'conventional' cane growing, the cane is burnt after harvest, leaving relatively bare earth. Now with green-cane harvesting/trash blanketing (GC/TB), the cane is cut green and not burnt, with the leaves from the cane stripped off by the harvester and shot out onto the ground to form a 'trash blanket' (a form of 'stubble retention'), resulting in reduced erosion (Rayment 2003).

The main farming practices, namely fertiliser management, minimum tillage and GC/TB, are used in the BN model described here to examine the generation and transport of nutrients and sediment from cane fields to the GBR lagoon via the Tully River.

Ecological endpoint – coral reefs

Corals are an assemblage of many individual polyps, which are multicellular organisms that feed on a variety of small organisms, from microscopic plankton to small fish. Most of the GBR corals obtain their nutrition from a symbiotic relationship with a class of algae called zooxanthellae. Under excess nutrient (particularly nitrate) conditions, the zooxanthellae population grows uncontrolled and the balance of the nitrogen–carbon fluxes between the coral host and zooxanthellae is disrupted, resulting in a reduction of calcification and weakening of the coral calcareous skeleton (e.g. Marubini and Davies 1996; Ferrier-Pages *et al.* 2000).

The relative dominance model has been proposed for coral reef systems where the final state following disturbance may be any of a number dominated by coral or different algal types (Littler and Littler 1984; Smith *et al.* 2001; Littler *et al.* 2006). In this model, the interaction between elevated nutrients and reduced grazing (mainly by fish, although others such as echinoderms and gastropods possible) can drive a coral reef system to one of three other states dominated by turf algae, frondose macroalgae or crustose coralline algae. Frondose macroalgae already dominate many inshore reefs of the Great Barrier Reef, with increasing nutrient inputs from the land (e.g. off Mackay) (Jupiter *et al.* 2008) and off Tully (Fabricius *et al.* 2005).

One of the key challenges in the management of coral reefs is to identify management responses that may possibly counteract the frequent and increasingly severe coral-bleaching events (Buddemeier and Fautin 1993; Hoegh-Guldberg 1999). A current concern of coral reef scientists is that when a disturbance, such as bleaching, is superimposed on other pressures, such as sedimentation and nutrient enrichment, rapid decline in coral reef communities is likely, potentially overturning their stability over geological time scales (Pandolfi *et al.* 2003).

There remains much uncertainty as to the relative importance of nutrient enrichment (bottom-up) and overfishing of herbivores (top-down) as factors resulting in major shifts in the coral–algae balance after disturbances (McCook 2001; Bell *et al.* 2007; Littler and Littler 2007), and hence the validity of the relative dominance model (Lapointe 1997, 1999; Hughes *et al.* 1999). Wilkinson (2004) and Hughes *et al.* (2005) identified the ecological attribute of 'resilience' in coral reef populations and ecosystem function as a key goal in the management of coral reef ecosystems.

The ecological endpoint selected for the BN model reported here was the relative change in the reef algal–coral proportions. It was hypothesised that the nitrate derived from the fertiliser applied to the cane farms in the Tully catchment can be linked to the nitrate discharged into the lagoon, and subsequently to increases in phytoplankton biomass in the GBR lagoon. Phytoplankton biomass was taken to be a proxy for lagoon water quality following Wooldridge *et al.* (2006) who specifically used dissolved inorganic nitrogen (DIN) as the most influential nutrient in driving Chl-*a* concentrations, because phytoplankton growth in the GBR lagoon was considered to be primarily limited by nitrogen availability.

Done (1999) has characterised the following two major conditions resulting in change in reef communities: (*1*) those places where the decline is strictly a consequence of water-column physics and chemistry, and (*2*) those places where, in spite of suitable water-column properties, there is net $CaCO_3$ loss because the reef-building community is too sparse as a result of diminution or failure of ecological processes. He considered the key ecological processes to include the following: recruitment of key functional groups such as corals, other invertebrates and fish; dampening by predators of outbreaks of destructive species such as crown-of-thorns starfish; and the prevention of a build-up of algal biomass by a sufficient abundance of herbivorous fishes and/or invertebrates.

Fabricius (2005, 2007) has developed semiquantitative conceptual models linking several water-quality factors to the condition of the reef ecosystem. For this first-stage BN model, we elected to focus only on the nitrogen to macroalgal–coral balance. It is possible that when other water-quality factors (particularly suspended sediments and pesticides) are considered, the effects of nitrogen enrichment may be modified.

Development of the Bayesian network model

Management decisions concerning risks associated with invasive species are difficult, because these decisions often have to be taken where there is scant scientific knowledge available. In these cases, managers do not have the luxury of running experiments. Such problems are characterised as 'incomplete', with differing forms and degrees of uncertainty, where the available data and knowledge can be quantitative or qualitative, pictorial, linguistic or diagrammatic. These types of information are often imprecise, ambiguous and fuzzy. Despite this, they constitute essential evidence that backs up reasoning under uncertainty and legitimately underpin judgement and decision-making. Expert opinion forms an indispensable aspect of risk-based decision-making when accurate data are unavailable, or understanding of the system is incomplete or uncertain.

Bayesian network (BN) models are one method for combining scientific data with expert knowledge and experience (Marcot *et al.* 2001, 2006). A BN model is a tool that can be used to build a decision support system, and these are increasingly being used to model uncertain and complex systems, such as ecosystems and environmental management (Uusitalo 2007; Hart and Pollino 2009). The BN model reported here to assess the impact of various cane-farming land management activities on the inner coral reef communities in the Tully estuarine region consists of the following three components: (*1*) a set of *nodes* representing the key variables of the management system, (*2*) a set of *links* that represent the cause–effect relationship ('conditional dependence') between the nodes and (*3*) a set of *probabilities* representing the belief that a node will be in a given state, given the states of the connecting nodes. The conditional probability relationships were based on available information, including experimental or field results, and expert opinion (Borsuk *et al.* 2006).

Relevant literature on cane farming in Queensland, water quality and coral reef communities was reviewed, and this knowledge was then translated into a formal conceptual model (Fig. 1), which highlights the main variables in the land, water-quality and reef-condition model and represents the main cause–effect relationships by arrows among variables. This cause–effect diagram was then used to build the BN model. As noted above, the ecological endpoint for the BN model was defined as 'reef ecosystem condition', with the measure of 'condition' taken as the relative proportion of coral to macro-algal dominance on a reef. The BN model recognises that the shift from coral to macro-algal dominance in a reef is not entirely due to nutrient enrichment or eutrophication, but may also be assisted by other factors such as overfishing of herbivorous fish (Pandolfi *et al.* 2005; Littler *et al.* 2006).

Model structure

The conceptual model for the Tully system consisted of three submodels (Fig. 1), and these three submodels made up the final BN model structure. The most important of the assumptions underpinning the model were as follows: (*1*) fertiliser residues associated with crops (sugarcane and bananas) have markedly increased nitrate loading of the Tully River, (*2*) the Tully River is a conduit transporting sediment and nutrients to the GBR lagoon, (*3*) most of the transport of dissolved inorganic nitrogen (DIN) to the inner reefs in the lagoon occurs during high flow events (in-stream processes are not considered to be important under these high flow conditions), (*4*) the Tully River is not phosphorus-limited and neither is the GBR lagoon, and (*5*) a dynamic equilibrium exists between coral and algal communities on the reef.

A rigorous evidence-based process was employed in choosing each node in the BN model. This process, together with the evidence and assumptions used in the model and the justification for each of the variables (nodes), is detailed in the Accessory Publication to this paper.

Submodel 1 (Fig. 1) links the cane farm land management activities (cropping technique, tillage, fertiliser management)

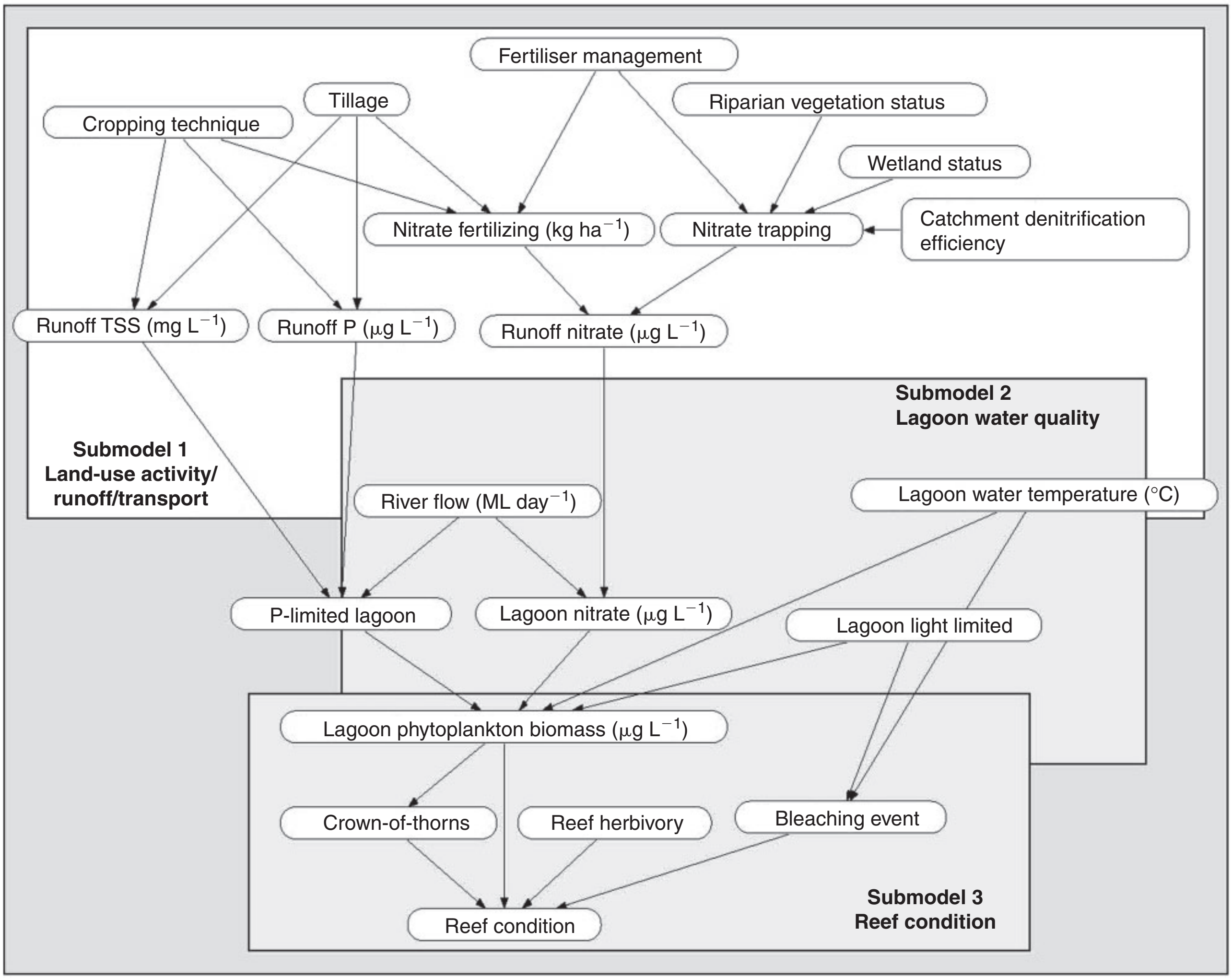

Fig. 1. Conceptual model showing the three submodels that link nitrogen management practice in sugarcane fields with GBR lagoon water quality and, subsequently, reef condition.

with runoff into the Tully River (runoff TSS, runoff P, runoff nitrate), and attempts to gauge the total nutrient loads transported, and the final nitrate concentration in the GBR lagoon (lagoon nitrate). The emphasis in this model is on nitrate losses associated with nitrogen-fertiliser management practices. Submodel 2 (Fig. 1) takes the nutrient inputs to the GBR lagoon from the Tully River submodel and combines these with other relevant parameters (e.g. lagoon water temperature, lagoon light limited) to predict phytoplankton biomass (lagoon phytoplankton biomass). Submodel 3 (Fig. 1) assumes that four factors influence the health of coral reefs (phytoplankton biomass, bleaching events, crown-of-thorns and reef herbivory). The model links the catchment activities (on-farm nitrate fertiliser loads and transport of DIN by the Tully River) to reef condition via the phytoplankton biomass. This model predicts the probability that the inshore reefs are either coral-dominated (good) or algal-dominated (bad).

Populating the network

The BN model was populated in two stages. The first stage involved defining the states of each node for this wet-tropics agro-ecosystem. These are listed in the Accessory Publication (Tables 1–3 of the Accessory Publication for the three submodels, respectively), together with the evidence supporting the states selected for each node. All nodes in the BN model were assumed to be categorical, with continuous variables defined in terms of thresholds. The second stage involved populating the conditional probability tables (CPT) for the Tully River case study. These were derived from the scientific literature and from expert opinion, and are specific to cane farming, the Tully River and the Great Barrier Reef lagoon. A full listing of all CPTs, together with the supporting evidence, is available in the Accessory Publication.

Application of the Tully River–reef BN model

The Tully River–reef BN model was used to predict the status of the coral reefs for four scenarios in which the influences of both fertiliser management and herbivorous fish are investigated. The results are aimed at demonstrating the utility of BN models as decision support tools.

The two sets of scenarios modelled compare the effect of the current fertiliser management with the alternative fertiliser-management practice known as ‘six easy steps’ on the condition of the coral reefs influenced by discharges from the Tully River. The modelled scenarios examine the effect of these land management strategies on the generation and transport of nutrients and sediment in high river-flow conditions. This choice assumes that the majority of nutrient and sediment transport in the Tully River occurs in high flow conditions, that crown-of-thorns are not present on the reef and that riparian and wetland conditions are reasonably good. The reef-condition endpoint in the model assesses the combined effect of changes in transported nutrients via the Tully and disturbance of coral reef communities.

Scenario 1 represents the current fertiliser management, nutrient transport and ecological conditions within the Tully catchment. The BN model (Fig. 2) predicts that under these conditions, there is a 68% probability of the inner reef being coral-dominated, with a 32% probability of being dominated by algal species (Table 1).

Scenario 2 assumes current fertiliser-management practices, but with severely reduced herbivory on the reef because of effects such as overfishing or disease. The BN model again predicts the reefs would be coral-dominated (59% probability), but with about a 10% increased probability of algal-dominance (41%) (Table 1).

Scenarios 3 and 4 considered a change in fertiliser management practice from the current practice to ‘six easy steps’ practice. In both cases, a reduction in nitrate runoff is predicted, with a subsequent decrease in GBR lagoon chlorophyll concentrations (Table 2) This resulted in an increased probability of improved reef health (*Scenario 3* – 73% probability of coral-dominance), although this improvement would be marginal if reef herbivory were reduced (Table 1).

This latter finding is important because it suggests that significant reductions in nitrate input to the GBR, achieved by improved fertiliser management, may result in very little improvement in the condition of the coral reefs if the reef ecosystem integrity is not maintained. Thus, *Scenario 4* predicts that even with improved fertiliser management, a loss of active herbivory would result in little improvement in the condition of the coral reefs (Table 2).

Discussion

The BN model

The current BN model reported here appears to behave plausibly. With the current fertiliser and tillage practice, the model predicts that the inshore coral reefs off the Tully River would be in moderate condition (60–70% probability of coral-dominance), with the condition also influenced by the level of grazing (herbivory) occurring on these reefs.

It has not been possible to fully validate the BN model because of a lack of data. However, the monitoring data on reef condition that are available show that inshore reefs have been algal-dominated for the past 10–20 years. For example, coral cover in the Cairns inshore reef sector, including reefs influenced by the Tully River discharge, has varied between 10 and 30% during 1993–2007, whereas algal cover has varied between 40 and 70% over the same period (fig. 4.11 in Sweatman *et al.* 2008). Algal dominance has existed for this entire period. It is believed that coral cover was higher (~50%) on all Great Barrier Reef reefs before 1900 (Bruno and Selig 2007), dropping to 35% overall coral cover in the period 1968–1983 and to 25% in the period 1984–2004 (Bruno and Selig 2007). This reduction in coral cover is attributed to a range of factors, including crown-of-thorns starfish outbreaks, bleaching episodes, poor water quality, cyclone damage, coral diseases and interactions among these factors.

In addition, this first BN model has focussed only on nutrients (nitrogen) as the main water-quality contaminant from the catchment leading to deterioration of the inshore reefs. However, in an extensive review of the world literature, Fabricius (2005, 2007) implicated several water-quality factors as potentially affecting the condition of the coral reef ecosystem. To make it more robust, the next iteration of this BN model should include the effect of other water-quality factors

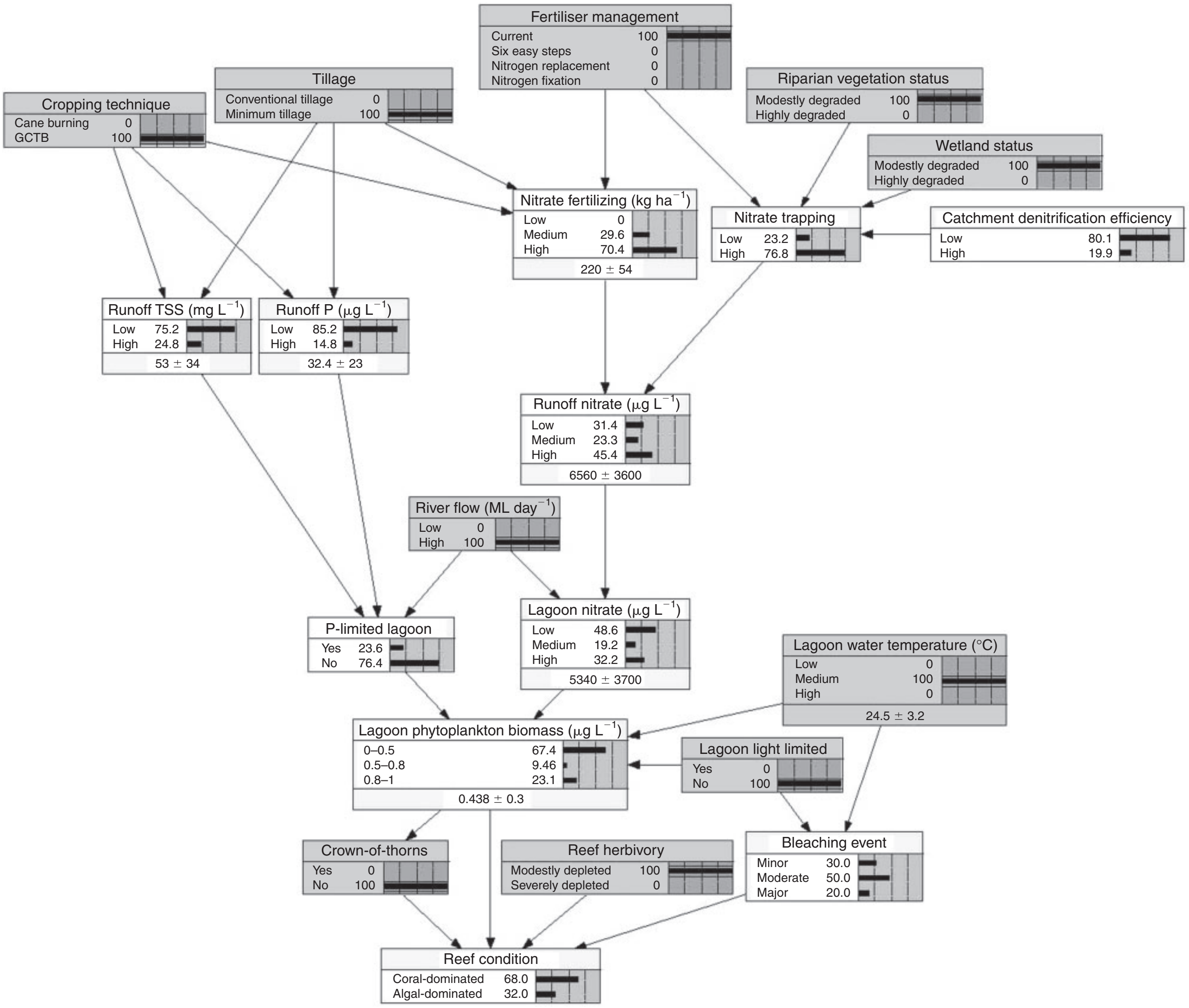

Fig. 2. Full Bayesian network model for Scenario 1.

Table 1. Predicted endpoint probabilities for each of the scenarios modelled

Scenario	Predicted endpoint probability (%)	
	Coral-dominated	Algal-dominated
1	68	32
2	59	41
3	73	27
4	62	38

(particularly suspended sediments and pesticides). The current model includes three marine factors likely to affect coral condition, namely herbivory, crown-of-thorns and bleaching. However, for the present application of the model, only changes in herbivory have been tested.

Management scenarios

The current BN model combines the effects of catchment inputs (nitrogen) and marine factors (grazing) on reef condition. There is still considerable uncertainty as to the relative importance of nutrient enrichment (bottom-up) and overfishing of herbivores (top-down) as factors resulting in major shifts in the coral–algae balance (Bell *et al.* 2007; Littler and Littler 2007).

The BN model predicted that improved fertiliser management (six easy steps), leading to less nitrogen runoff, should result in a marginal improvement in the condition of the inshore reefs. This improvement in reef condition was only ~5% (probability of coral dominance increased from 68% to 73%). However, this was expected because the change to the six easy steps fertiliser management practice is reported to result in ~20% improvement in the annual nitrogen application rate (170 kg ha^{-1} year^{-1} to 140 kg ha^{-1} year^{-1}; Thorburn 2004), and obviously a somewhat lesser percentage improvement in nitrate runoff. The importance of grazing in maintaining coral-reef condition is also shown by the modelled results. Thus, there was an increase of ~10% in the probability of algal dominance if herbivory was severely depleted as a result of overfishing (Table 1).

Bayesian network models for linking catchment management activities with coral-reef condition

Considerable resources are being applied worldwide to improve agricultural management practices in catchments draining to important downstream coastal regions. For example, in Australia the Federal government has allocated $A200 million through its Reef Rescue initiative to a range of activities aimed at reducing contaminant runoff to the Great Barrier Reef over the next 4 years (http://www.nrm.gov.au/funding/2008/reef-rescue.html, verified May 2010).

However, showing that these catchment management actions are resulting in improvements in the ecological condition of coastal regions is a difficult task. Monitoring needs to be conducted at an appropriate frequency and for a considerable period of time for meaningful trends to be determined and separated from the natural variability in such systems (Bainbridge *et al.* 2009). For this reason, there is increased interest worldwide in modelling approaches to quantify the effects of changed agricultural practices in the catchment with improvements in the condition of downstream coastal ecosystems (e.g. Lye and Ling 2006; Avila-Foucat *et al.* 2009). The BN model reported here, linking improvement in nitrogen-fertiliser practice on sugarcane farms in the Tully catchment with the condition on inshore coral reefs of the GBR off the Tully catchment, is to our knowledge the first of its kind. However, with the recognition of the strength of the BN modelling approach in these circumstances, parallel projects to link catchment management with Great Barrier Reef ecosystem health by using BN modelling in the Tully system are underway (Thomas *et al.* 2009).

The BN modelling approach reported here illustrates several advantages not currently available with any other approach. These include an integrating framework, transparency and a straightforward and flexible modelling process.

Integration and transparency are achieved through the explicit modelling process and thorough documentation. The process of developing a BN model is an effective way to formally and logically identify, structure and focus the available data and knowledge. Other advantages are that information and knowledge from different sources (actual data and expert knowledge) can be handled in the same modelling framework, that uncertainties are explicitly handled (e.g. data and predictions are given as probabilities), and the Bayesian approach allows the model to be formally updated as new information becomes available (Hart and Pollino 2009). Although not explored in the present application, BN models can be used very effectively to identify and prioritise where additional knowledge is needed to improve the model (Chan *et al.* 2009; Shenton *et al.* 2009). The BN modelling approach also revealed some weaknesses, the most important being (*1*) constraints on modelling spatio-temporal complexity, and (*2*) that feedback loops can be implemented only indirectly in a BN. Feedback loops and spatio-temporal complexity are inherent in linked agro-ecosystems, such as in this Tully case study; for this reason, when seeking to model such complex systems, additional modelling strategies are necessary to complement the BN modelling framework.

There are an increasing number of applications of BN models being used as very effective decision-making tools, particularly when the biophysical relationships are coupled with cost-effectiveness and cost–benefit analysis (Marcot *et al.* 2006; Uusitalo 2007; Hart and Pollino 2009). Although the Tully BN model did not include any cost–benefit analysis component, it nevertheless provided a very useful tool for presenting the causal links between catchment management practices and the ecological condition of the inshore reefs, and for indicating what levels of improvement in ecological condition may be achieved by the uptake of better management practices, at least for the sugarcane industry. BN models provide an ideal way of combining quantitative data with expert knowledge (where such data are lacking) to inform decisions on investments to improve agricultural practice so that downstream coastal-zone ecosystems are better protected.

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References

Armour, J. D., Hateley, L. R., and Pitt, G. L. (2009). Catchment modelling of sediment, nitrogen and phosphorus nutrient loads with SedNet/ANNEX in the Tully–Murray basin. *Marine and Freshwater Research* **60**, 1091–1096. doi:10.1071/MF08345

Avila-Foucat, V. S., Perrings, C., and Raffaelli, D. (2009). An ecological–economic model for catchment management: the case of Tonameca, Oaxaca, México. *Ecological Economics* **68**, 2224–2231. doi:10.1016/J.ECOLECON.2009.01.010

Bainbridge, Z., Brodie, J., Lewis, S., Waterhouse, J., and Wilkinson, S. (2009). Utilising catchment modelling as a tool for monitoring Reef Rescue outcomes in the Great Barrier Reef catchment area. In '18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation'. (Eds R. S. Anderssen, R. D. Braddock and L. T. H. Newham.) pp. 3301–3307. (Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation: Melbourne.)

Baker, J. (2003). A report on the study of land-sourced pollutants and their impact on water quality in and adjacent to the Great Barrier Reef. Queensland Government. Brisbane.

Bakker, H. (1999). 'Sugar Cane Cultivation Management.' (Kluwer Academic/Plenum Publishers: New York.)

Bell, P. R. F., Lapointe, B. E., and Elmetri, I. (2007). Re-evaluation of ENCORE: support for the eutrophication threshold model for coral reefs. *Ambio* **36**, 416–424. doi:10.1579/0044-7447(2007)36[416:ROESFT]2.0.CO;2

Borsuk, M. E., Reichert, P., Peter, A., Schager, P., and Burkhardt-Holm, P. (2006). Assessing the decline of brown trout (*Salmo trutta*) in Swiss rivers using a Bayesian probability network. *Ecological Modelling* **192**, 224–244. doi:10.1016/J.ECOLMODEL.2005.07.006

Brodie, J., and Furnas, M. J. (1996). Cyclones, river flood plumes and natural water quality extremes in the central Great Barrier Reef. In 'Downstream Effects of Land Use'. (Eds H. M. Hunter, A. G. Eyles and G. E. Rayment.) pp. 367–374. (Queensland Department of Natural Resources: Brisbane.)

Brodie, J. E., and Mitchell, A. W. (2005). Nutrients in Australian tropical rivers: changes with agricultural development and implications for receiving environments. *Marine and Freshwater Research* **56**, 279–302. doi:10.1071/MF04081

Brodie, J., Christie, C., Devlin, M., Haynes, D., Morris, S., Ramsay, M., Waterhouse, J., and Yorkston, H. (2001*a*). Catchment management and the Great Barrier Reef. *Water Science and Technology* **43**, 203–211.

Brodie, J., Furnas, M., Ghonim, S., Haynes, D., Mitchell, A., Morris, S., Waterhouse, J., Audas, D., Lowe, D., and Ryan, M. (2001*b*). Great Barrier Reef catchment water quality action plan: a report to ministerial council on targets for pollution loads. Parts 1, 2 and 3. Great Barrier Reef Marine Park Authority, Townsville, Qld.

Brodie, J., De'ath, G., Devlin, M., Furnas, M., and Wright, M. (2007). Spatial and temporal patterns of near-surface chlorophyll a in the Great Barrier Reef lagoon. *Marine and Freshwater Research* **58**, 342–353. doi:10.1071/MF06236

Brodie, J. E., Binney, J., Fabricius, K., Gordon, I., Hoegh-Guldberg, O., *et al.* (2008). Scientific consensus statement on water quality in the Great Barrier Reef. Queensland Department of the Premier and Cabinet, Brisbane. Available at http:www.reefplan.qld.gov.au/library/pdf/publicationsScientific%20Consensus%20Statement%20on%20Water%20Quality%20in%20the%20GBR.pdf [verified December 2008].

Brodie, J., Lewis, S., Bainbridge, Z., Mitchell, A., Waterhouse, J., and Kroon, F. (2009). Target setting for pollutant discharge management of rivers in the Great Barrier Reef catchment area. *Marine and Freshwater Research* **60**, 1141–1149. doi:10.1071/MF08339

Bruno, J. F., and Selig, E. R. (2007). Regional decline of coral cover in the Indo-Pacific: timing, extent and subregional comparisons. *PLoS ONE* **2**, e711.

Buddemeier, R. W., and Fautin, D. G. (1993). Coral bleaching as an adaptive mechanism. *BioScience* **43**, 320–326. doi:10.2307/1312064

Chan, T., Hart, B. T., Kennard, M., Pusey, B., Shenton, W., Douglas, M., Valentine, E., and Patel, S. (2009). Bayesian network models for environmental flow decision-making in the Daly River, Northern Territory, Australia. *River Research and Applications*.

Cheesman, O. D. (2004). 'Environmental Impacts of Sugar Production.' (CABI Publishing: Oxford, UK.)

Devlin, M. J., and Brodie, J. (2005). Terrestrial discharge into the Great Barrier Reef Lagoon: nutrient behaviour in coastal waters. *Marine Pollution Bulletin* **51**, 9–22. doi:10.1016/J.MARPOLBUL.2004.10.037

Done, T. J. (1999). Coral community adaptability to environmental change at the scales of regions, reefs and reef zones. *American Zoologist* **39**, 66–79.

Drewry, J., Higham, W., Mitchell, C., and Rohde, H. (2007). Modelling sediment and nutrient exports and management scenarios. Technical report, Mackay Whitsunday NRM Group, Mackay, Qld. Available at www.reefcatchments.com.au [verified December 2008].

Drewry, J., Higham, W., and Mitchell, C. (2008). Water quality improvement plan – final report for the Mackay Whitsunday Region. Mackay Whitsunday NRM Group, Mackay, Qld. Available at www.reefcatchments.com.au [verified December 2008].

Eberhard, R., Robinson, C., Waterhouse, J., Parslow, J., Hart, B., Grayson, R., and Taylor, B. (2009). Adaptive management for environmental planning – a pragmatic approach for the Great Barrier Reef. *Marine and Freshwater Research* **60**, 1189–1195. doi:10.1071/MF08347

Fabricius, K. E. (2005). Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. *Marine Pollution Bulletin* **50**, 125–146. doi:10.1016/J.MARPOLBUL.2004.11.028

Fabricius, K. E. (2007). Conceptual model of the effects of terrestrial runoff on the ecology of corals and coral reefs of the GBR. Marine and Tropical Sciences Research Facility (MTSRF), Cairns, Qld. Available at www.rrrc.org.au/publications/downloads/Project-371-Conceptual-Model-Report.pdf [verified May 2010].

Fabricius, K. E., De'ath, G., McCook, L. J., Turak, E., and Williams, D. (2005). Coral, algae and fish communities on inshore reefs of the Great Barrier Reef: ecological gradients along water quality gradients. *Marine Pollution Bulletin* **51**, 384–398. doi:10.1016/J.MARPOLBUL.2004.10.041

Ferrier-Pages, C., Gattuso, J. R., Dallot, S., and Jaubert, J. (2000). Effect of nutrient enrichment on growth and photosynthesis of zooxanthellate coral *Stylophora pistillata. Coral Reefs* **19**, 103–113. doi:10.1007/S003380000078

Hart, B. T., and Pollino, C. A. (2009). Bayesian networks for risk-based environmental water allocations. Waterlines Report Series No 14. National Water Commission, Canberra.

Hoegh-Guldberg, O. (1999). Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research* **50**, 839–866. doi:10.1071/MF99078

Hughes, T., Szmant, A. M., Steneck, R., Carpenter, R., and Miller, S. (1999). Algal blooms on coral reefs: what are the causes? *Limnology and Oceanography* **44**, 1583–1586.

Hughes, T. P., Bellwood, D. R., Folke, C., Steneck, R. S., and Wilson, J. (2005). New paradigms for supporting the resilience of marine ecosystems. *Trends in Ecology & Evolution* **20**, 380–386. doi:10.1016/J.TREE.2005.03.022

Hughes, T., Rodrigues, M., Bellwood, D., Ceccarelli, D., Hoegh-Guldberg, O., McCook, L., Moltschaniwskyj, N., Pratchett, M., Steneck, R., and Willis, B. (2007). Phase shifts, herbivory, and the resilience of coral reefs to climate change. *Current Biology* **17**, 360–365.

Jupiter, S., Roff, G., Marion, G., Henderson, M., Schrameyer, V., McCulloch, M., and Hoegh-Guldberg, O. (2008). Linkages between coral assemblages and coral proxies of terrestrial exposure along a cross-shelf gradient on the southern Great Barrier Reef. *Coral Reefs* **27**, 887–903. doi:10.1007/S00338-008-0422-3

Koop, K., Booth, D., Broadbent, A., Brodie, J., Bucher, D., *et al.* (2001). ENCORE: the effect of nutrient enrichment on coral reefs. Synthesis, results and conclusions. *Marine Pollution Bulletin* **42**, 91–120. doi:10.1016/S0025-326X(00)00181-8

Kroon, F. (2008). Draft Tully water quality improvement plan. CSIRO report to Terrain NRM, Cairns, Qld.

Kroon, F. J. (2009). Integrated research to improve water quality in the Great Barrier Reef region. *Marine and Freshwater Research* **60**, i–iii. doi:10.1071/MF09216

Lapointe, B. E. (1997). Nutrient thresholds for bottom-up control of macroalgal blooms on coral reefs in Jamaica and southeast Florida. *Limnology and Oceanography* **42**, 1119–1131.

Lapointe, B. E. (1999). Simultaneous top-down and bottom-up forces control macroalgal blooms on coral reefs. *Limnology and Oceanography* **44**, 1586–1592.

Littler, M. M., and Littler, D. S. (1984). Models of tropical reef biogenesis: the contribution of algae. In 'Progress in Phycological Research. Vol. 3'. (Eds F. E. Round and D. J. Chapman.) pp. 323–364. (Biopress: Bristol, UK.)

Littler, M. M., and Littler, D. S. (2007). Assessment of coral reefs using herbivory/nutrient assays and indicator groups of benthic primary producers: a critical synthesis, proposed protocols and critique of management strategies. *Aquatic Conservation: Marine & Freshwater Ecosystems* **17**, 195–215. doi:10.1002/AQC.790

Littler, M. M., Littler, D. S., and Brooks, B. L. (2006). Harmful algae on tropical coral reefs: bottom-up eutrophication and top-down herbivory. *Harmful Algae* **5**, 565–585. doi:10.1016/J.HAL.2005.11.003

Lye, K. H., and Ling, L. H. (2006). Catchment management modeling: from headwaters to the coasts. *Aquatic Ecosystem Health & Management* **9**, 261–268. doi:10.1080/14634980600704991

Marcot, B. G., Holthausen, R. S., Raphael, M. G., Rowland, M. M., and Wisdom, M. J. (2001). Using Bayesian belief networks to evaluate fish and wildlife population viability under land management alternatives from an environmental impact statement. *Forest Ecology and Management* **153**, 29–42. doi:10.1016/S0378-1127(01)00452-2

Marcot, B. G., Stevenson, J. D., Sutherland, G. D., and McCann, R. K. (2006). Guidelines for developing and updating Bayesian belief networks applied to ecological modelling and conservation. *Canadian Journal of Forest Research* **36**, 3063–3074. doi:10.1139/X06-135

Marubini, F., and Davies, P. S. (1996). Nitrate increases zooxanthellae population density and reduces skeletogenesis in corals. *Marine Biology* **127**, 319–328. doi:10.1007/BF00942117

McCook, L. J. (2001). Competition between corals and algae on coral reefs: a review of evidence and mechanisms. *Coral Reefs* **19**, 400–417. doi:10.1007/S003380000129

Mitchell, A. W., and Furnas, M. J. (2001). River loggers – a new tool to monitor riverine suspended particle fluxes. *Water Science and Technology* **43**, 115–120.

Mitchell, A. W., Reghenzani, J. R., and Furnas, M. J. (2001). Nitrogen levels in the Tully River: a long-term view. *Water Science and Technology* **43**, 99–105.

Moody, P. W., Reghenzani, J. R., Armour, J. D., Prove, B. G., and McShane, T. J. (1996). Nutrient balances and transport at farm scale – Johnstone River catchment. In 'Proceedings of Conference of Downstream Effects of Land Use'. (Eds A. G. Eyles, H. M. Hunter and G. E. Rayment.) (Department of Natural Resources and Water: Brisbane.)

Neil, D. T., Orpin, A. R., Ridd, P. V., and Yu, B. (2002). Sediment yield and impacts from river catchments to the Great Barrier Reef lagoon. *Marine and Freshwater Research* **53**, 733–752. doi:10.1071/MF00151

Pandolfi, J. M., Bradbury, R. H., Sala, E., Hughes, T. P., Bjorndal, K. A., *et al.* (2003). Global trajectories of the long-term decline of coral reef ecosystems. *Science* **301**, 955–958.

Pandolfi, J. M., Jackson, J. B. C., Baron, N., Bradbury, R. H., Guzman, H. M., *et al.* (2005). Are US coral reefs on the slippery slope to slime? *Science* **307**, 1725–1726. doi:10.1126/SCIENCE.1104258

Prove, B. G., and Hicks, W. S. (1991). Soil and nutrient movements from rural lands of north Queensland. In 'Landuse Patterns and Nutrient Loading of the Great Barrier Reef Region'. (Ed. D. Yellowlees.) pp. 67–76. (James Cook University: Townsville, Qld.)

Rayment, G. E. (2003). Water quality in sugar catchments of Queensland. *Water Science and Technology* **48**, 35–47.

Reef Plan (2003). Reef water quality protection plan for catchments adjacent to the Great Barrier Reef World Heritage Area. Queensland Department of Premier and Cabinet, Brisbane.

Schroeder, B., Wood, A., Hurney, A., and Panitz, J. (2007). 'Accelerating the Adoption of Best Management Practice Nutrient Management: Wet Tropics.' (BSES Limited/CSR: Bundaberg, Qld.)

Shenton, W., Hart, B. T., Chan, T. (2009). Bayesian network model for environmental flow decision-making in the Latrobe River, Victoria, Australia. *River Research and Applications*, in press. doi:10.1002/RRA.1348

Smith, J. E., Smith, C. M., and Hunter, C. L. (2001). An experimental analysis of the effects of herbivory and nutrient enrichment on benthic community dynamics on a Hawaiian reef. *Coral Reefs* **19**, 332–342.

Sweatman, H. P. A., Cheal, A. J., Coleman, G. J., Emslie, M. J., Johns, K., Jonker, M., Miller, I. R., and Osborne, K. (2008). Long term monitoring of the Great Barrier Reef. Status report no. 8, 2008. Australian Institute of Marine Science, Townsville, Qld. Available at www.aims.gov.au/source/research/monitoring/status-reports/status-report-08.pdf [verified May 2010].

Thomas, C. R., Gordon, I. J., Wooldridge, S., van Grieken, M., and Marshall, P. (2009). The development of an integrated systems model for balancing coral reef health, land management and tourism risks on the Great Barrier Reef. In '18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation', July 2009. (Eds R. S. Anderssen, R. D. Braddock and L. T. H. Newham.) pp. 3301–3307. (Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation.) Available at www.mssanz.org.au/modsim09/J3/thomas_cr.pdf [verified July 2009].

Thorburn, P. J. (2004). Influences of N fertilizer management on off-site loss of water contaminants. In 'Cane Farming to Improve Water Quality'. (Eds L. N. Robertson and R. J. Troedson.) pp. 32–34. (Sugar Research Development Corporation (SRDC): Brisbane.)

Uusitalo, L. (2007). Advantages and challenges of Bayesian networks in environmental modelling. *Ecological Modelling* **203**, 312–318. doi:10.1016/J.ECOLMODEL.2006.11.033

Wachenfeld, D., Oliver, J., and Morrissey, J. (1998). State of the Great Barrier Reef World Heritage Area, Townsville (Australia). Great Barrier Reef Marine Park Authority, Townsville.

Wilkinson, C. (2004). 'Status of Coral Reefs of the World.' (Australian Institute of Marine Science: Townsville, Qld.)

Wolanski, E., Richmond, R. H., and McCook, L. (2004). A model of the effects of land-based, human activities on the health of coral reefs in the Great Barrier Reef and in Fouha Bay, Guam, Micronesia. *Journal of Marine Systems* **46**, 133–144. doi:10.1016/J.JMARSYS.2003.11.018

Wooldridge, S., Brodie, J., and Furnas, M. (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**, 1467–1479. doi:10.1016/J.MARPOLBUL.2006.05.009

Wrigley, T. (2005). Canegrowers public environment report 2005. Australian Cane Growers Council Ltd, Brisbane.

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