# Developing local environmental decision tools using BBNs

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**ABSTRACT**

*Following the Millennium Ecosystem Assessment, the concept of ecosystem services promoted the idea of a holistic assessment of an ecosystem to inform environmental management. It can be difficult to put this idea into practice as the manager has to consider all aspects including the functioning of the environmental components and how these may react to change, as well as the social and economic context for any decision process. Different actors in any community have different perspectives on the exploitation of their surroundings and there are often many layers of environmental regulation reflecting the policy concerns of differing governance levels.*

*We propose the use of a Bayesian belief network (BBN) set within a decision support tool for local communities and individual land or environmental managers. While these users do not have access to the range of complex models available to policymakers and environmental scientists, they do benefit from local environmental knowledge and data. The BBN is set up with the user in the central position. The user constructs a network of the required complexity using an ecosystem services framework, so the basic graphical structure is enhanced by more specific detail relevant to the proposed decision. The user is also empowered to choose between data sources, using either their own local knowledge to build parts of the network structure or retrieving information from libraries of accessible general data resources. The tool exploits the advantage of a BBN allowing use of different types of information (including expert opinion) with various levels of uncertainty and tracks that statistical error into multiple outcomes, allowing transparency in balancing these values when making a decision. The decision tool also has the ability to flag regulatory constraints on any proposed course of action.*

*The aim of this decision tool is to exploit the BBN as a rigorous statistical method for pooling environmental, social and economic data and to develop the information sources to promote its use within local communities. Improved information and better local decision processes also benefit all levels of rural environmental governance.*

A decision support tool requires some agreement on the elements to be considered, the measures of these elements to be adopted and the methods used to analyse these measures.

Ecosystem services are the benefits people obtain from ecosystems, and quantifying these was promoted by the Millennium Ecosystem Assessment (MA) (MA, 2003; MA, 2005) as providing a holistic assessment of the value of the natural environment. The concept of ecosystem services can be applied to environmental decision-making generally at different scales and across scales, is conceptually simple, and embraces the full range of services of interest to all levels from local stakeholders to international policymakers. Ideally this concept identifies the elements and measures for environmental decision tools, but its strengths also amount to a major weakness: its all-embracing nature has made the operationalisation of the ecosystem service framework very challenging.

Different definitions and modified frameworks have been developed since the MA (for further discussion see Dick et al. (2011a) and Smith et al. (2011)) and attempts to operationalise an ecosystem services assessment range from the national scale UK National Ecosystem Assessment in 2011 (uknea.unep-wcmc.org) to more geographically constrained site or feature based ventures (Dick et al., 2011b; Mangi et al., 2011). Sectoral advances include frameworks reflecting ecological and social flows (Haines-Young et al., 2010) and improved application of economic assessment methods (Bateman et al., 2011), but these discipline dependent approaches can bias the focus of the assessment. Ensuring a balance of information between the ecological, social and economic sectors along with quantifying and linking uncertainty between the components remains a challenge for these transdisciplinary studies.

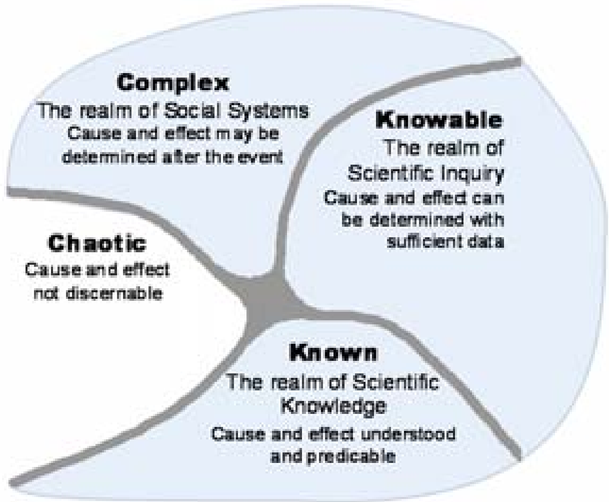
Statistics provides a range of methods to analyse dependencies and quantify uncertainty within the different elements of an ecosystem services assessment (Smith et al., 2011). Statistical graph theoretical methods have an obvious similarity to elements of the social and economic toolboxes, and there are a number of recent environmental applications of a particular directed acyclic graph, the Bayesian Belief Network (BBN): example applications include Hamilton et al. (2007) for ecological/environmental studies, Johnson et al. (2010a) for wildlife management, and Langmead et al. (2009) for socio-ecological modelling.

Bayesian graphical methods can be applied across the disciplines, have the structural flexibility to include the varied elements of an ecosystem services valuation and also track the uncertainties. This study therefore explores an application of this methodology to local scale environmental decision modelling.

## Environmental decisions

The management of the natural environment requires complex decision-making. Broadly speaking, both policy makers and local people strive to use the environment to obtain societal benefits in the short-term while ensuring that the capacity to obtain these benefits is maintained in the long-term. This principle of sustainable use of the environment, however, faces several major challenges, including failure to consider the long-term consequences of actions taken over the short-term due either to lack of knowledge of these consequences or to economic or policy drivers that promote unsustainable use of natural resources (Ring et al., 2010; Klug and Jenewein, 2010). Most environment-related decisions are taken or implemented locally, so the scalability of expected outcomes from the policy level to local land use decisions is important.

***Figure 1:*** **The Cynefin model (areas highlighted to be included in a local decision support tool)**




(modified from Snowdon, 2002)

The local land manager has to consider all aspects of their ecosystem including the functioning of the environmental components and how these may react to change, as well as the social and economic context for any decision process. Different actors in any community have different perspectives on the exploitation of their surroundings, and there are often many layers of environmental regulation reflecting the policy concerns of differing governance levels. When faced with an assessment of any complex environmental impact of land use change and recognising that the human brain has limits to its cognitive capacity, the need to decompose the system into many subsystems, consider each separately, and then assemble an overall synthesis is well recognised (French and Geldermann, 2005). For land use decisions a generic core structure can be chosen to handle this complexity with detailed analysis in sub-models and associated data which are case specific.

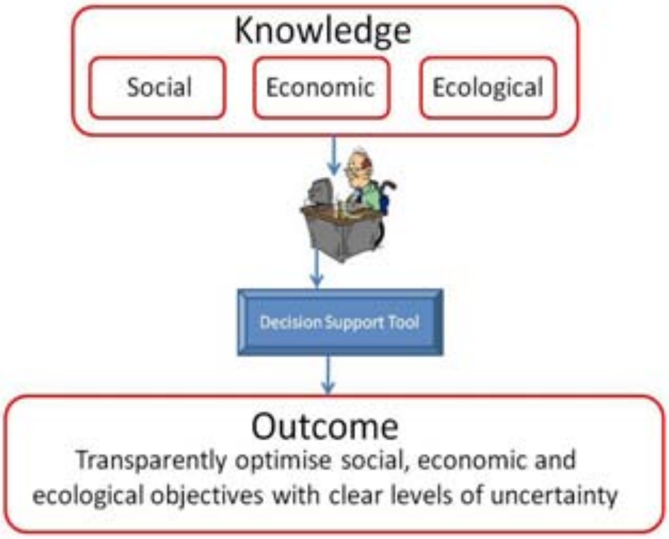
Decisions may have to be made with less than perfect knowledge, and the Cynefin model is useful in this respect as it clearly identifies four decision spaces (Snowdon, 2002) (Figure 1). In the known space, cause and effect are completely understood and decisions relate to actions the consequences of which may be completely known and accurately predicted e.g. planting a woodlot results in a 1:1 substitution so that less land area is available to plant crops. Cause and effect are also understood in the knowable space, but insufficient data are immediately available to make complete forecasts of the consequences of an action, e.g. the crop yield loss associated with planting a woodlot can be predicted from the area of land lost, but there may also be losses from shading effects or predation from an increased bird population using the woodlot as shelter. In the complex space there are so many interacting causes and effects that predictions of system behaviour are affected by a wide range of uncertainty. Decisions must be made without a clear or complete understanding of their potential consequences, e.g. some local residents may view the creation of a woodlot as a valuable landscape feature while for others it may block their view of the wider landscape or create shade in their garden. Finally in the chaos space things happen beyond previous experience and there are no perceived candidates for cause and effect, e.g. an unexpected earthquake or landslide at a specific location. For local land use decisions it is likely the complex space will not be parameterised well and the chaotic space will be omitted. The analysis highlights that different types of decision-making are appropriate in these differing decision spaces and that the very different levels of informational uncertainty should be recognised.

## Transactional Environmental Support System

The Transactional Environmental Support System (TESS) project, funded under the EU Framework 7, seeks to improve environmental decisions at a variety of spatial scales by giving broader access to the wide range of environmental data and models available. The project studied information flows through governance structures, identified many sources of environmental information, and developed mapping and other tools to allow user access and manipulation facilities. A systematic analysis of stakeholder needs and available tools concluded that, due to conceptual inconsistencies, pipelining of all simulation tools to a universal environmental supermodel is impossible. Recognising that decisions are made by individuals, groups, and organisations at local, national or international levels, the ethos of TESS is to bridge the gap between these types of decision maker by providing the knowledge necessary for each to make sound, explicitly justified and transparent decisions within agreed societal aspirations. Therefore, now with the emphasis more towards local rather than national decisions, the challenge became how to bring this information together allowing non-experts (e.g. local communities and individual land or environmental managers) to use a spatially-aware decision-support expert system to assist with assessing proposed changes in environmental management using current technology.

A framework for land use decisions is envisaged where the user is positioned squarely in the middle of the system (Figure 2). The user will drive the process by selectively determining the variables (data and model outputs) and the information sources to be included in the decision support process. While these users may not have access to the range of complex models available to policymakers and environmental scientists, they do benefit from local environmental knowledge and data. Therefore the user is empowered to choose between data sources, either using their own local knowledge to build parts of the network structure or retrieving information from libraries of accessible general data resources. When individuals consider some data or processes irrelevant from their perspective, they may be prompted to further consider this omission if it raises an important consideration from the wider societal perspective or it may breach any regulatory constraints on the proposed course of action. Through these choices the user will construct a Bayesian belief network of the required complexity, so this process will build from a basic graphical structure to enhance it by more specific detail relevant to the proposed decision. The tool exploits the advantage of a BBN allowing use of different types of information (including expert opinion), pooling environmental, social and economic data with various levels of uncertainty, and tracking that statistical error into multiple outcomes so allowing transparency in balancing these values when making a decision.

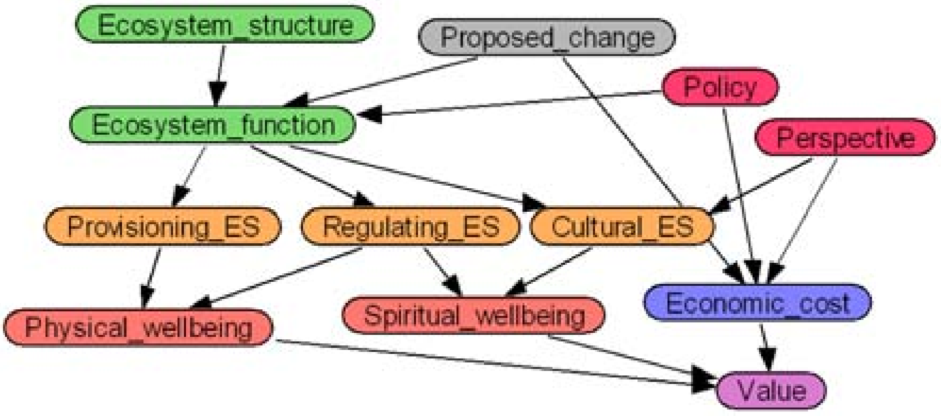
***Figure 2: Schematic of the decision framework***




As discussed earlier, the measures and processes within the framework are based on the ecosystem services paradigm. Not only is this approach at the heart of policy on land use, but it provides the convenient structure where this environmental decision tool can (i) capture the diversity of costs and benefits, (ii) explicitly recognise the conflicts that may arise, and (iii) include constraints like a requirement for sustainable use of the environment (operating at multiple scales).

**Developing a generic BBN structure**

***Figure 3: Generic land use decision BBN***




The generic approach adopted for the BBN used in this local decision tool came from a series of meetings considering the quantification of ecosystem services at long-term monitoring sites in the UK and Europe. In it the relevant functions of the ecosystem are considered but brought together where possible to construct broad categories. The links in these diagrams will vary depending on the decision, but the basic framework shows that proposed changes within a policy context will affect ecosystem function and economic costs. The MA categories of provisioning, regulating and cultural ecosystem services are outputs from ecosystem function combined with other influences, for example there may be a personal perspective which does not value a particular service highly while others take an alternative view. The summary outcomes are measures of physical and spiritual well-being and these combine with economic considerations to provide a value, which may be a single or a multiple metric.

The approach taken is to simplify as much of the top layer of the BBN as possible, so keeping the computational burden down, but allow for sub-nets (see Johnson et al., 2010b) or lower layers where more detailed calculations can be incorporated.

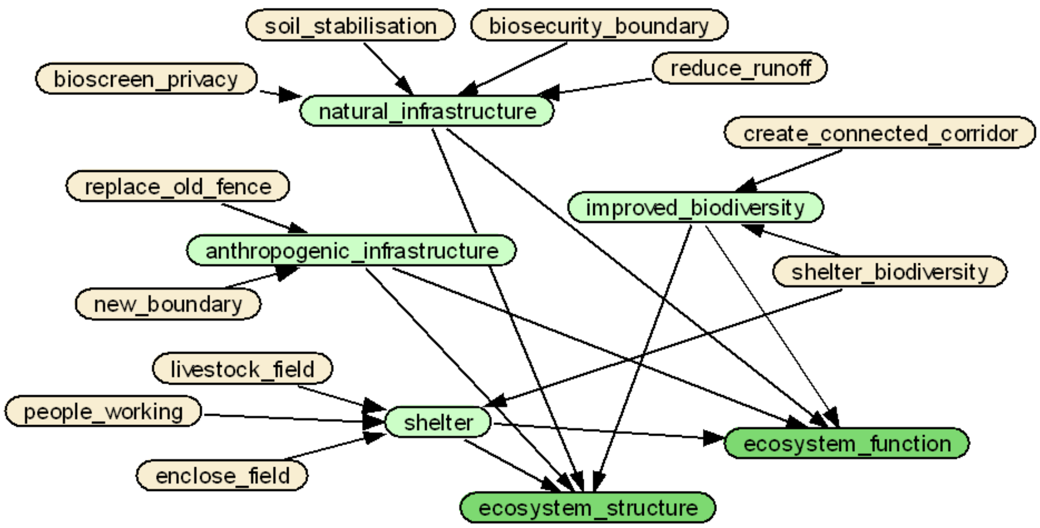
## Test case using farm decisions on planting hedges

A simple test case was derived to test how such a model may be applied in a local decision context. A number of farmers were consulted on the decisions they made on planting or not planting hedges – at present there are subsidies in the UK for hedge planting for improved environmental stewardship and so this decision interacts with a policy desire. Information was collected on 231 potential hedges on Scottish upland farms and another 40 hedge decisions on a contrasting English mixed farm.

Around 50 different issues were raised by the farms as reasons for planting or not planting hedges, but there were several related variables so some grouping was desirable. Primary variable groups were linked to shelter, natural infrastructure, anthropogenic infrastructure, and ease of management which were joined by economic support through policy and improved biodiversity habitat as a stated aim of policy. One of the challenges of this decision analysis is to consider how far the personal perspectives on biodiversity of individuals in the farm business affect their value assessment of that component of the decision. In Figure 4 part of the greater detail is illustrated with components of the decision variables for some of the groups. For example, the variables that affect the value of improved shelter may include whether or not a field is used for livestock, if enclosing a field is a positive benefit, or if it helps people working in the area. Some variables may affect the value in more than one group node and there can be conflicts within a node – for example some birds benefit from tall hedges while these can be detrimental to other bird species.

The illustrated hedge decisions in Figure 4 feed into the assessment of value of ecosystem structure and ecosystem function. Since there are policy, management and economic consequences of hedge planting, the variables collected will also feed into other nodes on the generic BBN (Figure 3). The preliminary analyses show that there is no single important factor in these decisions, and in discussions with farmers it was clear there is far more local detail required to predict their specific decisions than was possible or useful to capture for analysis. This effectively becomes part of the uncertainty in the decisions, further emphasising the requirement for any decision tool to track the levels of uncertainty through the network.

***Figure 4: BBN to explore decisions on hedge planting***



## Conclusions

The ecosystem service approach implemented within a Bayesian Belief Network framework was helpful in identifying the information required and the linkages for the hedge planting study. As expected, it rapidly transpired that there were some core ideas, though expressed in different ways, which drove the decision process. One challenge in deriving a decision tool for local scale application is to ensure simplicity and transparency, so looking at parts of the problem initially and reducing redundancy has a positive benefit. The BBN can provide a degree of clarity and it can be used both to simplify the structures and to inform the user of the confidence they should place on the outcome.

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