Operationalising ecosystem service assessment in Bayesian Belief Networks: experiences within the OpenNESS project

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Abstract

Nine Bayesian Belief Networks (BBNs) were developed within the OpenNESS project specifically for modelling ecosystem services for case study applications. The novelty of the method, its ability to explore problems, to address uncertainty, and to facilitate stakeholder interaction in the process were all reasons for choosing BBNs. Most case studies had some local expertise on BBNs to assist them, and all used expert opinion as well as data to help develop the dependences in the BBNs. In terms of the decision scope of the work, all case studies were moving from explorative and informative uses towards decisive, but none were yet being used for decision-making. Three applications incorporated BBNs with GIS where the spatial component of the management was critical, but several concerns about estimating uncertainty with spatial modelling approaches are discussed. The tool proved to be very flexible and, particularly with its web interface, was an asset when working with stakeholders to facilitate exploration of outcomes, knowledge elicitation and social learning. BBNs were rated as very useful and widely applicable by the case studies that used them, but further improvements in software and more training were also deemed necessary.

Keywords: Decision scope; spatial modelling; uncertainty; stakeholder participation; web interface

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Highlights

- BBNs modelled ecosystem services for 9 different case study applications
- BBNs are flexible, transparent, and useful for participatory stakeholder work
- BBNs recognise socio-ecological uncertainty and stakeholders welcomed this
- Spatial BBN/GIS is a useful tool, but correct uncertainty estimation is vital
- Web interfaces helped promote interactive stakeholder participation

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1. Introduction

A fully integrated ecosystem service (ES) assessment will have components linked to different spatial and temporal scales, and a diverse set of stakeholders with plural values of benefit (both monetary and non-monetary) (Barton et al. 2016, Jacobs et al. 2016). The combination of biophysical and socio-cultural heterogeneity leads to substantial variation in possible outcomes, resulting in uncertainty in the predictions from any management strategy for these systems. Bayesian belief networks (BBNs) have been used widely in natural and social sciences to model various phenomena, including environmental and resource management, and are an appropriate decision support tool to be explored in the context of ecosystem services.

BBNs are a tool for *decision analysis under uncertainty* and the literature indicates there are a number of practical advantages when using BBNs for the appraisal of ecosystem services. Their graphical representation helps in *problem structuring* (e.g. Rumpff et al. 2011) and focusing ideas in the development phase, facilitating *participatory* open discussion between stakeholders and co-production of the network structure (e.g. Newton 2009). This can also promote *social learning* processes between scientists and users (Davies et al. 2015). BBNs encourage *transparency* about the system structure (e.g. Henriksen et al. 2007), explicitly addressing interactions between variables and uncertainty (Henriksen & Barlebo 2008, Landuyt et al. 2013). Options can be quickly explored, helping to *build an understanding* of the strength of relationships between inputs and outcomes of scenarios (Haines-Young 2011). These can include cost-benefit analyses of alternative scenarios and of different management interventions to meet agreed objectives (Barton et al. 2012, Landuyt et al. 2014). They provide a suitable framework in which to handle *small and incomplete data sets* (e.g. Hamilton et al. 2015), but are still applicable to *large data sets*. The BBN can "learn" from new data so that it always reflects the current state of knowledge (e.g. Trifonova et al. 2015), and can also be used in a structure learning mode to identify the important nodes and links in the model. As extensions, object-oriented Bayesian networks allow the development of a *hierarchical model* structure enabling experts to work on different components independently (Pérez-Miñana 2016), while dynamic Bayesian networks support models with a *time* dimension (Nicholson & Flores 2011). There are various *reliability and sensitivity analyses* (e.g., parameter and evidence sensitivity analysis, value of information analysis) that can be performed on the models and their results. These procedures aid model selection, model comparison, model testing, and evaluation of strength of evidence (see Johnson et al 2013 for an example application of these techniques), and are generally readily available in commercial software (e.g. HUGIN EXPERT).

BBNs differ from other similar model frameworks by their use of (conditional) probabilities to express the relationships between variables. Typically a BBN uses (i) a visual graphical representation (see an example in Figure 1) specifying the dependence relations (links) between random variables (nodes), and (ii) a set of probability distributions for the states of each child node conditional on the states of its parent nodes, and these quantify the strength of each dependence relationship. An advantage of this approach is that conditional probability distributions are specified independently of each other, so allowing very complex structures to be built from relatively simply-specified elements. These are parameterised and assessed, often by domain experts (Johnson et al, 2013), using a variety of possible sources to provide either hard evidence or, if that is not possible, an expert opinion; for example, experts may use knowledge elicitation to gather and process opinions, data mining to extract information from large data resources, and historical data or literature review to quantify dependences. The model development process may also identify when new knowledge or data are necessary to understand the system. It is important when defining the structure to take the complexity of the network into consideration. The knowledge requirement to parameterise the BBN grows exponentially with the number of parents for each child and the number of states that each child node can be in, so it is worth controlling both these numbers. As uncertainty is an implicit element of the BBN structure, estimates of uncertainty will reflect the weight of supporting evidence for each possible outcome. The conditional independence property also means BBNs can be used as a meta-model or knowledge integration tool (Barton et al. 2008).

The EU FP7 OpenNESS project looked at the operationalisation of ecosystem services, with each case study team having different expertise and being able to choose from a fairly wide range of tools (Harrison et al, 2018). The use of the BBN as a tool was explored by a number of case studies and this paper considers the outcomes from 9 very different example applications developed for the OpenNESS case studies.

2. Method and Background

BBNs were among the most frequently applied ES assessment methods in OpenNESS, and the project planned from the outset to test the BBNs as a tool for hybrid ES valuation (See Harrison et al. 2018 and Dunford et al. 2018) for details of other methods). One of the OpenNESS sub-objectives was to explore the development and commercial potential of BBNs in ES appraisal. To this end, OpenNESS included as an SME partner one of the world leaders in BBN software, HUGIN EXPERT A/S. They have provided technical support for case studies, particularly developing software functionality to support ES appraisal, and case studies also were able to disseminate their models on a HUGIN web-platform (http://openness.hugin.com/).

Table 1. The 9 case study BBNs developed during the OpenNESS project (for further information see ‘Ecosystems in Operation case studies’ brochure (EU FP7 OpenNESS Project 2016).) The BBN examples are listed in order of increasing technical sophistication.

Case study	Issue studied	Location	Country code
KEGA	Mapping supply and demand of fuelwood	Kakamega	KEN
DANU	Adaptive management plan for Lower Danube River	Braila	ROU
BIOF	Forest bioenergy production	Finland	FIN
CNPM	Mitigation of *Cryptosporidium* in water supplies	Glenlivit	GBR
LLEV	Impact of water policy on fisheries	Loch Leven	GBR
ALPS	Regional and national forest management planning	Vercors	FRA
SPAT	Effect of forest transitions on ES	Patagonia	ARG
OSLO	ES liability value of city trees	Oslo	NOR
IVEM	Integrated valuation of eutrophication mitigation	Norway	NOR

Nine case study BBN examples are presented here, in order of increasing technical sophistication, moving from basic structures to more complex models and introducing temporal and spatial dimensions. There were a range of issues investigated (Table 1) across different ecosystems and different *a priori* reasons for each case study opting to try a BBN (Table 2). Further details of the ES and issues investigated by each case study can be found in Dick et al. 2018. A further two BBNs (see Supplementary Material) were developed, one for classifying ecosystem services and the second as an expert system helping to select valuation methods for the Oppla website (http://oppla.eu), a virtual hub for the latest thinking on natural capital, ecosystem services and nature-based solutions from across Europe.

Table 2: Assessment of the a priori reasons why BBN methods were chosen by each of the OpenNESS case studies. Coloured boxes indicate that the characteristic was very relevant to their choice and grey boxes indicate some relevance. The different colours relate to the reporting of these questions in Dunford et al 2018.

	Ecosystem services				Context				Research		Spatial	Specific						System			Stakeholder			
Case Study Code	Provisioning ES	Regulating ES	Supporting ES	Cultural ES	Explorative	Informative	Decisive	Technical policy design	Interested in new method	Needed to create a new method	Spatially explicit	Addresses uncertainty	Across spatial scales	Across temporal scales	Future scenarios	Monetary output	Non-monetary output	Many ecosystem services	Allows trade-offs	System understanding	Stakeholder participation	Selected with stakeholders	Easy to communicate method	Easy to communicate results
KEGA																								
DANU																								
BIOF																								
CNPM																								
LLEV																								
ALPS																								
SPAT																								
OSLO																								
IVEM																								

Four decision contexts along a continuum of possibilities were identified by Barton et al 2018 as relevant to the various tools for ES assessment used in OpenNESS, and these are

Explorative	Conduct research aimed at developing science and changing understanding of research peers
Informative	Change perspectives of public and stakeholders
Decisive	Generate action in specific decision problems by stakeholders
Technical policy design	Produce outcomes through design and implementation of policy instruments with stakeholders

Only one case study, LLEV, did not choose all three of Explorative, Informative and Decisive contexts, maybe an expected result for a decision support tool. Only four, in many ways quite different case studies, identified Technical policy design as a relevant context for their work on BBNs, though another 2 saw this as of some relevance.

All case studies, except IVEM, chose to develop BBNs because they were interested in applying a new method. The ability of the BBN to address uncertainty was also highlighted as being important for selecting the BBN in the majority of cases. Their ability to be spatially explicit was only highlighted in four cases, while working across both spatial and temporal scales and exploring future scenarios were identified as important to the majority of cases, though in different combinations. Of more relevance to choice of method was the fact that BBNs could be used in conjunction with stakeholders and that they were perceived to have results and methods that were easy to communicate (although one case mentioned that the ideas are easier to communicate than the underlying maths).

An area of considerable discussion during the OpenNESS project was the role of spatial information in informing BBN developments - what is the appropriate spatial structure for the development of the BBN in order to answer the questions posed? The BBN will be combining ecological considerations with other environmental, social and economic pressures, many having no strong spatial referencing. If the spatial component is not the critical aspect of the study then the BBN may quite satisfactorily use non-spatial information and spatial summaries of environmental/ecological inputs. If spatial referencing is more critical, one approach uses the simple insertion of a BBN into a GIS; this relies on using exactly the same BBN at each spatial location, replacing the rule-based method of combining information across GIS layers with a probabilistic procedure. This can be done using the QUICKScan integration and spatial analysis framework (Verweij et al. 2016) along with the HUGIN Decision Engine. However, this technologically simple solution does not address a number of concerns, especially if the GIS/BBN is being proposed for use as a decision support tool. Variants of this approach were used in a number of case studies and these are discussed in the light of the case study experiences.

The diversity of ES studied and the varying abilities of the different teams mean that the BBNs developed are not directly comparable. However the focus, and thus the main research question, was whether or not the BBNs could deliver to the expectation of the case study teams involved in terms of operationalising the ES concept in a real-world situation, noting the variable constraints of limitations on time and effort. Collateral information on the whole experience of applying BBNs is also reported, and there were some common themes that developed across case studies. We also report where extensions to standard procedures were required to enable a satisfactory BBN model to be developed.

3. Case study examples

Kakamega forest case study

The development of a BBN for forest management in the Kenyan case study (KEGA) used an explorative approach based on expert opinion of ecological and social processes.

Kakamega forest is the easternmost relic of tropical rainforest located in the western region of Kenya, East Africa. This forest is rich in unique flora and fauna, which includes endemic species dependent on a range of socio-economically important tree species. The majority of the Kakamega forest communities are highly dependent on the forest for their livelihood and well-being, and for vital provisioning ES such as fuelwood (firewood & charcoal), timber, grass (pasture/fodder and roof thatching), herbs, honey, mushrooms, fruits etc. The forest includes areas under the management of either the Kenya Forest Service (KFS) or the Kenya Wildlife Service (KWS), and, along with the surrounding farmlands, are socio-ecologically and administratively linked as the Kakamega Forest Ecosystem (KFE) with an integrated management plan.

The BBN focused on fuelwood provision, central to local livelihoods and for trade with other communities (Kiefer and Bussman, 2008). The development highlighted the pressures of what are effectively two parallel but interacting systems within the management plan, since the different aims for the areas managed by the Forest Service and the Wildlife Service have a significant impact on both the ecology and the social utilisation of the forest environment. Therefore while the structure of the BBN for fuelwood provision could be identical (or very similar) for the 2 forest areas, the parameterisations were quite different. With very limited resources it was not possible to pull apart the data to satisfactorily parameterise and so validate either BBN individually, or to model the important and potentially complex interactions between them, The explicit visualisation of interconnectivity and relationships provoked debate on structure, boundaries and parameterisation, exposing the issues with the two different sets of priorities for forest areas. While only limited progress was possible at this stage, the exercise was regarded as beneficial with longer-term aims to resolve the parameterisation issues, facilitate comparison of the existing management plan vis-à-vis alternative management and future scenarios, and support a move to integrated iterative decision processes.

Lower Danube River case study

The substantial quantity of ecological data available for the Danube River allowed the Romania case study (DANU) to explore HUGIN's structure learning capabilities for determining a core BBN model and then use the Expectation–Maximization (EM) learning algorithm to estimate its conditional probability distributions. This network can then be extended to include habitat and fisheries management.

The Lower Danube River Wetlands System is a complex regional system which includes the Danube River stretch, and surrounding lakes, wet meadows, alluvial forests, agricultural polders, and fish ponds. It covers a number of important sites including the Danube Delta Biosphere Reserve, the Small Island of Braila Natural Park and several Natura 2000 sites. The aim of the case study (DANU) is to enhance the effectiveness of integrated and adaptive management planning and implementation in the Lower Danube River watershed, through mainstreaming the improved understanding and use of operational tools associated with implementing an ES-focused strategy.

The BBN developments focused on the drivers and pressures that result in changes in water and habitat quality, fish stocks and resultant catches. An initial water BBN, predicting water quality, was developed using a set of monthly water parameter data including depth, transparency, dissolved oxygen, various forms of nitrogen, phosphate and chlorophyll, and different algal groupings (Fig 1). These data were available over a 20 year period at 16 locations, but due to the sporadic nature of the data only 624 records were initially used. HUGIN's structure learning capabilities identified the nodes, their dependence relations and their appropriate states, with HUGIN's EM-learning algorithm then used to estimate conditional probability distributions. This learning activity provided a plausible structure, but the parameterisation provided some outcomes that were counter-intuitive. A possible reason for this was that the dynamics of the system change between 2 states, one characterised by normal river flow and the other by a flooding regime, and the learning algorithm could not separate these states adequately without additional information. This water BBN can form a basis for a number of other studies. For example, in this case study a second BBN for fish was created which took outputs from the water BBN to generate a management model. The fish BBN, a development based on annual data, added variables for water level, water quality and nutrient availability with their consequences for habitat quality, and how these in turn affected fish stocks and management of the fisheries. There are several ways of linking the time scales to make an overall management model from these 2 BBNs, and this choice will affect the assessment of uncertainties in the combined model.

This case study application revealed that, even with a substantial dataset, purely focussing on a data-driven approach did not deliver a reasonable model, especially with underlying effects of different states of the river system. Expert opinion to assist in defining the BBN structure was really helpful. The initial work did not explore fully the potential issues with linkage of different time scales.

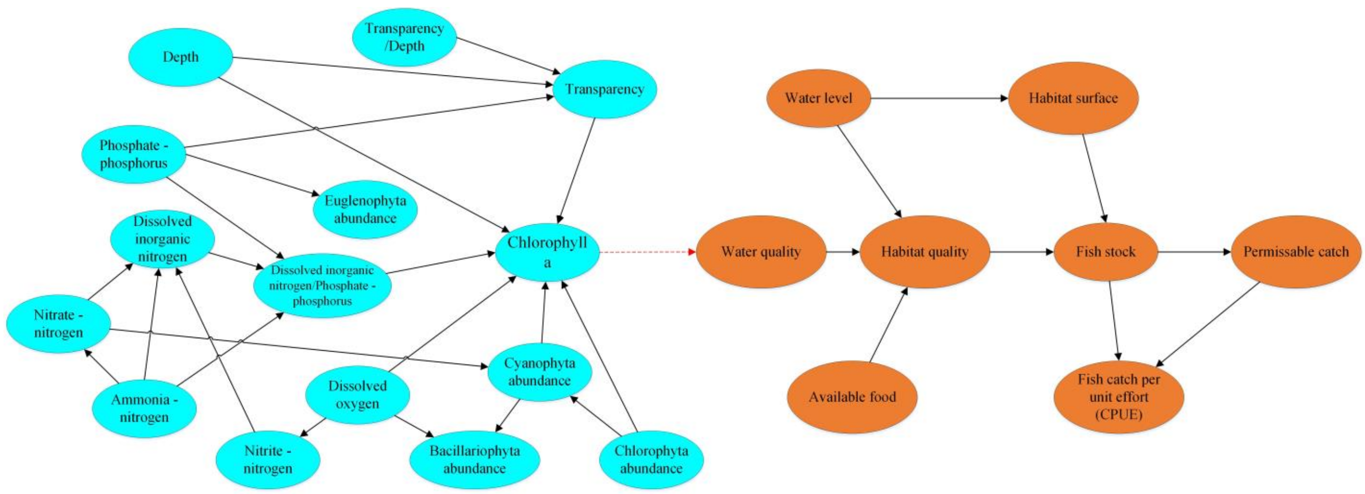

Figure 1. Construction phase of the Romanian BBNs, with the water BBN (blue) to the left and the fish BBN (orange) to the right. The water BBN shown is one of the versions created by HUGIN's structure learning capability and still requires further testing.

Forest management case study

The Finnish case study on forest management (BIOF) initially explored their system using influence diagrams and a multi-criteria decision analysis (MCDA) approach, but discussions with stakeholders confirmed that uncertainties and interactions were an important feature of the system. A lack of uncertainty tools within MCDA and the ability of BBNs to use expert judgement indicated that the BBN was the more useful approach.

This case study focused on how intensification of forest bioenergy production can influence provision of forest ES. In order to meet the EU renewable energy targets, Finland plans to increase the use of logging residues (such as branches, stumps, thinning wood, etc.) for energy production. While the aim is to reduce carbon emissions, removal of organic material from forests can have a major impact on soil carbon storage capacity, and perversely increase atmospheric CO_2 in the short run. Removal of decayed wood from forest ecosystems can have negative consequences on biodiversity and water quality in nearby water bodies, and also reduce long-term productivity as nutrients and organic matter are removed from forest soils.

The research process started with a biophysical assessment on the impacts of forest bioenergy production in the Hämeenlinna case study area (Forsius et al. 2016). The results fed into a multi-criteria decision analysis process, which was carried out with regional level stakeholders to assess the trade-offs related to ES provision in alternative forest bioenergy scenarios. The analysis revealed several uncertainties and interactions in the biophysical assessment: the rotation period of forest management is long and changes take place slowly, and long-term climate trends may have important influences on the productivity of forest ecosystems. Due to the uncertainties, the research team decided to use a BBN, which also can make use of expert judgements about the probability of changes in forest ecosystems.

When constructing the BBN, ten national level stakeholders from different interest groups were involved in framing the problem domain and in building an influence diagram representing related variables and their dependencies. The initial influence diagram was presented in a first workshop with the stakeholders and modified following stakeholder feedback. For instance, a number of forestry actors pointed out that some consequences on soil productivity are not likely to take place because of the new forest bioenergy extraction recommendations. The modified model was sent out for a second round of consultation and further modification. The agreed graphical model structure was then transformed into a quantitative form (BBN) by inserting probabilistic information provided through interviewing expert researchers.

At a second workshop, the constructed BBN model was reviewed with both the stakeholders and researchers. Here, one of the challenges was to present the results to stakeholders in an illustrative way to facilitate discussion.

The case study scientists had considerable concerns about how to discuss the information in the conditional probability tables with stakeholders and other researchers, noting that the tables became so complex that it was challenging even for the researchers to fill them in and that the stakeholders had difficulty in following the logic. They used several workshop discussions with stakeholders to enable them to co-create the BBN model, possibly more so than the other case study examples, and they suggest that improvements in software and visualisation would be helpful. Initial tentative conclusions are that the participatory model building exercise was very helpful, both to clarify differences in views and to build shared understanding. It remains a challenge to improve the BBN software interface to assist stakeholder understanding of these large conditional probability tables, and present the findings in an illustrative fashion.

Cairngorms Glenlivit case study

The Cairngorms (CNPM) Glenlivit case study used a BBN including statutory environmental regulations on contamination of water supplies, which introduced some measure of value and the recognition of a potential trade-off or payment for ES (PES). The case study also used the web-based graphical interface provided by HUGIN EXPERT to allow the regulatory element to be accessible in an easy format to staff in the field.

Cryptosporidium parasites are a risk to human health as well as a significant cause of enteric disease in neonatal livestock, and are also major contaminants of the environment and of water supplies in particular. The parasites can survive for up to 2 years in water, and normal water treatments such as chlorination are not effective against them. The research examined whether nature-based interventions within the catchment areas could improve the quality and safety of water supplies by minimising this parasitic contamination. In recent years the area has occasionally experienced contamination of the public water supply from small catchments close to farming activity, resulting in cases of illness and requiring the supply of bottled water.

A BBN for oocyst transmission in a specific catchment was constructed using an understanding of the scientific processes and of engineering interventions that are used to prevent the oocysts onward progress into the public water supply, e.g. fine mesh filters. However, the BBN required parameterisations to model the transport of oocysts from livestock (domestic and wild) to streams, and this proved to be challenging. It was concluded that current scientific knowledge was inadequate to provide much evidence supporting a nature-based solution at this time.

Additional information from the water company enabled the BBN development to proceed in a different direction. In Scotland, there is a statutory requirement to test public water supplies, with monitoring frequency determined from a scoring system for assessing the risk of *Cryptosporidium* in a catchment. As more frequent sampling is directly related to increased analysis costs to the water company, this generic scoring system is implicitly related to a monetary value.

After several iterations, the BBN (Fig 2) was chosen as the best representation for the scoring system. It allowed for recognition of uncertainties in assessment of the land use in the area and in the scores allocated to different management strategies, and fostered discussion with stakeholders on how these should be included in future. The BBNs were also implemented as a web tool (http://openness.hugin.com/caseStudies/GlenLivet_Scottish_Water), which was greatly welcomed by stakeholders as they could explore the system themselves. The web tool was setup so they could store a permanent record of any catchment assessment, a regulatory requirement.

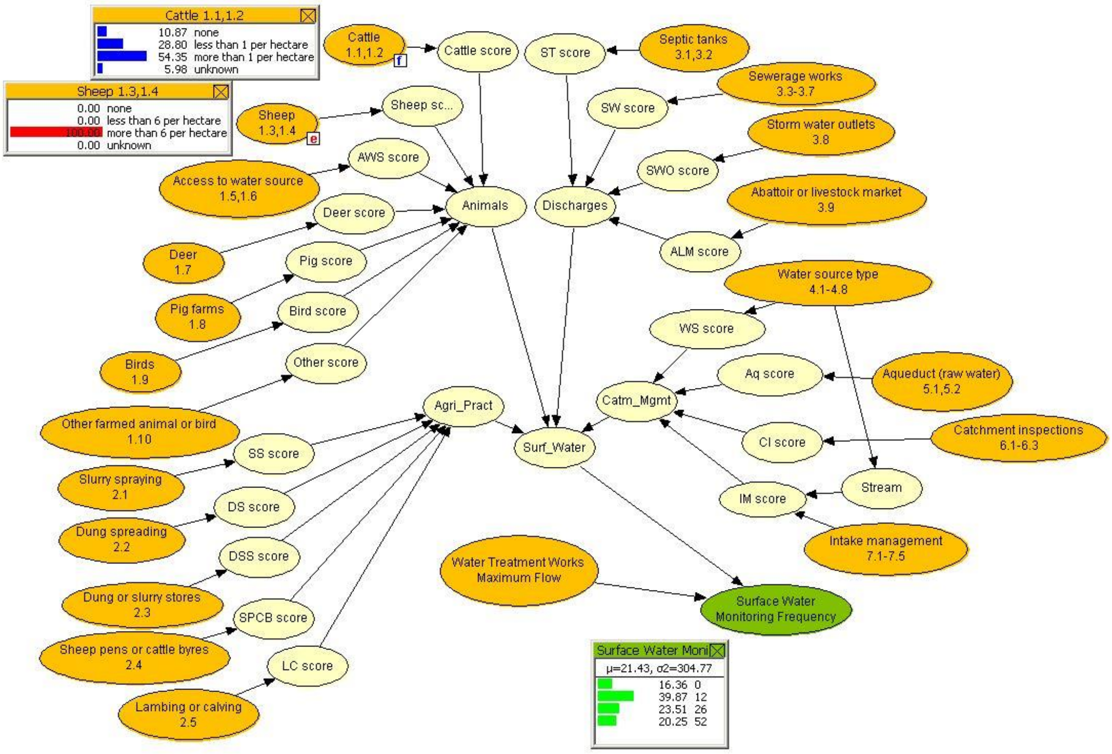

Figure 2. Partial BBN for Glenlivit based on a regulatory scoring system to determine sampling frequency (a proxy for value) of the water supply for *Cryptosporidium*. The histograms are shown as examples of how selection of node states (top left) influences the outcome measure (lower right). The selection of proportional areas of cattle in a catchment (multiple states) and selection of a sheep density for the whole catchment (single state) leads to the illustrated spread of the probability distribution on the sampling frequency, partly also reflecting an uncertainty about the choices to be made at the other nodes. Further information is available from the website – see the web link given in the text.

In the Glenlivit case study, the structure of the initial BBN was helpful to the scientific community, but it was recognised that there was insufficient data or expert knowledge to parameterise the BBN and make it useful to the wider group of stakeholders. This has now led to setting up another scientific project to improve our understanding of oocyst movements, so allowing the BBN development to continue. Since the water company's scores determined the frequency of monitoring for water quality, this is a useful proxy for value as the laboratory analysis of each monitored sample has a cost to the company. In the long term these proxy values would allow the exploration of trade-offs and payments for ES. As well as fulfilling expectations in terms of all four of the decision contexts (explorative, informative, decisive, technical policy design), the BBNs provided a useful way of considering the effects of the uncertainties in the scores and a route towards improved risk assessment procedures and new policy instruments.

Loch Leven fisheries management case study

A dynamic BBN developed for the Loch Leven case study (LLEV) allowed the inclusion of time when examining the relationship between the ecological condition of the lake and the delivery of ES such as recreational angling. A web interface was used to aid information transfer and participatory involvement of the stakeholders.

Loch Leven is a large, shallow lake in Scotland, UK. It is a site with high conservation value, designated as a European Special Area of Conservation particularly for its wetland birds. Furthermore, the wild brown trout population at Loch Leven has supported a world-renown recreational fishery for over a century. The case study aimed specifically to investigate the relationships between the ecological status of Loch Leven (with good status a target of the Water Framework Directive), the quality of the recreational fishery and the demand for the fishing service.

The Loch Leven case study illustrates a simple development of a dynamic BBN. The static BBN (Fig 3a) links the drivers habitat quality (chlorophyll-a concentration) and rainbow trout stocking to the quality and provision of a recreational ES. This is measured by the two proxies, catch per unit effort (CPUE) (number of brown trout caught per hour of fishing – a measure of fishing quality) and boat effort (annual number of hours of fishing – a measure of fishing service) during a single year. Both drivers also affect the reputation of the loch, which influences the demand for fishing. The dynamic BBN (Fig 3b) has an annual time step running from 1987 to 2027, with additional transition probabilities specifying how driver(s) change from one time step to the next – in this case only habitat quality. It is assumed transition probabilities do not change over the study period and each year is dependant only on the year before.

The website (http://openness.hugin.com/caseStudies/LochLeven_Habitat) displays outputs as a map (Fig 4). The user can select and change specific variable states on the screen to see the effects in current and subsequent years, such as the impact of changing habitat quality or fish stocking on both fishing quality and the demand for fishing. The map display uses a combination of colour and intensity to display the most probable ecological state of the lake for the selected node at different times. The website example is a demonstration of the potential use of dynamic BBNs and state-and-transition models (discussed further in the Patagonian (SPAT) example) for modelling ES.

This case study application focused primarily on the informative context and delivered, particularly to stakeholders. The only issue raised was that the model was not complex enough to reflect a wider range of management options.

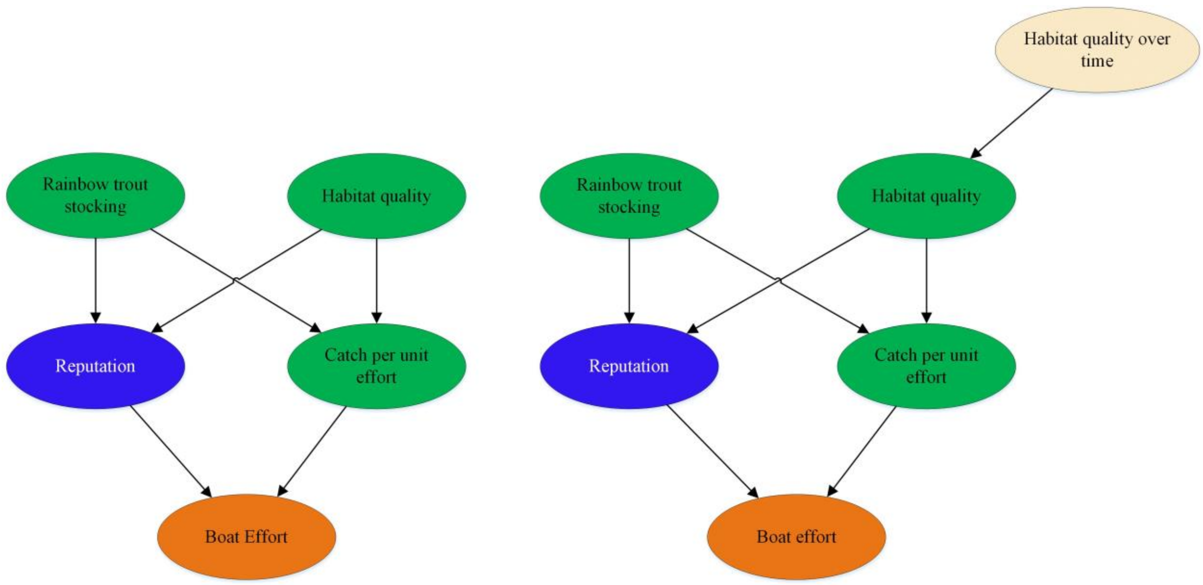

Figure 3. The static (a) and dynamic BBN (b) structures for the Loch Leven case study (see text for more detail).

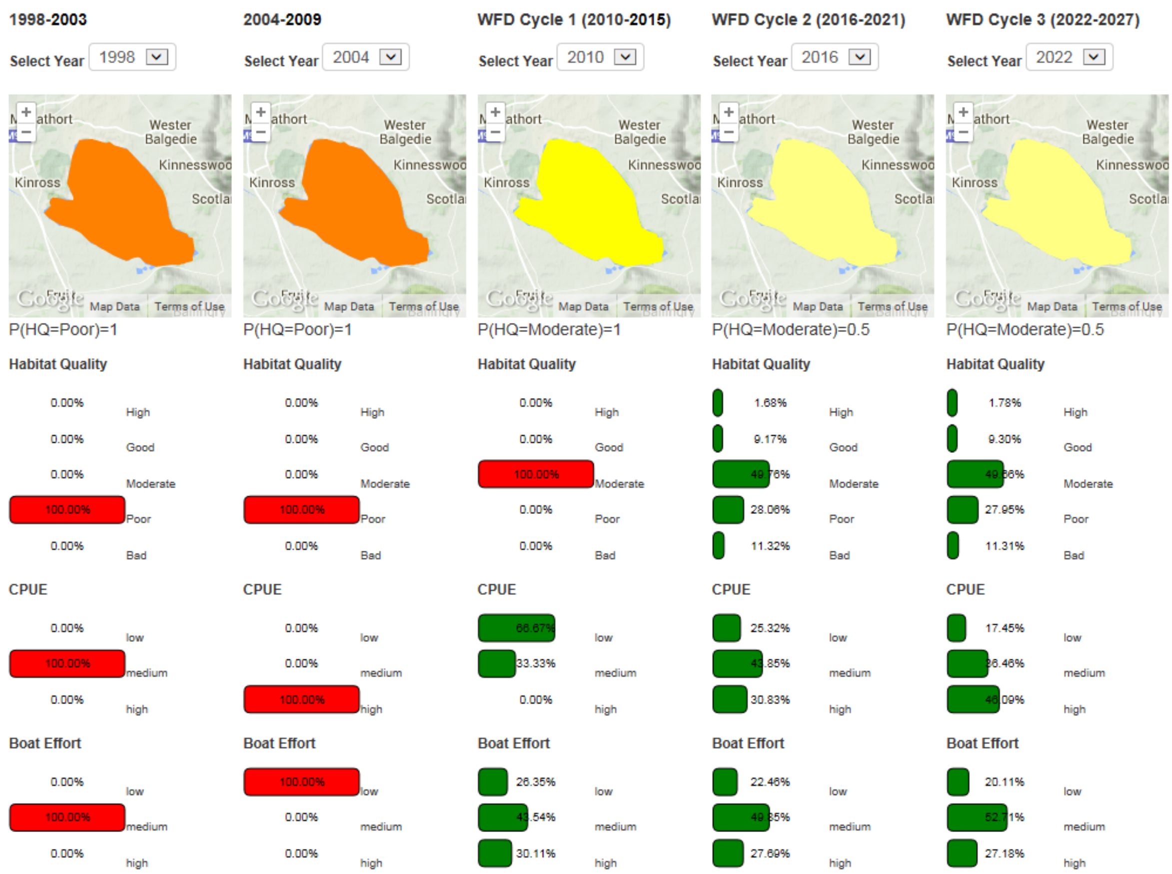

Figure 4. Partial screenshot of the web implementation of the dynamic BBN for Loch Leven fisheries, with the loch colour related to Water Framework Directive targets. Further information is available in the text or from the website – see the web link given in the text.

<u>*Vercors case study*</u>

The Vercors case in the French Alps (ALPS) introduced a spatial dimension by integrating a BBN within a GIS. This spatial approach helped to facilitate shared understanding of the human-landscape relationships and foster future inclusion of collective management into landscape planning.

The French National Forestry Office and other regional stakeholders wished to target management options for the French Alps region to support stakeholders and policymakers in reconciling biodiversity conservation with increased demands for natural resources, especially in managed forests. The case study focussed on 25,000 ha in an area to the north of the Vercors Regional Natural Park known as Quatre Montagnes", which has substantial areas of forestry but is subject to pressures for land use change.

The spatial dimension was a key issue for local stakeholders as their interest was in knowing 'where' to implement planning rather than 'why'. They had clear ideas of local and regional problems, but they need operational and spatial solutions (Fürst et al., 2014). A BBN was developed from theoretical principles using GeNIe® and this was embedded in a GIS package to provide a suitable spatial model to address the question of how to maintain long-term economically and ecologically sustainable forestry at the landscape scale, whilst still targeting suitable areas for conservation. The BBN specifically focused on assessing the trade-offs between management for biodiversity conservation and for timber production (Fig 5).

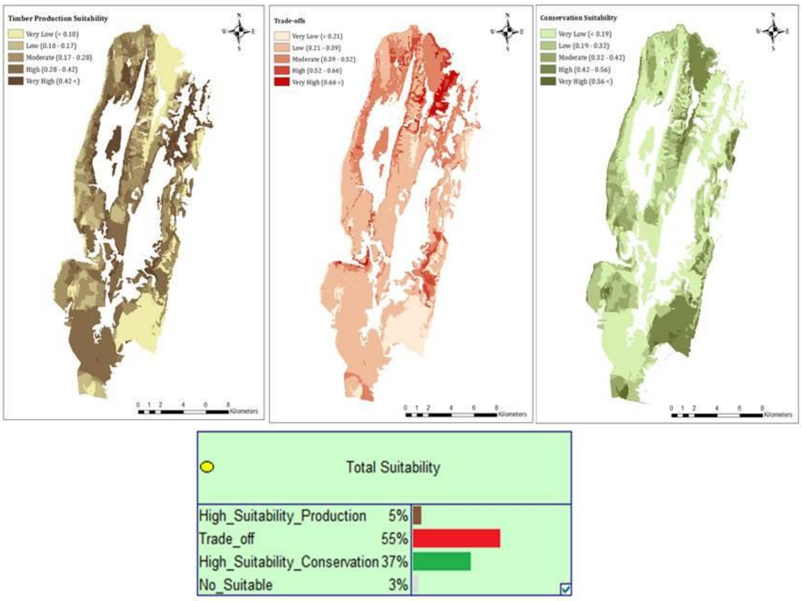

Figure 5. The final map in red (centre panel) represents areas of conflict where trade-offs between forest production (left panel) and forest biodiversity conservation (right panel) will need to be balanced (adapted from Gonzalez-Redin et al. 2016).

The development of spatial models highlighted suitable uncontroversial areas for either conservation or timber production, and areas which are more susceptible to conflicts arising between various stakeholders' interests. Input information for this software was based on biophysical data in addition to expert knowledge and outcomes from a participatory process that took place in the region (Lardon et al., 2013). The outputs contributed to the development of multiple alternative solutions and helped prioritize different management options in synergy with decision makers. The findings provided information for land use planning, which identified strategies that would provide a balance between biodiversity conservation and development activities. These land suitability assessments (LSAs) set within the context of a spatial model enhances the support for new regional planning initiatives (Gonzalez-Redin et al. 2016).

It was a challenge to develop an integrated GIS/BBN model for this case study application and further work is necessary to take this further. The process of co-construction of the BBN fulfilled the expectation of delivering within all four decision contexts, though, at this stage, the BBN outputs were only indirectly supporting a potential policy instrument so still a proof of concept.

Patagonia case study

The Patagonian case study (SPAT) utilised a dynamic BBN to implement a state-transition model on how management drivers of forest transitions influence the production of ES in livestock rearing farms.

The case study aimed to integrate ES in order to operationalise sustainable use of *Nothofagus antarctica* (Ñire) forest in northern Patagonia, both for management at the farm level and for policy implementation in the region. The degradation of the native forest cover is a pervasive problem in Argentina. In response, the national Forest Law was enacted to maintain '*forest ecosystems and the goods and services they provide'* and the National Program for Native Forest Protection was established, which considers the design of financial and economic instruments to ensure the implementation of the Law. However neither sustainable levels of use have been achieved nor have the instruments to motivate the application of sustainable practices been established.

The case study developed a framework, implemented as a development of a dynamic BBN, to analyse the impacts of farmers' management decisions in silvopastoral farms (i.e. levels of cattle grazing, fuelwood extraction, tree planting) on the capacity of the forest to generate multiple ES linked to specific private and public benefits. The case study used three conceptual and methodological approaches for the analysis: i) a state-and-transition model (STM) of ecosystem dynamics (Briske et al. 2006; Rusch et al. in press) (Fig 6), ii) the 'cascade model' of ES (Potschin & Haines-Young 2014), and iii) a BBN integrating the two approaches where the drivers of change are management alternatives (Rusch et al. submitted) (Fig 7).

The STM enabled modelling of the short and long term consequences of management practices on ecosystem condition and identification of thresholds beyond which changes in ecosystem structure and function are likely to be irreversible within the time frame of farm management. The Cascade Model helped structure the problem and identify the indicators of ecosystem structure (state variables), ES, the benefits derived from these services, and their value in monetary and non-monetary terms (Rusch et al. *submitted*). Implementing the model as a BBN helped define levels of use, ecosystem condition and ES, as well as the likelihood that the system would generate different levels of ES as a result of the ecosystem condition (de Groot et al. 2010). An influence diagram (ID) was implemented to identify the management options that best satisfied private benefits in the short and long term, and to analyse trade-offs between private and public benefits (Rusch et al. *submitted*).

This technically challenging implementation of an STM using a BBN with a temporal component was successful, though more flexibility in specifying the time dimension would be helpful. The model fulfilled expectation of being useful in explorative, informative and decisive contexts.

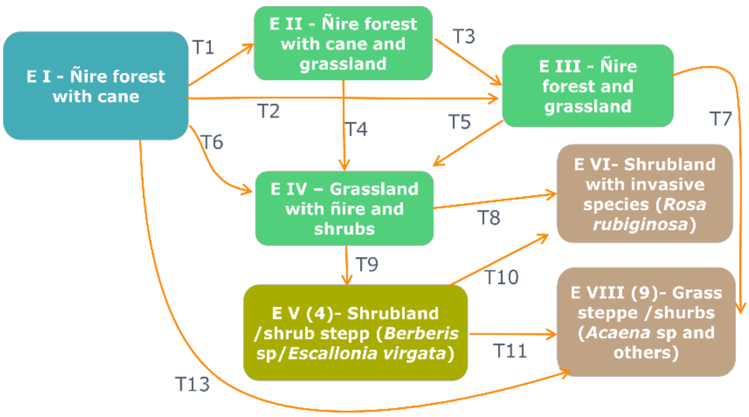

Figure 6. State-and-transition model for the *Nothofagus antarctica* forest in northern Patagonia case study (adapted from Rusch et al. *in press*). Each possible transition is indicated by a numbered T on an arrow.

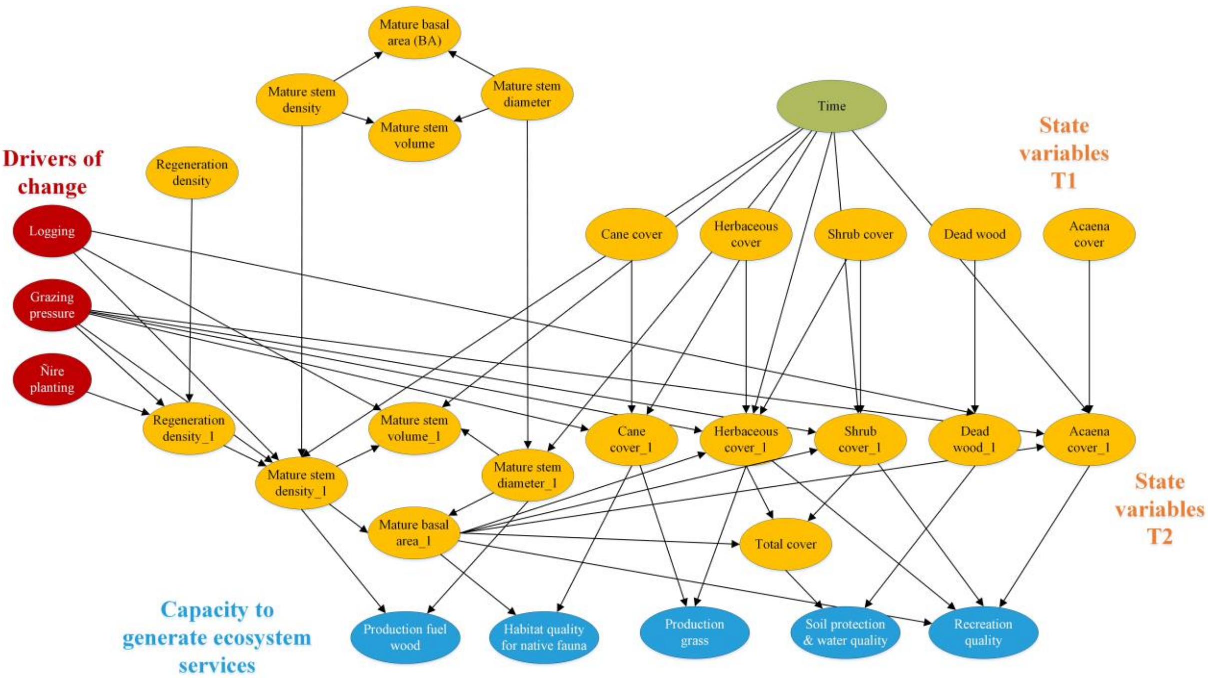

Figure 7. State-and-transition model of the capacity of *Nothofagus* forest under silvopastoral use to generate ES, implemented as a BBN (http://openness.hugin.com/caseStudies/Patagonia). Further information is available from the website.

Oslo city trees case study

The Oslo case study (OSLO) used BBNs which combined spatial aspects with monetary value assessment to determine the value of trees within the city.

The majority of Oslo's over 700,000 large city trees are on private land, with little or no information on their location, species or quality. Rapid population growth and urban development has led to a loss of trees across the city. Liability value is assessed by the municipality in cases of damage or killing of city trees, for example during construction works. The modelling of the compensation value of individual city trees is based on the so-called "Valuation of Trees 2003" methodology (VAT03) developed by Randrup (2003) in Denmark. Oslo Municipality's Environmental Agency uses VAT03 to assess the fine to be paid by responsible parties in the case of individual trees.

The BBN model (Fig 8) estimates the compensation value for all city trees in Oslo for the purpose of municipal accounting. In particular, it assesses uncertainty in valuation due to heterogeneity across an urban landscape and scarcity of detailed information on individual trees. Individual trees were identified based on mapping of individual tree locations using remote sensing LiDAR data interpretation. For further information on the application of the VAT03 methodology see Barton et al. (2015). HUGIN EXPERT has linked the BBN model to a web platform which is available at: http://openness.hugin.com/caseStudies/Oslo_urban_trees. Further details on the valuation methodology and the extensive input data used for this study are available in Barton et al. (2015 a,b).

This BBN was part of a more extensive set of valuation exercise examples which demonstrated the practical use of economic valuation of ES for awareness-raising purposes, with the web platform using a BBN a very visible awareness-raising tool. The BBN was developed over a longer period than some case study examples and delivered to expectation of being useful in all four decision contexts.

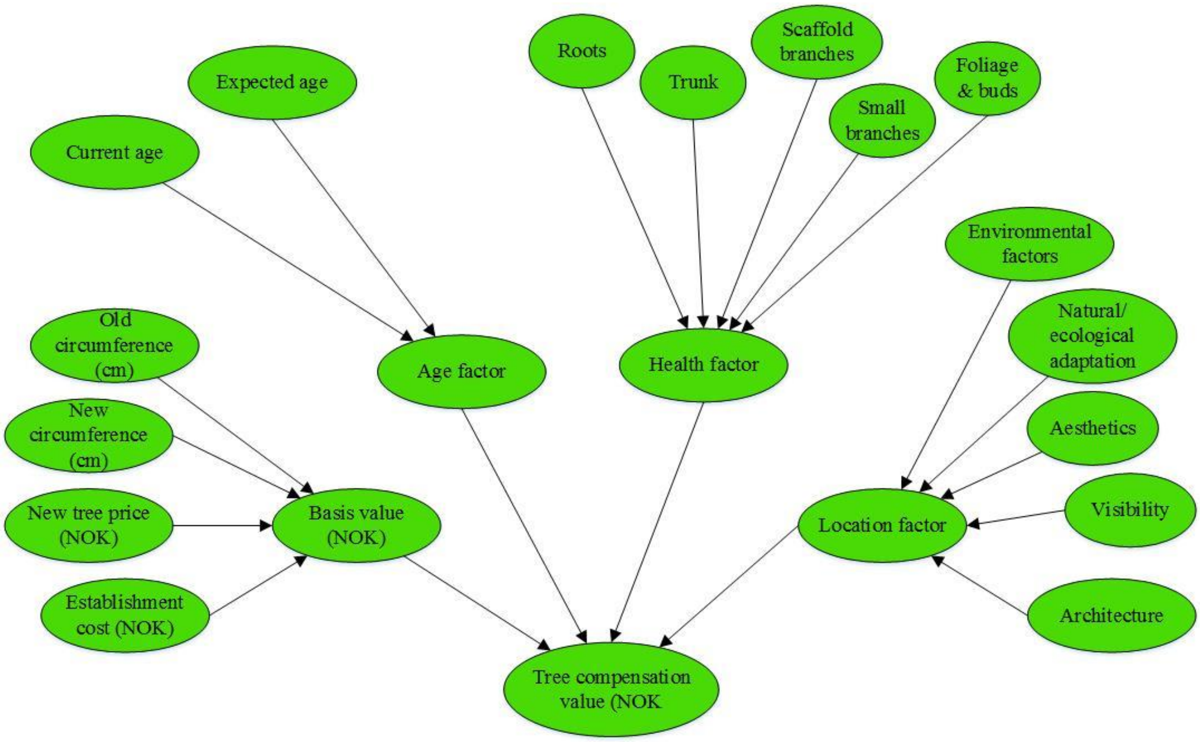

Figure 8. BBN for assessment of compensation value of individual trees. The lowest node calculates the compensation value/tree. The intermediate nodes are thematic factors (basic compensation value, age, health, location) which are multiplied to determine compensation value. Thematic factors are determined by a series of characteristics of the individual tree and its environment (outer nodes).

Integrated valuation of eutrophication mitigation

A second example from Norway (IVEM) demonstrated a map interface for integrated valuation of eutrophication mitigation in a catchment.

The Vansjø Lakes in south-eastern Norway have, since 2001, suffered toxic algal blooms in summer, which have been attributed to a combination of increased run-off and erosion from climate change, and farm tillage and fertilisation practices. An object-oriented Bayesian network had previously been used to link a cascade of sub-models across drivers, pressures, states, impacts and societal responses to lake eutrophication (Barton et al. 2016). This was developed using systems dynamic, empirical and expert judgement models integrated in a spatial BBN, illustrating an operational interpretation of 'integrated valuation' of ES. It assessed trade-offs between ecological, social and economic benefits resulting from improving lake ecological condition using nutrient abatement measures (Fig 9). The integrated valuation BBN makes it possible to assess the combined uncertainty in eutrophication mitigation management predictions from natural temporal variability, spatial heterogeneity, monitoring data resolution, sub-model prediction error and information loss at model interfaces. It is also possible to demonstrate the spatial mapping of predicted household willingness-to-pay (WTP) for a sewage fee.

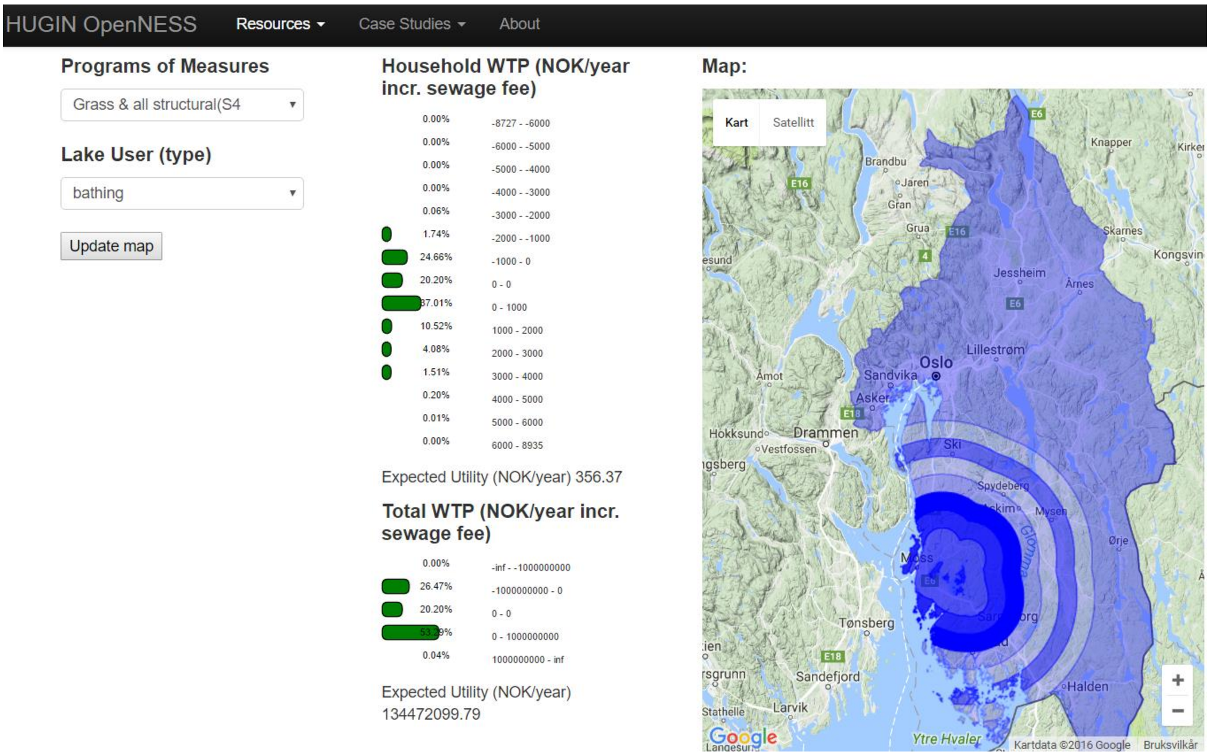

Figure 9. Online map interface to the integrated eutrophication model for the Vansjø Lakes showing predicted change in willingness-to-pay (relative to the status quo) for eutrophication abatement measures at different distances from the Lakes.

In the interface the user can select three programmes of measures corresponding to two different baseline situations without additional mitigation measures (“post2006/07”, “pre-2006-07”), a scenario where all cropping areas in the catchment are converted to pasture resulting in less fertilisation and ploughing, and the implementation of all blue-green structural rehabilitation measures (constructed wetlands, vegetation buffers, nutrient point sources treated). Different user groups can also be selected and their WTP displayed. In Fig 9, the spatial change in WTP of households who go bathing for the most ambitious program of measures is shown. The model captures that WTP is higher closer to the lakes, but with considerable spatial variation as we move towards the outskirts of Oslo.

The spatial elements of this BBN, along with how it pulls together a number of strands of previous work, make the development of this valuation model of interest. Although there is an element of policy application through estimated potential willingness to pay, the BBN primarily delivers on the first three decision contexts of explorative, informative and decisive application.

4. Discussion

Synthesis and summary of experiences

This synthesis does not rely on a formal mechanism to capture the feedback from experts; Dick et al. (2018) reflect more generally on the stakeholder feedback collected by the case studies. Rather, this synthesis summarises the experiences of the experts leading the development of BBNs in the case studies.

Most case studies started from a position of little immediately available data but a lot of expert knowledge about the ecosystem, as illustrated by the early work on the Kenya case study. A key feature of the BBN is its ability to combine (sparse) data and expert knowledge, and this allows some initial progress to be made – for example by exploring possible structures and checking for sensitivity of outputs to various inputs allowing the knowledge acquisition phase to be more focused. The Romania case study explored the use of a data driven, theory free, model structuring approach, but found the results were not ideal and needed interpretation and modification using expert knowledge. The supporting system that delivers ES is often complex, making it challenging to derive the structure of that system without guidance from an expert. This case study also highlighted an issue, common to many ES models, in that data for the different inputs are not necessarily on the same time scale, so an element of rescaling is often required and that has consequences for the uncertainty assessment.

Two case studies (BIOF and CNPM) explicitly noted that an important attraction of using a BBN was its handling of uncertainties, and that this aspect was specifically raised in discussions with stakeholders. While recognising that there are potentially difficult issues with the interpretation of uncertainties that challenge both scientists and stakeholders, the importance of determining explicit uncertainties for the outputs when developing new models to better aid management and policy decisions outweighed any disadvantages.

Three case studies (LLEV, ALPS, IVEM) explored the use of dynamic BBNs introducing a temporal component, and a fourth case study (SPAT) had a dynamic BBN implementing an STM. The basic dynamic BBN is easy to develop in HUGIN, and the case studies all used equally spaced steps in the time dimension and not too many thus keeping control over the number of temporal transition probabilities. There was a desire to implement a more flexible approach to the time component, e.g. having variable time steps, finding ways of accommodating different time steps for different processes, and having temporal transition probabilities that themselves varied over time.

Several case studies (CNPM, LLEV, OSLO, IVEM) found the ability to explore (even partly specified) models using a web front-end was an important element of the knowledge elicitation process and model testing/validation, and one which many stakeholders felt was very beneficial. Three case studies (ALPS, OSLO, IVEM) used a BBN within a GIS because the spatial locations were important for interpretation of the results, but generally these GIS/BBNs did not fully explore the spatial dependences within the BBN structures.

All case studies appreciated the value of the BBN to their work, but also recognised that developing the BBNs was not a trivial task, and local expertise was a very important factor in a successful implementation of a BBN. The BBN models were not only understood as a 'tool' for a decision-making (e.g. a managing authority choosing between alternative actions), but also as a tool that helps structure a decision-making problem. Using a BBN also allowed uncertainty to be explored explicitly and brought the quality of information available in support of a decision into focus.

On the other hand, populating the conditional probability tables was definitely challenging for stakeholders (and many researchers) and this was seen as a concern. The case studies generally would have benefitted from more guidance on elicitation and discussion of these types of values with stakeholders or stakeholder groups, rather than relying on the more common situation in the earlier stages of BBN development of getting values from experts, which then have less acceptance within the wider stakeholder community.

The decision scope of BBNs

The overall goal of the OpenNESS project has been a search for appropriate approaches, methods and tools to operationalise natural capital and ES concepts so that they can inform decisions at various scales; these range from the design of policy instruments (national), planning implementation (regional), to decisions made by land and water managers (local). These approaches need then to address the core characteristics of the ES framework including the modelling of socio-ecological interactions.

Several characteristics of BBNs made them an appropriate method for this purpose. BBNs had been used to model natural resource management systems (e.g. Frayer et al. 2014; McCann et al. 2006; McVittie et al. 2015), but these applications seem to have been mainly exploratory and kept within the research sphere. While many BBNs have been co-designed with stakeholders (e.g. Fletcher et al. 2014;

Mamitimin et al 2015; Schmitt & Brugere 2013), fewer have been used to support decisions directly. BBNs bring added value to the ES framework when used in this way, as they link support for decisions about the management and use of the natural resource with explicit modelling of the interactions in the socio-ecological system.

The experiences from OpenNESS show examples that move the application of BBNs a step further towards decision-making. All, but one, of the OpenNESS BBN case studies covered three of the four decision context categories (*Explorative, Informative and Decisive*) and this was given as one of the main reasons for selecting BBNs to operationalise the ES concept in their case study (Table 2), though these aspects were implemented to varying degrees.

Most case studies had a strong component of stakeholder interaction when developing their BBNs. The process of model building is initially very simple and transparent when discussing the structure of the system. In all cases, the BBN development promoted a common understanding between researchers and stakeholders of the reasons for the choice and role of the variables within the BBN, including the availability and quality of data and/or expert opinion, the critical elements in the decision-support chain, and the degree of complexity required to provide a satisfactory model. Therefore both the *Explorative* and *Informative* decision contexts were addressed simultaneously. Additionally, the process of co-production of BBNs promoted social learning about the role of ES within decisions, especially when stakeholders were able to use the web-based interfaces themselves to explore how alternative actions affect the outcomes.

The use of a BBN within the *Decisive* context was not fully addressed within the OpenNESS case studies, and this aspect has potential for further exploration. Several case studies (CNPM, LLEV, ALPS, OSLO, IVEM) developed an aspect of decision-making potential through valuation, though only the Oslo case studies approached a monetary valuation within a BBN. All had the longer-term goal of developing BBNs for decision support. However, the additional structure and information to move from a decision support tool to a decision implementation tool was lacking.

Four case studies (DANU, CNPM, ALPS, OSLO) identified that *Technical policy design* was an important factor. These were situations where close collaboration between the research community and stakeholders who were developing policy initiatives allowed an easy transfer of knowledge, with the development of the BBNs enabling that flow of information.

Finally, two additional BBNs (see Supplementary Material) demonstrate how the BBN can be used to create or manage useful information within a project. The classification example was *informative*, whereas the method selection BBN was *decisive*. Both were designed and implemented by experts and fulfilled their intended aims.

Further considerations of appropriate modelling of spatial processes

The experience from the case studies showed that the need to incorporate spatial structure to assess ES was very case dependent.

With the Glenlivit BBN (CNPM), the system is modelled for general conditions in the catchment and will not depend on a farmer changing the use of particular fields or the rainfall amount in a particular year. In contrast, in the Vercors case study (ALPS) the spatial element was very important in stakeholder discussion to make detailed local management decisions. While local spatial dependence in the data can come into the model through the GIS, the simple GIS/BBN combination used in Vercors will not resolve the BBN spatial structural dependencies. For example, the optimal management strategy for one forest parcel may depend on the outcome of a BBN somewhere else in the area. If so, the BBN structure would need to be more flexible and spatially dependent, an issue raised by scientists in the Patagonian (SPAT) case study. Information on neighbours can be used by including extra nodes representing properties of the surroundings, as was done in the city trees (OSLO) case study to allow the value of one tree in the city to depend on both where it is located and the number of surrounding trees.

Potentially more complex to resolve, is the dependence across the entire landscape of the value of ES delivery. For example, the economic value of a bird-watching area depends not just on the neighbouring locations but also on the number and relative accessibility of such locations across the region. The second location will tend to be less valuable than the first and the marginal value of additional bird watching locations will continue to diminish. This has implications for integrated spatial modelling of ES delivery and may lead to misleading assessments if not carefully estimated and modelled.

In the recent literature, Landuyt et al. (2015) developed a QGIS plug-in to promote the use of BBNs to model and map ES delivery, an approach also being implemented by HUGIN EXPERT. Landyut et al. discuss the appropriate presentation of outputs to reflect uncertainty, but the paper does not look at uncertainty with more complex spatial dependencies. In a different development, Chee et al. (2016) have an interesting prototype for extending a state-and-transition dynamic Bayesian network to model spatial and temporal changes, so partly addressing some of the issues mentioned above. Assuming that hierarchical structuring of ecological systems allows them to simplify the system of dependencies and that their assumed temporal links are indeed deterministic, then the paper is a proof of concept and provides a possible basis for addressing these issues more completely in the future.

These more complex, but quite typical situations, all require more specific spatial dependencies to be set up, and the problems of properly assessing the spatial covariances now needed for the conditional probability tables become much more challenging. None of the case studies in OpenNESS resolved this issue though some recognised that the models available to them at the time would not be adequate to represent the spatio-temporal dependences with future BBN developments.

In conclusion, a simple embedding of a BBN in a GIS will not resolve the spatial dependencies between the spatial structure of the ecosystem and the value of the services (e.g. Termansen et al. 2013). Just assuming that an over-simplistic model reflects the true situation is no solution, and without that extra work one of the major benefits of using a BBN to rigorously assess evidence will be lost.

5. Conclusions

BBNs were used in 9 case studies within the OpenNESS project by researchers and stakeholders with a wide range of previous experience. As it was a new methodology for many researchers, the initial use was to explore the capabilities. This was aided by one of the partners in the project, HUGIN EXPERT, a software company developing BBN software. Their web platform, providing interfaces to the BBNs developed in the project, proved to be very beneficial for stakeholder consultation. This is an important element for both the knowledge elicitation and the model testing phases of BBN development.

All case studies found that the BBN provided a useful approach to ES analysis and satisfied their *a priori* expectations, but that there were some aspects that could benefit from further development. The case studies used BBNs in different ways and the diversity shows the tool's flexibility with many potential roles in ES operationalisation. The BBNs delivered particularly well on three aspects.

- Firstly, the co-production of a BBN with stakeholders helped to generate a common understanding of the structures and the role of ES within decision processes, leading to social learning about the concepts as well as the tool itself.
- Secondly, the transparency of a BBN structure was important for stakeholders and researchers exploring the behaviour of the BBN for themselves and seeing how outputs reflect changes in the network.
- Thirdly, the expected fear of handling uncertainties did not become a major issue as most stakeholders working with a BBN recognised why uncertainties were important to the modelling and why it was important to understand the level of evidence in support of any conclusions.

However, these benefits came at a price in that BBNs continued to be seen as difficult to use and required specialist expertise. The case study examples highlighted that more work was necessary to resolve issues with the spatio-temporal modelling of more complex socio-ecological dependences, but also, more basically, that more targeted training of staff and some new software and interface developments would help to increase the BBNs usefulness in ES operationalisation.

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SUPPLEMENTARY MATERIAL

Additional example 1: classification of ecosystem services

There are now a number of different ways of classifying ecosystem services in the user community, including definitions outlined by the Millennium Ecosystem Assessment (MA) and by The Economics of Ecosystems & Biodiversity initiative (TEEB). At national scales, other systems have also been designed, as is the case of the UK National Ecosystem Assessment (UK NEA). A Common International Classification of Ecosystem Services (CICES) has been developed to help people navigate between these different systems, not as a replacement but to allow the easy translation between them, though it does then represent a new classification system in its own right. CICES was developed as part of the work carried out in Europe on ecosystem accounting (see Haines-Young and Potschin, 2013; Potschin and Haines-Young, 2016). It has also been taken up by the European working group on Mapping and Assessment of Ecosystem Services (Maes et al. 2012).

Given that different approaches start from different perspectives, BBNs were recognised as one way of representing the sometimes ‘fuzzy’ and often nested correspondences that exist between various systems. CICES provides a framework for classifying final ecosystem services that are dependent on living processes (i.e. ’biodiversity’). CICES is hierarchical in structure (Fig 10), with each level providing a more detailed description of the ecosystem service being considered. The hierarchical structure means that studies undertaken at different thematic and spatial resolutions can more easily compared. It also enabled a translator to be built, using the categories at the most detailed level in CICES, This classification is an output derived from expert opinion and is implemented as a deterministic model, though the CPT could be modified to include ‘fuzzy’ correspondences at a later stage.

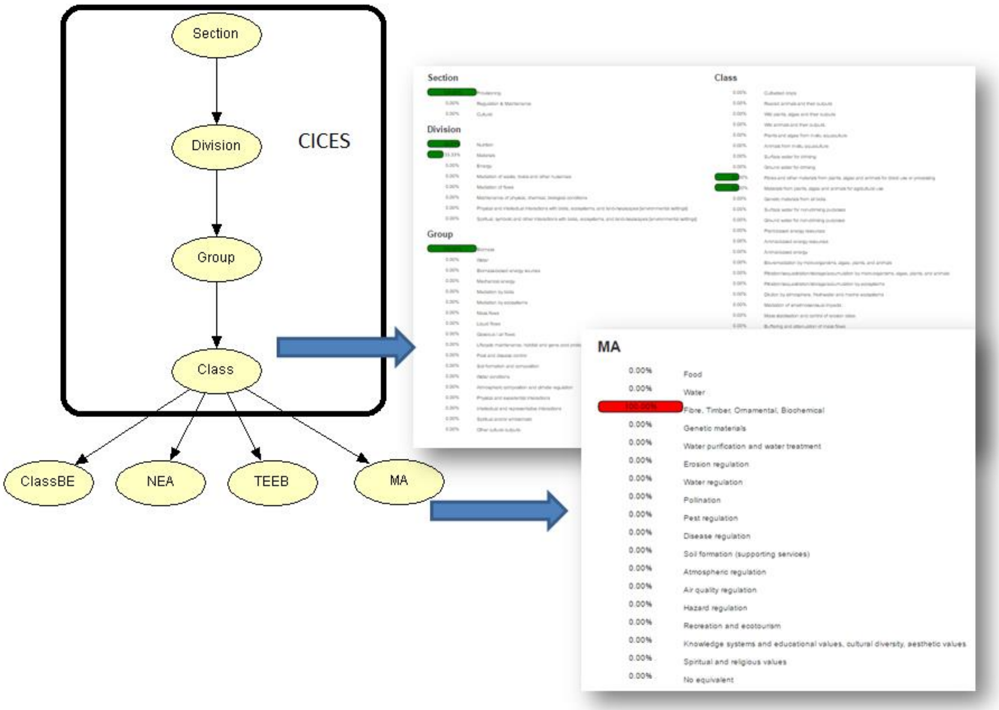

Figure 10. Structure of the ecosystem service classifier based on HUGIN; CICES Classes are used as the basis for translation between systems.

BBNs generally express the chance that a node is in a particular state as a probability. Here the probabilities merely indicate how likely you are to be taking a category in one classification given the category selected in another system, or at one of the higher levels in CICES. In the example of the web-based tool shown in Fig 10, the MA category for 'Fibre, Timber, Ornamental and Biochemical' materials has been selected, and the correspondence to two CICES classes is shown (Fibres and other materials from plants, algae and animals for direct use or processing, and Materials from plants, algae and animals for agricultural use). The web-based system was considered especially useful in this application. The prototype is being developed to include a wider range of ecosystem service typologies, including those arising from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), and the work on 'Final Ecosystem Goods and Services' being undertaken by the US Environmental Protection Agency (Landers et al. 2016).

Additional example 2: method selection

Oppla is a new online platform, provided jointly by OpenNESS and OPERAS (a related EU FP7 project), offering advice on the selection of ES appraisal methods. For this, OpenNESS designed a BBN as an expert system for users to explore the relevance of different ES assessment and valuation methods to their studies (http://openness.hugin.com/oppla/ValuationSelection).

This BBN is populated with method characteristics collected from ES assessment and valuation practitioners and builds on previous methodological expertise shared and tested within OpenNESS case studies during several training sessions.

The BBN method selection network can be used in two ways:

(1) Model selection support mode: the user selects method characteristics that are relevant for his/her context. The portfolio of tools that are relevant for those conditions will be shown online.

(2) Model description mode: The user opens an interface to the "BBN" network. The user can inspect the characteristics of each particular method and where the characteristics of the methods are uncertain a probability distribution is displayed.

The BBN method selection tool provides a further step beyond the decision-trees for users wishing to explore method possibilities and constraints more in detail.