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Investigating the Use of a Bayesian Network to Model the Risk of *Lyngbya majuscula* Bloom Initiation in Deception Bay, Queensland

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Running Head: A Bayesian Net for Lyngbya in Deception Bay

ABSTRACT

Modelling the risk factors driving an environmental problem can be problematic when published data describing variables and their interactions are sparse. In such cases, expert opinion forms a vital source of information. Here we demonstrate the utility of a Bayesian Net (BN) model to integrate available information in a risk analysis setting. As an example, we use this methodology to explore the major factors influencing initiation of *Lyngbya majuscula* blooms in Deception Bay, Queensland. Over the past decade *Lyngbya* blooms have increased in both frequency and extent on seagrass beds in Deception Bay, with a range of adverse effects. This model was used to identify the main factors that could trigger a *Lyngbya* bloom. The five factors found to have the greatest effect on *Lyngbya* bloom initiation were: the available nutrient pool, water temperature, redox state of the sediments, current velocity and light. Scenario analysis was also conducted to determine the sensitivity of the model to different combinations of variable states.

The model has been used to identify knowledge gaps and therefore to direct additional research efforts in Deception Bay. With minor changes the model can be used to better understand the factors triggering *Lyngbya* blooms in other coastal regions.

Key Words: algal bloom, probabilistic modeling, management, expert opinion.

INTRODUCTION

Ecological problems are often complex and multifaceted. The traditional method of dealing with this complexity is to focus on small rather narrow aspects of the problem then try and interpolate across the results. Although it is often necessary to study microcosms of the overall problem in order to progress understanding, it is equally important that this detailed information is integrated to provide an overall understanding of major factors influencing the problem. It is only with this broad understanding of the relative importance of the key factors that we can hope to better manage the problem.

This process of integrating the available knowledge is demanding because it involves bringing together the best scientific information from a variety of disciplines, and coupling this with a range of possible management actions that could minimise the risk of the problem occurring (Holling 1998). In many complex environmental systems the best available scientific information may be in the form of the knowledge of experts who have the capacity to inform the structure of an appropriate model together with form of interaction that may occur among variables. It is important to evaluate appropriate methodologies in a risk setting that model the complexity of environmental systems together with mechanisms for incorporating the best possible information.

This complexity is particularly evident with nuisance algal blooms where a number of possible interactions between key factors have the potential to influence the probability of a bloom occurring. These include high incidence irradiance and water temperature, various anthropogenic influences such as different land uses and point source outflows leading to high nutrient concentrations in waterways and bays (Dennison *et al.* 1999; Thacker and Paul 2001; Watkinson 2005), and even nutrient levels in groundwater (Anderson *et al.* 2002; Ahern *et al.* 2006). In coastal marine environments, it is also necessary to consider currents, tides and other hydrodynamic features. To complicate matters still further, these variables may operate at different spatial and temporal scales. Due to the number and complexity of interacting variables, empirical evidence will often describe only part of what is required to model such systems.

The success of any model used to assist in the prediction and management of algal blooms will depend on its capacity to include and simultaneously examine these multiple interactions. While process-based models are often used for this purpose, and can be useful for exploring mechanisms, they tend to be overly complex and thus are less useful for predicting algal blooms (Clark 2001). Additionally, they rarely account for the uncertainty inherent in predicting the behaviour of ecological systems, another essential characteristic of predictive ecosystem models (Clark 2001).

By comparison, Bayesian Network (BN) models have the capacity to incorporate interactions between multiple variables at different spatial and temporal scales, and do this within a probabilistic framework. BNs provide a range of advantages for investigating complex ecological problems such as algal blooms, and their management. The use of conditional probabilities implicitly incorporates uncertainty into the results (Sadoddin *et al.* 2005). BNs provide a rational method for the integration of the best possible data from a variety of sources, including expert opinion, simulation results and empirical data (Wooldridge and Done 2004). Thus they allow information from a variety of sources, and potentially of different quality, to be merged and easily updated. A BN can also incorporate prior knowledge in order to more accurately model a complex system, which may be difficult when using other techniques (Pollino *et al.* 2005).

BNs have been successfully used to model management scenarios, and are also emerging as an efficient means of integrating the scientific knowledge of complex ecological problems that serves as a necessary precursor to effective management (*e.g.*,, Borsuk *et al.* 2004; Pollino *et al.* 2005). Unlike determinstic methods, probabilistic models deal effectively with the uncertainty inherent in environmental systems through the use of probabilities. Rather than being ignored, this uncertainty flows through to the results, which are likely to be framed in terms of the probability of some outcome. BNs have previously been been promoted as effective tools for risk assessment (*e.g.*,, Hart *et al.* 2006), although to our knowledge there are no examples to date examining marine algal blooms. One purpose of this paper is to describe the development and demonstrate the utility of a of a BN model to better understand the major drivers that trigger blooms of a nuisance cyanophyte (*Lyngbya majuscula*) in a system where much of the information needed to model the system is not published. This study focusses on modelling the initiation of blooms of *Lyngbya majuscula* in an area of particular concern, Deception Bay, an embayment within Moreton Bay, Queensland. This area was selected for a number of reasons, including the fact that data and modeling output needed for input into the Bayesian Net model were most readily available for Deception Bay, and that this embayment is the area in which

Lyngbya has the greatest impact in terms of the number of people affected. It is thus important to closely link the risk factors found in the current study into a future management model.

One further purpose of this paper is to demonstrate that an important function of a model can be to refine ideas and to organise and integrate existing information, and that appropriate methodology such as BNs allow ongoing improvement through further iterations. While the long term goal of the current BN model is to predict the conditions under which *Lyngbya* blooms will be triggered in Deception Bay, the process of creating and refining the model was valuable as a means to direct ongoing research efforts and to generate new hypotheses. Future stages will be to examine other features of the bloom cycle (*e.g.*,, bloom maintenance and senescence), and to couple these BN models with a complementary management BN model so that we can predict the best management actions for minimising the risk of *Lyngbya* blooms in Deception Bay.

Bayesian Networks

Bayesian Networks have been well described elsewhere (*e.g.*, Jensen 2001; Borsuk *et al.* 2004). They consist of a fusion between a graphical model and an underlying probabilistic framework. The graphical model depicts the most important variables in the system (often represented as circles or boxes), and shows causal dependence relationships among those variables with unidirectional arrows. The variable from which an arrow originates is said to be the parent of the variable that the arrow connects to (the child).

This representation of conditional dependence is important because of the probabilistic nature of a Bayesian Network. *Conditional probability distributions* for a child node are constructed using every possible state of the child's parent node(s), and when distributions can be discretised, these are encoded in conditional probability tables (CPTs). These probability relationships may be based on empirical data, other models (*e.g.*, process or simulation models) or the opinions of experts, which may include scientists or others with expert knowledge in the problem domain. Nodes that have no parents are described by unconditional (marginal) probability distributions.

BNs have been successfully used for a variety of environmental problems, including phosphorus management in a watershed in Northern Utah (Ames *et al* 2005), algal bloom management in a North Carolina estuary (Borsuk *et al* 2004), a survival model for a freshwater clam exposed to bottom water hypoxia (Borsuk *et al* 2002), assessing the viability of native fish in the highly regulated Goulburn River in Victoria (Pollino *et al.* 2006), and providing advice on best management practice for an area of endangered swamp eucalyptus trees (Pollino and White 2005). BNs have been recognised as being a flexible modelling approach for quantifying ecological risks (Burgman 2005; Hart *et al.* 2006).

The *Lyngbya* Problem

Moreton Bay is a large, sheltered bay adjacent to the city of Brisbane in southeast Queensland and the subject of significant scientific study (Dennison and Abal 1999). *Lyngbya* is normally present in trace amounts in the coastal marine sediments here (Arquitt and Johnstone 2003), and occasional *Lyngbya* blooms may have been a natural occurrence (Dennison *et al.* 1999). However, the size and frequency of these *Lyngbya* blooms has increased since the early 1990s (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 blooms in Moreton Bay occur on shallow seagrass banks on both sides of the Bay, and can grow rapidly having been observed to cover over 8 km^2 within several days (Watkinson *et al.* 2005) and it is know known that biomass can vary considerably across the area of Lyngbya coverage. Once established, blooms often persist for 3 to 6 months before declining (Arquitt and Johnstone 2003). During a bloom *Lyngbya* displays a progression from being sediment derived to forming thick mats, covering and damaging sea grasses. Much of the bloom may become free floating and under windy conditions be carried ashore. When floating *Lyngbya* washes ashore it not only decays but represents a potential health risk, necessitating its removal by the local authorities at considerable cost. These blooms therefore represent a significant economic impost on the communities of South East Queensland and directly affect commercial and recreational fishing, tourism, human health and possible future land development in the coastal zone.

Lyngbya has a range of adverse effects on both human health and aquatic ecosystems. 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). 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), and movement of turtles (Arthur *et al.* 2005) out of seagrass beds. There is also some evidence that toxins associated with *Lyngbya* can cause fish kills (Sadek *et al.* 1986). The toxins have also been found to distribute to other biota such as damselfish (Marnane and Bellwood 1997) and sea hares (Capper *et al.* 2006).

MODEL DEVELOPMENT

Despite a considerable research and monitoring effort over the last six years, the causes of *Lyngbya* blooms are not yet well understood. Construction of a BN provided an opportunity to integrate existing knowledge within a single statistical framework and identify knowledge gaps. Development of the model was commenced during a workshop with a group of individuals who had specialist scientific, planning and impacts knowledge of *Lyngbya*. Initially, a conceptual model was formulated so that a *Lyngbya* bloom could be understood within its environmental context. This conceptual model incorporated critical natural cycles relating to physical, biochemical, and biological processes in Moreton Bay, as well as adjacent land based systems, and placed these within appropriate spatial and temporal frames (Hamilton *et al.* 2005).

Once a firm conceptual basis for *Lyngbya* blooms was established, the BN modelling process commenced. In important initial stage in this process was identification of the modelling focus. Although the primary interest for stakeholders affected by *Lyngbya* was to identify possible mechanisms for the reduction or even elimination of blooms, it was recognised that any management actions must be scientifically defensible. The modelling focus for the BN was agreed on as the early (initiation) phase of a *Lyngbya* bloom.

Once the modelling focus had been decided, construction of a graphical structure continued by discussion during two further workshops in order to identify the hierarchy of variables that influenced *Lyngbya* bloom initiation; those that immediately influenced *Lyngbya* bloom initiation (*i.e.*, nodes preceding bloom initiation), then nodes preceding them, and so on. The initial model consisted of 13 nodes and 20 links.

Following the group meetings a series of small group and individual meetings was instituted to enable/allow clarification of specific details relating to parts of the BN and the definitions to be used in population of the individual conditional probability tables. Each of the changes made by individuals and small groups were scrutinised and confirmed by the entire group, and the initial 13 node model was expanded in an iterative fashion during this process.

Participants also agreed to use a 12 month time frame for the model in the first instance, anticipating a subsequent model at a time frame of two to three months around the specific period when initiation takes place.

Graphical Model Description

The current model (Figure 1) consists of 23 nodes and 41 links. The central node, *Bloom Initiation*, considers the process in which the biomass of *Lyngbya majuscula* in Deception Bay accelerates dramatically over the course of 1-4 weeks, leading to its domination of the benthic algal assemblage. The model focuses on the probability of *Lyngbya* bloom initiation over a 12 month period.

The remainder of the model can be logically considered in terms of 5 interacting subunits: *Nutrient sources*, *Dissolved nutrients*, *Nutrient interactions*, *Light and Temperature* and *Hydrodynamics*. A description of the graphical model is provided below, starting from the model endpoint *Bloom Initiation* and the following the causal chain to variables directly affecting this endpoint.

Light and temperature

The growth of *Lyngbya* will be affected by both incident light at the sediment surface and water temperature. The growth of cyanobacterial blooms has previously been shown to be strongly temperature dependant (Sellner 1992), and warm water temperatures have been implicated in the onset of *Lyngbya* blooms in Deception Bay (Watkinson *et al.* 2005). Thus, the *Temperature* variable is directly connected with *Bloom Initiation*. *Light Climate* at the sediment surface directly affects photosynthetic production and therefore the growth of *Lyngbya* (Sellner 1992). *Light climate* is influenced by the characteristics of sunlight, *Light Quality* (spectral composition) and *Light Quantity* (total available light) (Longstaff *et al.* 2001). However, it will also be influenced by the variable *Turbidity*, with low turbidity (clear water conditions) seemingly optimal for *Lyngbya* blooms (Watkinson *et al.* 2005). *Bloom Initiation* is thus considered to be directly influenced by two environmental variables, *Light Climate* and *Temperature*.

Hydrodynamics

There are four nodes within the *Hydrodynamics* subunit that describe the speed of the current across the benthic surface, and the factors that affect this speed. *Bottom Current Climate* describes the rate of water movement across the sediment surface. As the velocity of water currents in Deception Bay increase, they tend to carry more suspended solids, thus increase *Turbidity*. Current speed is in turn affected by the tide and by wind characteristics. Neap tides aid in water column stability (Watkinson *et al.* 2005), and empirical observations show that currents in Deception Bay are stronger under south to south east wind conditions.

Dissolved nutrients

A third node that directly affects *Bloom initiation* is the *Available Nutrient Pool*. This is a composite node that describes the levels of available nutrients (*Dissolved Iron*, *Dissolved Nitrogen* and *Dissolved Phosphorus*) in Deception Bay. It is affected not only by the relative concentrations of these bioavailable nutrients in the dissolved phase, but also by *Bottom Current Climate*. This is because of the belief that, during calm conditions when light and temperature have maximum influence, dissolved nutrients can accumulate in sediment interstitial spaces and are thus available for *Lyngbya* initiation. As water currents increase the geochemical conditions change so that the pool of some dissolved nutrients in the surface sediments may decrease due to oxidation, and the removal of materials also increases. This decreases the overall availability of some nutrient species to Lyngbya. The dissolved nutrients that have been included in this model have each been implicated in the growth of *Lyngbya*. Nitrogen and phosphorus have often been associated with algal blooms, and are suspected to contribute to the initiation of *Lyngbya* (Dennison *et al.* 1999; Elmetri and Bell 2004; Watkinson *et al* 2005; Albert *et al.* 2005). *Dissolved Nitrogen* and *Dissolved Phosphorus* are thus two key nutrients. Bioavailable dissolved iron is often a limiting factor for cyanobacteria as iron assists in the fixation of nitrogen and is a key element for a range of energy transfer reactions (Paerl 1994; Arquitt and Johnstone 2003). *Dissolved Iron* is therefore also believed to be a key factor in the initiation of *Lyngbya* blooms (Watkinson *et al.* 2005; Albert *et al.* 2005). *Dissolved Organics* are included in the model because they can complex with iron, which acts to substantially extend its bioavailability (Rose and Waite 2003a,b).

We note that in this section we consider the availability of dissolved N and P as being important factors in the initiation of a bloom, since it is the dissolved form of these nutrients that is required for organism uptake. A valid alternative approach to represent the issue of nutrient uptake would be to account for the Redfield ratio (the N:P ratio of nutrient availability versus nutrient composition of the organism). This was not included in our model, however, as we had no useful data that would allow its inclusion as a relevant node.

Nutrient interactions

The concentration and availability of different nutrients in the dissolved phase also depends on the relative redox state of the sediment, indicated by the variable *Sediment Nutrient Climate*. This node is affected by *Particulate Matter*, *Bottom Current Climate* and *Temperature*. Oxygen is more soluble in cold water, and thus an increase in water temperature leads to a decrease in oxygen saturation and a more reducing environment. As *Particulate Matter* in the water increase, the environment becomes more reducing as the particles absorb energy from sunlight, leading to an increase in water temperature. *Particulate Matter* also scatters light, decreasing the photosynthetic productivity of plants, which increases this effect. When currents are strong, however, the benthic environment receives more oxygen leading to a more oxidising environment.

Nutrient inputs

This subunit consists of 2 marginal and 4 conditional nodes. The four conditional nodes in this subunit (*Groundwater*, *Land Run-off*, *Air* and *Point Sources*) describe the sources of nutrients that flow into Deception Bay. Although *Groundwater* could be considered in terms of shallow and deep groundwater, it is believed here that it is shallow groundwater that has the greatest potential to contribute nutrients to the system (Ahern *et al.* 2006). *Land Run-off* considers the overland flow of water bearing nutrients both into waterways and directly into Deception Bay. This might include the run off from agricultural land, urban areas and natural habitats. *Point Sources* of nutrients include elements such as waste water treatment plants, aquaculture operations and quarries. Aeolian sources of nutrients (including dust or other pollutants) may be a significant contributor of nutrients to marine environments. This source of nutrients is considered within the variable *Air*.

The volume of rain that has fallen within the past 5 days (the marginal node *Rain*) is a major influence on all of these nodes, influencing the level of nutrient output from each nutrient source. In addition, for *Air* the *Number of previous dry days* (*i.e.*, the number of days in which there was no rainfall) in which aerosol concentrations can build will also determine levels of wet deposition with rainfall.

Quantification of Relationships

Nuisance outbreaks of *Lyngbya majuscula* have been reported in Deception Bay since 1996. Despite a significant research effort, however, the identification and broad consideration of factors that trigger bloom initiation, and their interactions, have only recently been considered. As a consequence of this, there are as yet few data to describe the relationship between variables at this early stage. An ongoing research programme is currently being undertaken on several fronts, and more data will become progressively available with time. Indeed, the BN modelling process has been integral to the strategic identification of critical but data poor areas, lending focus to the ongoing research effort.

The software in which the BN was constructed (Netica®) requires distributions to be discretised. The probabilities underlying marginal nodes, and relationships between nodes, were described using a combination of empirical data, simulation results and expert opinion (Table 1). A number of published and unpublished data sources were used to populate CPTs (see below for access to reports on data sources). Data for marginal nodes relating to environmental features (*e.g.*, *Rain, Number of Dry Days*) were available from sources such as the Bureau of Meteorology. Simulation results from a hydrodynamically driven numerical model of water quality in Moreton Bay, the Receiving Water Quality Model (RWQM) were used to populate CPTs for several nodes, including *Turbidity* and *Bottom Current Climate*. This model predicts flows and nutrient sediment loads coming off the Moreton Bay catchment area, being transported by waterways to Moreton Bay. Where no data or simulations were available, the opinions of the expert members of the group that constructed the BN were used to define the conditional relationships. These members have extensive experience in their respective fields, from both practical and theoretical perspectives, and thus formed an important source of knowledge for this project.

Although it is impractical to detail the inputs for all nodes here, three nodes will be used as exemplars. These three nodes were: *Rainfall, Land Run-off* and *Turbidity*. Priors for these nodes can be found in Figure 2. Note that the complete details of the model, including quantification of categories, sources of information for CPTs and inputs for nodes, will be included in a technical report as part of a series of reports to be prepared for the Moreton Bay Healthy Waterways Partnership. These will be available on request by contacting the Partnership once completed.

RESULTS

With no evidence entered, the probability of *Lyngbya* bloom initiation was 13%. One particular aspect of interest in this BN analysis is the sensitivity of the *Bloom Initiation* node to other variables (sensitivity to findings analysis) to determine which factors most strongly influence *Lyngbya* bloom initiation. In Netica®, this is determined by calculating an Entropy Reduction Value (ERV) (Pearl 1991), a means of showing how much one node affects another, with larger ERV values showing greater impact. The 5 nodes which strongly influence Bloom Initiation, together with ERVs, are reported in Table 2.

One way in which a BN can be used is to 'enter evidence' and generate scenarios that show the effect of interactions between the different nodes. Obviously a model with a substantial number of nodes such as the current model makes it prohibitively time consuming and unlikely to be useful to exhaustively compare all possible scenarios. Therefore, the BN was used to test the influence of a number of scenarios that empirical studies (Watkinson *et al.* 2005), dynamic systems models (Arquitt and Johnston 2003), and the opinion of the expert group highlighted as potentially important in promoting or preventing *Bloom initiation*. It is generally believed that algal blooms occur during times of high light intensity and high water temperature. Furthermore, it has been noted that blooms will often follow a period of high rainfall, with clear conditions afterwards. Water clarity is another element believed to be important in bloom initiation. In this particular region, it has been argued for some time that the availability of dissolved iron from freshwater inputs contribute to *Lyngbya* blooms in Deception Bay (Dennison *et al.* 1999; Albert *et al.* 200; Ahern *et al.* 2006).

<u>Scenario 1 - Temperature and Light climate</u>: With the current model, initiation would not occur if *Temperature* was set to low (water temperature below 24^{o} C), regardless of the values at any other nodes. If sufficient nutrients were available (*Available Nutrient Pool* set to 'enough'), high temperatures and suboptimal light increases probability of bloom initiation to 25%. When *Light Climate* is optimal, this rises to 100%.

Scenario 2 - Turbidity: The clarity of water has been highlighted as being important by a number of experts. The influence of *Turbidity* on *Bloom initiation* was determined by setting *Light Quality* and *Light Quantity* to high and adequate respectively, and setting the *Temperature* node to high in the presence of adequate nutrients. When *Turbidity* is low, the probability of initiation was 100%. When *Turbidity* is subsequently set to high, leaving all other nodes as described, the probability of initiation dropped to 85%.

Scenario 3 - Dissolve Iron Concentration and Organics: The role of *Dissolved Iron Concentration* was initially assessed by leaving other nodes unknown and changing this node from low (probability of initiation 8%) to high (probability of initiation 18 %). When *Light Climate* and *Temperature* were both set to maximum values, setting *Dissolved Iron* to low resulted in a probability of initiation of 25%. Conversely, the probability of initiation was 48% when this node was set to high. Appreciable differences to these probabilities were made when evidence was entered for the *Organics* node. When *Organics* were set to low (with high *Dissolved iron*, and high *Light* and high *Temperature*), the probability of initiation was 43%; when set to high, this rose to 51%. Indeed, increasing the level of *Organics* from low to high in the absence of any other evidence increased the probability of high *Dissolved Iron* from 31% to 59%

Scenario 4 - Rain: *Rain* was believed by a number of experts to be a major driver of bloom initiation, in that substantial rain increased the rate of nutrient inflow to the Bay from various sources. When all other nodes were unknown, low *Rainfall* gave rise to a probability of *Bloom initiation* of 11%, while high *Rainfall* only increased this to 16%. However, under conditions of high *Light* and high *Temperature* that are generally believed to promote bloom initiation in Deception Bay, the probability of initiation rose from 31% under low rainfall to 50% under high rainfall.

Scenario 5 - Contribution of Land Run Off and Point Sources: These are considered to be the major sources of nutrients added to Deception Bay. Their contribution was initially tested, as in other scenarios, by setting *Temperature* and *Light Climate* to maximum values. With both *Land Run Off* and *Point Sources* set to low, the probability of *Bloom initiation* was 26%. When both were set to high, this rose substantially to 49%. A further analysis was run, considering low levels of oxygen in the benthic environment (*Sediment Nutrient Climate* set to reducing) and low current (*Bottom Current Climate* set to low). Under these conditions, low *Land Run Off* and low

Point Sources give rise to a probability of *Bloom initiation* of 44%, while setting these nodes to high increased the probability to 69%. The relative contribution of these nodes to *Bloom initiation* is also interesting to examine. Under these conditions, setting *Land Run Off* to high and *Point Sources* to low gives a probability if initiation of 54%. Reversing this brings about a marginal change to 50%.

DISCUSSION

Using the scientific BN model to test scenarios has allowed different combinations of risk factors to be analysed using the most recent knowledge from the various scientific disciplines. Unsurprisingly given the biology of marine cyanophytes such as *Lyngbya*, these scenarios confirm the importance of warm water, a high light environment and sufficient nutrients in order for blooms to occur (Watkinson *et al.* 2005). More interesting in this analysis has been the effects and interactions among other nodes on *Bloom initiation*. Turbid water by definition decreases the penetrability of the water column to light, reducing the photosynthetic energy production of the organism that is necessary for growth. Thus turbid water severely reduces the probability of bloom initiation even when other conditions are ideal. Increasing the concentration of *Dissolved Iron* in the marine environment also has appreciable effects. Under high light and temperature conditions, increasing *Dissolved Iron* from low to high almost doubled the probability of bloom initiation. *Organics* also make a noticeable difference to initiation probabilities, probably playing a role in extending the bioavailability of dissolved iron. This is interesting in light of a previous *Lyngbya* bloom model (Arquitt and Jonstone 2003), that suggested the importance of complexed iron in the initiation of *Lyngbya* blooms. During clear and hot weather, rain also appears to be an important precursor to bloom initiation, increasing the probability of bloom formation by about 20%. From a modelling perspective this is particularly interesting given the number of linkages that separate the *Rain* and *Bloom Initiation* nodes.

Nodes that are closest to a node of interest (within one or two linkages) will typically have the greatest effect on that node, since the effects of more distant nodes are "filtered" through intermediate probability relationships that introduce more conditional uncertainty (Cain 2001). The minimum path between *Bloom Initiation* and *Rain* contains 4 intermediate nodes, suggesting that rain has major effects on nutrient input into Deception Bay. It should be noted at this point in the model's evolution that alternative key process pathways for the influence of rainfall and catchment inputs may exist, however. For example, here it has been assumed that immediate short-term rainfall plays a key role mainly through the supply of some waterborne nutrients, given that the catchment inputs actually reach the site of algal bloom formation. Conversely, rainfall may have a longer term influence by delivering a sediment and nutrient load that is deposited in the bay and only becomes available when conditions such as high temperature, light and low currents support dissolved nutrient evolution.

Land runoff and point sources are commonly held to be the major sources of nutrients entering most marine environments, including Deception Bay. Increasing these sources from low to high approximately doubled the probability of bloom initiation. Under otherwise ideal conditions for bloom initiation, increasing both of these nodes from low to high resulted in an almost 70% probability of bloom initiation. Interestingly, and contrary to the expectations of some experts, Land Run Off and Point sources contribute approximately equally to the effect under the current model. While this may be a reasonable conclusion, *a priori* it would be expected that land run off from the catchments surrounding Deception Bay would provide a larger source of nutrients than point sources from this moderately populated region. This suggests either that the particular nutrient mix that comes from Point sources has a relatively greater effect than those from Land run off, or that the available data and opinion used to populate one of both of these nodes is somewhat uncertain. In fact, it is a methodological challenge to accurately model the nutrient load into Deception

With this study, we have aimed to highlight the utility of BNs in incorporating diverse sources of information to analyse the risk of occurrence of a problem cyanophyte that has considerable adverse ecological, economic, and human health effects. There have been a number of benefits from this approach. First, it is a quantitative methodology, allowing a diverse range of factors to be integrated and their effects on *Lyngbya* bloom initiation to be refined. As a probabilistic method, uncertainty is inherently dealt with. As an iterative method, typical of Bayesian approaches, incorporating new information is easy and increases the power of the method to provide useful answers to a complex ecological question. This is an important point in the current research programme. The BN model has helped to define research priorities, and as new research comes to hand the model will be adapted to incorporate the new knowledge.

No less important than the quantitative aspects, however, has been the usefulness of the BN as a means of communicating between experts from a number of different fields. A typical problem with such groups is that a lack of common understanding and consensus surrounding concepts which are important to the problem – they often tend to speak different ‘languages’. Creating and refining this scientific BN has allowed conceptual misunderstandings between group members to be identified and resolved, allowing for increased communication and fostering the ability to examine the problem from different perspectives.

While this BN has been formulated for Deception Bay, *Lyngbya majuscula* outbreaks have been recorded in a number of locations throughout Queensland (Great Keppel Island, Shoalwater Bay, Hardy Reef and Hinchinbrook Island; Dennison *et al.* 1999, Albert *et al.* 2005, Arthur *et al.* 2005), and in other tropical and sub-tropical marine environments worldwide. It would be easy to adapt the structure of the current model for application to the problem domains, although the underlying relationships between variables may vary (*i.e.*, the CPTs may change) necessitating the inclusion of appropriate regional data. Nonetheless, as shown in this study, BNs present as a flexible and robust method to assess the risk factors and probability of outbreak of *Lyngbya majuscula*. This in turn will assist in identifying appropriate management actions to minimise the risk of such algal blooms.

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Table 1. List of nodes for the Lyngbya bloom initiation BN, and the information used to populate CPTs (conditional probability tables). Information types are A. Data B.Expert Opinion and C. Simulation results (information sources in parentheses; BOM, Bureau of Meterology; RWQM, Receiving Water Quality Model).

Node	Definition	Information Type (source)
Rain	Daiy volume of rain falling in the catchment area	A (BOM)
Number of Dry Days	Number of days (cumulative) where rainfall is <5mm anywhere within the catchment	A (BOM)
Ground Water	The nutrients supplied by underground water sources	A (*)
Air	Nutrient load from aeolian sources that are, after a dry period, brought down from the atmosphere by the rain and deposited	B
Point Sources	Discharge of nutrients from sources which can be pinpointed (*e.g.*, Waste Water Treatment Plants, urban stormwater drains)	B
Land Run Off	The overland flow of water bearing nutrients both into waterways and directly into Deception Bay	C (RWQM)
Dissolved Organics	the carbon incorporated in organic matter from natural sources	B
Dissolved Iron	Bioavailable iron in the water column	B
Dissolved Phosphorus	Bioavailable phosphorous in the water column	B
Dissolved Nitrogen	the total amount of dissolved nitrogen in the water column	B
Turbidity	a measurement of the amount of light scattered by particle matter in the water column	C (RWQM)
Bottom Current Climate	The velocity of the movement of the water column immediately above the bentho	C (RWQM)
Particulate Matter	Nutrients (nitrogen and phosphorus) attached to particulate matter and remaining in suspension in the water column	B
Sediment Nutrient Climate	the relative state of the sediments associated with the supply of nutrients and trace elements to the adjacent alga (measured as redox state)	B
Wind Speed	The rate at which the wind travels over the surface of the water	C (RWQM)
Wind Direction	The measured course of the wind, relative to the compass	C (RWQM)
Tide	The periodic variation in the surface	A (RWQM)

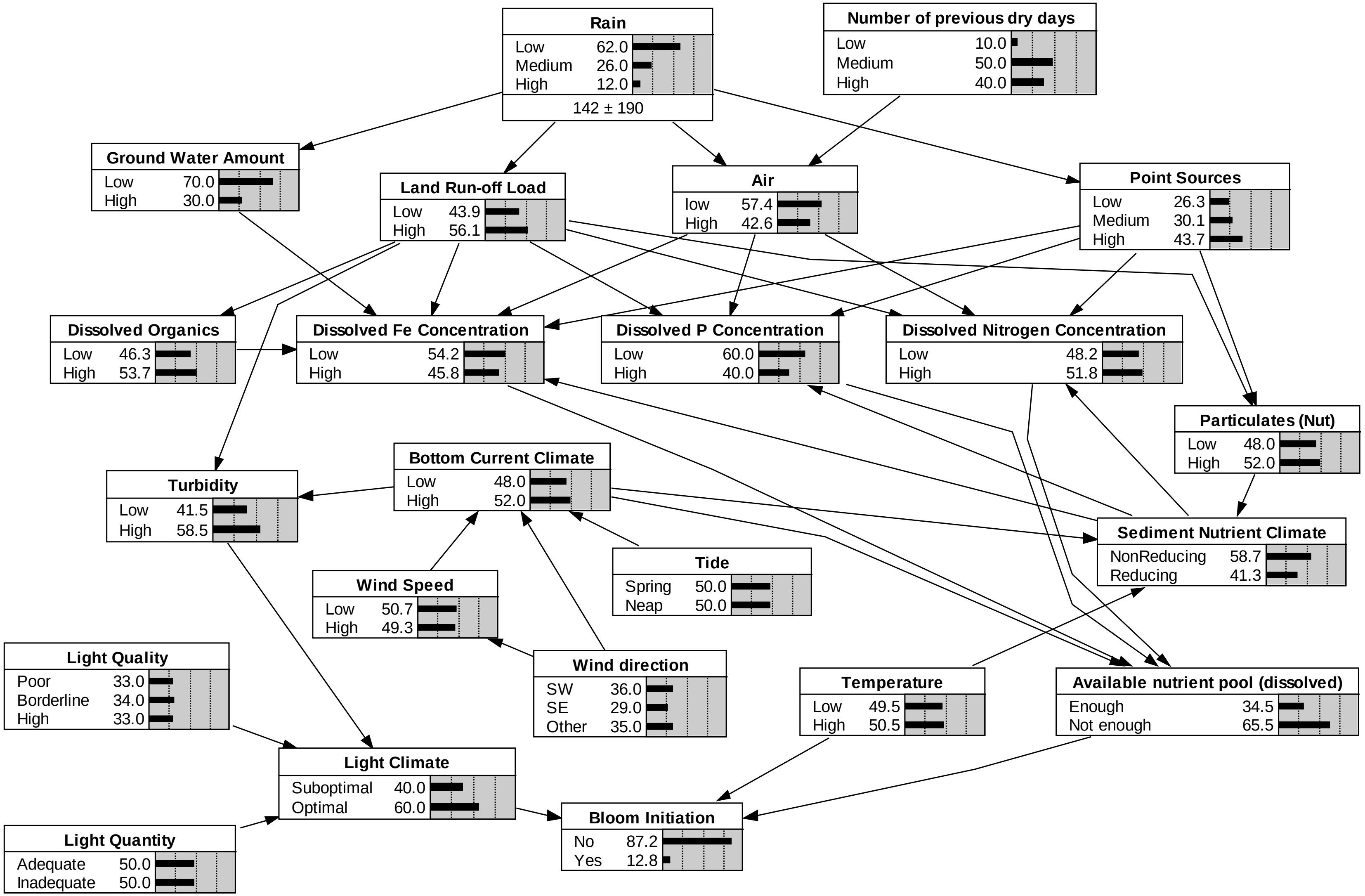
	level of the oceans caused by gravitational attraction of the moon and sun	
Light Quantity	The total available light (photosynthetically active radiation) as measured at sediment surface	B
Light Quality	The spectral composition of the light	B
Light Climate	The amount and quality of natural sunlight that penetrates to the benthic surface	A (Watkinson *et. al* 2005)
Temperature	The temperature of the water column (average daily temperature)	A (BOM; Watkinson *et. al* 2005)
Available Nutrient Pool	the sum total of all nutrients necessary for, and available to, the growth of *Lyngbya*	B
Bloom Initiation	The early phase of algal bloom growth	B

*Note that some CPTs have been in part informed by unpublished studies. However, the details of data sources for all CPTs will be available, once completed, from the Healthy Waterways Partnership.

Table 2. Sensitivity to findings analysis. The top 5 ranked variables that influence the *Bloom Initiation* node. Entropy reduction values (ERV) provide a means of evaluating the sensitivity of each node.

Node	**ERV**
Available Nutrient Pool	0.22
Temperature	0.14
Sediment Nutrient Climate	0.05
Bottom Current Climate	0.034
Light	0.033

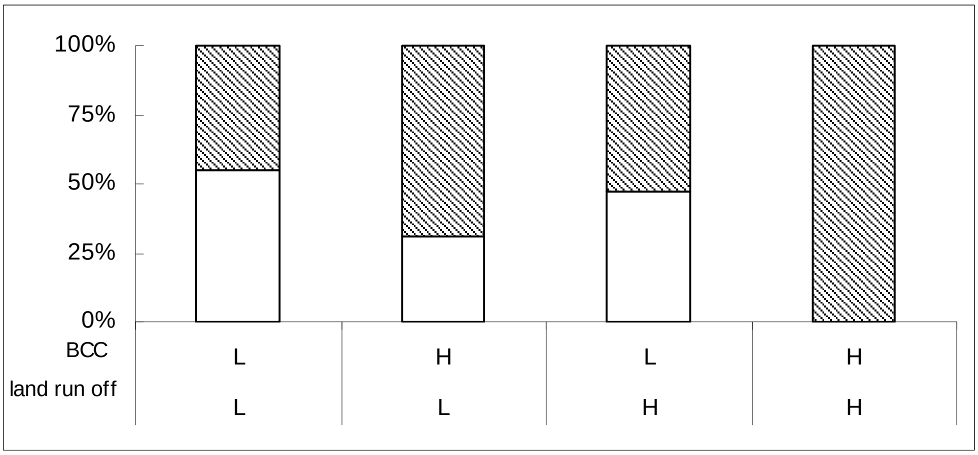
Figure 1. Complete Bayesian net for bloom initiation of *Lyngbya majuscula*.


Rain
Low 62.0
Medium 26.0
High 12.0
142 ± 190
Number of previous dry days
Low 10.0
Medium 50.0
High 40.0
Ground Water Amount
Low 70.0
High 30.0
Land Run-off Load
Low 43.9
High 56.1
Air
low 57.4
High 42.6
Point Sources
Low 26.3
Medium 30.1
High 43.7
Dissolved Organics
Low 46.3
High 53.7
Dissolved Fe Concentration
Low 54.2
High 45.8
Dissolved P Concentration
Low 60.0
High 40.0
Dissolved Nitrogen Concentration
Low 48.2
High 51.8
Particulates (Nut)
Low 48.0
High 52.0
Bottom Current Climate
Low 48.0
High 52.0
Turbidity
Low 41.5
High 58.5
Sediment Nutrient Climate
NonReducing 58.7
Reducing 41.3
Tide
Spring 50.0
Neap 50.0
Wind Speed
Low 50.7
High 49.3
Light Quality
Poor 33.0
Borderline 34.0
High 33.0
Wind direction
SW 36.0
SE 29.0
Other 35.0
Temperature
Low 49.5
High 50.5
Available nutrient pool (dissolved)
Enough 34.5
Not enough 65.5
Light Climate
Suboptimal 40.0
Optimal 60.0
Bloom Initiation
No 87.2
Yes 12.8
Light Quantity
Adequate 50.0
Inadequate 50.0

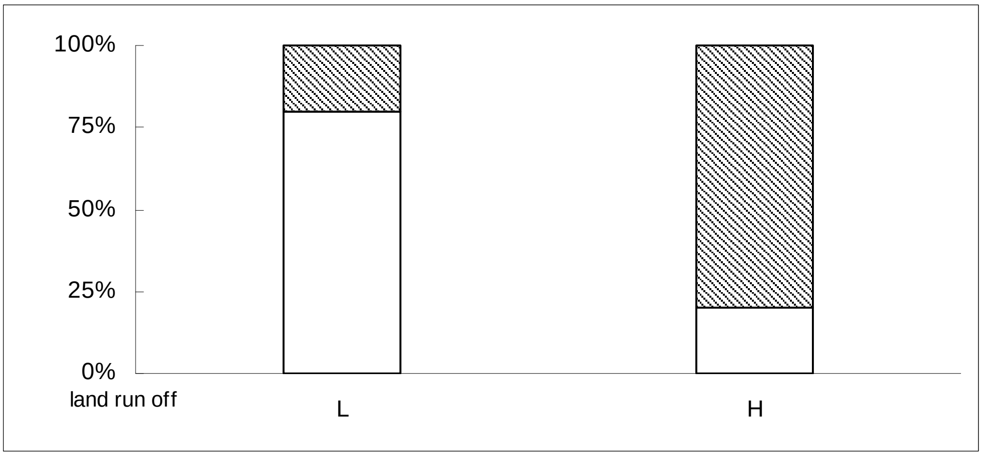
1

Figure 2. Node priors for a) Turbidity b) Particulates and c) Dissolved Organics. Each column shows the probability of a node being in a high or low state g en the states of the parent(s). Parent states are labelled L (Low) or H (High) below each column (BCC- Bottom Current Climate).

2a) Turbidity.



b) Dissolved Organics



c) Particulates