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A cognitive map framework to support integrated environmental assessment

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ABSTRACT

In this work we present the rational and design of a methodology to support Integrated Environmental Assessment using the DPSIR (Driving Forces–Pressures–State–Impact–Response) causal-effect framework and non-monotonic Fuzzy Cognitive Maps. The methodology is based on key pillars in environmental management, namely connecting the socioeconomic and the natural environment dimensions into a policy oriented context; integration of stakeholders with inter-sectorial synergies and tradeoffs; handling of ambiguities and uncertainties intrinsic to environmental modeling and representation of complex non-linear cause-effect relationships in the form of Fuzzy Inference Systems, capable of adapting dynamically the influence between indicators. The methodology has the potential to support the development of informed policies and improves reliability through transparent, traceable and reproducible results. The illustrative example assesses the impact of air pollution abatement policies according to expert perceptions using proactive scenarios; the results revealed that, despite some positive changes, air protection activities are missing an overall strategic vision.

1. Introduction

Modeling of environmental issues in an integrated approach is recognized as a major challenge because of the variety of conflicting socioeconomic and environmental aspects that govern them. Successful management and resolution of environmental issues requires, therefore, the adoption of an interdisciplinary approach that brings systems-based thinking to decision-making and provides a mechanism to bridge between different disciplines. Integrated Assessment (IA) (Jakeman and Letcher, 2003; Jakeman et al., 2008; Hamilton et al., 2015) is a 'meta-discipline' that has emerged to establish the foundation for a perspective that accounts for sustainability. It has been defined as "integration of knowledge from different disciplines" with the goal to enlighten environmental modeling with a comprehensive understanding of complex problems which arise from the socioeconomic and environmental dynamics. To yield its expected results, IA "must be conducted within an interactive and transparent participatory framework that is enriched by stakeholder involvement with team-shared objectives, norms and disciplinary equilibration".

Any method that attempts to successfully apply IA to environmental management must support multi-scale analysis of anthropogenic, economic, as well as the natural environment factors and should link these dimensions in a "policy oriented context". It should account for the non-linearity of environmental interactions and support possible feedbacks. It should also use a unified model to consolidate expert and lay expert knowledge and deal with uncertainty and ambiguity due to the rather subjective viewpoints of participants, and as such it must be capable of emulating and quantifying the natural language.

In order to address the challenges that might hinder the operationalization of IA, we make use of the conceptual Driving forces–Pressures–State–Impact–Response (DPSIR) framework and the soft computing technique of Fuzzy Cognitive Maps (FCMs).

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The DPSIR framework was adopted by the European Environment Agency in 1995, and was described as a "causal framework for clarifying the interactions between society and the environment". According to DPSIR terminology, socioeconomic activities are considered *driving forces* that exert *pressures* on the environment and, consequently affect its biological, chemical or physical *state*. This change might lead to *impacts* on ecosystems, human health, and society, which may trigger *responses* as an attempt to prevent, eliminate or compensate impacts, which feeds back on driving forces, on state or on impacts (Smeets and Weterings, 1999; Gabrielsen and Bosch, 2003). The framework has been used as an interdisciplinary approach for indicator selection and development, and as a problem structuring method in policy relevant research and decision making support (Gari et al., 2015; Maxim et al., 2009; Karageorgis et al., 2006; Bidone and Lacerda, 2004; Holman et al., 2005; Svarstad et al., 2008). DPSIR is mainly used to help with the modeling of environmental indicators and demonstrating causal links to policy and decision makers.

A Fuzzy Cognitive Map is a system model, that is on the structural level represented in the form of a graph whose nodes represent the concepts of the system being studied and edges represent causal relationships between these concepts (Axelrod, 1976; Kosko, 1986). The graph structure facilitates causal reasoning to study system dynamics. The dynamics of the inference are very close to neural network mechanisms; influence relationships are mathematically calculated using normalized state and matrix multiplication. The inference might indicate the convergence of the system to a steady state, the repetition of a cycle of states, or the divergence of the system to a chaotic state with no recurrences (Kosko, 1986; Özesmi and Özesmi, 2004; Taber, 1991). During simulation, the activation level of every concept is computed based on its value at the preceding iteration as well as on the propagated weighted values of all concepts that exert an influence on it.

Many implementations of FCMs exist in the literature but rely on representing the cause-effect relationships between concepts using monotonic and symmetric weight values, which is not very effective considering the dynamic aspect of most environmental systems. Among the first to reveal the several shortcomings of conventional FCMs that can be overcome by using fuzzy rules are (Carvalho and Tomé, 2000, 2009). Their developed FCM is essentially a rule-based system, where relations other than monotonic causality are made possible. They added feedback mechanisms, like the Fuzzy Carry Accumulation and different kind of relations to deal with the complexity of qualitative systems. Another approach that can be employed as adaptation mechanism is the use of algebraic equations to represent the causal relationships. The approach is useful only if a cognitive map is connected to a real system where parts of it have been modeled using crisp relations (Aguilar, 2013; Aguilar and Contreras, 2010).

FCMs offer a convenient way in modeling environmental issues because they include feedback (Kontogianni et al., 2012; Samarasinghe and Strickert, 2013; Gray et al., 2014). Feedback excludes the graph-search algorithms used in rule-based expert systems and causal trees. These inference algorithms tend to get stuck in infinite loops in cyclic knowledge networks. Furthermore, the core component of an expert system is a decision tree with graph search, the result of merging two trees is not a tree but a cyclic graph (Taber, 1991). Unlike with FCMs, cyclic graphs prevent the extension of an expert system's knowledge base through the combination of knowledge from multiple experts which is a key feature in environmental modeling. FCMs have shown a good promise in modeling complex systems and supporting environmental management and policy development (Özesmi and Özesmi, 2004; Kafetzis et al., 2010; Samarasinghe and Strickert, 2013; Zhang et al., 2013; van Vliet et al., 2010; Kontogianni et al., 2012; Henly-Shepard et al., 2015; Jetter and Kok, 2014). They have also applications in a wide spectrum of scientific fields; a recent review on FCM research during the last decade can be found in (Papageorgiou and Salmeron, 2013; Jetter and Kok, 2014).

Furthermore, FCMs are also capable of taking into consideration the uncertainties usually inherent to complex systems modeled by experts. Sustainability of one system can compromise sustainability of other systems; subjectivity and uncertainty imply that management of natural resources must involve continuing compromise across different sectors. Transfer and sharing of tacit knowledge about a complex system can help achieving coordinated actions and reducing uncertainty about the problem. Sharing of tacit knowledge can be facilitated using Fuzzy Logic (Zadeh, 1965; Mamdani and Assilian, 1975; Takagi and Sugeno, 1985) that has known an increased interest during the last few decades in ecological and environmental modeling (Shepard, 2005; Silvert, 1997; Salski, 2006; Janssen et al., 2010). Fuzzy Logic allows modeling of vague qualitative perceptions of experts related to a problem where uncertainty is high and where there is little data that can be used to build empirically a model and calibrate it. It is particularly suitable for adding human subjective reasoning by means of comprehensible fuzzy rules that map the tacit knowledge of experts and lay experts expressed using linguistic terms.

The aim of this research is to present a methodology for the application of IA in environmental management. The methodology can give feedback to decision makers and communicate stakeholder opinions on environmental issues. It also allows decision makers to explore future implications from current states, and to assess the resulting impacts of the simulated policy choices made or to be made in the future. The main features of our approach are:

- Decision support for sustainable environmental management by framing the selection of relevant indicators within the so-called 'triple bottom line of a socially, economically and ecologically acceptable future' (Jeffrey and McIntosh, 2006) using the DPSIR framework.
- Dealing with subjective and vague linguistic variables used by experts and lay experts and handling uncertainties due to their approximate knowledge using Fuzzy Logic.
- Modeling of cause-effect relationships between DPSIR indicators using a FCM model capable of adapting the influence weights dynamically. Like a conventional FCM, the concepts represent causes or effects that collectively represent a system state at a given time. However, one merit of our proposed framework is that, unlike conventional maps that represent the influence between two concepts as monotonic weights, the model can adapt the weights dynamically by describing causal relationships using Fuzzy Inference Systems.
- Promoting social learning that advocates for involvement of actors from different disciplines, and modeling of inter-sectorial synergies and tradeoffs into one aggregated knowledge model; which reduces uncertainty about the problem at hand and helps in reaching consensus.
- Answering "what-if" questions using simulation of scenarios, an activity that helps decision makers understand the impact of different policy alternatives on key variables in a given environmental problem according to multiple expert and lay expert perceptions.
- Last but not least, the approach allows decision makers to choose among a set of alternative scenarios by ranking and comparing them with regards to prospective objectives.

The reminder of the paper is organized as follows. Section 2 describes the proposed methodology, followed in Section 3 by the application of the methodology to the air pollution issue. Finally,