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Mapping indicator models: From intuitive problem structuring to quantified decision-making in sustainable forest management

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Most commonly, sustainability indicator sets presented as lists do not take into account interactions among indicators in a systematic manner. Vice versa, existing environmental indicator systems do not provide a formalized approach for problem structuring and quantitative decision support. In this paper, techniques for considering indicator relationships are highlighted and a coupled approach between a qualitative and a quantitative method is analysed. Cognitive mapping (CM) is used for structuring indicators and three different causal maps are derived based on established sustainability concepts: (a) criteria and indicators (C&I hierarchy), (b) indicator network, and (c) Driving Force-Pressure-State-Impact-Response (DPSIR) system. These maps are transferred to the Analytic Network Process (ANP) to allow their application in multi-criteria decision analysis (MCDA).

In an application example, Pan-European indicators for sustainable forest management (SFM) are utilized in an ANP-based assessment. The effects of the model structure on the overall evaluation result are demonstrated by means of three reporting periods on Austrian forestry.

In a comparative analysis of CM and ANP it is tested whether their measures of indicator significance do correspond. Both centrality in CM and single limited priorities in ANP have been reported to identify key indicators that play an important role in networks. We found out that the correspondence between CM and ANP is the stronger the more rigidly cause-effect relationships are interpreted, which is the case for the DPSIR system of SFM indicators.

It is demonstrated that using indicator sets without consideration of the indicator interactions will cause shortcomings for evaluation and assessment procedures in SFM. Given strict and consistent definition of causal indicator relationships, a coupled use of CM and ANP is recommendable for both enhancing the process of problem structuring as well as supporting preference-based evaluation of decision alternatives.

1. Introduction

Since the beginning of the 1990s, an enhanced understanding of sustainable forest management (SFM) has entered the stage of forest policy worldwide. In Europe, the initiative to promote SFM is driven by the Ministerial Conference on the Protection of Forests in Europe (MCPFE, now Forest Europe). The MCPFE is steering a process that has to deal with definition, assessment and revision of policy targets with regard to SFM.

The concept of criteria and indicators (C&I) is one of the cornerstones for SFM implementation worldwide (Wijewardana, 2008). In Europe, a set of national-level indicators was established to initialise and standardise Pan-European reporting. This set was adopted at the third MCPFE in Lisbon (MCPFE, 1998) and improved towards a corpus of 35 quantitative indicators at the fourth MCPFE in Vienna (MCPFE, 2003).

In the meantime, increasing experience in assessment and analysis of indicators has shown that listings and hierarchical arrangements of C&I reflect but a partial view on the complex nature of SFM combining ecological and human systems under a common umbrella (Kelly, 1998; Prabhu et al., 2001). Following this argument, indicators should be designed for considering their potential interactions and feedbacks within a given set. This would help to gain more insight into systemic cause-effect relationships and – by identifying key processes and indicators – help to make data collection and analysis more efficient (Requardt, 2007).

On the other hand, there are approaches originating from environmental policy to allegorise large-scale environmental problems. They are tackling comprehensible indicator models such as Pressure-State-Response (PSR; OECD, 1993) or Driving Force-Pressure-State-Impact-Response (DPSIR; EEA, 1999) that utilise causal chains among their clustered indicators. Since they are

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designed for better communication of meta-scale problems, they offer no regular features for quantitative systems or decision analysis (Wolfslehner, 2007; Wolfslehner and Vacik, 2008).

Considering the state of the art, it can be observed that methodological approaches to consider networks of indicators are still scarce in the field of natural resource management. Among few examples, causal networks of environmental/ecological indicators have been highlighted by Niemeijer and de Groot (2008a,b) and Lin et al. (2009). In sustainability issues, network approaches have been demonstrated for forest policy (Requardt, 2007) and local level indicators (Mendoza and Prabhu, 2003; Wolfslehner et al., 2005).

Still, there is only weak attempt to formalize the building of SFM indicator networks from a systems analysis point of view, which could be seen as a prerequisite for an expansion towards a consistent indicator-based assessment and evaluation. In this respect, methods such as cognitive mapping (CM) can be employed to facilitate a formalized problem structuring process, where interactions among concepts (i.e., indicators in our sense) are constructed and analysed (Eden, 2004). This approach has been developed to depict cognitive pictures into a commonly interpretable network structure and help to identify crucial indicators within complex networks (e.g., Mendoza and Prabhu, 2005).

Yet, soft systems approaches are limited in terms that they are not designed to provide quantitative evaluation and assessment of alternative options, e.g., in policy and decision support. Multi-criteria decision analysis (MCDA) methods have been reported as tools for decision-support in SFM in a multitude of cases (e.g., Vacik and Lexer, 2001; Seely et al., 2004; Mrosek et al., 2006). Methodological approaches to cover interactions among SFM indicators in the field of MCDA are limited in number. Wolfslehner et al. (2005) employed the Analytic Network Process (ANP) to analyse a network model based on ratio scales of influences, which was expanded to other indicator models such as PSR (Wolfslehner and Vacik, 2008) and DPSIR (Vacik et al., 2007).

A common finding of these studies was that ANP applications are embedded in a very technical environment that makes it applicable for MCDA experts rather than for non-scientists. Hämäläinen and Seppäläinen (1986) argued that the ANP could build a bridge between structural modelling and decision analysis. Since then, stronger emphasis was put on ANP calculations than on the process of structuring network models.

Against this background, we examine the research question if a coupled use of CM and ANP creates an additional value for sustainability assessments compared to using them singularly. A characterisation of indicator sets from a system analysis point of view is investigated in combination with a multi-criteria evaluation of interactions among SFM indicators. By transferring causal maps to ANP models it is explored (a) under which conditions the measures of indicator significance in CM are consistently represented in ANP, and (b) how different modes of interlinking indicators generated in CM will affect ANP-based sustainability assessment results.

2. Material and methods

2.1. Pan-European indicators for sustainable forest management

Generically, SFM indicators are instruments that are employed by political processes (e.g., MCPFE, 2003; Montreal Process, 2009) to support assessment and reporting of national and international progress towards sustainable development. In addition, indicators are used in certification initiatives to support monitoring and reporting for marketing purposes (Rametsteiner and Simula, 2003) and for a variety of science-based monitoring and evaluation purposes down to the management unit level (Franc et al., 2001; Raison et al., 2001; Vacik and Wolfslehner, 2004).

In Europe, a basic set of 35 quantitative Pan-European indicators was adopted by 40 European Countries and the European Community in 2003, which is designed to report on the status of forest management on national level for defined time steps (so far 1990, 2000, 2005). Each indicator is assigned to one of six sustainability criteria, to give information on the state of Europe's forests and to depict changes in ecological, economic and social forestry-related issues. Data collection and reporting of MCPFE indicators is supported by the United Nations Economic Commission for Europe (UNECE) and by the Food and Agriculture Organization of the United Nations (FAO). They provide templates including relevant definitions and reporting notes for data collection in a recently re-launched database (UNECE, 2009).

For using SFM indicators in our application, a comprehensive dataset was a prerequisite. In addition to the Austrian national reporting to UNECE, missing information in the database was filled with additional data from the Austrian Forest Report (BMLFUW, 2009) and national studies as well as expert estimations to a minor extent (Table 1).

2.2. Problem structuring: cognitive mapping (CM)

An enhanced understanding of natural resource management includes the participation of stakeholders in decision-making to incorporate value pluralism at different levels. This fact generates stronger relevance for alternative information sources such as informal and tacit knowledge, e.g., in local communities (Mendoza and Prabhu, 2006). To address ill-structured problems soft-systems or soft-operations research approaches offer some methodological responses. In particular, cognitive mapping (Axelrod, 1976) has a long record in facilitating problem structuring and participatory modelling to provide a better understanding of complex problems under poor data situations (Mendoza and Martins, 2006). It has been used in forest-related issues to support planning processes (Tikkanen et al., 2006; Lee and Kant, 2006), involve stakeholder groups and enhance public participation (Hjortso, 2004; Robson and Kant, 2007), and to retrieve local knowledge (Isaac et al., 2009). Moreover, CM has been mentioned as tool for expert consultation in policy analysis (Eden and Ackermann, 2004).

Compared to open approaches such as mind mapping (Buzan and Buzan, 1996), CM is a formalized modelling technique providing rules to represent cognitive modes of thinking into networks of concepts and links. The method allows creating a model where thoughts are held as concepts formulating short 'bi-polar' phrases and adding contextual richness to the information by collecting issues, goals, aspiration and strategies related to the problem as well as their relationships (cf. Eden and Ackermann, 2001). In addition, a variety of analytical features is available to get more insight into network structures and their implications. For instance, the complexity of a map (i.e., the ratio of nodes and arrows), the effects of direct and indirect linkages (domain and centrality), the identification of positive and negative loops within the system, the discovery of potent nodes (i.e., their multiple appearance in thematic clusters), and the possibilities for simplification and removing redundancies are explored (Eden, 2004).

Beyond its merits, CM does not provide measures for the strength of influences nor does it allow an evaluation of different modes of action. Recently, efforts have been made to use qualitative operators in reasoning maps to open the mapping concept towards MCDA (Montibeller et al., 2008; Montibeller and Belton, 2009). For a combined use of indicator network maps and MCDA a strong interface between CM and quantitative decision analysis has to be defined.