Environmental Research 144 (2016) 15–26

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Spatial Bayesian belief networks as a planning decision tool for mapping ecosystem services trade-offs on forested landscapes

Julen Gonzalez-Redin [a], Sandra Luque [b,c,*], Laura Poggio [a], Ron Smith [d], Alessandro Gimona [a]

[a] The James Hutton Institute Craigibuckler, Aberdeen, AB15 8QH Scotland, UK
[b] University of St Andrews Centre for Biological Diversity (CBD), St Andrews, Fife, KY16 9ST Scotland, UK
[c] IRSTEA, National Research Institute of Science and Technology for Environment and Agriculture, France – 2, Rue de la Papeterie, Saint-Martin-d'Heres cedex 38402, France
[d] Centre for Ecology and Hydrology Bush Estate, Penicuik, Midlothian, EH26 0QB Scotland, UK

ARTICLE INFO

Article history:
Received 5 May 2015
Received in revised form
4 November 2015
Accepted 7 November 2015
Available online 18 November 2015

Keywords:
Spatial Bayesian belief networks
Ecosystem services
Trade-offs
Spatial planning
Sustainable forest management
Biodiversity

ABSTRACT

An integrated methodology, based on linking Bayesian belief networks (BBN) with GIS, is proposed for combining available evidence to help forest managers evaluate implications and trade-offs between forest production and conservation measures to preserve biodiversity in forested habitats. A Bayesian belief network is a probabilistic graphical model that represents variables and their dependencies through specifying probabilistic relationships. In spatially explicit decision problems where it is difficult to choose appropriate combinations of interventions, the proposed integration of a BBN with GIS helped to facilitate shared understanding of the human–landscape relationships, while fostering collective management that can be incorporated into landscape planning processes. Trades-offs become more and more relevant in these landscape contexts where the participation of many and varied stakeholder groups is indispensable. With these challenges in mind, our integrated approach incorporates GIS-based data with expert knowledge to consider two different land use interests – biodiversity value for conservation and timber production potential – with the focus on a complex mountain landscape in the French Alps. The spatial models produced provided different alternatives of suitable sites that can be used by policy makers in order to support conservation priorities while addressing management options. The approach provided provide a common reasoning language among different experts from different backgrounds while helped to identify spatially explicit conflictive areas

1. Introduction

Forests cover more than one third of the total land area of the European Union. They represent a key natural resource, which has been managed for decades to meet growing societal demands for diverse forest ecosystem goods and services. Forest ecosystem services (ES), the benefits that humankind obtains from forests both directly and indirectly, are important not only at regional levels but also at national and global scales (MA, 2005). For instance, flood regulation or soil erosion control services provided by forests have a direct impact on local populations, whereas carbon sequestration has a global influence. The incorporation of the ES concept into the framework of forest management leads to a more holistic perception of the role of forests, recognizing not only their economic value but also their cultural and ecological values, including their regulation capability. Yet, despite this improved understanding of the potential of forested landscapes and their land use systems to provide human well-being and socio-economic benefits, further conceptual and empirical work is needed to implement operational frameworks for integrating ES into management and decision-making (Carpenter et al., 2009). The concept of multifunctional landscapes, which assumes that landscapes have always fulfilled more than just a single aim such as producing basic ES like food, fibre, timber and fuel (Knickel and Renting, 2000; Mander et al., 2007; Gimona and van der Horst, 2007), has attracted the attention of scientists over the last few years (e.g. Brandt et al., 2000; Mander et al., 2007; Vejre et al., 2007). This approach has become of major importance in forest resource management and rural development (Dwyer, 2007; Bagstad et al., 2013) and is directly linked to the ES concept (Luque

---

* Corresponding author at: IRSTEA, National Research Institute of Science and Technology for Environment and Agriculture, France – 2, Rue de la Papeterie, Saint-Martin-d'Heres cedex 38402, France.

E-mail addresses: Julen.Gonzalez@hutton.ac.uk (J. Gonzalez-Redin), sl208@st-andrews.ac.uk, Sandra.luque@irstea.fr (S. Luque), laura.poggio@hutton.ac.uk (L. Poggio), ris@ceh.ac.uk (R. Smith), alessandro.gimona@hutton.ac.uk (A. Gimona).

http://dx.doi.org/10.1016/j.envres.2015.11.009
0013-9351/© 2015 Elsevier Inc. All rights reserved.

and Iverson, 2016). Within the framework of multifunctional landscapes, quantitative relationships between biodiversity, ecosystem functioning and ecosystem services are still poorly understood. In recent years, many publications have appeared on this topic (e.g. Elmqvist et al., 2010; Mace et al., 2012; Bastian, 2013), but many questions remain. There is also an on-going discussion as to whether biodiversity is (or should be understood as) an ecosystem service itself (e.g. Mace et al., 2012). Especially this latter question hints at the important point that the link between biodiversity and ecosystem services is not just a matter of biophysical relations, but also one related to value dimensions and different emphases of conservation strategies and human perceptions. It is still unclear under what circumstances an emphasis on ecosystem services in planning and decision making is (conceptually and practically) supportive of biodiversity conservation, or when the two aims may be conflicting. The complexity of ecosystem functioning still poses uncertainties about the role of individual species and other components of biodiversity in the supply of ecosystem services, specifically within coupled social-ecological systems. It becomes clear that one important challenge is to identify preferred trade-offs among several services (Schwenk et al., 2012) in evaluating forest management options (Carpenter et al., 2009; Chan et al., 2012; Gramfeld et al., 2013), and to see which trade-offs are relevant at different scales and contexts when integrating forest management into territorial planning.

Multi-criteria analyses can help forest owners and forest managers consider the best pathways to potential 'win–win' situations, or at least good compromises to enhance sustainable use of multiple ES. Accounting for trade-offs provides an alternative support to forestry planners who normally lack the funding, time and certainty to explore alternative management options. Thus, with growing interest in using ES for decision making, demand has grown for systematic methods and tools to quantify ecosystem service values (McCloskey et al., 2011; Pullin et al., 2004). Within this framework, the requirement for spatially explicit ecosystem valuation is based on the recognition that ES are context dependent in terms of their provision and their associated benefits and costs.

1.1. *The importance of visual methods*

When trying to facilitate the participation of stakeholders, especially (but not only) if they are not professional experts, a particularly efficient way to convey complex information is by the use of visual presentation. Visual information appears often easier to absorb than verbal information (think, for example, of the comparison between a lengthy table and a bar chart encoding the same information) Psychologists hypothesise, with some evidence (Evans, 2003; Sternberg and Leighton, 2004), that this is due to our evolutionary history, given that verbal skills have appeared much later than visual ones (e.g. Paivio, 2007; Mattson, 2014). Stanovich and West (2000) coined the term 'System 1' and 'System 2' to refer to the visual system that does 'implicit' and approximate processing, and the verbal system that does 'explicit' processing of information, often more accurate but also slower. Some authors even speculate that the ability to make and interpret maps might have played an important role in our evolutionary history (Landau and Lakusta, 2009). Others disciplines have already realised, empirically, the superior ability of the visual system to process information quickly: Tufte (1983) and Card et al. (1999) are seminal works, but the use of graphs and charts obviously predate these authors.

The upshot is that there are empirical and theoretical reasons why using visual methods are a valid and powerful way to communicate with others. A Bayesian belief network (BBN) is one of a family of graphical models that exploit the visual channel of perception to make information that would otherwise be difficult to grasp, especially for non-statisticians, more accessible. They do this by providing a pictorial representation - with a well understood corresponding mathematical description – of the conditional probabilistic dependency between variables. When co-constructing a system model, this enhances the ability of all participants to contribute. Within this context, BBNs are a powerful instrument to represent relationships (conditional dependence) and uncertainty, but they are unable to provide a direct, at a glance, representation of the spatial relationships between the variables that appear in them as nodes.

The spatial dimension of an environmental model is a key issue for local stakeholders, since they are more interested to know 'where' to implement planning than 'why'. Usually, they have clear ideas of local and regional problems, but they need operational and spatial solutions (Fürst et al., 2014). For the perceptual reasons discussed above, a GIS providing maps and other diagrams is an obvious and natural tool to visualise such information efficiently, as the pattern of dependency between variables, the context in which local values are situated, the local variation and the long distance trends are relatively easily captured. An approach combining BBNs with geographical information systems (GIS) therefore has the benefit of conveying a large amount of information to stakeholders, of performing inference on a potentially very large amount of data, and of propagating uncertainty using a well-established Bayesian framework.

1.2. *BBNs and their use in the environmental planning processes*

A BBN is one type of directed acyclic graph, where nodes are used to hold information on the random variables (including parameters) in the model and their conditional interdependencies are represented by links or edges. The graph is directed, so there are one-way 'parent' to 'child' relationships shown by the links, and it is acyclic, meaning there can be no closed loops in the graph, i.e. no node can influence itself. Feedback loops are accommodated by introducing a time step, so a node can influence its corresponding node in the next time step. Child nodes depend only on their direct parent nodes, which means that nodes that are not directly connected are assumed to be independent of each other. This independence feature allows the joint probability distribution over all variables, which gives the outcome probabilities for the decision process, to be built up from the set of conditional probabilities that express the links between the parent and child nodes. Within a BBN, each node has a defined set of states along with a conditional probability table (CPT), which defines for each child node state the probability of it occurring given all possible combinations of parent node states. Kjærulff and Madsen (2013) give the theory of Bayesian Networks and a detailed guide to their construction.

Because uncertainty is integral to Bayesian decision analysis, these models help decision makers to be aware of and include uncertainties regarding natural and social systems by organizing and presenting information in coherent and simple frameworks (Cowell et al., 1999; DEWHA, 2010; Jensen, 2001; Pearl, 1988). The BBN structure is flexible in terms of enabling the direct integration of new variables or states into the graph (Haines-Young, 2011; Landuyt et al., 2013; Smith et al., 2007), so allowing exploration of new scenarios and alternative options which can be useful for decision and policy makers. BBNs can also be updated easily as new information becomes available. The Bayesian framework accommodates the impact of beliefs and preferences on the decision process, drawing together diverse sources of evidence into a single coherent description of a given problem, and providing a transparent model where the outcomes from conflicts of objectives and of evidence can be challenged (Smith, 2010).