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The Role of Strategic Behaviour in Ecosystem Service Modelling: Integrating Bayesian Networks With Game Theory

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ABSTRACT

Humans fulfil an active role, through management and economic activities, in the production of ecosystem services and related benefits. Different human groups may pursue different objectives, and their actions may affect each other's well-being. Bayesian networks have gained importance in ecosystem service modelling and we show how, in recent literature, this approach has attempted to address strategic behaviour issues. Using simple simulations, we illustrate that the strategic behaviour of stakeholders could be better modelled with an integration of game theory concepts in Bayesian networks. This approach may help to understand the rationale behind stakeholders' behaviour and foresee their actions. Furthermore, the comparison of environmental results with cooperative and strategic behaviours raises questions about the role of humans in the production of ecosystem services, and on the correct way to value their benefits.

Contents

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1. Introduction

The ecosystem service (ES) concept emerged in the 1990s (Costanza et al., 1997; Daily, 1997) and was mainly created to emphasise the importance of ecosystems for human well-being (e.g. provisioning services, regulating services, cultural services). Every ecosystem service definition identifies an unequivocal relationship between ecosystems and human life (Boyd and Banzhaf, 2007; Fisher et al., 2009). Several frameworks have been developed to stress the interrelationships between ecosystems and human benefit. One of the most cited approaches, the ecosystem service cascade (Haines-Young, 2011; Haines-Young and Potschin, 2009), describes the services as nature's gifts that linearly flow from biophysical structures and processes to human populations. Not all the ES cascade versions explicitly show the active role of humans in the generation of benefits, but several scholars recognize that benefits result from the combination of ESs and human inputs, such as the investments of labour, time, resources, and money (Boyd and Banzhaf, 2007; Lamarque et al., 2011). According to Fisher et al. (2008), the opportunity cost of these inputs must be subtracted in order to calculate the well-being generated by ESs. Cascade frameworks that explicitly include a human role are found in TEEB (2010) and Lamarque et al. (2011). Following these approaches, human contributions clearly emerge with management functions (especially in the case of public actors), and with processing/use functions (especially in the case of private actors) (see Fig. 1).

Theoretical ESs frameworks have given impulse to different types of mathematical models, most are focused on the biophysical component of the cascade (Gómez-Baggethun et al., 2010; Kareiva et al., 2011; Villa et al., 2014). Kelly (Letcher) et al. (2013) included Bayesian networks (BNs) in a large review of five approaches (together with Systems Dynamics, Agent-Based Models, Knowledge-Based Models, and Couple Component Models) for modelling complex environmental systems. Landuyt et al. (2013) and Mcvittie et al. (2015) showed the conceptual fit between BNs and the ES cascade framework, especially for economic valuation. Barton et al. (2012) discussed BNs in environmental and resource management using the driver-pressure-state-impact-response (DPSIR) framework.

Bayesian networks (also known as Bayesian belief networks) have recently gained importance in ES modelling thanks to its' high transparency, the possibility to combine empirical data with expert knowledge, and explicit treatment of uncertainties (Landuyt et al., 2013). An evolution of BNs are influence diagrams (IDs) also known as Bayesian decision networks, used to represent and analyse decision making under uncertainty. IDs are able to model and evaluate a complex decision-making process, where the process is not influenced by other participants. In reality, many decisions are made in complex environments, where a number of decision makers are involved in the same process (Zhou et al., 2013). IDs are not able to capture 'gaming situations' where people want to consider opposing agents that act according to beliefs about ones' own actions (Brynielsson and Arnborg, 2004). Actually, this is the field of game theory (GT), which is a theory of decision making under conditions of interdependence.

Bayesian networks and game theory have traditionally been regarded as orthogonal bodies of work (Lee and Wolpert, 2012). Several attempts have been recently made to integrate GT into BNs and into IDs (Brynielsson and Arnborg, 2004; Koller and Milch, 2003; Zhou et al., 2013). These studies have essentially regarded theoretical considerations and algorithms for computation, while a few applications can be found in the fields of military strategies (Bryan et al., 2010), pilot behaviour (Lee and Wolpert, 2012) and internet security (Yan et al., 2012). To the best of the authors' knowledge, no attempt has been made to integrate these two approaches in the field of ESs studies.

The objective of this paper is evaluating the possibilities and benefits of integrating Bayesian networks and game theory for the analysis of ecosystem services. We want to stress how the strategic behaviour of stakeholders is strongly related with many BN applications found in the literature. In several cases it is indirectly (i.e. unintentionally) included in the model. In others, conflicting objectives between stakeholders are clear, but ignored, or modelled with approaches different from GT. Finally, there are studies where strategic behaviour is not perceived in the BN, but only because the model focuses on a limited section of the ES cascade, deliberately ignoring human connections.

The paper is structured as follows. Section 2 presents the main characteristics of BNs and GT. In Section 3, we explain the criteria adopted to select, classify, and illustrate the BN related papers in the field of ESs; a similar procedure is followed to select a sample of papers that use GT. In Section 4, results of this literature review are presented. Section 5 discusses the results and presents a framework, based on a simulated situation, for the integration of BNs and GT. This is done at conceptual level using, as far as possible, commercial BN software as a tool for the analysis; the development of algorithmic applications for solving these cases is beyond the objectives of the paper. Section 6 concludes the paper.

2. Background

2.1. Bayesian Networks

BNs are a semi-quantitative modelling approach based on two structural model components: (a) a qualitative part represented by a directed acyclic graph (DAG) that denotes dependencies between the model's variables; and (b) a quantitative part represented by conditional probability tables (CPTs) denoting the strength of the links. Each variable contains a limited number of states. The dependencies between different variables are indicated in the DAG by arrows, which represent cause-effect relations and, since the graph is acyclic, feedbacks are not allowed. Both the DAG and the CPTs can be based on expert and stakeholder knowledge, or can be learned by empirical observations.

Prior (unconditional) probabilities express the probability that some input parameter is in a particular state. Conditional probabilities represent the likelihood of the state of a parameter, given the states of input parameters affecting it. Finally, posterior probabilities represent the likelihood that some parameter is in a particular state, given the input parameters, the conditional probabilities, and the rules governing how the probabilities combine. Inference is based on the notion of evidence

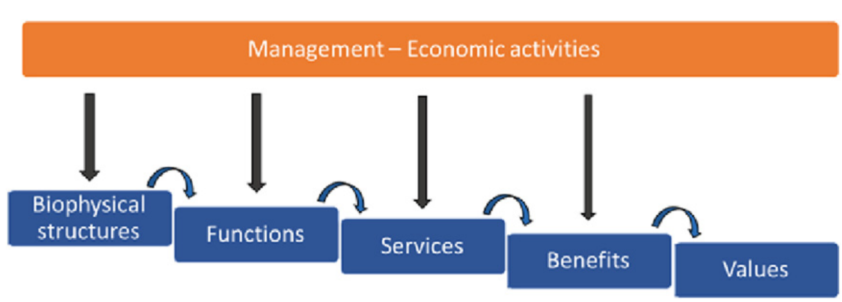

Fig. 1. Ecosystem service cascade with explicit human roles.