Bayesian Belief Networks as an Interdisciplinary Marine Governance and Policy Tool

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Abstract

*This paper details the major output and interdisciplinary processes adopted within the VNN project **"Interdisciplinary methods to build a socio-ecological decision-making tool to inform marine governance and policy".** A Bayesian Belief Network (BBN) was constructed using expert and stakeholder knowledge and datasets from the Western Indian Ocean. We provide 'proof of concept' evidence that a tool such as this has the potential to visually communicate to marine policymakers and planners the main impacts of implementing a policy – herein the example used is a Marine Protected Area (MPA) - on the environmental, economic and social components of fishery dependent communities.*

1. Introduction

This paper describes the main processes and output from the VNN project *"Interdisciplinary methods to build a socio-ecological decision-making tool to inform marine governance and policy"*[1]. In this project we developed a prototype tool to establish and communicate clearly and directly to marine policymakers or managers the simultaneous impacts of a proposed policy on three key components of a marine community; marine health; economic output; and social wellbeing. This tool, allows for scenarios to be built that makes essential inherent trade-offs and implications visible to the policymaker *before* the policy is implemented. It is noteworthy that marine policies worldwide are failing to achieve sustainability goals because there are few mechanisms to enable policy-makers, scientists and stakeholders to coherently assess future policy outcomes (Tobey and Torell 2006; Torell, Crawford et al. 2010). User-friendly tools are required to systematically analyse and then subsequently visualise for marine managers and policymakers the effect of measures such as Marine Protected Areas (MPAs) on coastal livelihoods in a predictive manner. The tool developed in this project is therefore an important first step in overcoming a barrier to valuing marine ecosystems and measuring policy impact on human communities which are socially and economically dependent on vulnerable resources.

The initial interdisciplinary team consisted of a core group of four environmental economists, five ecologists (two of whom are further specialized in ecological modelling), one marine socio-economist, one planner, specialising in Environmental Impact Assessment (EIA), and one landscape planner. Three external, international academics with expertise in marine ecology and policy were also included. We recruited additional 'social scientists' including a planner with expertise in livelihood studies in developing countries and three stakeholders from the marine policymaking community (Marine Management Organisation (MMO), DEFRA and Marine Scotland in the early stages of the project. While two of the ecologists represented the marine ecology as a discipline, the other three ecologists, specialized in the BBN approach, acted largely as facilitators and stepped back from representing ecology as a discipline.

The results of this project should be viewed as a 'proof of concept' in that its primary purpose is to demonstrate the potential for developing and operationalizing an approach in the field in the future. Equally importantly in developing the tool we were provided with a context and problem to focus upon which allowed us to assess and reflect on the challenges and opportunities posed by the need for integrated, interdisciplinary approaches to marine policymaking. In our view the process that developed within the project can be considered as a further 'output'. As such, we also provide a detailed description of our procedures within the project. The remainder of the paper is structured as follows. We first ground the work in its wider context and reflect briefly on the different types of values that must be taken into account in order to accord with the VNN conceptual framework for valuing nature (

[1] Contract No. NE/1015086/1

http://www.valuing-nature.net/news/2012/valuing-nature-network-conceptual-framework). We then set out the aims and objectives of the project, followed by a detailed description of the technical model that underpins the decision-making tool and the procedures we followed to build conceptual and BBN models and, ultimately, the decision-making tool. It is important to emphasise that the ethos of interdisciplinarity was embraced in all stages of the process, although disciplinary expertise was relied on as and when appropriate. We then move onto report our external validation exercises (academic and stakeholder). In addition, we report the results of an independently-led group ‘reflection’ exercise to explore our experiences of working in such a close manner with the aim of transcending disciplinary boundaries. We finish with a critical assessment of the project and offer concluding remarks on future research direction and the future potential of such a tool for marine policymaking and governance, as well as the challenges and opportunities it provides.

2. Background

Humans live in close relationship with the environment, which they directly and indirectly use and depend on for food resources, building material, protection, relaxation, to mention but a few examples.. While in earlier decades management was driven by 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). In the context of the marine environment, while marine eco-systems are of great importance as they provide the main source of protein in many developing countries around the world (FAO 2010), they also contribute to the building of environmental e.g. biodiversity, and social capital e.g. supporting the formation of cohesive and cooperative community groups comprised of fishers or gleaners. Economists have developed methods to place monetary values on the ecosystem services that natural environments provide, in an attempt to resolve the ‘missing markets’ problem by allowing a like-for-like comparison of the value of preserving the resource *in situ* (and hence the associated flow of ecosystem services) compared to using or developing it for commercial purposes. However, even this approach fails to take into account the social, cultural and community values that might be associated with or generated by a particular environment. One reason for this is that monetary valuation exercises are grounded in the views and preferences of the individual, whereas social and community values apply at the group level. In addition, many cultural values cannot be quantified or captured using traditional economic methods and are difficult to identify from ‘outside’ a particular socio-cultural system.

Thus, while it may be possible to ascertain a monetary value of a healthy ecosystem through the services it provides, it is important to capture its contribution to maintaining or increasing the well-being of a community or communities. This may be a direct and quantifiable value (and in this case it could possibly be valued as an eco-system service), such as nutrition, fresh air or employment, however it may also be something not as easily discernible, such as providing a nucleus around which the community forms, providing a belief system and the basis for many traditional practices associated with that ecosystem. The challenge is therefore to develop a mechanism in which all these different types of values can be integrated into policymaking in an equitable manner allowing a combined analysis of the impact of a marine intervention on economic and ecological health and community well-being, as opposed to being considered, if at all, as an 'add on' after the policy decision is made. This is a particular danger as far as social values are concerned. Within this project, we addressed this challenge directly by integrating it into our two main aims:

(i) *To support marine governance and policy by developing and implementing reproducible methods for valuing and integrating data from social science, economics and natural science into a dynamic decision-making model.*

(ii) *To provide a framework by which to integrate different disciplinary sciences into marine policy analysis to provide a more comprehensive assessment of its impacts.*

3. Objectives, Modelling Approach, and Data

The model building process as a whole was guided by the following objectives:

1) *Conceptualise and develop a dynamic model representing marine ecosystem and coastal community which updates predicted values of all factors in the model following a policy change - capturing interactive relationships within the modelled ecosystem and community.*

2) *Include user body representatives in the model development process as soon as possible*

3) *Identify an overall "Integrated Ecosystem Value" based on equilibrium of social, economic and ecological performance in the model -capturing trade-offs within policy and allowing decision-makers to manipulate factors to predict effects on the Integrated Ecosystem Value.*

4) *Obtain policymaker evaluation and debriefings to highlight strengths and limitations, to validate/improve methods and confirm first translation of valuation for dynamic marine ecosystems into valid tools directly informing coastal policy making.*

5) *Obtain academic evaluation from independent, international members of the network.*

We identified Bayesian Belief Networks (BBN) as our chosen modelling approach. BBNs are directed graphs/networks of causal relationships based on Bayesian principles. They have the ability to incorporate different types of data, such as quantitative data, expert or local knowledge and are capable of dealing with missing or incomplete data. 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 between different stakeholders and disciplines (Kragt 2009; Korb and Nicholson 2011).To date BBNs have not been explored as, and actively incorporated in, the decision making process in many countries; however there have been advances in the use of BBNs as decision support tools within all levels of the Australian government in the last decade, such as a decision support making tool for water managers incorporating socio-economic and ecological considerations (Merritt, Ticehurst et al. 2010). We believed that building and developing such a model could provide a useful framework for examining the problems expressed in our research aims and would provide the team with a focus and serve as our primary vehicle for cross-disciplinary communication.

We used, with the Principal Investigator's permission, two existing datasets, held at Newcastle University, containing socioeconomic and ecological data collected from small-scale fishing communities in different countries in the Western Indian Ocean. Datasets included information collected by face-to-face interviewing, ecological surveying and institutional analysis. Socioeconomic data included household income, economic activity, and reliance on coastal livelihoods, perceptions of the marine environment and indications of social connectedness of individuals. Further to this estimates of existing governance structure and estimates of marine ecosystem health were available for several villages. Additionally a number of team members had previous experience in the region which would, to a degree, mitigate problems arising from missing data within our exercise, through applying their expert knowledge.

4. BBN Conceptualisation and Implementation

4. 1 Methods

Bayesian Networks (BN)

Bayesian Networks (BN), including both, Bayesian Belief Networks (BBN) and Bayesian Decision Networks (BDN), are directed acyclic graphs providing a visual representation of direct and indirect causal linkages between sets of variables. Nodes (or variables) are connected by causal, unidirectional links (or arrows)(Figure 1a). For example, in figure 1, node A affects node B, and node A and B affect node C. Node A affects node C directly and indirectly through node B. A is referred to as parent of node B and C, B is referred to as child of node A and parent of node C, C is the child of A and B. Node A is the input node, node C the output.

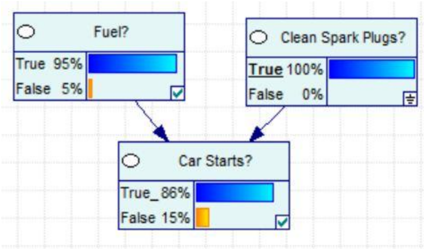
As an easy example, Figure 1b shows a simple network deciding whether my car will start or not- this is a very simplified version, in reality there will be very many more possibilities, why a car might not start, however, this example has got 2 parent nodes: Do I have fuel, and are my spark plugs clean. In this case, each variable has two states (e.g. true and false; Figure 1 c), there could however be nodes/variables with more states, or the variable Fuel? could have states low medium and high. In the car start case we assume that 95% of the time the car has sufficient fuel and that in 98% of the time the spark plugs are clean. Each child node (in this example there is only one)is associated with a set of probabilities, specifying the belief, or probability, that a variable is in a specific state given the state of its parents.

a) b)

c)

Clean Spark Plugs?	True		False	
Fuel?	True	False	True	False
True_	0.9	0	0	0
False	0.1	1	1	1

d)



e)

Figure 1. Example Bayesian Belief Networks (BBNs) and underlying conditional probability table (CPT*).*

This set of probabilities is also referred to as a nodes' conditional probability table (CPT) (Figure 1d). In the car start example the car will start (i.e. the state is True) will have a 90% probability if the car does have fuel and its spark plugs are clean. There is a remaining10% probability that it will not start even though it has got fuel and its spark plugs are clean due to other unaccounted options, e.g. it might be winter and the battery is flat. The car will not start (i.e. 100% probability that the node car start is "False"), if I have either got no fuel or the spark plugs are dirty. The car will not start if I have no fuel and the spark plugs are dirty. Figure 1c shows that the probability that the car will start, calculated from the CPT table and the assumed knowledge about the car (in 95% the car has fuel, in 98% the spark plugs are clean), based on Bayesian principles is 84%.

CPTs increase exponentially with the number of parents, the number of states of each parent and the number of states of the child. Probabilities can be entered directly into the table by an expert, local knowledge, literature or some other readily available data, or can be learned through a learning algorithm from raw data; different methods of populating CPT tables in one network can be combined. A complete network, or model, consists of the structural design of the nodes and causal links, the parameterization (i.e. the states) and the complete CPTs. Once a network is constructed it can be used to display the outcomes (does the car start?) given a specific input state or scenario. Once new evidence or data becomes available (i.e. we know that the spark plugs are clean, Figure 1e), the network (CPTs) can be updated and the scenarios re-evaluated- the probability that the car will start has increased from 84 to 86%.

A basic BDN, in literature also referred to as an influence diagram, has additional types of nodes, in particular decision and utility nodes and allows for the choosing of an alternative decision that has the highest expected gain (utility).

Bayesian Network Process

Building a good BN is a highly iterative process. The approach taken in this project (Figure 2) is based on that in Marcot et al (2006), but is adjusted to the specific needs of our study and the resources available. Initially, the goals and objectives of the network should be specified as precisely as possible (Figure 2). Once the objectives are set, the next, and most central, aspect is the creation of conceptual models (Figure 2), which can be broadly considered as the structure of the network, including the variables and directed links between them. The next step is to parameterize the variables, clearly define the states of the variables and to populate the CPTs (Figure 2). Both of those processes are highly iterative; they include the gathering and review of data from various sources and feedback from stakeholders and independent experts on the structure, states and CPTs. In this case study we decided to split the process into two parts, creating initially three independent networks for each sector (social-wellbeing, ecology and economy) and only later combining them into one network. The process concluded with an evaluation and review of the network, followed by scenario analysis.

The conceptual models were created using using the software package Inspiration 8.0b by Inspiration Software Inc., the BBN and BDN models were created using the software package GeNie 2.0 available from http://genie.sis.pitt.edu/.

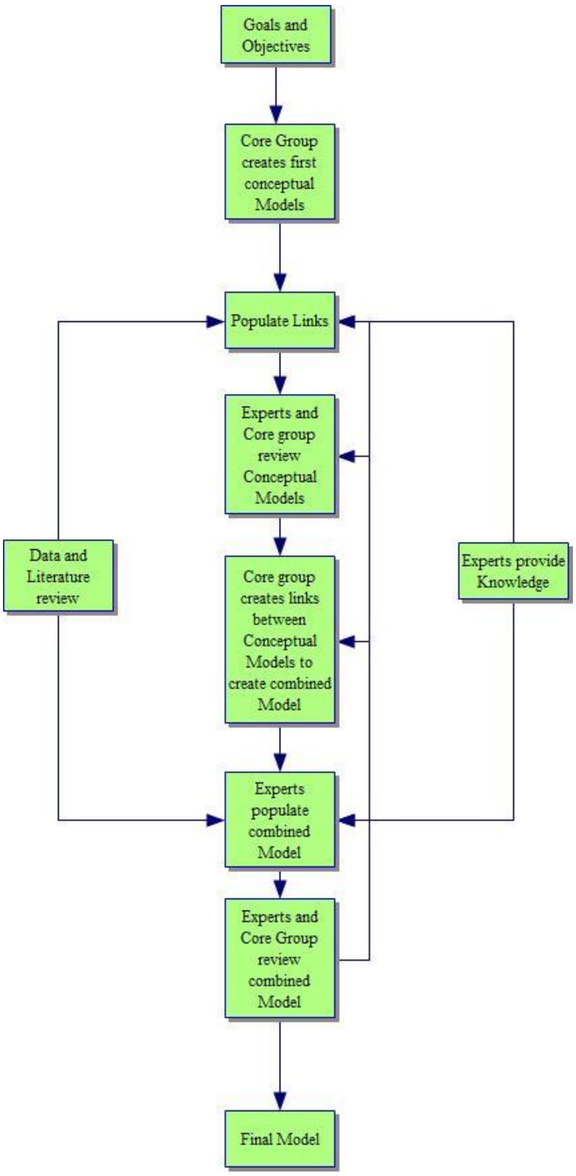


Figure 2: Flowchart describing the process of building the BNN applied in the VNN project pilot study.

4.2 VNN cross-disciplinary process

The project was based on an iterative and reflective, discussion and development process to ensure good communication between researchers and to capture thinking that emerged during the group sessions within the construction of the BBN framework. During the course of the project we held a series of formal and informal meetings as outlined in the original project proposal. Those meetings followed the steps in Figure 2 and are described in some detail below. In summary, the official meetings consisted of a one-day kick-off meeting and three two-day workshops or Full Team Meetings (following the project proposal). Additionally informal small group meetings were held in-between, further encouraging cross-disciplinary discussion and BBN building. Between the second and third two-day workshop the BBN and progress was presented in a short workshop to decision makers at the Marine Management Organization (MMO) in Newcastle as a way of evaluation and review from the prospective users. The one-day kick-off meeting was held primarily for the marine ecologists and modellers to introduce and agree the basic BBN process to the social scientists (economists and landscape planners). The three 2-day workshops were held to obtain team input into all the critical modelling phases and provide opportunity for critical reflection at the end of the project. In the meantime, interdisciplinary sub-groups met with disciplinary experts on a regular basis to support the ecological modellers in specifying and populating the analytical BBN. In addition, smaller groups of individuals met to focus upon particular aspects of the work and synthesise ideas, such as in relation to non-use values, which were then discussed further and discussed further within the wider team in the second workshop. Two test-bed focus groups were also held with representatives from the marine policymaking community.

The process of the project was thus highly iterative, with parts of the models being reviewed and improved repeatedly in small groups and then fed back to the larger group for further discussion and final agreement. We note here that, ideally, communities of place and interest and other stakeholders would have been involved in the development of the model and its resulting analytical tool from the very beginning. However, due to the obvious difficulties with doing this (since we were using Western Indian Ocean datasets), resource constraints and the fact that this was primarily a ‘proof of concept’ exercise as opposed to a ‘live’ policy application, we chose to involve stakeholders with expert knowledge once the conceptual model had been established. Hence, the BBN model was based on literature and expert knowledge and opinion and existing or synthesised datasets with feedback in the second workshop from MMO and Marine Scotland representatives[2].

[2] Ideally, we would have included a wider range of potential stakeholders such as householders and representatives of community groups within the process.

5. VNN Meetings/Workshops

One-day Kick-off meeting

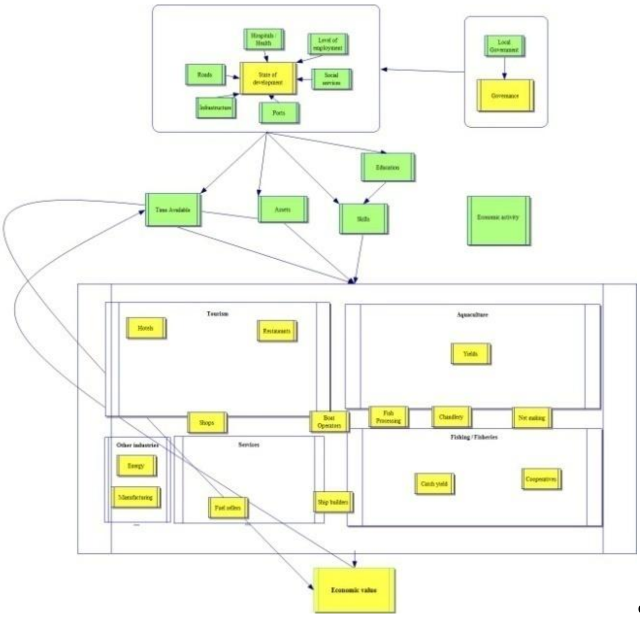
The first kick-off meeting set the focus of the project and team members had the chance to get to know each other and begin the interdisciplinary dialogue necessary to progress the project. This meeting served as a forum to introduce the research area (Western Indian Ocean) as well as discuss the need for a tool to combine social, ecological and economic concepts and processes. Various possible tools for building a research framework were discussed and in particular the concept of BBNs was debated and a focus on examining its usefulness for addressing the research questions agreed upon. Ultimately this led to a discussion on the desired objectives of the BBN.

First two-day workshop: (VNN Full Team Meeting I)

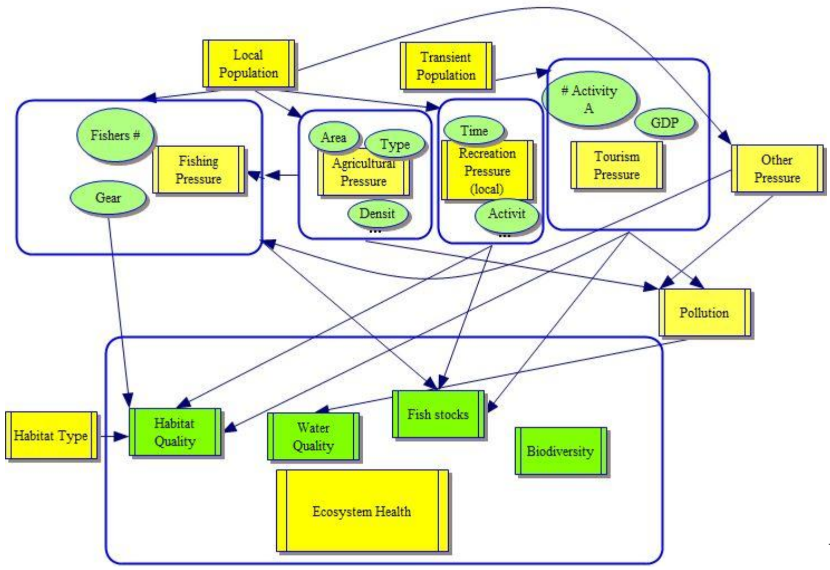
Participants discussed and set the objectives and desired outcome for the network and the project (Figure 2).In this context the concept of values was widely discussed, including economic non-market value and socio-cultural values. In addition, the concept of ecosystem services was considered both in the broad and narrow (marine) sense. As noted, many values have a different meaning in the three disciplines involved and it was essential for the success of the project to develop a common language to ensure effective communication and that everyone involved had an understanding of the others' terminology.

A major challenge was to identify the appropriate scale and scope for the network, bearing in mind that, initially, each sector would have a separate BN with a separate output i.e. Headline Indicator, although all three models networks would be created in an inter-disciplinary manner, before merging them into the final integrated model. It was agreed that the model should initially represent one village/settlement/community and the associated coastal area including near-shore waters utilised by community members. It was also decided to use a Marine Protected Area (MPA) as an exemplary management tool to investigate how the BBN would be used as a policy aiding/ decision making tool. It is important to understand that the MPA in our pilot study would be a total no-take zone for the whole area of the community, i.e. socio-economic and economic consequences would be the total loss of any income from fishing for the community. We are aware that this is highly unlikely in a real world environment and that a large number of alternatives would be available. However, this was considered an exploratory study with small time and monetary resources.

Three cross-disciplinary sub-groups created separate conceptual models, or alpha models, representing the 'concepts' (entities) involved and the relationships between them, for each of the sectors - Ecology, Economy and Social-Wellbeing[3]. The whole team then reconvened for a plenary session in which all resulting conceptual models were discussed and changes agreed on or further possible alterations suggested. Subsequent break-out session further refined the initial conceptual models (Figure 3).

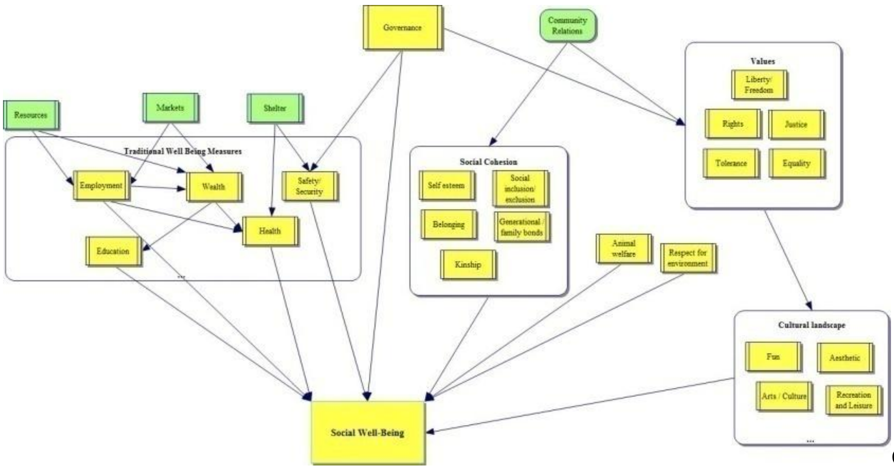


a)



b)

[3] These reflect the sectors of the community most affected by the policy and could be considered analogous to the three types of capital central to the concept of sustainability (i.e. environmental, economic and human).



c)

Figure 3: Conceptual networks created during the first two-day workshop, a) Economy, b) Ecology, c) Social Well-being.

Between first and second workshop

The time between the first and the second workshop was used by the core group to verify the causal links and relationships between the variables (concepts) in the network. This was achieved by reviewing the available data (define the data set here if possible) as well as the relevant literature, summarised in Schuchert *et al*. (2012).The modelling group transposed the conceptual models into BBNs[4]. CPTs were established by using the available data from the Western Indian Ocean and expert knowledge. They consulted with disciplinary experts, both members of the VNN team and independent, to verify, review and update the existing models as part of a peer-review progress following the BBN process outlined in Figure 2. The CPT for the non-market values were populated by results of synthesised data (*Campbell et al., 2012*). Each conceptual sub-model went through further scrutiny with at least two independent experts in their fields, to assure that causal links were correct and the models were as complete as possible (Figure 2).The socio-cultural information was reviewed in light of recent policy developments reported in the literature and discussed with an expert in the field of livelihood studies in the global south.

The modelling group then carried out a preliminary combination of the three networks based on their experience and knowledge of the study area.

[4]For algorithm descriptions please refer to literature review or Kragt, M. E. (2009). A beginners guide to Bayesian network modelling for integrated catchment management. Landscape Logic Technical Report. D. o. t. E. Australian Government, Water, Heritage and the Arts. **9**.

In addition to a BBN a Bayesian Decision Network (BDN), or Influence Diagram, was constructed. The BDN partly replaced the economic sub-model, and provided the opportunity to include a single financial profit/loss "result" for inclusion of a management decision, in our case the inclusion of a Marine Protected Area (MPA) versus no MPA. e.g. a community which owns boats (imagine the cost of having a boat is £20/month) and has an average income of fishing of £50/month, would have a monetary value of not-including an MPA of £50 (income from fishery)-£20(costs for boat)=£30 versus introducing an MPA £0 (income from fishery)-£20 (costs for boat)= -£20. There is a £20 loss against a £30 gain upon inclusion of an MPA. It would on the other hand mean that only one combined, monetary, value for the three sectors would be displayed. The monetary value would, eventually, include other monetary values as well, e.g. there could be an additional gain when including the MPA through improved Marine Health, however, this would mean giving Marine Health a monetary value. Again, those values are arbitrary example values, they do not have any currency attached to them.

Second two-day workshop: Progress meeting - model evaluation and interdisciplinary model linkages (VNN Full Team Meeting II)

At the second workshop the finalized three sub-networks and the combined BBN and BDN were presented to the wider team. Three policymakers (representing the MMO, DEFRA and Marine Scotland) accepted our invitation to attend and join the network at this stage and fully participated in this phase of development.

The models were once again reviewed as separate models, giving the whole group a chance to discuss and the opportunity to spot problems (Figure 2). Finally the combined model was discussed and the group once again broke up into interdisciplinary sub-groups to establish and finalise the links between the separate models and to identify key links or nodes missing.

In a plenary session the identified links and missing nodes were discussed and either included or discarded. The model outcomes were reviewed as well as their usefulness analyzed.

The second day focussed on the understanding of the non-use value data synthesised by the economists. The concept of "values" was discussed once again, demonstrating the difficulties in defining the outcome. Points of concern were whether to have one final outcome value for the full network, or to have three outcome values for each of the sub-models. The question arising would be, whether policy makers would just like to see one final outcome, or alternatively see changes in all three sectors that occur given a policy option. One single outcome, as in the BDN, would also have to be defined with one measure, which would lead to have to assign a monetary value to ecosystem health and social well-being. A single value would also be likely to mask changes in one of the sub-nets. The decision-makers and policymakers present also agreed that they would be happier with three separate values, as this would in fact be more informative, allowing them to simultaneously observe changes in all sectors and assess the importance of the implied trade-offs that would take place were the policy to be implemented. This resulted overall in the BDN being discarded in favour of the BBN. An animated discussion also took place in respect of the way in which the value of marine health and social well-being should be represented. The final decision was that a monetary value should not be used but rather a categorical or qualitative scale/ indicator should be adopted for this prototype decision tool, possibly in form of a traffic light system or "happy faces" ☺ /☹.

The plenary then identified a number of possible scenarios on which to apply the BBN to establish the impacts of implementing an MPA, which was carried out between Full Team Meetings II and III.

Following the second workshop the changes were implemented in the BBN and tested with some example scenarios (see below). In addition to this, we carried out our first test-bed focus group with a small group of representatives from the MMO in Newcastle.

Presentation to Marine Management Organisation

The purpose of this was to carry out a preliminary assessment/validation of its likely usefulness to marine policy stakeholders. The meeting focussed largely on determining how useful a BBN in general could be as a decision-support tool and to establish the main advantages and disadvantages of a BBN in the format created in the project.

The feedback from the decision makers at the MMO was generally positive. The BBN developed by the research team was viewed as a potentially useful tool, for a number of UK policy contexts. However in the short to medium term the MMO are bound by legislation which focuses on the environment so it has less flexibility in respect of taking into account all possible economic and social impacts, although this is expected to change in the future. The MMO observed, that they would need such tools which they could use to incorporate all aspects (social, ecological and economic) into marine spatial planning or licensing. BBNs were also considered helpful tools to construct and compare realistic scenarios. It was also noted that the visualization of relations between variables was an advantage, as was visualization of the effect of a change in one parameter propagated through the network. This tool would also be valuable for communication between different departments. Finally, the MMO representatives believed that a BDN with monetary values rather than a non-monetary BBN would be useful for policy purposes, although they understood the inherent difficulties in this and felt that our scaled indicators were an acceptable compromise.

Third two-day workshop: Evaluation (VNN Full Team Meeting III)

Results
BBN

Three initial conceptual networks (Figure 3) were re-viewed and improved over time, and eventually combined into one network and translated into a final BBN (Figure 4). Most CPTs were populated by expert knowledge gained from discussions in and outside the group, while some CPTs were populated by using the Western Indian Ocean dataset and a training algorithm. The BBN incorporates all three sectors and the links between and relations between them. The three sectors are maintained in form of sub-models, which are represented as larger labelled boxes with “Ecology”, “Economy” and “Social Well-being” in the BBN. The internal nodes underlying the network are hidden from the user at this stage, but can be easily expanded and viewed on demand. For a total list of all nodes and their states please refer to Appendix 1.The final network in figure 4 assumes no knowledge on the particular community; the outputs suggest that a typical community is likely to have an average (or possibly poor) level of well-being, medium to low economy, and a poor ecosystem state.

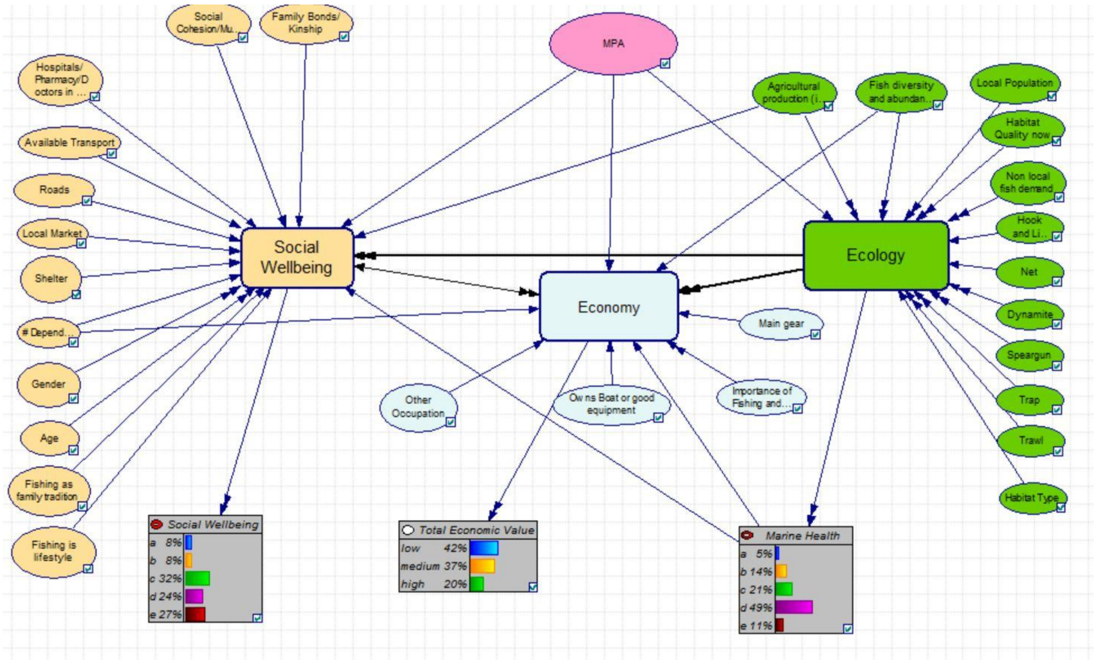


Figure 4: The final, full BBN. For simplicity reasons the figure displays the input nodes for each sector; intermediate nodes are hidden in “black boxes” (sub-models) labelled Ecology (green), Economy (blue) and Social Wellbeing (orange). Black arrows between the sub-models are causal links between nodes in one sub-model with nodes in another sub-model. The three output nodes(in grey) represent the Social Well-being and the Marine Health states in scales of a-e, a- very good, e- very poor and c- average. The Economy output (Total Economic Value) has got three states, low, medium and high. The state displayed in the figure assumes that nothing is known about the village- no information on population size, current state of the environment, current state of the economy or the social structure. This network does not necessarily represent the real world; the different numbers of states of the output nodes are examples- Marine health could also be labelled low, medium and high, etc.

The following scenarios were tested with the network:

Baseline: No information about the community is available, i.e. all possible states of each input node have got the same probability.

Poor State of Reefs: As baseline, but the current fish stock is low, habitat type is a reef

Heavy Fishing: As above, but trawling is used in the community, there is a high demand for fish, the community has a dense population and 80% of the fishers own their own boats.

Small Scale Fishing: Medium local population only using hook-and-line fishing and traps, fish stock at current time is average.

The probabilities for the three output nodes are displayed in Table1. As can be seen, in each of the scenarios the Marine Health is likely to improve with introduction of an MPA, (i.e. in the Baseline scenario, without including an MPA, the probability that Marine Health is either poor or very poor – state D or E- is 71%, while with an inclusion of an MPA, the probability of Marine Health to be in either state D or E reduces to 48%, Table 1.) Social wellbeing seems to have a higher probability of being very poor upon inclusion of an MPA, (i.e. under the baseline scenario a community which does not opt for an MPA has got a probability of 21% of being in a very poor social wellbeing – state E-, while the same community, implementing an MPA has a probability of 32% of being in state E (Table1).) However, many of those shifts in Social wellbeing are small and would benefit from further examination. Changes in Social wellbeing are also more difficult to judge and would benefit from further knowledge about the community structure and the internal causal links and nodes- at the current state most CPTs were populated by expert knowledge, however, the expert knowledge would have to be fortified by data collected from the region to be explored. The total Economic Value- which is calculated from the use- and non-use value of the marine resource, displays an interesting characteristic; i.e. in the Baseline Scenario (Table 1) The inclusion of an MPA increases the probability of the economic value to be low from 40% in the no-MPA alternative to 41%. At the same time, the probability of the Marine resource having a high Economic value for the community increases with the introduction of an MPA from 18% to 21%. This displays the impacts of the two economic values, use and non-use. While the use-value might, at least initially, decline due to the removal of gain from the fishing industry, the non-use value would increase upon an inclusion of an MPA. The use – value might also increase with a possible increase of income through marine based tourism.

Table 1: Outputs for the four different community scenarios, with inclusion of an MPA and without. The values represent the probabilities of the output variable being in a given state. States A-E go from very good to very poor, while for the economy output low, medium and high.

MPA		NO			Yes		
Scenario	State	Social Wellbeing	Marine Health	Economic Value	Social Wellbeing	Marine Health	Economic Value
Baseline	A/ Low	11	2	40	6	8	41
	B	8	8		9	20	
	C/ Medium	33	19	42	32	24	38
	D	27	56		21	42	
	E/High	21	15	18	32	6	21
Poor Ecosystem State	A/ Low	9	0	56	5	0	60
	B	7	0		7	0	
	C/ Medium	32	0	35	32	0	32
	D	29	67		22	80	
	E/High	23	33	8	34	20	8
Heavy Fishing	A/ Low	8	0	56	5	0	60
	B	6	0		7	0	
	C/ Medium	32	0	36	32	0	32
	D	30	52		22	73	
	E/ High	23	48	8	34	27	8
Subsistence only	A/ Low	11	1	36	6	9	39
	B	8	10		9	17	
	C/ Medium	33	27	43	32	35	39
	D	27	53		21	39	
	E/ High	21	9	21	32	1	23

6. Policymaker/Stakeholder Evaluation

Evaluation was undertaken with representatives of organisations which formulate, implement and influence marine policy in the UK:

Niall Benson: Durham Heritage Coast Management Officer

Joanna Redhead: Marine Management Organisation Senior Marine Planner

Mavra Stithou: Marine Management Organisation Marine Economist

David Harvey: Rural Agriculture Policy – President of the Agricultural Economics Society UK.

Susan Clark: Professor of Wildlife Ecology and Policy Sciences

Estelle Jones: Doctoral Candidate Marine Coastal Management

Policy makers were introduced to the BBN concept, the model produced in this project and proposed uses of the model in terms of manipulation through to decision support. Discussion was then conducted around applicability in real policy decision scenarios, value calculation and limitations of the BBN approach:

Spatial Contextualisation

Senior Marine Planner Joanna Redhead noted that Geographic Information System models are currently used to visualise potential options for "physical management" and location of measures and facilities. Co-location, i.e. specification of sites suitable for multiple measures is also of importance in improving current policy development. Physical constraints are applied to existing models to indicate where particular policies fit particular sectors or areas. The analysts can then see based on physical factors where a wind farm or similar may "work". She noted that the BBN approach, if integrated with existing models, would reveal whether the same measure or facility would "work" in social terms. Johanna Redhead noted that social values could be included in many other examples but require combination with a spatial element to be useful to MMO analysts.

Value representation

Niall Benson stated that the possibilities for participation and input by communities and the mixing of quantitative and qualitative measures were valuable. He also noted that the removal of "pound signs" but the retention of a more neutral indication of value was useful. Susan Chilton explained the non-use value inclusion and that a physical monetary value affected the system values displayed. Marine Economist, Mavra Stithou noted that an overall value would be desirable from her perspective as the location and/or co-location of measures and facilities requires cost-benefit analysis. An overall system value would in her opinion provide a de facto result of the cost-benefit analysis, rendering the BBN model valuable.

Timescales and Model Dynamism

The element of dynamics and time were raised and it was agreed that time and/or dynamic feedbacks would be necessary in many policy modelling situations. It was suggested that short term effects need to be included in the BBN models if possible in accordance with policy cycles of less than five years, but that the influence of those effects on the long-term vision are important. Joanna Redhead also noted that a further complexity which needs to be addressed in future is that combined effects of multiple policies should be reflected in the model to be applicable in realistic decision support. It was agreed that in many cases a specific BBN may not be easily applied to another community at a different scale without considerable re-contextualisation.

Fundamental Revaluation

Both Susan Clark and David Harvey warned against simply viewing the BBN model and similar models as a way to "patch" social aspects into or onto an existing policy formation paradigm. David Harvey argued that BBN models offer a way of viewing systems more holistically and forces users to view the policy within the context of the entire representative network being modelled. Susan Clark argued that not only the entire system needs to be considered but that the modelled system must be viewed from the perspective of the problem to be addressed.

Application

When asked where the model would be useful responses differed among policy-makers. Joanna Redhead stated that the model could be directly used by herself and colleagues, i.e. at Senior Planning decision-making level, whereas Mavra Stithou thought that the model would be more useful for identifying scenarios and options to be inserted into a cost-benefit analysis. David Harvey noted that the model was valuable in its strength in helping policy makers see things differently, rather than directly aiding decisions. Niall Benson suggested that the BBN model was graphic and thus a powerful tool to "take back to the community" to display results and get iterative feedback from the community studied. It was agreed that the graphic display in BBN was useful in revealing frameworks and effects potentially to all stakeholders in the policy process and that it was able to rapidly display policy intervention effects.

7. Interdisciplinary Research: Reflections on our Experience

While the BBN-based tool is the major output of this project, it was also necessary to simultaneously build the foundations for an interdisciplinary network. The BBN process clearly served as a focus for this, necessitating as it did the development of a language that was commonly understood across the multi-disciplinary group. The ethos adopted was one in which all disciplines were equally respected, but that there must by necessity be a degree of disciplinary compromise since we were all ultimately constrained by the overall objective of the project - that of designing a model-based tool (that by its very nature can be described as reductionist)that must ultimately meet user body needs. Concerns existed as to whether each discipline could be represented to the same degree and especially from the social scientists, concerns were raised as to the difficulties of trying to capture all aspects of social well-being and cultural values in such a model, while ecologists and economists seemed more happy that their concerns were reflected within the model. We thus felt it important to carry out a independently-led, reflective session on our experiences as well as carrying out a more general (critical) assessment of the project as a whole, including the resulting decision tool (reported at the end of this paper). This was primarily to answer some of the questions above but also to identify some best practices to continue with in future projects as well as any major concerns to address.

The reflection exercise comprised two parts – disciplinary[5] semi-directed discussion groups and individual letters to "a friend" describing our personal experience within the project, Combined together, they were designed to provide insights into the positive and negative experiences of the interdisciplinary processes we adopted but also, as importantly, to provide a basis for future interdisciplinary endeavours by the team. The report from the survey research company is available for reference (VNN website). Here, we provide a brief summary of some key insights pertaining to a number of different aspects:

• *Understanding of the Model and Framework*: initial misunderstanding of the overall BBN framework reduced as the project proceeded and it was generally felt that it gave us a focus for the interdisciplinary conversation. The planners had to 'concede' the most in terms of using this particular type of model. This led to questions as to how easy it is to develop interdisciplinary methods using such a model , although on balance the team viewed the usage and potential for further development as a tool for marine planning and policymaking positively.

• *Roles and Responsibilities*: The mix of individuals in terms of career stage (senior through to early stage) meant that the network has strong potential for capacity development in this area, since it was felt that there was a good level of engagement by all. However, some members of the team (particularly the PI) were more central to decision making than others, but this was generally accepted as a necessary 'price to pay' given the resource constraints.

• *Meetings*: The larger, full team meetings were considered to be central to the project as a whole, particularly from the perspective of giving everyone an opportunity to express their views but also from the social/networking angle. It seemed, though, that it was easier to reach a consensus in the small group meetings, where individuals could speak more informally. On balance, the mix of large and small meetings was deemed important although it was observed that the overall process could have been better if there had been an extra, explicit communication channel between the two sets of groups. Instead, small group decisions were often not disseminated until the larger team meetings.

• *The Network*: the general feeling was that the project achieved its objective in respect of developing a network and that it enabled interactions and relationships between individuals that they would not normally collaborate with. The prevailing view is to keep any project-oriented future network relatively small as in this case the feeling was that it worked particularly effectively. The fact that the network was based largely in one Institution meant that there were more opportunities for short, informal meetings in which individuals go tr to know each other on a personal level much more than would have been the case if we had been a bigger network drawing from a wider range of institutions.

[5] On the advice of the survey research company.

• *Communication between Disciplines*: The biggest challenge was to overcome the 'language barrier, particularly in terms of explaining methods and ideas to each other, although by the end of the project it was felt that while disciplines might still hold different meanings for the same words, there was much less misunderstanding about terminology. There were some concerns that the social perspective may have had less of a 'voice'. How much of this was due to the adopted framework (BBN), how much due to the methodology, or the composition of the team remains an open question, one that would be borne in mind in future studies. On balance, while challenging, communication did not break down and all disciplines commented positively on this aspect

• *Outcomes*: the project was considered academically liberating and the team were confident that it had met the aims and objective s of the project. One striking feature was the lack of certainty about the status of any interdisciplinary papers and the level of Journal that could realistically be targeted, contrasting sharply with the knowledge that individuals have in respect of outputs within their own discipline.

• *Constraints*: More resources (time and money) would have allowed for increased participation. While some network members had a small time buyout and others were incentivised by 'one-off' payments (to their respective Institutions) for specific duties/inputs there remained a heavy reliance on peoples' goodwill. As the projects entered the final phase, the team perceived a shift in emphasis from the external VNN Steering Group - from a scoping and network building focus to a more conventional outputs/publications based one. This caused some concerns with respect to how useful our non-conventional outputs – not least our BBN – might be viewed.

Suggested improvements for the future included setting aside more time at the beginning of a project to establish a common language, mutually agree the major research agendas and authorship of planned outputs. Moderation/reflection on the interdisciplinary approaches adopted should be embedded in the project from the outset. Consideration should be given to the inclusion of exercises or activities specifically designed to improve the level of inter disciplinarity within a project and also to develop special interdisciplinary working skills under the guidance of an expert, in our case Professor Susan Clark (Yale University) a natural resource policy analyst who specialises in interdisciplinary approaches to policy support.

8. A Critical Reflection: Challenges and Opportunities

In this section we provide a critical reflection based on both our experiences and a 'brainstorming' session within the final Team Meeting. Overall, the project was both, challenging and exciting. Thus, we turn to a more general assessment of the project, recalling that it was primarily aimed at developing the tool to the 'proof of concept' stage, given the limited time and resources. Whilst not necessarily exhaustive, the following list of issues nevertheless provides us with a basis on which to build on and improve in the future.

Cross-Disciplinarity or Interdisciplinarity?

Although much has been written about interdisciplinary, cross-disciplinary, transdisciplinary and multidisciplinary approaches the terms are often used interchangeably. In general it is not that clear where the boundaries lie and hence what constitutes a truly interdisciplinary project and even whether this is the most appropriate approach given the particular problem. We refrain from adding to this debate here, except to say that we concluded that our project was highly cross-disciplinary, but that we have built a firm foundation on which to develop a truly interdisciplinary approach for marine policy support in the future.

Defining 'Value'

One of the great challenges was the definition of "values". While the task was to "value nature" experts from the different disciplines had differing conceptions of what values were. This meant that, prior to commencing building the BBN, the biggest challenge was to get a common understanding of the definition of value. The other challenge was then to understand how different disciplines then measure values. In the future, the discussion should be broadened to consider in which contexts measurement is appropriate and those where it might be more fruitful to try first to understand it, for example when trying to capture and incorporate cultural values and perceptions.

Framing the Problem at the Outset

There is a need in the future for more time to develop front end conceptual part of any problem from an interdisciplinary point of view. We were somewhat data-driven in the end and constrained by lack of time, but achieved a lot in terms of process outcomes, as well as substantive outcomes which can be further refined for publication. Nevertheless, more time spent at the beginning of a larger project would almost certainly help the smooth transition from research findings to outputs.

Considering the BBN in particular:

How to Incorporate/Weight Public Preferences

As well as the issue of how best to incorporate social and cultural values in such a framework an issue also arises in how to weight the outputs from a BBN, here marine health, economic output and social wellbeing. They remain unweighted (within the model) at the moment, although in principle it would be possible to weight them – either in accordance with public preferences (elicited via a survey) or by some other metric e.g. expert or policymaker opinion[6].

The Need for a Well Defined Question

It is important to clarify this at the outset as it guides BBN conceptual model development and mitigates against the inclusion of irrelevant (to the policy impact) variables in the nodes.

[6] Although we note here that a representative from the MMO felt that incorporating it internally in the BBN might be less flexible and unrepresentative if preferences change.

Stakeholder involvement from the Beginning:

Identification of all relevant communities of interest, place and practice is highly desirable and improves the validity of the resulting BBN. These include experts and stakeholders such as the MMO who have an interest in the subject of constructing a decision-support tool for MPAs (if not a 'stake' in the geographical area of study we were examining) and lay members of an affected community. In our case, members of the team 'substituted' for such stakeholders, some of whom had experience of working in the West Indian Ocean, while the others had considerable experience in working in developing countries in general.

Data

The data available from the Western Indian Ocean was not sufficient to populate the social well-being nor the economic output CPTs, hence many of the probability tables underpinning the BBN were approximated from expert knowledge meaning that conventional validation techniques e.g. Structural Equation Models were not available to us.. Instead, we subjected it to face validity tests with disciplinary experts and peer review as we went along. The principle of BBN usage in marine policy support was evaluated and validated in the final Team Meeting.

Scope/Scale

The scope of the available database available for developing the BBN in this project was a small (local scale) coastal community socially and economically dependent on fishing as a source of food and for income generation. More generally, one of the strengths of the BBN is that it can incorporate data at different stages of development and from different scales, that is local (individual or community), national (country), regional (Western Indian Ocean) and International (global). Similarly a BBN can be designed, provided you have initially developed the survey instruments to address the particular research question or issue so that you can examine differences vertically (e.g., from local to national) and horizontally (e.g., across sectors like aquaculture, fishing, tourism and so forth). Furthermore, temporal patterns can be built in.

Dynamism

Our BBN was effectively a one period model demonstrating the short-medium term impacts of implementing an MPA on a human community. We acknowledge though that policymakers may also wish to know about the longer term impacts before making an assessment thus by building in outcomes from different future scenarios the BBN model could be extended to be used in development of proactive decision-making to inform choice in management options, e.g. implement an MPA or not. In principle a BBN could be constructed to account for these although acquiring the data is likely to be more difficult and can be time consuming and costly

Available Software

Currently we explored the use of two scientific BBN software packages for our purposes, Netica and GeNIe. Both have got advantages and limitations to what we could incorporate them to do. Both software have new releases, and it will have to be reviewed which one will be the more appropriate for use in future projects.

9. Concluding Comment

On the basis of the findings presented herein, we conclude that this 1 year scoping project has provided 'proof of concept' evidence that a Bayesian Belief Network could be a useful and robust mechanism by which to integrate environmental, economic and social impacts into marine governance and policymaking. Its strengths lie in its ability to integrate and include data of different types and scales and its visual properties, which are very important in communicating such complex interactions to marine policymakers and planners. A strong and cohesive interdisciplinary network of landscape planners, economists, marine ecologists and modellers has been established who look forward to further opportunities to build on and strengthen the approaches to transdisciplnary research developed so far. The rapid and increasing rate of competition for using marine resources necessitates urgent action by governments around the globe to apply good governance principles in ensuring that any decisions about marine management give equal weighting to the social, economic and environmental impacts. We conclude that the interdisciplinary approach adopted is the way forward for ensuring that the UK fully adopts an ecosystem approach to management of its marine resources and thus recommend that future work validates methods like BBNs among others thus allowing the UK and other countries to satisfy its obligations to meeting important policy instruments and Directives such as the Marine Strategic Framework Directive.

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Appendix 1

All nodes of the final BBN and their states, sorted by either their type (i.e. whether they are an input or output node) or the sub-network they are in, if they are internal nodes.

Type/ Sub-Model	Node	States
Input	#Dependents	Low/Medium/High
	Age	Low/Medium/High
	Agricultural production (intensity)(per unit of population)	Low/Medium/High
	Available Transport	True/False
	Dynamite Fishing	True/False
	Family Bonds/Kinship	True/False
	Fish Diversity and Abundance at current state	Low/Medium/High
	Fishing as Family tradition	True/False
	Fishing as Lifestyle	True/False
	Gender	Male/Female
	Habitat Quality now	Low/Medium/High
	Habitat type	
	Hook and Line	True/False
	Hospital/Pharmacy/Doctors in Village	True/False
	Importance of Fishing and Gleaning on Income	Low/Medium/High
	Local Market	True/False
	Local Population	Low/Medium/High
	MPA	True/False
	Net	True/False
	Main Gear	hook-and line, spear, trawl, net
	Non-Local Fish Demand	Low/Medium/High
	Other Occupation	True/False
	Boat/ Equipment Owner	True/False
	Roads	True/False
	Shelter	True/False
	Social Cohesion/Mutual Respect	Low/Medium/High
	Speargun	True/False
	Fish Trap	True/False
	Trawler	True/False
Ecology	Change in Fish stock from now to the next year	increase/same/decrees
	Destructiveness of gear	Low/Medium/High
	Fish demand	Low/Medium/High
	Fishing Effort	Low/Medium/High
	Fishing time/ Number of Fishers	Low/Medium/High
	Habitat Quality in next year	increase/same/decrees
	Impact of a given gear on a given habitat in the	Low/Medium/High

	current year	
	Local Catch	Low/Medium/High
	Water Quality	Low/Medium/High
	Ecosystem Quality	Traffic light a-e
	Fish Stock abundance and diversity in the next year	Low/Medium/High
	Catchability	Low/Medium/High
Economy	Fishing Income	Low/Medium/High
	Other income	Low/Medium/High
	Possible income from marine based tourism	Low/Medium/High
	WTP	Low/Medium/High
	Possible Total Income including Tourism	Low/Medium/High
	Non-Use Value	Low/Medium/High
	Total income	Low/Medium/High
Social Wellbeing	Ability/ Willingness to help others	True/False
	Access to markets	True/False
	Access to doctors and medicines	True/False
	Adequate Livelihood	True/False
	Affluence and Prosperity	Low/Medium/High
	Community Support	Low/Medium/High
	Continuity/expression of culture	True/False
	Education	Low/Medium/High
	Enjoyment of Eco-system	True/False
	Fishing Impact on personal well-been	True/False
	Health	True/False
	Fishing Impact on Tradition	True/False
	Indigenous Knowledge	True/False
	Infrastructure	good/bad
	Participation/Inclusion/Involvement	True/False
	Personal Safety	True/False
	Personal well-being	Low/Medium/High
	Secure Access to Resources	True/False
	Sufficient Notorious Food	True/False
	Traditional Way of Life	True/False
Outputs	Marine Health	Traffic light a-e
	Social Wellbeing	Traffic light a-e
	Total Economic Value	Low/Medium/High