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An ecological risk assessment for managing and predicting trophic shifts in estuarine ecosystems using a Bayesian network

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ABSTRACT

Estuaries are dynamic systems at the transition between freshwater and marine ecosystems. In this study, a spatially and temporally explicit Bayesian network (BN) was developed for a tidally connected estuary in southeastern Australia. The BN provides an environmental risk assessment (ERA) for the probability of a shift to a eutrophied state based on markers of pelagic and benthic primary production. The model was created to provide an initial framework of system knowledge based on empirical data, with the intention that the model and its linkages be iteratively developed as more information becomes available. The BN was investigated for its potential to predict trophic shifts and provide a framework for evidence-based decision making. Model assessment was conducted through both sensitivity analysis and scenario tests. Through evaluation and updating, the BN can provide information on the key nutrients and bio-physical mechanisms regulating changes in trophic state in estuarine ecosystems.

1. Introduction

Estuaries are dynamic ecosystems at the interface of freshwater and marine systems and are often characterised by high rates of primary production (Mortazavi et al., 2012). Shifts to a eutrophied trophic state within aquatic ecosystems occur when increased nutrient availability stimulates rates of primary production. Nutrient enrichment leading to a shift to a eutrophied state is one of the main stressors effecting aquatic ecosystem processes and poses a risk to the sustainability of aquatic resources (Altman and Paerl, 2012; Turner and Rabalais, 2003). A eutrophied trophic state can ultimately produce hypoxic conditions, which may lead to both a decrease in biodiversity and the capacity of the system to support or generate ecosystem services (Fox et al., 2012). Managing the sources and bioavailability of macro-nutrients and identifying the biophysical and chemical drivers of shifts in trophic state are essential to regulating primary productivity in aquatic ecosystems (Domingues et al., 2011).

In the past substantial scientific effort has been invested in improving and attempting to quantify thresholds for trophic shifts in multi-state ecosystems (Scheffer, 1989; Beisner et al., 2003; Smith and Schindler, 2009; Wang et al., 2012). However, the failure to explicitly quantify thresholds in addition to the lack of robust diagnostic indicators and tools for predicting shifts among trophic states is a limitation to the effective management of eutrophication (Renjith et al., 2013). A difficulty in quantifying trophic shifts arises from the existence of alternate states where one or more stressor can exceed a critical threshold of resilience. When this occurs, a cascade of multiple threshold exceedances can emerge where the ecosystem remains in the new state even after the initial stressor is reduced or removed (Downing et al., 2012). Restoring these ecosystems to the previous state can be expensive and difficult due to the trophic cascade requiring another critical shift to initiate a change in state. The transition between trophic states can occur frequently without detection by monitoring programs if a critical threshold is not detected or natural ecosystem variability masks the quantification of thresholds for trophic shifts (Renjith et al., 2013). Consequently, the use of long-term empirical data in a framework that integrates physical, chemical and biological factors, and incorporates the ability to assess spatial and temporal variability is required to investigate thresholds for trophic shifts and their underlying mechanisms in aquatic ecosystems (Rigosi et al., 2014).

Bayesian networks (BNs) are an increasingly common method for modelling ecological risk in circumstances of uncertainty, non-linear relationships, a combination of qualitative and quantitative information availability, and multiple ecosystem variables (Schmitt and Brugere, 2013). The BN approach is a useful method for

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predicting, assessing and characterizing environmental stressors (Liu et al., 2013), and can be developed using an ecological risk assessment (ERA) framework that defines the risk of change in complex systems (in this case, eutrophication and trophic shifts in an estuarine ecosystem). A BN approach incorporates an explicit causal structure that indicates conditional dependencies between child variables (with incoming conditional dependencies denoted by arrows) and unconditional dependencies for parent variables in the network (further information on BN configuration and causal structure is published in McDonald et al., 2015). A BN created using an ERA framework is intended to be repeatedly assessed and adapted as more information becomes available (Stewart-Koster et al., 2010). The development of such a BN also guides the collection of further data to refine system linkages and conditional probabilities, equations or constants within each node configuration. Variables in the network have a number of user allocated/defined states with conditional probability tables (CPTs) populated from the available data; the relationships between variables define the structure of the BBN (Tighe et al., 2013). Sensitivity analyses of model outcomes can be used to identify the chemical or biophysical variables that have the strongest influence over predicted probabilities (Ayre et al., 2014). The development of ERAs that apply BNs can be used to provide an informed framework for management decision making (McDonald et al., 2015). The conceptual diagram of complex interactions between ecosystem variables provided by the network structure of BNs can assist in the communication of quantitative models among scientists, managers and the broader community. This in turn can improve the integration of probabilistic modelling and scientific practice into adaptive management processes that seek to better understand the spatially and temporally variable interactions between the drivers of trophic shifts in aquatic ecosystems (Smith et al., 2012).

The application of BNs that integrate numerous interacting variables that regulating primary production is being increasingly used to investigate and predict eutrophication in estuarine ecosystems (Borrett et al., 2014). However, previously developed BNs (Borsuk et al., 2003, 2004; Hamilton et al., 2007) for predicting eutrophication within estuarine and coastal ecosystems commonly lack integration of the spatial and temporal variability of the biophysical and chemical drivers (e.g., geomorphology, nutrient availability and flow rate) regulating shifts to a eutrophied state (Nojavan et al., 2014). Given the current knowledge gaps inherent in eutrophication models, an approach such as a BN that explicitly incorporates a spatial and temporal framework and quantifies uncertainty in both the predicted probabilities derived from the *a priori* data and the lack of knowledge of a perfectly accurate outcome is potentially of great use to scientists and managers (Pang and Sun, 2013; Alameddine et al., 2013). Furthermore, a best-practice BN framework that incorporates multiple spatial and temporal scales within an ERA approach could applied by end-users to investigate the complex interactions in the mechanisms regulating estuarine eutrophication at scales relevant for efficient management of these dynamic systems.

In this study, we present a BN that incorporates complex physical, chemical and biological ecosystem attributes into operationally discretised variables that provide an ERA assessment of current understanding of the system based on the available data. The approach is aimed at simplifying the quantification of processes that influence tropic shifts into probabilities that incorporate the spatial and temporal complexity of the system. The spatially and temporally explicit BN framework presented in this study is an initial run for a model that, with continued development and evaluation, could provide probabilistic predictions on scales relevant to managers and scientists. The model links sources of available knowledge and system-specific empirical evidence to facilitate exploration of complex biogeochemical interactions, with a focus on further understanding the system drivers of trophic shifts. Scenario tests are conducted as examples to assess the potential for the BN framework to be applied by scientists and managers to investigate of the drivers of trophic shifts and predict the probabilistic occurrence of a shift in trophic state. The BN provides both probabilistic reasoning of interactions between variables and the quantification of uncertainty to aid informed decision making (Haines-Young, 2011; Stow et al., 2011; Smith et al., 2012). This approach incorporates the principles of best-practice ERAs (McDonald et al., 2015) that includes the iterative development, assessment and adaptation of the model in the future as new information becomes available. In this way, the integration of science into management decision making is improved and the application of such models by scientists and managers to test scenarios and investigate ecosystem responses under user-defined environmental conditions is facilitated, promoting adaptive management.

2. Methods

2.1. Study area

The study was conducted in the estuary of the Camden Haven (31.64°S, 152.84°E) catchment on the north coast of New South Wales (NSW), in south eastern Australia (Fig. 1). The Camden Haven catchment covers an area of 589 km^2 and the river spans a length of 40 km (New South Wales Department of Environment and Heritage, 2014). The mean annual rainfall in the catchment is 1543 mm. The estuary has an area of 32 km^2 with a volume of 113 802 ML (New South Wales Department of Environment and Heritage, 2014). The mean tidal range in the estuary is 1.2 m. The Camden Haven estuary has important recreational values and supports crustacean (24 t/year) and oyster (155 t/year) industries (New South Wales Department of Environment and Heritage, 2014; Northern Rivers Catchment Management Authority, 2012).

The estuary of the Camden Haven River exhibits the typical geomorphic features of an immature estuarine system including a large central basin (comprising over 60% estuarine area) (Kennish and Paerl, 2010). The estuary has three shallow, open tidal lagoon systems located along the main channel of the Camden Haven estuary: Gogley's Lagoon, Queens Lake and Watson Taylors Lagoon (Fig. 1). The historical clearing of native riparian and mangrove corridors, drainage of wetland areas for agriculture and urbanization exposing acid sulfate soils, drainage of treated effluent from the wastewater treatment plant (upstream of Watson Taylors Lagoon) and altered water quality from urban and agricultural runoff have all impacted the estuary. The upper estuary (upstream of Watson Taylors Lagoon) is characterised by persistent anoxic benthic conditions and high concentrations of nutrients and chlorophyll *a* consistently exceeding the *Australian Water Quality Guidelines for Fresh and Marine Waters* for total nitrogen and phosphorus (ARMCANZ/ANZECC, 2000) (Ryder et al., 2012). However, water column chlorophyll *a* regularly exceeded the *Australian Water Quality Guidelines for Fresh and Marine Waters* (ARMCANZ/ANZECC, 2000) in the upper estuary but rarely in the lower estuary and lagoons (Ryder et al., 2012).

Generally, the Camden Haven estuary is an oligotrophic to mesotrophic (low to moderate nutrient concentrations and primary production (Bass et al., 2010; Chen and Taylor, 2011)) with low algal biomass dominated by Chlorophyta or Bacilliophyta algal communities (Ryder et al., 2012). Consequently, a spatial and temporally explicit framework can assist in predicting shifts as the physical and chemical characteristics of the catchment change in the future.