Using a Bayesian Belief Network to Integrate Ecology, Economics and Social Sciences to Improve Policy Making: a Literature Review

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Introduction

"We need a new economic paradigm that recognizes the parity between the three pillars of sustainable development. Social, economic and environmental well-being are indivisible. Together they define gross global happiness."(Ban 2012)

Humans live in close relationship to the environment, which they directly and indirectly use and depend on for food resources, building materials, protection, relaxation, to mention but a few examples. Recent years have seen depletion of the health of many natural environments leading to a stronger focus on natural resource based management approaches. While in earlier decades management was driven by either purely ecological conservation or economic goals, more recently there is a greater awareness of the need to integrate ecological, social and economic factors into management decision-making (Gjertsen 2005; Ban, Adams et al. 2011). Related to this is an increasing body of research investigating how and to what degree social-wellbeing (or human-wellbeing) and ecosystem-health is related and how these should be considered in natural resource management. As yet, though, identifying a reliable mechanism to incorporate these three elements simultaneously into natural resource management and policy formation has proved difficult. The development of such a mechanism was the challenge undertaken in the Valuing Nature Network (VNN) Project **"***Interdisciplinary methods to build a socio-ecological decision-making tool to inform marine governance and policy*"[1]. This paper reviews available literature for the modelling framework adopted in that project - Bayesian Belief Networks (BBNs). We begin with an overview of ecosystem based management in the context of coastal environments and then consider decision support tools in general before focussing on the strengths and limitations of BBNs in particular.

Ecosystem based management and its application to coastal environments

Ecosystem functions have numerous and highly diverse implications on human communities. Measuring these functions in an integrated way remains a challenge. A broad range of literature focuses on the high level of dependence of people in developing countries on the environment they

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live in for food and basic livelihoods, along with various implications for their social and cultural life; e.g. fishing (and in particular small scale) is perceived by many as a way of life and “invokes a strong sense of social identity and [...] establishes a sense of being in the world” (Coulthard, Johnson et al. 2011) . The ecosystem provides water, food, fuels, timber, climate regulation and protection from erosion, floods, storms and waves among others (Millennium Ecosystem Assessment (2005)).

Various researchers (Leisher et al. (Leisher, Mangubhai et al. 2012), Ban et al. (Ban, Adams et al. 2011) and Gjertsen (Gjertsen 2005) have tried to find direct links between how the social environment (i.e. governments, social networks, education and so forth) and infrastructure impacts and dictates success or failure of conservation strategies. To illustrate, Ban et al (Ban, Adams et al. 2011) discuss advantages and disadvantages of bottom-up, i.e. often opportunistic, community based, versus top-down, i.e. systematic planning at regional or national scale, conservation and review major unresolved issues. They focus on the differences in spatial scale of marine conservation, from local (e.g. Marine Protected Areas (MPAs) of $1km^2$) to regional, relatively large approaches (e.g. MPAs of 10km diameter). Local and regional approaches often have different foci and involve different stakeholders (local communities versus representatives of industries, different aspects of governance and representatives of communities. Ban et al (2011) show that data available at the local level often reflects local values (such as cultural sites), threats and socio-economic considerations while on the regional level data often covers whole regions at the cost of coarse resolution. The objectives and applied actions also differ largely between local and regional management; local management focuses on the household and community level (social well-being, livelihood, etc) and communities implement and enforce the management actions, while on the regional level objective focus on regional concerns of governments or NGOs, such as fisheries and biodiversity and management actions hence require large scale-enforcement.

Ban et al (2011) further discuss the combination of local, bottom-up, approaches with regional, top-down, approaches on marine management and highlight one specific example of integration from Fiji. They suggest that a successful MPA approach lies in “finding the synergies between regional and local scale objectives, and to implement MPAs in an iterative process, with progressive adjustment of regional designs and local actions, informed by both perspectives.” Ban et al (Ban, Adams et al. 2011), suggest the incorporation of decision support tools to assist systematic conservation planning if tailored to the specific region without implying that the computers modelling or data are superior to people’s knowledge. In this light a Bayesian Network (BN), as constructed as a pilot in our VNN approach, appears to have the potential to be a powerful tool to aid regional and local conservation planning.

Many developing countries have fishery-dependent communities relying on marine and freshwater fisheries for food security and employment. Previous studies have tried to establish links between fisheries and impacts on local communities, e.g. Nunan (Nunan 2010) focuses on movement of fisher-folk following their target species in Lake Victoria and social implications on landing sites, while Gjertsen (Gjertsen 2005) fails to establish a direct link between marine protected areas (MPA) and human nutrition in the Philippines.

Developing nations show evidence of a stronger focus on social well-being and communities. This is particularly the case in relation to the fisheries sector. To demonstrate, Symes and Phillipson (Symes and Phillipson 2009) discuss a “displacement of social objectives which were subsumed under goals of economic growth and wealth creation and a belief that the benefits would inevitably trickle down to enrich the whole community" in the developed world, such as in small fishing communities in Ireland and Scotland, and compare this to more social-wellbeing approaches in the developing world. This is strengthened by Urquhart et al (Urquhart, Acott et al. 2011) who acknowledge the of social science in developing Fisheries Policy in the EU and other developed areas, and partly attribute this small impact to the small amount of qualitative research into the field, and the ontological conflict between social sciences and Economy/Ecology. Urquhart hypothesises that both disciplines, Ecology and Economy, are based on quantitative methods, large-scale modelling and system approaches while social sciences needs a different set of approaches due to the fact that social life can hardly be seen as a "set of systems" (Urquhart, Acott et al. 2011). Urquhart also mentions the lack of journal articles and research programs in Europe that focus on larger fishing communities. Ross (Ross 2012) showed strong social dependency on fishing in small fishing communities in Scotland extending far beyond employment and personal income. The community involved in the fishery see themselves as part of a "chain" or social network, where everybody heavily depends on their relations with other members of the same network. The loss of a large part of the fishing fleet had great implications on the whole community; while on the one side it is seen as difficult to find alternative employment for the people employed in the fishing industry, with every vessel that was decommissioned over the last few years local businesses lose customers, which in the investigated town led to businesses not accepting new apprentices and a decline of employment possibilities for young local people. There was also evidence of a shift in attitude of the local fishing community to more egotistical decisions being more made rather than ones benefiting the community as a whole.

Ross (2012) also focuses on the emotional aspect of the fishery, the changing sense of independence, freedom and strong community feeling, due to shared work in highly demanding environments, fears and hardships. In another article (Britton and Coulthard 2012) Britton and Coulthard elucidate the '3D' wellbeing (subjective, material and relational) for Northern Ireland (NI) fisheries and highlight the significant impact that EU policy has on the well-being of NI fisheries, the "disconnectedness" between them and the need to create meaningful communication between and within policy, science and the fishing communities. Emphasis is placed on the major role fisheries play as a safety net in economic hard times, e.g. young people returning to fishing in recent years, similar to the small scale fisheries in developing countries. Alternative income generation is seen as an important aspect of successful conservation projects, both in developing countries (Ban, Adams et al. 2011; Olale and Henson 2012) as well as in developed ones, however often this is not a straight forward solution as fishers, and people involved in the fishing industry, often have a strong attachment to their occupation which goes far beyond material benefits (Coulthard, Johnson et al. 2011; Ross 2012).

Decision support tools

With increasing awareness and an increasing body of literature on sustainable use of ecosystems, services provided and social implications of management strategies, methods that can deal with complex datasets are needed to help decision-makers analyse their effects and consider these prior to developing related policies. Decision support tools should, ideally, be transparent, have the ability to incorporate different types of data, such as qualitative and quantitative data, be able to combine models from different disciplines involved, be able to deal with incomplete and non-normal data which is often the case for ecological or social science data. Furthermore, it is important that local communities get the chance to be involved in the decision-making modelling process from an early stage so that they will be able to take ownership and/or relate to the recommendations (Kragt 2009; Ban, Adams et al. 2011). Traditional statistical methods, such as basic regression models, have been applied to evaluate the impact of marine management decisions (MPAs) on child health or the impact of factors such as alternative income on success of those management measures (Gjertsen 2005). However, these methods are restricted in the way that they perform and depend on quantitative data which is often poor. Lynam et al (Lynam, DeDong et al. 2007) compared a number of tools for incorporating community knowledge, social values, and preferences into resource management, such as Bayesian Belief Networks, Discourse –based valuation, 4Rs frameworks, Venn diagrams, Participatory mapping amongst others. While all tools have their strength and weaknesses they suggest that facilitators choose the tool best suited to the task. They also advise on a “mix and match” approach of methods to increase robustness and reach the envisaged result. Given the specific aims and objectives of the VNN project - to develop a visual, *ex ante* based decision tool - we identified BBNs as the most appropriate for our needs. Thus, in the following section a number of publications using BBNs will be explored.

Uses of BBN

Bayesian Belief Networks (BBN, also known as Bayesian Networks, BN) are graphical models that represent a set of variables connected by directed, acyclic graphs which can be used to explore and display causal relationships between factors based on Bayesian principles. They have the ability to incorporate, model and combine different types and sources of data, such as quantitative data, expert or local knowledge and outputs from other models, and are capable of dealing with missing or incomplete data and are hence particularly useful in areas such Ecology or Social Science. While they can provide modelling solutions in a number of disciplines their graphic representation also makes them a powerful tool in knowledge representation and communication, since they display final outcomes of a system in a straightforward manner (Kragt 2009; Pollino and Henderson 2010; Korb and Nicholson 2011). BBNs have been widely described in literature, and for further introductory reading please refer to (Jensen and Nielsen 2007; Kragt 2009; Pollino and Henderson 2010; Korb and Nicholson 2011).

A large variety of BBN applications can be found in a growing number of disciplines. Successful ecological applications can be seen in species distribution and response to habitat (Marcot 2006), evaluation of wildlife and native fish populations (Marcot, Holthausen et al. 2001; Pollino, Woodberry et al. 2007), and in conservation planning (Marcot, Hohenlohe et al. 2006; Steventon 2008). On the other hand BBNs have been applied to landscape management (Bacon, Cain et al. 2002; Ticehurst, Curtis et al. 2011). Goudie et al. used BBNs to explore relationships between variables in large social science surveys (Goudie, Mukherjee et al. 2011) while Whitney and Walsh applied a BBN to represent and analyze political radicalization mechanisms (Whitney and Walsh 2010). Little et al used BBNs to analyze information flow between fishing vessels in Australia (Little, Kiukka et al. 2004) and Daniel et al presented a BBN which uses social capital theory to address critical issues in intercultural collaboration learning (Daniel, McCalla et al. 2007).

Combined Ecology, Economy and Social Sciences

With growing demand for integrative modelling, incorporating Physical Sciences, Social Sciences and Economics, Bayesian Networks approaches provide an alternative to expert systems, coupled component models, meta-models etc. (Ticehurst, Letcher et al. 2008; Pollino and Henderson 2010). BBNs, with their visual advantages and flexibility with data types, can play a central role in combining knowledge across disciplines and providing an interface between specialists and non-specialists. Some BBN studies focus on the incorporation of stakeholder opinion into management: Salerno et al (Salerno, Cuccillato et al. 2010) successfully use a BBN as a framework in the management of mountainous protected areas and use hard and soft participatory approaches. They devised a 5-module framework where all participants are involved in the first two modules (system bounding and qualitative model, including conceptual models and formal conceptual models) while the third module focuses on domain experts (data requirements, gap analysis, ...), the fourth module, the quantitative model, depends on the core team and the final module represented different scenarios. They emphasize that the need for iterative process and the importance of communication.

Haapasaari et al (Haapasaari and Karjalainen 2010; Levontin, Kulmala et al. 2011; Haapasaari, Kulmala et al. 2012) demonstrated how a BBN was used in combining Biology, Economics and Social Sciences in Fisheries research; they focus strongly on the interdisciplinary processes and the difficulties and advantages arising from it. They conclude that “Learning between the disciplines meant acknowledging and analysing the disciplinary differences, and searching for a common territory and a common language to enable the understanding of each other’s role in relation to the problem as well as searching for bridges to integrate knowledge.” They found BBNs a successful bridge between the three conceptually different disciplines Ecology, Economy and Social Sciences.

While in most countries BBNs have not been explored as, and actively incorporated in, the decision making process, there have been advances in the use of BBNs as decision support tools within all levels of the Australian government in the last decade (Merritt, Ticehurst et al. 2010).

Merrit et al (Merritt, Ticehurst et al. 2010) show two approaches applying BBNs as a tool in decision-making support for water managers and management of native vegetation. Neither of the models is intended for day-to-day use but for the use of planning over annual to decadal time spans. The models help policy makers in decision making by scenario modelling and exploration of the sensitivity of the model responses. The authors also discuss the criticism of their models that they could be very specific and argue that, while being true, there is a compromise between generality of design and modelling approach and the need for an approach tailored to the users (Merritt, Ticehurst et al. 2010). In a later feasibility study Ticehurst et al (Ticehurst, Curtis et al. 2009; Ticehurst, Curtis et al. 2011) compare conventional methods of analysing social data such as social-psychological models, theory of planned behaviour, cognitive hierarchy theory and value-belief-norm theory with BBN approaches. They summarize that BBNs and social-psychology models use conceptual models of relationships and processes that affect outcome variables. The advantages of BBNs are that a wide range of variables can be represented whereas in social-psychology models relationships parameters such as environmental or economical factors need to be established using regression modelling or other statistics. Ticehurst et al (Ticehurst, Curtis et al. 2009; Ticehurst, Curtis et al. 2011) explore the use of conventional methods and BBNs in a case study and conclude that BBN analysis was useful in exploring causality and was particularly helpful to the social scientist researcher to explore interactions between variables and to investigate the relative influence of variables on the final outcome. BBN also provided a platform to increase understanding between social-scientists, non-social scientists and interested stakeholders. Once a BBN was developed it provided a helpful tool for structuring, clarifying and communicating the results to stakeholders and policy makers in a way beyond what would have been possible with traditional analyses. However it was highlighted that, with limited resources, a combined approach of conventional and BBN methods can fast-track and guide the BBN process (Ticehurst, Curtis et al. 2011).

A special case of BNs, often used in Agricultural- and Ecological- Economics, are Decision Support Networks, sometimes also called Bayesian Decision Networks (BDN)(Ticehurst, Letcher et al. 2008). Decision support networks are similar to a BBN with added features such as ‘decision’ (scenario choices) and ‘utility’ (expected monetary values) nodes. They are designed to test the “monetary value” outcome between different scenarios or decisions.

There is a wide range of applications for decision support networks, with Bacon et al (Bacon, Cain et al. 2002) first investigating a possible land-use change amongst Welsh farmers based on their current land-use, costs of setup and possible incentives/ subsidies to change land-use. Bryan and Garrod (Bryan and Garrod 2006) employed a BBN as an Ecological Risk assessment framework which incorporated information on erosion, biodiversity, human health and financial risk as well as the marginal cost to calculate cost effectiveness of each proposal bid for a fencing auction. Ticehurst et al (Ticehurst, Letcher et al. 2008) used a BDN for coastal lake assessment and management and created an interactive tool for decision makers to study scenarios. Their software package included information on the facts and backgrounds as well as maps of the area. Interested people could than choose an area and set different scenarios. Their network was populated by data analysis, model simulation, assumptions from peer reviewed literature and expert opinion. Their test of the BDN as a decision support tool was a workshop and training on the software with policy makers and feedback was generally positive, however key questions were not able to be answered, as to how much detail and certainty would be required to make someone make a decision using the tool.

Disadvantages and Limitations

Frequent limitations of BBNs stated by authors are the lack of feedback loops (Kumar, Holzkaemper et al. 2008; Ticehurst, Curtis et al. 2011) and temporal dynamics. This can be a significant disadvantage for ecological and social-wellbeing applications, as both are complex systems which are dynamic and unpredictable across space and time (Moore, Wallington et al. 2009). Kumar et al (2008), Pollino and Henderson (2010) and Korb and Nicholson (2004) among others propose a Dynamic Bayesian Network (DBN) to address the problem. This approach deals with contiguous time slice models based on the Markov assumption that the current state of the model depends on its previous state and incidents happening in its current state. Currently a number of alternative solutions to the feedback loops and dynamic models are being explored, but research is still in its early stages (Kumar, Holzkaemper et al. 2008). Another aspect is, although not a pure BBN issue, that poorly defined states and variables may mask the impact of a particular scenario or input condition and poorly structured networks will not be able to provide an insight into the issues of concern (Ticehurst, Curtis et al. 2011). It is also important to acknowledge that BBNs and BDNs, like all models, are a simplification of reality (Ticehurst, Letcher et al. 2008). It is essential to find the balance between detail and complexity to represent a system. While too few variables and states will make it difficult to extract accurate information and the amount of information and assumptions contained in one link will become too complex. Too many variables on the other hand may lack in information to describe each link in detail (Ticehurst, Letcher et al. 2008). Additionally the amount of data required to populate BBNs grows exponentially with the number of parent nodes (as well as the number of states and states of the parent node). The number of probabilities to be filled in equals the number of states in the child node multiplied by the number of states of each parent nodes. A child with three states and three parents (three states each) has $3*3*3*3=3^4= 81$ probabilities, while the same child node with four parents (three states each) has $3*3*3*3*3=3^5= 243$ probabilities; a child with two states and three parents (two with 3 states, one with two states) has 2*3*3*2=34 probabilities. In the absence of empirical data, causal relationships can be specified based on “expert opinion” however it has to be remembered that the sheer volume of questions to be answered (and probabilities to be filled in) will pose a considerable cognitive barrier for the expert if a given node has a large number of parent nodes (Kumar, Holzkaemper et al. 2008). It is therefore advised to limit the number of parent nodes to three and choose appropriate and practicable numbers of states.

Summary

Ecosystem based management and integrative modelling provide major challenges for future policy making and resource management. To date policy and decision makers have no reliable tools to incorporate social wellbeing, ecology and economy (pers. comm. Marine Management Organisation), and data is not readily available. We provide a summary of the few projects exploring the use of Bayesian approaches in policy making / management which include at least two of the elements to be addressed in the current VNN project and note that a significant gap exists in current knowledge and research (Table 1). Earlier studies focussed on developing models only for a single sector. But the existence of such studies suggests their potential and, further, of particular relevance to our project, they have proved suitable for use in a marine context.

In summary, BBNs provide a framework to visualize interactions between variables and a vehicle to communicate between scientists, stakeholders and decision makers. It also functions as a tool to encourage inter-disciplinary research and has the ability to identify data requirements. While the range of applications and possible uses is wide, a BN has to reflect the needs of the stakeholders and end-users or is useful in answering a particular question- there is no point in creating a BN if it is not useful (Ticehurst, Letcher et al. 2008).

Table 1: Policymaking and Resource Management BBN Studies in the Literature

Reference	Ecology/ Landscape	Economy	Socio-economics	Social Wellbeing	Marine Focus	comments
(Bryan and Garrod 2006)	x	x				
(Haines-Young 2011)	x	x	x			
(Kumar, Holzkaemper et al. 2008)	x				x	
(Haapasaari and Karjalainen 2010; Levontin, Kulmala et al. 2011; Haapasaari, Kulmala et al. 2012)	x	x	x		x	
(Merritt, Ticehurst et al. 2010)	x	x				
(Newton, Marshall et al. 2006)	x	x	x	x		
(Salerno, Cuccillato et al. 2010)	x	x	x	x		No BBN, just cognitive map
(Stelzenmüller, Lee et al. 2010)	x	x			x	
(Ticehurst, Newham et al. 2007), (Ticehurst, Letcher et al. 2008)	x	x		x	x	Included cultural values, but no deeper evaluation of social system

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