Environmental Modelling & Software xxx (2014) 1–8

Contents lists available at ScienceDirect

Environmental Modelling & Software

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

A Bayesian network approach to model farmers' crop choice using socio-psychological measurements of expected benefits of ecosystem services

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A R T I C L E I N F O

Article history:
Received 11 June 2013
Received in revised form
12 March 2014
Accepted 13 March 2014
Available online xxx

Keywords:
Bayesian network
Theory of planned behavior
Ecosystem services
Decision-making support
Analytical Hierarchy Process

A B S T R A C T

Models of ecosystem management typically measure the benefits of ecosystem services in terms of ecological or biophysical variables, which are influenced by management decisions and biophysical/ecological conditions. This study uses farmers' expected benefits of ecosystem services as input variables to model their decision between planting rice, annual crops or perennial crops. Based on the theory of planned behavior, a Bayesian network is constructed to model crop choice depending on attitudes toward the ecosystem services of biomass production, reduction of soil erosion, and water quality improvement. The relative importance of these decision-making criteria is quantified using the Analytical Hierarchy Process. Results indicate that Bayesian networks can use socio-psychological measurements to model decision-making. Especially as an extension to biophysical or economic models, they can serve as a powerful tool for grasping the more abstract socio-psychological dimensions of benefits of ecosystem services, and how they translate into the decisions of ecosystem managers.

1. Introduction

With growing recognition of the importance of ecosystem services (ES) (MA, 2005), ecosystem management is becoming an increasingly multilayered task that has to account for the interests of numerous stakeholders. With benefits being derived from both tangible and intangible services, ecosystem management options need to incorporate biophysical, economic and socio-political factors. While praised for its multidisciplinary approach on a conceptual level, the idea of ES poses substantial difficulties when it comes to practical decision-making. Daily et al. (2009) attributes these difficulties to our poor understanding of the decision-making processes of individual stakeholders, and the lack of integrated research in institutional design and policy implementation. Their suggestions for possible solutions include: (1) stakeholder collaboration in order to define which services are important to them; (2) development of monetary and non-monetary methods evaluating ES at the decision-making level; and (3) using flexible, transparent models that can deal with both biophysical and social values of ES. Technically, modeling such multidisciplinary decision-making problems requires tools that can use input from various data sources in a comprehensive and efficient manner.

One approach that has drawn considerable attention is the use of Bayesian network (BN) models, which are graphical decision support tools representing causal and correlative relationships between variables, based on their conditional probability distributions (Cain, 2001). By definition, a BN is a directed acyclic graph, which means it represents conditional dependencies between variables with directed links that are not allowed to form feedback loops. BNs use nodes as representations of discrete random variables, which are characterized by a finite set of mutually-exclusive states. As probabilistic dependencies between variables are indicated via directed links, every link from one node (A) to another node (B) requires the quantification of a conditional probability table (CPT). A CPT indicates the probability (P) of a state of 'child' node (B) given the state of its 'parent' node (A) according to $P(B|A)$. Nodes without parents are quantified with tables of unconditional (marginal) probability distributions $P(A)$. Probability distributions can be updated when new information becomes available using Bayes' rule $P(b|e) = P(b,e)/P(e)$, where b represents a specific state of node B, and e represents evidence on a parent of B. A detailed description of the mathematical properties of BNs can be found in Pearl (2009) or Kjaerulff and Madsen (2008).

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http://dx.doi.org/10.1016/j.envsoft.2014.03.006
1364-8152/

BN models are used to support ecosystem management decisions in a great number of environmental studies (see Aguilera et al., 2011). Their increasing popularity is mainly due to their: (1) explicit way of handling uncertainty and complexity; (2) ability to incorporate both quantitative and qualitative data; (3) capability of being easily updated, extended or modified when new knowledge becomes available; and (4) their intuitive nature that facilitates stakeholder communication and engagement (Chan et al., 2012; Smith et al., 2011). However, despite the ample indications that BNs are capable of dealing with challenges such as those put forward by Daily et al. (2009), few applications of BNs are being used to model ES (Landuyt et al., 2013).

Most of the existing BN models in ES research address one single, typically well-documented, service like genetic resources, recreation, water regulation or food supply (Landuyt et al., 2013). As such, a majority of these models are limited to a natural science perspective. They depict the effects of management decisions on the biophysical structure of an ecosystem, which in turn influences ecological or biophysical response variables that determine the level of service provision (McCann et al., 2006). Changes in the level of service provision are usually evaluated in terms of monetized costs and benefits that are represented by means of utility nodes (e.g. Ames et al., 2005; Gawne et al., 2012; Kragt et al., 2011). Fewer models take a more integrative approach and include factors identified as relevant for decision-making by the stakeholders. Typically, this stakeholder information is elicited in consultation workshops, where a BN is constructed based upon the viewpoints of every stakeholder group, and conditional probabilities are derived from either raw data, other process-based models or expert opinion (e.g. Barton et al., 2008; Bromley et al., 2005; Cain, 2001; Celio et al., 2012; Chan et al., 2010; Varis and Lahtela, 2002; Zorrilla et al., 2010).

An example of a more multidisciplinary approach is the study by Ticehurst et al. (2011) that included socio-psychological factors, and combined social survey results with data describing other factors relevant for farmers' decisions about the fencing of bushland. The BN used to merge these data sets was constructed with the help of conventional (i.e., non-Bayesian) statistics for the 'other factors', and expert opinion for the social survey results. Castelletti and Soncini-Sessa (2007) investigated the decision-making process of stakeholders by linking hydrological models with a BN representing farmers' choices of cultivated crop type and irrigation technique. Lacking, as they put it, a 'physical law' to determine behavior, they modeled farmers' choices based on direct interviews that address farmers' reactions to two given actions under different psychological conditions. Haines-Young (2011) took another approach that used several case studies for developing two BNs: one mapping the standing crop of vegetational carbon based on land-cover stocks and the other identifying stakeholders' social valuation of different landscape scenarios as a cultural entity.

In conclusion, previous studies indicate that BNs can handle the multidisciplinary aspects of ES approaches. Moreover, they provide the kind of analytical-deliberative tools that Fish (2011) considered necessary for dealing with the socio-scientific challenges he identified as being inherent to the field of environmental decision-making and ES. Thus, the BN approach is suited for: (1) combining analytical rigor with the interpretive complexity of socio-psychological data; (2) investigating and representing links across knowledge domains in an exploratory manner; and (3) facilitating communication about new ideas and perspectives among new communities of interest (Haines-Young, 2011).

Another challenge put forward by Fish (2011), that has not yet been addressed in a BN approach, originates from our limited perception of the relationship between ES and human well-being. In its current form, the concept of ES considers ecosystems as providers of different services that endow people with benefits contributing to their well-being. Concurrently, human activities induce a cascade of impacts that change the level of service provision (Haines-Young and Potschin, 2010). Human well-being is then determined in terms of costs and benefits, which are derived as a function of changes in service provision (Landuyt et al., 2013). This focus on 'services provided', however, omits operational links characterizing how well-being and service provision might be related in the first place (Fish, 2011). Thus, the ecosystem benefits derived from specific ES are a driving force that is often neglected in analyses about the decision-making behavior of ecosystem managers.

This study extends this train of thought by modeling management decisions as a function of expected benefits of ES. A BN approach is chosen, since the reliance on probabilistic rather than deterministic dependencies between variables makes BNs particularly well-suited for management applications and decision-making support under uncertainty (Kelly et al., 2013). Data for populating the model is derived from interviews based on the theory of planned behavior (TPB) (Ajzen, 1991), a well-established socio-psychological method for decision-making analysis. It was used by Poppenborg and Koellner (2013) to study farmers' decisions in a South Korean watershed, where the choice between planting rice, annual crops or perennial crops was analyzed as a function of farmers' attitudes toward biomass production, erosion protection and water quality improvement. Furthermore, elements from the Analytical Hierarchy Process (AHP) are used to account for trade-offs between ES.

The approach presented here aims to show how the relationship between benefits of ES and agricultural decision-making can be operationalized in a BN modeling framework, based on socio-psychological data. Drawing upon elements from the AHP, it also addresses farmers' priorities among ES benefits, which makes it capable of dealing with multiple ES. The result can be particularly useful for policy-makers interested in fostering specific services, as it shows the importance of ES for the decisions of those who directly influence service provision. Moreover, the use of a standardized socio-psychological method such as the TPB in combination with flexible models such as BNs, allows for repeating and adapting the presented methodology to various decisions and ES. Thus it can be used as a versatile tool that is adjustable to the respective contexts of different research questions.

2. Methodology

2.1. Decision-making data

Data about farmer decision-making originated from a study by Poppenborg and Koellner (2013) in the Haean watershed, South Korea, where agricultural production causes severe environmental degradation. Interspersed with plots of perennial crops, the research area's basin-like topography is dominated by rice paddies in the flat core terrain, while predominantly annual crops are grown on steeper slopes toward the rims of the catchment. Approximate share in the total number or agricultural plots of these land use categories amounted to 23% for rice, 65% for annual crops, and 12% for perennial crops in 2009 (Korean Ministry of Environment, personal communication). The agricultural land use practices in the Haean watershed result in heavy soil erosion and water pollution, as sediment is washed away during the monsoon season and accumulated in rivers within and outside of the catchment. Political efforts to mitigate these issues aim at promoting the cultivation of more perennial crops, which should stabilize soils throughout the year.

In this context, interviews to examine farmers' land use decisions with respect to their choice of cultivating rice, annual crops or perennial crops were conducted in Poppenborg and Koellner (2013). Questions were based on the TPB (Ajzen, 1991), which measures intentions to perform a particular behavior based on a decision-maker's: (1) attitudes toward the behavior[1] (AttB), which evaluate the expected outcome of performing the behavior; (2) perceived behavioral control (PBC), which addresses the volitional control over performing the behavior; and (3) subjective

[1] 'Attitudes toward the behavior' and 'expected benefits' are used interchangeably throughout this paper.