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Integrating Science through Bayesian Belief Networks: Case study of *Lyngbya* in Moreton Bay

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EXTENDED ABSTRACT

Bayesian Belief Networks (BBNs) are emerging as valuable tools for investigating complex ecological problems. In a BBN, the important variables in a problem are identified and causal relationships are represented graphically. Underpinning this is the probabilistic framework in which variables can take on a finite range of mutually exclusive states. Associated with each variable is a conditional probability table (CPT), showing the probability of a variable attaining each of its possible states conditioned on all possible combinations of it parents. Whilst the variables (nodes) are connected, the CPT attached to each node can be quantified independently. This allows each variable to be populated with the best data available, including expert opinion, simulation results or observed data. It also allows the information to be easily updated as better data become available

This paper reports on the process of developing a BBN to better understand the initial rapid growth phase (initiation) of a marine cyanobacterium, *Lyngbya majuscula*, in Moreton Bay, Queensland. Anecdotal evidence suggests that *Lyngbya* blooms in this region have increased in severity and extent over the past decade. *Lyngbya* has been associated with acute dermatitis and a range of other health problems in humans. Blooms have been linked to ecosystem degradation and have also damaged commercial and recreational fisheries. However, the causes of blooms are as yet poorly understood.

The initial phase of model development consisted of a series of workshops and individual meetings with participants, in which important hydrologic, nutrient, light and temperature variables were identified and their causal relationships defined. This systematic approach allowed for the construction of a conceptual model describing factors and their interactions that contribute to the initiation of *Lyngbya*. This early model was subsequently refined, balancing model complexity against research costs. The CPT were then populated by the group based on their scientific knowledge. In some cases this was via a process, simulation, mathematical or statistical model; in others it was via expert opinion and round-table agreement. The software package Netica® was used to construct the model. Note that further refinements to the model are expected.

There have been a number of important outcomes from the process of building the preliminary BBN. The interchange among scientists and other stakeholders during workshops led to: a greater understanding of important variables and their interaction by building on the experience of the group, in turn leading to a greater maturity in reasoning about the problem during successive iterations of the model; a greater awareness of the role of individual scientists' research in the larger picture; and a recognition of the need to coordinate data and models arising from the different research projects. Significant outcomes are that the BBN has provided a framework to prioritise and integrate the ongoing research contributions and to quantify the data needs.

At this stage, a range of longer term goals have been identified. The model will be further refined as new research or better information becomes available, and serve as a focus for the coordination of data and models arising from the various research projects on *Lyngbya* . This BBN will also be used to contribute both to the design of monitoring programmes for *Lyngbya* in Moreton Bay, and the analysis of data from these and other programmes. The model should be validated by applying the Bayesian network to other locations in order to identify local and global characteristics and assess the robustness of both the conceptual model and the network inputs. Importantly, it is planned to develop a similar conceptual model and BBN for the management aspects of *Lyngbya*, and integrate this into the scientific model with the aim of identifying possible management strategies, predicting their potential impact and developing scenarios relevant to future planning.

1. INTRODUCTION

Ecological problems are often complex and multifaceted. The traditional method of dealing with this complexity is to concentrate on small areas of the problem, thus addressing the issue from a variety of narrow perspectives. However, when using a reductionist approach it may be difficult to simultaneously bring to bear the best scientific information from a variety of fields, allow the participation of multiple stakeholders and identify management objectives (Holling 1998). Bayesian Belief Networks (BBNs) perform just such a function, providing a rational method for the integration of the best possible data from a variety of sources (Wooldridge and Done 2003). A BBN can also incorporate prior knowledge in order to more accurately model a complex system, which may be difficult when using other techniques (Pollino 2005).

We report here on the progress of a collaborative project between QUT and the Moreton Bay and Waterways Partnership. This project, currently in its preliminary stages, has been designed to construct a BBN to better understand the initiation of a marine cyanobacterium, *Lyngbya majuscula*, in Moreton Bay, Queensland and to improve the long term management of this harmful algae. Even at this early stage of development, the modelling process has shown considerable benefits, and future additions, refinements and uses of the BBN have been identified.

2. BAYESIAN BELIEF NETWORKS

A BBN is a fusion of a graphical model and an underlying probabilistic framework. The graphical model consists of a set of key variables (represented as nodes) connected by directed edges. These directed edges show the causal relationships between variables. This graphical structure allows experts to articulate their knowledge about a particular system and to connect those variables into a causal chain. Associated with each variable is a range of mutually excusive states and a conditional probability table (CPT). This table contains the probability of a variable attaining each of its possible states conditioned on all possible combinations of its parents, the variables that influence it (Pollino 2005).

Although variables are causally connected, the probability tables associated with each of the variables can be quantified independently (Borsuk *et al*. 2004). This allows each CPT to be separately populated with the best data available, including expert opinion, modelling data and experimental data. Thus, a variable can be effectively incorporated into a model even when the CPT associated with the variable is not exact. This independence also allows the information to be easily updated if better data become available, since only the CPT needs to be changed (Jensen 2001). Taken together, these factors mean that a BBN can be useful even before scientific knowledge for a particular problem is complete (Borsuk *et al*. 2004).

BBNs provide a range of advantages for investigating complex ecological problems and their management. The use of conditional probabilities implicitly incorporates uncertainty into the results (Sadoddin *et al*. 2005). BBNs allow information from a variety of sources, and potentially of different quality, to be merged and easily updated. They provide a management framework for making informed decisions in the face of incomplete knowledge. Also, they are extremely valuable in evaluating the consequences of alternative "what if "scenarios. Thus BBNs provide a powerful means of investigating complex problems.

3. THE *LYNGBYA* PROBLEM

Moreton Bay is a large, sheltered bay adjacent to the city of Brisbane in southeast Queensland. While *Lyngbya* has probably always naturally occurred in the Bay, the size and frequency of *Lyngbya* blooms has increased since the early 1990's (Dennison *et al*. 1999, Dennison and Abal 1999), such that it is now considered to be a major threat to the safe and effective use of Moreton Bay and its beaches. *Lyngbya* has a range of adverse human health and ecosystem effects. It has been shown to cause severe contact dermatitis, eye irritation and respiratory symptoms (Osborne *et al*. 2001). *Lyngbya* blooms have caused significant economic effects, reducing recreational and commercial fisheries, and decreasing the recreational use of an affected region (Dennison and Abal 1999). Moreover, these blooms represent a significant economic impost on the communities of South East Queensland and directly effect commercial and recreational fishing, tourism, human health and possible future land development in the coastal zone. While ecological damage is poorly understood, it is known that *Lyngbya* blooms can lead to seagrass loss resulting from a reduction in light availability and anoxia (Dennison *et al*. 1999), movement of fish (Savage pers. com.) and also turtles (Arthur *et al*. 2005) out of seagrass beds, and there is some indication of the toxins associated with *Lyngbya* having been implicated in fish kills (Sadek *et al*. 1986). The toxins have been found to distribute to other biota such as damselfish (Marnane and Bellwood 1997)

The cause of *Lyngbya* blooms is just beginning to be understood due to a considerable research and monitoring effort over the last six years. It was decided that present understanding needed to be further integrated at a systems level, collecting together the available knowledge on *Lyngbya* and identifying knowledge gaps, in order to allow a management driven focus in the next phase of research.

An integrated research and management framework is being developed using a BBN to generate a more holistic understanding of *Lyngbya* dynamics in the Bay, to formulate suitable management strategies and tools for long term management, and to optimize the benefits from funding.

4. THE *LYNGBYA* PROJECT

The project has several aims from the Bayesian Network modelling viewpoint:

- To iterate towards a conceptual model that identifies the major factors and their pathways leading to the initiation of *Lyngbya* blooms in Moreton Bay,
- To use the network as a framework for integrating these various contributions in order to estimate the probability of *Lyngbya* bloom initiation,
- To undertake an initial quantification of the model CPTs in order to identify areas of relative strength and weakness with respect to knowledge about the drivers of initiation of *Lyngbya*,
- To identify existing and potential research contributions and place them within the conceptual model,
- To build an extended model as a management options assessment tool in formulating policy and on the ground management actions at State and Local Government level.

4.1. MODEL DEVELOPMENT

The task involved a series of workshops with the *Lyngbya* Scientific Expert Panel - a group consisting of scientists, facilitators and stakeholders, with expertise ranging from sediment and dissolved nutrient dynamics, hydrology, and algal physiology to the effects of *Lyngbya* blooms on commercial fishing.

The first three workshops revolved around constructing the conceptual model by describing factors and their interactions that contribute to the initiation of *Lyngbya*, and proceeding from this to a BBN using both consensus among the group and a series of individual meetings with participants. Key steps in the process were:

1. Defining the management objectives: It was necessary to clearly articulate these as the first step since they were used, and will continue to be used, to drive the modelling and assessment process.

2. Defining the scope of the modelling exercise: *Lyngbya* bloom initiation and its relationship with the environment must be understood across a range of space and time scales. The spatial and temporal scope of the assessment was stated in terms of natural cycles relating to physical, biochemical, and biological processes in Moreton Bay, as well as adjacent land based systems (Figure 1). Each colour in Figure 1 (following page) represents a different scale of interaction that needs to be considered in the modelling of *Lyngbya* growth initiation. Green represents interactions at the cell wall (μm); yellow, the interactions of groups of cells with the immediate environment (mm); white the changes that occur as the organism develops in life cycle terms (cm to tens of cm); pink, the interactions of *Lyngbya* biomass in a bloom with its surrounding environment (cm to m); dark blue, ecosystem level interactions in Deception Bay (m to km); and the larger yellow, catchment scale processes that influence the Deception Bay environment (km to tens of km). In many respects time and space scales are related so that scales of cm are reflective of time scales of seconds to minutes whereas space scales of km are reflective of time scales of days.

3. Establishment of assessment endpoints: Specific endpoints needed to be clearly identified in order to allow for quantification of the CPTs. The endpoint adopted was change in biomass during the initiation period of growth.

4. Formulation of a probabilistic model: The understanding of important processes needed to formulate a BBN was developed using a systems approach so that key linkages could be identified. An initial conceptual model was constructed in which the main processes that impacted on Lyngbya initiation were broadly identified (Figure 2). In converting the conceptual model to a BBN, it was decided to simplify the model, allowing the Expert Panel to familiarise themselves with the process of BBN building and populating CPTs (Figure 3). In this model, the key, were current identified as light climate, conditions.

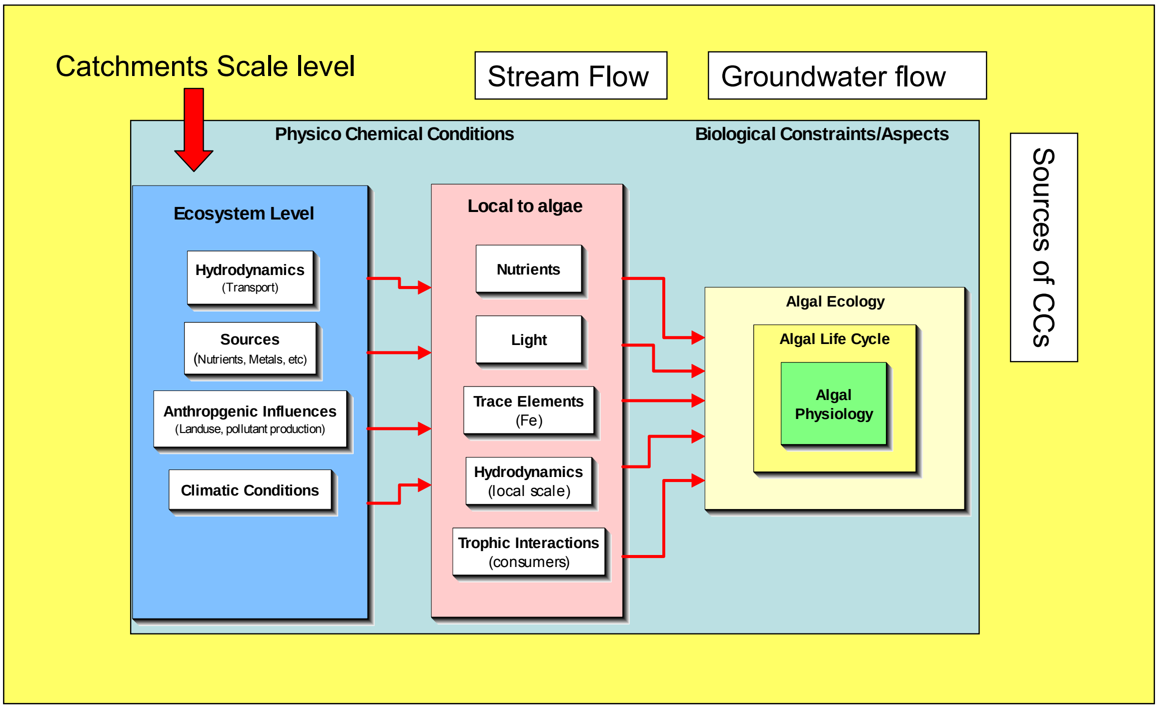

Figure 1. Systems level conceptual model of key *Lyngbya* processes/interactions showing key pathways leading to bloom initiation. CCs - chemicals of concern. Fe - iron compounds. Refer to text for further explanation of figure.

for *Lyngbya* bloom initiation, temperature, bottom sediment, nutrients and dissolved nutrients. The scope of the model was limited to bloom initiation rather than biomass. Here, it was necessary to derive a scientifically acceptable model structure that included key variables and important interactions, but such variables and interactions had to be quantifiable. The BBN was then constructed and compiled using Netica®. The CPT were populated over several sessions using available data and expert opinion from within the Working Group (Figure 4). In some cases this was via a simulation, process, mathematical or statistical model; in others it was via expert opinion and round-table agreement. For example, the bloom initiation CPT was filled in based on consensus using expert opinion; a receiving water quality model was identified as a source of results to inform the diffuse and point source CPTs; and data from a data logger in Deception Bay were available to populate the light climate CPT. The progression of models (Figs 2 to 4) illustrate the developing maturity of reasoning that was a key outcome of the project.

5. Assessment of knowledge gaps or needs: One important outcome of the model formulation process (Step 4) was the identification of areas where there was not enough understanding to provide information to populate the model with any confidence. For example, there were insufficient data associated with sediment nutrient climate and point sources. Also, this step included the identification of areas in which data may exist but had not been suitably processed e.g. while some data for temperature were available, and preliminary statistical analysis had been undertaken, more was needed. Based on the knowledge gaps identified, the Terms of Reference for the next set of scientific tasks was developed.

5. MANAGEMENT

In the last workshop, nodes in the model at which management interventions might be taken were identified. These included: diffuse sources; point sources; particulates; and sediment nutrient climate. It was recognised that each of these nodes will require further evaluation in order to better understand the implications of management activities. This process, together with the construction of a parallel BBN focussed on management actions, have developed into a separate and on-going project. This will entail developing a similar conceptual model and BBN for the management aspects of *Lyngbya*. This will be integrated into the scientific model with the aim of identifying possible management strategies, predicting their potential impact and developing scenarios relevant to future planning

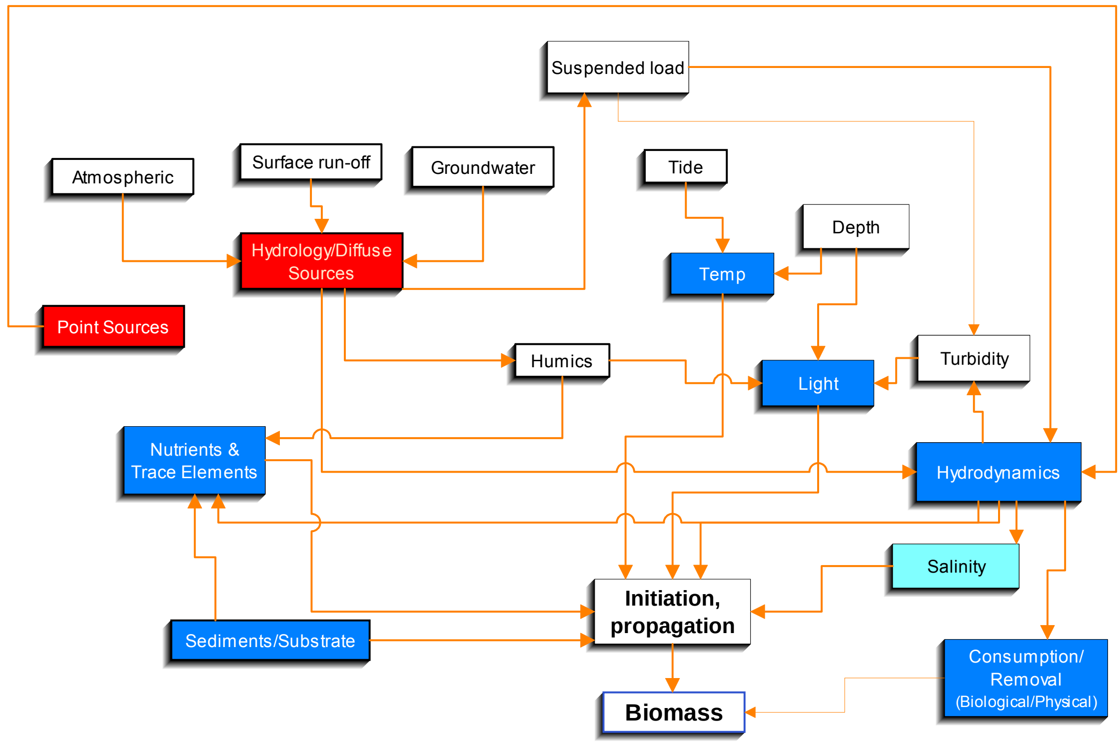

Figure 2. Initial conceptual model for Lyngbya bloom initiation. Box colouring was used here as a visual aid to identify research contributions. Salinity was removed from later models.

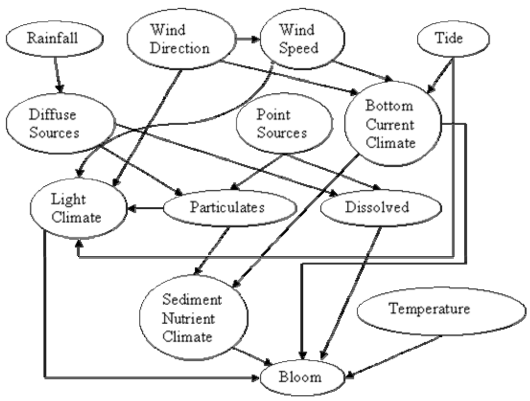

Figure 3. Simplified conceptual model for *Lyngbya* initiation

6. FUTURE PROJECT GOALS

As this is an ongoing project a number of longer-term activities are required. As well as continuing and developing the aims outlined in section 4, the following major areas were identified :

Targeted Information Coordination: Continue to use the BBN to coordinate data and models arising from the various research projects on *Lyngbya*, focusing on how these outputs further contribute to the overall *Lyngbya* model. For instance, at this point several key variables for bloom initiation have been identified (nutrients, light and temperature), and it will be important to attempt to simultaneously measure these before, during and after *Lyngbya* bloom initiation in Deception Bay, and to analyse the data

Contribution to Monitoring Design: The structure of the BBN will be used to inform experimental and study design, particularly with sensitivity analyses and alternative scenarios allowing the most important combination of variables to be identified.

Lyngbya Biomass changes, ecophysiology and nutrient dynamics: Develop an associated systems dynamics model and corresponding BBN for key factors leading to change of biomass of *Lyngbya* in Deception Bay.

Model Validation: Apply the current Bayesian network to other locations in order to identify local and global characteristics and assess the robustness of both the conceptual model and the network inputs

7. RESEARCH ACTIVITIES

There is considerable scope for the theoretical development of BBNs in order to achieve the future project goals. These include:

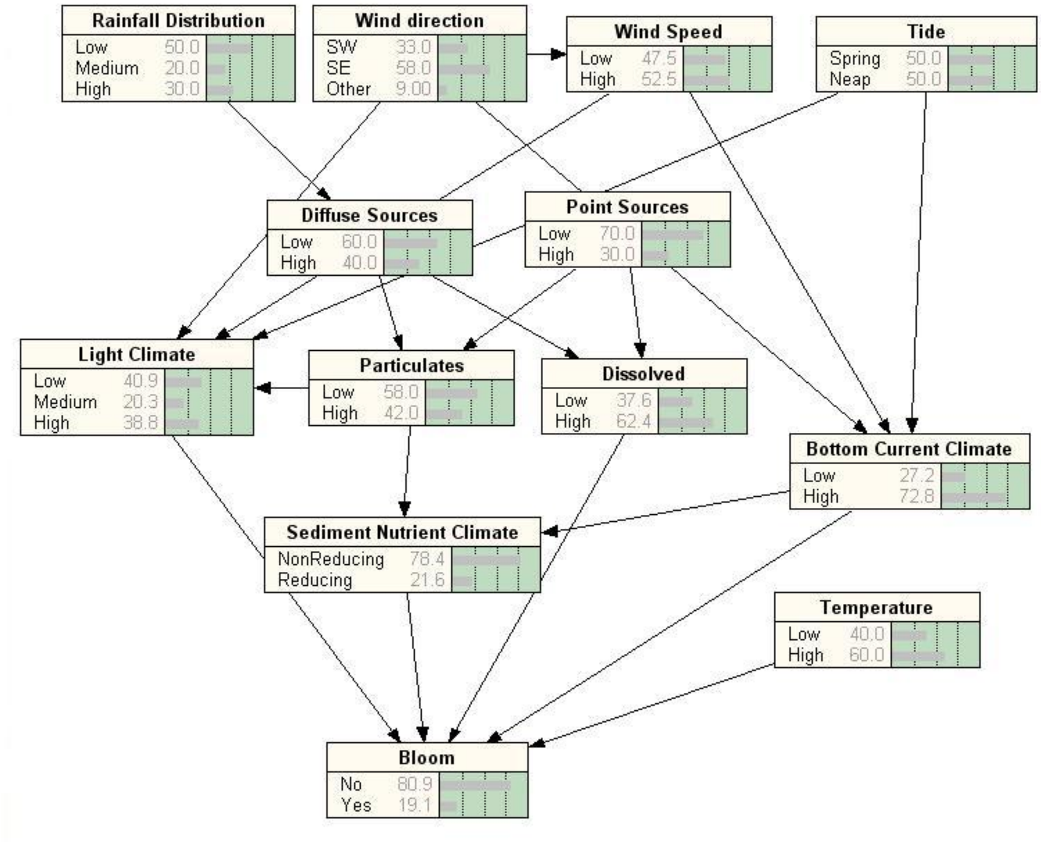

Figure 4. Current Netica© model for *Lyngbya* initiation (with data). Arrows represent causal linkages between variables. The numbers displayed for each category represent prior belief based on the data contained within CPTs

Optimising the integration of different types of models in a Bayesian network. Examples of this include using a process model for characterization of nutrients, a mathematical model to describe the role of water, data on groundwater, spatial maps on land use and vegetation type, and expert opinion on the role of light. This aims to best utilise and integrate individual research efforts.

Synthesis of different types of models addressing the same research question, and modification of methods of modelling in order to better incorporate the 'best' aspects of all methods. Examples of this include incorporating nutrient cycling at different scales; building uncertainty in process models; incorporating feedback in directed models; and including differential equation models within statistical models.

Improved methods for adjusting for the certainty and quality of the information input into the model, particularly in light of the diverse sources of such information.

Proof of concept of the dynamic nature of the network, so that updates to the model in light of new data are easily undertaken and provide consistent and correct outputs.

Better understanding of the ability of Bayesian networks to identify areas of most influence, least information and greatest sensitivity.

8. CONCLUSION

Implementation of a BBN has proved useful for the *Lyngbya* project for several reasons. The systematic approach taken to the planning and construction of the BBN led to a rigorous evaluation of key variables and interactions involved in *Lyngbya* bloom initiation. It provided a logical, accessible and transparent means of collecting together the available knowledge on *Lyngbya*. Further, it assisted in identifying knowledge gaps that could be filled with ongoing research. Importantly, the *Lyngbya* BBN has provided an encompassing statistical modelling framework for the various data sources which can be readily tested and updated. Even at this preliminary stage, the BBN has the potential to be used to inform future experimental design and coordinate research objectives.

Preliminary analysis suggests that light, temperature, and nutrients, possibly including iron, play an important role in *Lyngbya* bloom initiation. As an example of a scenario that was run,, when temperature, light climate and dissolved nutrients were high, sediments were reducing and bottom current was low, the probability of *Lyngbya* bloom initiation was found to be 95%. This points to further possible areas of research, particularly the role of iron compounds in *Lyngbya* growth, light and temperature requirements for bloom initiation, and the measurement of nutrients entering Deception Bay along with identification of specific sources of those nutrients.

Ongoing development of the *Lyngbya* BBN with updated data and associated theoretical developments will improve the capacity of the BBN to effectively integrate different models. It will also enable model uncertainty to be accounted for, thus enabling the BBN to better identify the major drivers of *Lyngbya* initiation in Moreton Bay. This will then flow on to improved long term management decisions.

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10. REFERENCES

Arthur K.E., C. J. Limpus, C. M. Roelfsema1, J. W. Udy, G. R. Shaw (2005) A bloom of *Lyngbya majuscula* in Shoalwater Bay, Queensland, Australia: an important feeding ground for the green turtle (*Chelonia mydas*), in press

Borsuk, M.E., C.A. Stow and K.H. Reckhow. (2004) A Bayesian network of eutrophication models for synthesis, prediction, and uncertainty analysis. *Ecological Modelling*, 173, 219-239

Dennison, W.C. and E.G. Abal. (1999) *Moreton Bay Study: A Scientific Basis for the Healthy Waterways Campaign.* South East Queensland Regional Water Quality Management Team, Brisbane.

Dennison, W.C., J.M. O'Neill, E. Duffy, P. Oliver, and G. Shaw. (1999) Blooms of the cyanobacterium *Lyngbya majuscula* in coastal waters of Queensland. *Proceedings of the International Symposium on Marine Cyanobacteria*. Bulletin de l'Institut Oceanographique, Monaco.

Holling, C.S. 1998. Two cultures of ecology. Conservation Ecology [online] **2**(2): 4. Available from the Internet. URL: http://www.consecol.org/vol2/iss2/art4

Jensen, F.V. (2001) *Bayesian Networks and Decision Graphs*. Springer, New York.

Osborne, N.J.T., P.M. Webb and G.R. Shaw. (2001) The toxins of Lyngbya majuscula and their human and ecological health effects. *Environment International*, **27**, 381-392.

Marnane, M.J. and D.R. Bellwood. (1997) Marker techniques for investigating gut throughput rates in coral reef fishes. *Marine Biology* **129**, 15-22.

Pollino, C.A., O. Woodberry, A.E. Nicholson, and K.B. Korb. (2005) Parameterising Bayesian networks: a case study in ecological risk assessment. *Proceedings of the 2005 International Conference on Simulation and Modelling*, Bangkok, Thailand , January 2005.

Sadek, S., I. Ittawa and R. Martello. (1986) Culture of mullet species in ponds receiving iron crush effluents at El-Baharia Oasis, Egypt. *Aquaculture* **59**, 23-39.

Sadoddin, A., R.A. Letcher, A.J. Jakeman and L.T.H. Newham. (2005) A Bayesian decision network approach for assessing the ecological impacts of salinity management. *Mathematics and Computers in Simulation*, 69, 162-176.

Wooldridge, S. and T. Done. (2003) The use of Bayesian belief networks to aid in the understanding and management of large-scale coral bleaching. *MODSIM 2003 International*

Conference on Modelling and Simulation, Townsville, July 2003