Extending a Bayesian Belief Network for ecosystem evaluation

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Abstract

This paper explores the use of a Bayesian Belief Network (BBN) to model ecosystem services valuation. It links the stages of the process from the functioning of the natural ecosystems through the delivery of service to the human stakeholders to the valuation stakeholders put on the service delivery. The BBN is a graphical decision tool with nodes representing the states of the system and links encapsulating the evidence for dependence between parent and child nodes. A BBN differs from other decision tools because it uses probabilistic reasoning throughout, and so these networks can propagate uncertainty and can adjust for differing spatial and temporal scale dependences. The framework has been developed through application to case studies and through consideration of the requirements of one of Scotland's National Parks. Further developments to improve the use of the tool for ecosystem services and environmental impact assessment are discussed.

Keywords: Integrated framework, environment, ecosystem services valuation

1 Introduction

The concept of ecosystem services (benefits humans obtain from ecosystems) is recognised as a useful conceptual framework at global, regional and local scales to enable assessment of human-ecological systems (EEA 2006, MA 2005). The approach has been used in numerous national and regional studies: for example, in Europe the Joint Research Centre (JRC) of the European Commission provided a refined European Assessment of ecosystem service provision (Maes et al. 2011) while the UK National Ecosystem Assessment (NEA) was the first analysis of the UK's natural environment in terms of the benefits it provides to society (www.uknea.unep-wcmc.org). At the local scale Dick et al. (2011) used the concept to compare the human benefits delivered by 11 sites in the UK including a 200 ha farm in middle England, a 1000 ha nature reserve site in Scotland and a 1120 ha mountain site in north Wales.

The analytical framework of the ecosystem service concept is based on the dynamic systems approach linking indirect drivers (e.g. economy, demography, policy) and direct drivers (e.g. land management) to ecosystem changes, and linking ecosystem changes to ecosystem service changes and consecutively to human well-being (Collins 2012, Rounsevell et al. 2010). As such the ecosystem service concept is important to aid local management decisions as well as policy. A number of tools and models have been developed in support of the integration of human and ecological systems either in support of policy impact assessment or decision support systems for managers (Helming et al. 2011; Van Ittersum et al. 2010, Melbourne-Thomas et al. 2011)

It is well recognised that the human brain has limits to its cognitive capacity. When faced with an assessment of human-ecological systems it is difficult to rely on holistic judgement alone to predict and evaluate consequences. Rather, in decision theory, the need to decompose the system into many subsystems and consider each separately before then assembling an overall synthesis is well recognised (French & Geldermann 2005).

Integrated assessment of ecosystem services is hampered by the many uncertainties we have about how ecosystems function and how they will respond to external changes. Furthermore, only some of the external changes themselves are under human control - through management - whereas others such as climate change are beyond the control of local managers and cannot be predicted accurately. These external and internal uncertainties force us to use a statistical approach in our studies, in which all uncertainties are represented by probability distributions. Statistics provides the tools for manipulating such distributions, and key here is Bayes' Theorem which is used for updating probability distributions when new information arrives. Bayesian Belief Networks (BBN) allow us to graphically represent the uncertain variables, both external and internal ones, that we consider in our study, as well as the uncertain cause-effect relationships between them. Because the ultimate aim of ecosystem assessment is to assist in decision-making, a Bayesian approach may be particularly apt as human beings have been shown to update their opinions and form their decisions by combining information in a largely Bayesian way (e.g. Lange & Dukas 2009).

In this paper we explore the value of BNNs as a tool to identify influential ecosystem components and to link together the elements of an ecosystem services assessment.

2 Bayesian belief networks

Graphical models represent variables as nodes, with links between nodes showing the influence of one variable on another. Bayesian belief networks (BBN) are a class of directed acyclic graphs where these links have a direction (from “parent” node to “child” node) showing the flow of influence through the system being modelled, and where there are no closed loops so that no node can influence itself. With a further development into dynamic BBNs the use of time steps allows for the representation of feedbacks so overcoming the acyclic constraint, though this is not a wholly satisfactory solution to the problem. The conditional probability structure within a BBN allowed the development of efficient computing algorithms for inference and learning, and hence their recent applications to decision problems.

The Bayesian approach allows the linking together of quantitative and qualitative information as well as expert knowledge within a model, and so there are strong attractions for this approach when a holistic ecosystem assessment is required. A Bayesian network differs from alternative expert system approaches to decision analysis including rule-based decision trees, the use of fuzzy logic, or neural network representations by its use of a rigorous probabilistic methodology to handle uncertainty within the framework (see, for example, Spiegelhalter et al 1993, Smith 2010).

BBNs have been successfully applied in the social sciences proving very helpful in looking at scenarios and eliciting responses in participatory meetings (e.g. Chan et al. 2010). They also have been used in setting up elements of ecological models. Amstrup et al. (2008) forecast the future status of polar bears by using four arctic ecoregions where modelled climate change and sea ice projections were combined with a range of population stressors. Hamilton et al. (2007) generated an ecosystem function model for the risk of algal blooms and to identify significant knowledge gaps, while Johnson et al. (2010) develop an integrated Bayesian network to bring an ecosystem function BBN including a process-based simulation model and an environmental management BBN within an integrated structure (see Smith et al 2011 for further examples). Therefore it does seem to have potential to bridge disciplinary boundaries and to be an integrating tool which can be used to link together the individual components of an ecosystem evaluation, which has already been done within some ecosystem services studies (e.g. Haines-Young 2011).

Developing a BBN

The developments of nodes and links within a BBN will be illustrated with two elements of a farm scale ecosystem services valuation based on a livestock enterprise. One element of the ecosystem determining the level of ecosystem services provided is the area of productive grass sward, here assumed to rely on available nitrogen and on the rainfall amounts as reflected in soil wetness. The area of productive sward will help to determine the livestock numbers for the farm which directly affect the amounts of ecosystem services delivered.

Figures 1a to 1c illustrate how a BBN can be developed to capture elements of this ecological function: using equations for processes (Fig. 1a); building in an element of uncertainty (Fig. 1b); adding extra terms including management (bought fertiliser) and weather (rainfall leading to soil wetness) to the prediction of areas of productive sward, as well as identifying a potential violation of regulation (Fig. 1c).

Figure 2 shows an example of a BBN more related to a decision tool application with combinations of a small number of states in each parent node producing changes in the child node states, and it does not interpret an underlying model. This type of relatively simple relationship between parent and child nodes is readily applicable to many socio-economic studies, such as Langmead et al. (2009) where BBNs were used to model socio-economic drivers in the north-west Black Sea.

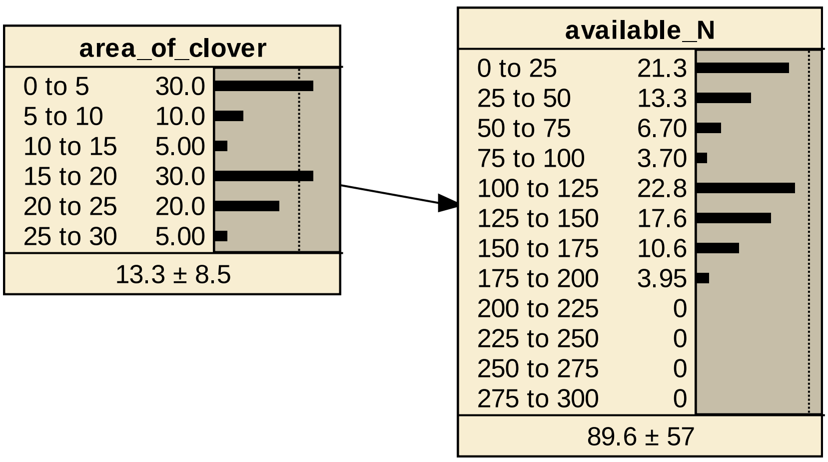


Fig. 1a. Graphical representation of two linked nodes with numbers and bar graphs showing the distribution of beliefs (probabilities) of occurrence of that state as a percentage. The link between the area of clover (expressed as a percentage) and the available nitrogen for the grass (kg N ha^{-1}) is set up as an equation where each 5% of clover cover results in 33 kg N ha^{-1} of available nitrogen. When the program randomly samples from the category 0% to 5% clover then the results will be spread between the two categories of 0 to 25 and 25 to 50 kg N ha^{-1} available nitrogen.

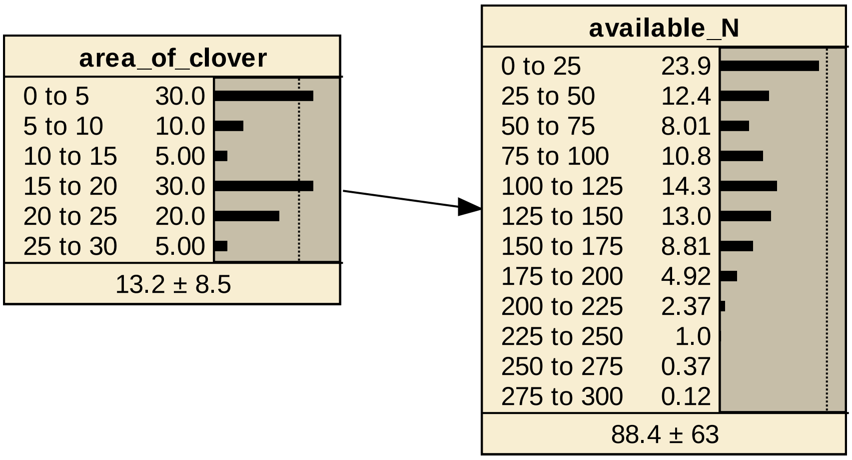


Fig. 1b. As there is no exact relationship between % cover of clover and the amount of available nitrogen produced in the soil, an element of uncertainty is introduced by using a Normal distribution with a standard deviation as 25% of the mean. The distribution of probabilities for available nitrogen is smoother than in fig. 1a.

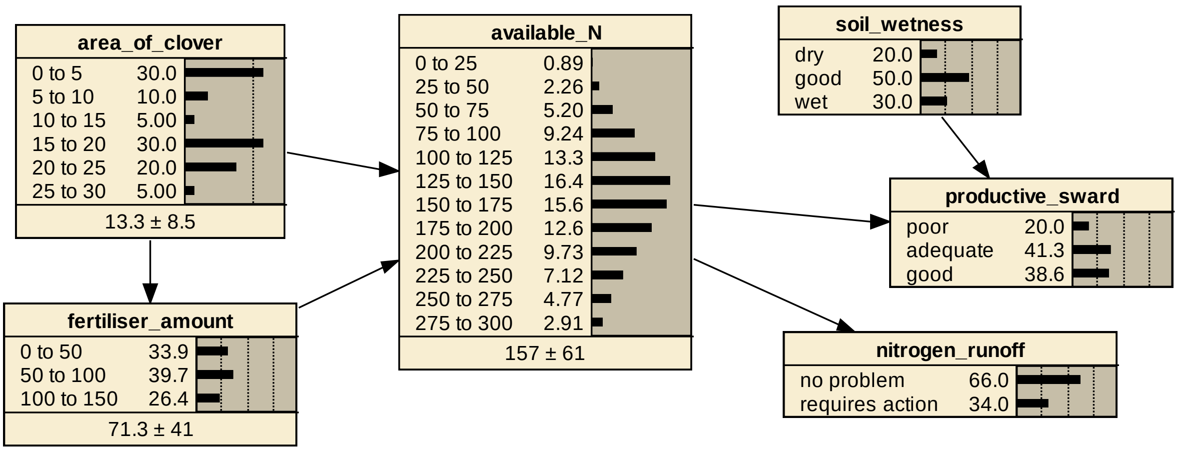
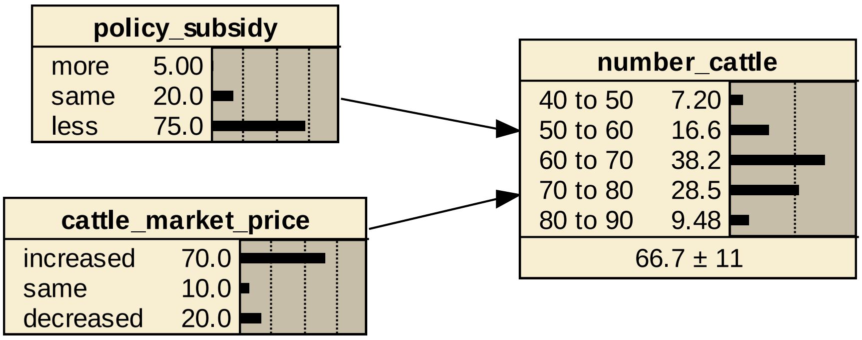


Fig. 1c. A second source of nitrogen is from bought fertiliser, and it is assumed that the less clover visible on the pastures the more fertiliser might be bought. However, in this simulation, the bought fertiliser is applied randomly so does not have the desired effect of generally bringing up the available nitrogen to the target of between 100 to 200 kg N ha^{-1} for productive sward, and it also generates a problem with nitrogen runoff. An extra node in the BBN to apply the bought fertiliser correctly is required. The soil wetness reflects the chances of drought and excess rainfall and this also affects the predicted area of land within the poor, adequate and good categories of productive sward.



policy_subsidy	cattle_market_price	40 to 50	50 to 60	60 to 70	70 to 80	80 to 90
more	increased	0	0	10	20	70
more	same	0	0	25	70	5
more	decreased	0	20	70	10	0
same	increased	0	0	5	45	50
same	same	0	5	90	5	0
same	decreased	30	60	10	0	0
less	increased	0	10	50	40	0
less	same	0	15	85	0	0
less	decreased	40	50	10	0	0

Fig. 2. A simple BBN with two input nodes for possible changes to cattle subsidy and cattle market prices. These relate to how many cattle are on the farm assuming a current baseline number of 65. The user can choose how likely they think these changes may be by altering the probabilities in the parent nodes policy_subsidy and cattle_market_price. The conditional probability table (CPT) for the node number_cattle is shown. Note that the CPT rows have to add to 100, so every combination of parent node states (in rows labelled down the left of the table) must end up in one of the child nodes states (columns to the right of the table). As example, if the subsidies and market prices stay the same, there is a 90% chance the cattle numbers will be in the same class and 5% chance for each of the outcomes that they will have moved either up or down by one class. If these probabilities were all either 100% or 0% then there would be no uncertainty in the outcome of combinations of two parent node states, so the BBN outcome would be the same as for a deterministic or rule based decision process.

3 The farm-scale Bayesian belief network

A BBN that is more representative of a farm scale tool is illustrated in Figure 3. The notional farm is a livestock enterprise within the Cairngorm National Park in Scotland, with sales of cattle and sheep providing the main income but with some diversification into tourism. The focus of the BBN (Figure 3) is on three ecosystem services, but this substantially underestimates the number of recognised ecosystem services likely to be supported by the farm's management strategy. A truly holistic ecosystem assessment for a notional farm in this area would likely value the delivery of more than 50 services.

The drivers of the system are from policy and current markets, with good stewardship covering a desire for good practice in both the farming and environmental aspects of the enterprise. Land allocation covers both the geographical aspects (what activities occur where) as well as the financial aspects, so an investment in tourist accommodation includes both the land use and financial implicationss of building or renovating cottages, for example.

The chosen ecosystem services present different challenges for valuation. With the debate continuing on the use of monetary and non-monetary metrics, this BBN has multiple endpoints at present so it is developed as a decision support tool with endpoints using possibly different ecosystem services value systems. The extension to a decision tool with a single endpoint, where the relationships between values would have to be defined, is technically straightforward. Valuing the provisioning service, using the terminology of the Millennium Ecosystem Assessment (MA 2003), of food production in the form of meat or livestock sold is possibly the easiest in that there is a market system to value the product. The cultural service labelled good environmental condition is more difficult to assess, because part of the service is an income stream for the farm and part is a contribution to the feel-good factor of living in the area. Clearly it is possible to reduce the service to just the economic benefit, but in discussions with residents of the area that does not properly represent the service. The service of visitor experience of the area has been separated off because it is definitely not part of the farm income stream (though there will be costs for maintenance of paths, etc.), and many visitors to the tourist attractions in this landscape never have contact with the land owners and managers so their ability to value that service is limited. In this case the use of re-scaled regional or national data, if available, would be helpful. Assigning values to these services could either be incorporated into the nodes as shown in the graph, or the nodes could reflect the quantity of the service and a second stage would be assigning values using an extra set of nodes. This could be done by using the CPT directly (as in Figure 2), by setting up a model using simple equations (as in Figure 1b), or by developing a subnet underneath the new node.

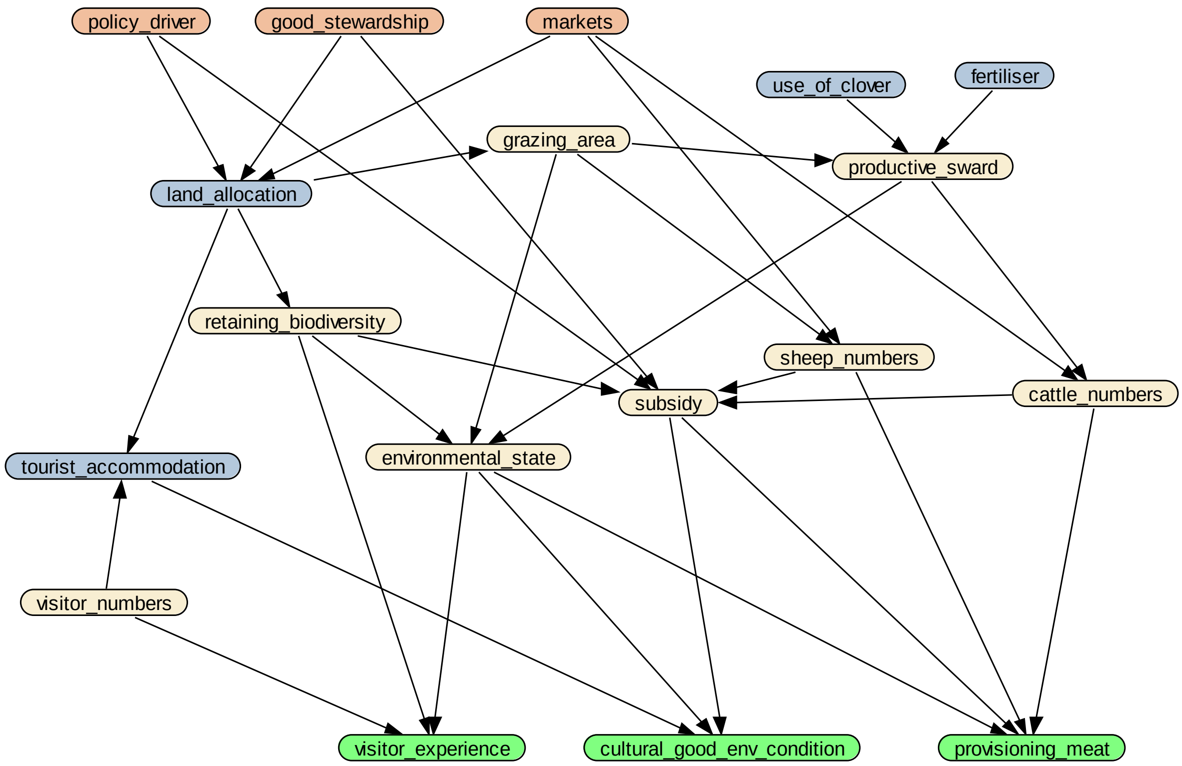


Fig. 3. Potential BBN for assessing changes in values of ecosystem services on a farm.

The quantification of the links in the BBN is only different from entering values into other decision support tools in that there must be some assessment of uncertainty. On the farm, therefore, a lot of the economically related data are available for a range of sources such as farm accounts, market reports, agricultural support policies, etc. with supporting information from standard agricultural and environmental models. However it is easier to estimate the effect of clover on available nitrogen than the change in biodiversity from an increase in migratory bird numbers following land management changes. The latter has a lot of potential interactions with unknown drivers elsewhere, but this can be incorporated into the BBN by either putting on a larger estimate of uncertainty or by inserting a subnet to look in more detail at that response. The BBN can use expert opinion where data are not available and again the uncertainty must be quantified. However there are a range of sensitivity analyses available to identify the nodes within the network which have more or less influence on the outcomes, so that further knowledge acquisition can be targeted to improve the usefulness of the tool for decision support.

4 Regional policy

Within Scotland, the government sets the framework for rural policy in terms of legislation, institution formation and policy implementation, but in some areas such as the Cairngorm National Park there is a Park Authority that develops a National Park Partnership Plan (NPPP, see www.cairngorms.co.uk/park-authority/national-park-plan/cairngorms-national-park-plan-2012-2017/) to guide all public bodies operating in the Park. This is designed to deliver a place-based approach to management that crosses organisational remits and delivers multiple benefits. One element of the plan is to have research to support an ecosystems approach to management and clearly an ecosystem services assessment tool could play a major role in these developments.

The Scottish Government has a policy to increase forest cover across the country and there is a Scottish Forestry Strategy (www.forestry.gov.uk/sfs) developed by the Forestry Commission. Within the Cairngorm area, woodlands figure prominently in the new NPPP, but the Park Authority has rather limited capacity to reconfigure grants and subsidies to provide the necessary incentives for landowner engagement, and relies on partners either using national grants and subsidies to best effect, or tailoring their use, to deliver National Park policy.

In preparation for the 2012-2017 Cairngorms NPPP and as an extension of the NorTosia project in the area (www.northerntosia.org/portal/case_study_in_scotland/), the Forestry Commission scientists used GIS-based sustainability impact assessment tools to identify opportunities for forest expansion within the park. The rule-based approach to a spatial plan provided hard boundaries indicating areas where forest expansion was potentially desirable, and provides a valuable basis to start to tailor and target discussions with land managers and government support. Taking this further, developing an ecosystem services approach using a BBN to assess uncertainty would identify where the flexibility exists in interpretation of these maps. There is further benefit in that these softer boundaries could aid the subsequent negotiations between different local stakeholders.

The BBN (fig. 3) developed at the farm scale did not have a forestry component, but an extra node could be included as a child of the land_allocation node (fig. 4) and the benefits of the forest establishment in terms of forest products, extra winter shelter for cattle, etc. modelled. This modification (fig. 4) would allow for exploring the scenario of forest development as proposed in the NPPP to see if these changes would be appropriate to this enterprise.

The process of developing the BBN at the National Park scale is no different to that used for the farm. The National Park will be interested in a wider range of ecosystem services than most individual land management units, so would be expected to have a different emphasis. For example, there is a winter sports and mountaineering industry in the area which may have a marginal effect on some farms but will not be a main component of their assessment of ecosystem services. A National Park Authority will also have easier access to some types of data than the farmer, so regional surveys on visitor experience will, for example, fit within the National Park assessment while data on the visitor experience of tourists passing by a farm is likely to be less complete and more anecdotal. The valuation of some ecosystem services can only be considered at a district or regional level. For example, the effects on a river of nitrate runoff or flood management schemes is a cumulative effect of the actions of all land managers in the area and there will be economic trade-offs and possibly environmental interactions between the different management units.

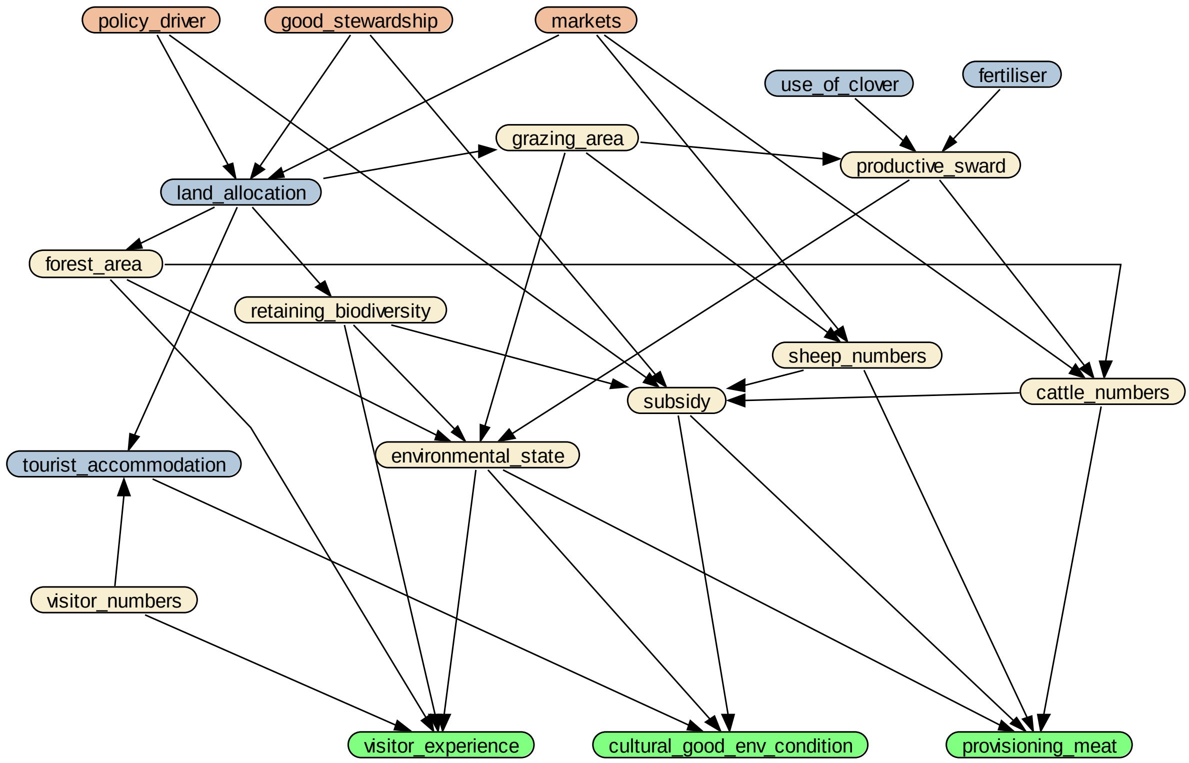


Fig. 4. BBN for assessing changes in values of ecosystem services on a farm with additional node for forest expansion. As the total area of land is fixed, an allocation of land to forestry would reduce the land available for other farm activities, with the node land_allocation including a constraint to ensure that occurs.

The challenge for the use of ecosystem services at different land management levels, as illustrated by the farm and National Park scales here, will be to ensure a consistency of approach with models and data across geographic and temporal scales. The BBN is a flexible tool with the potential to provide that consistency to ecosystem services valuation.

5 Discussion

Ecosystem services and impact assessment

The ecosystem services concept promotes a holistic approach to understanding how ecosystems function and how humans interact with ecosystem services. In a more general, policy-related arena, the UK Government in its Impact Assessment Toolkit (www.bis.gov.uk/assets/biscore/better-regulation/docs/i/11-1112-impact-assessment-toolkit.pdf) states that "An Impact Assessment is both:

(i) a *continuous process* to help think through the reasons for government intervention, to weigh up various options for achieving an objective and to understand the consequences of a proposed intervention; and (ii) a *tool* to be used to help develop policy by assessing and presenting the likely costs and benefits and the associated risks of a proposal that might have an impact on the public, private or civil society organisation, the environment and wider society over the long term". In both cases when applied in an environmental context, any tool for either ecosystem services valuation or impact assessment must link together and assimilate a lot of information from a variety of sources. The reduction of the investigation to just those elements easily quantifiable by the assessor is a danger, particularly obvious in the ecosystem services applications where interdisciplinary assessment is required but may be difficult to deliver. A Bayesian approach has the ability to perform this linking of different elements of the assessment with the ability to track uncertainty (and hence use information of differing quality with confidence) and so makes it well suited to provide the framework for either type of assessment.

An impact assessment implies that some change is being contemplated. Though this is not necessarily true for an ecosystem services valuation where a static assessment of natural capital may be desired, generally information is being gathered which will form part of a policy development or decision process. As BBNs can be a decision tool, their use for the linkages within an assessment helps to take forward the information content in a structured fashion.

Scale and complexity

Two important considerations when developing more complex BBNs for ecosystem services assessment are (a) identifying the boundaries of the ecosystem and (b) deciding what nodes and links to include. This is illustrated by the discussion of the differences between the focus of the farm and national park examples. The statistical philosophy tends to favour parsimony, so the reduction of the network to the smallest size that performs the task well is the usual aim. On the other hand, the developments of BBNs within the artificial intelligence community do not take this approach, but rather include all links and nodes that might occur and then let the data decide how the network is structured; however this requires a large volume of data which is not generally the norm in ecological studies.

A BBN can be seen as a model of our incomplete knowledge of a system. It is a graphical model that represents a network of causal relationships between variables as a joint probability distribution. In other words, a BBN is a probabilistic model. This makes it hard to assess the quality of a BBN, because even observations initially deemed improbable will have some positive probability in the BBN. Therefore the model cannot be falsified. However, the strength of BBNs is that they are self-correcting: the conditional probability distributions are adjusted after each arrival of new data.

Therefore in ecosystem services applications, BBNs are models to describe the links between different elements of an ecosystem assessment and they will be tuned to individual application, so the National Park BBN will differ from the farm BBN in its boundaries, nodes and links. The Bayesian methodology allows for development of hierarchical models to transfer information across spatial scales, and this is a research development that would benefit the application of BBNs to ecosystem services. One positive aspect of the graphical approach in BBNs is that the transparency of the process allows individuals to clarify what information is included and what is required, so it also becomes a tool for extracting relevant further information. As new data become available the BBN can easily be updated so it's a tool which can accumulate information and improve the quality of ecosystem services assessments.

The relationship between a BBN and an ecological process-based model

Dynamic, process-based models (PBM) are used in many ecological studies to explain or predict the behaviour over time of soil-plant-atmosphere systems and their response to natural or anthropogenic environmental change, including management activities (e.g. Fontes et al. 2010). The relationships between variables in both PBMs and BBNs represent causality. PBMs allow, like BBNs do, representation of uncertainty, by assigning probability distributions to the models' parameters or structures - and Bayesian calibration can be employed to update the distributions when new data arrive (Van Oijen et al. 2005). However, there are important differences between the two modelling approaches. PBMs tend to represent causal relationships between variables in much greater and more mechanistic detail than BBNs do and this allows them to simulate feedbacks that dampen or strengthen the response of the system to environmental perturbation. Such feedbacks could be represented in BBNs as well, but at the cost of increasing the number of nodes and the more so when multiple timescales are considered. BBNs are not convenient tools for simulating time series. On the other hand, BBN are the more flexible tools when our mechanistic knowledge of the system is limited, and when all we can say is which variables affect each other without knowing exactly how and by how much (Reckhow 1999). BBNs are also the easier tool to use when the study requires combining information relevant to different spatial scales, for example by having regional policy decisions affect local management choices.

When a new BBN is designed, the relationships between its variables and their conditional probability distributions tend to be based on expert information rather than measurement or calculation. However, synergy with PBMs is possible in those cases where the variables linked in the BBN correspond to input and output variables of a PBM. PBMs might then help to quantify conditional probabilities. An example is the relationship between fertiliser input and productivity, which may be linked directly in a BBN but through complex physiological mechanisms in a PBM. In such cases we can explore the parametric uncertainty of the PBM to generate the conditional probability distribution used in the BBN.

Linking sciences to policy application

The models presented in this paper are considered at the level of the local land manager and on a regional policy scale. They start with uncertain science, as we cannot predict exactly how an ecosystem will respond to a change, and then move through to the human-environment interface in terms of services delivered, followed by various elements of societal response and valuation. Decisions are made using the information available at the end of the process, but the process is similar whatever scale is being used from the farmer through to the government department.

The BBN tools however have the basic characteristics needed for scientific tools to be useful and acceptable in the policy making process i.e. accuracy, relevancy, and legitimacy (De Smedt 2010). The transparent assessment of uncertainty afforded by the BBN has direct relevance to the practitioner understanding the accuracy of the results. The framework supported by the BBN is equally applicable to an ecosystem evaluation for services or for impact assessment.

This paper has shown examples of how a BBN could be applied at the local and regional level and Haines-Young (2011) showed examples of applications at a national level. The BBN technique is flexible enough to accommodate many more spatial scales, variables and interactions than have been shown. However further work on the combination of scales within a single BBN and on changing scales to allow different BBNs to be connected would be valuable to develop the tool’s potential.

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