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Review

Navigating uncertainty in environmental composite indicators

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ABSTRACT

Composite indicators (CIs) are increasingly used to measure and track environmental systems. However, they have faced criticism for not accounting for uncertainties and their often arbitrary nature. This review highlights methodological challenges and uncertainties involved in creating CIs and provides advice on how to improve future CI development in practice. Linguistic and epistemic uncertainties enter CIs at different stages of development and may be amplified or reduced based on subjective decisions during construction. Lack of transparency about why decisions were made can risk impeding proper review and iterative development. Research on uncertainty in CIs currently focuses on how different construction decisions affect the overall results and is explored using sensitivity and uncertainty analysis. Much less attention is given to uncertainties arising from the theoretical framework underpinning the CI, and the sub-indicator selection process. This often lacks systematic rigour, repeatability and clarity. We recommend use of systems modelling as well as systematic elicitation and engagement during CI development in order to address these issues. Composite indicators make trends in complex environmental systems accessible to wider stakeholder groups, including policy makers. Without proper discussion and exposure of uncertainty, however, they risk misleading their users through false certainty or misleading interpretations. This review offers guidance for future environmental CI construction and users of existing CIs, hence supporting their iterative development and effective use in policy-making.

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1. Introduction

Human activities have large impacts on natural systems (Halpern et al., 2008; Buma & Wessman, 2011) that are likely to increase in the future, given growing human population and demand on natural resources (Kraxner et al., 2013; McCauley et al., 2015). The resultant changes in natural systems have important consequences for biodiversity (Chapin et al., 2000), but also for people through our reliance on provision of ecosystem services for human well-being, health, livelihoods and survival (Costanza et al., 1997, 2014; Millennium Ecosystem Assessment, 2005). Managing these complex interactions to ensure nature thrives and continues to provide benefits to people requires integrative and interdisciplinary approaches to management that emphasise the complexities of whole social-ecological systems (Folke et al., 2005). Effective ecosystem management requires measuring the status and trends of ecosystems to inform which management actions are likely to be effective and if these actions have had their intended effect (Jones et al., 2011). Measuring all aspects of complex systems is impossible due to the range of variables and processes present. Variables deemed to be characteristic of the wider system and which are simple enough to be easily measured are often employed as indicators, to act as simplified summaries of system condition and behaviour (Dale and Beyeler, 2001).

Good indicator design has been widely discussed (Failing and Gregory, 2003; Fulton et al., 2005; Parr et al., 2010), with general agreement that indicators should: be cost effective; provide reliable information on status and trends; provide information at multiple extents and resolutions; allow frequent reporting; be meaningful to the public; and respond predictably to policy change (Jones et al., 2011). In practice, the EU's Streamlining European Biodiversity Indicators project used a stakeholder-based process to apply stringent criteria and reduce over 140 biodiversity indicators to a final 26, while the European Commission assesses indicators based on RACER guidelines; where they should be 'Relevant', 'Accepted', 'Credible', 'Easy to Evaluate' and 'Robust' (Best et al., 2008; EEA, 2010). Indicators also provide a powerful tool for communicating with stakeholders about the status and trends of ecosystems, as well as helping identify or illuminate linkages between environmental, human and economic subsystems (Jørgensen et al., 2013). However, multi-dimensional processes (such as complex ecosystem dynamics) are notably difficult to track with individual indicators due to challenges in linking trends across dimensions (Munda, 2005) and capturing interactions between and within sub-systems (Dale and Beyeler, 2001). Multiple indicators are recommended to capture different aspects of the relevant systems (Fulton et al., 2005), but without techniques to distil or summarise them, can be overwhelming in volume of information (Chatziparadeisis, 2007). For example, the marine "Good Environmental Status" goal for EU countries contains 11 descriptors with 29 criteria and 62 individual indicators (European Comission, 2010).

"Composite indicators" (CIs) offer a means of aggregating multiple indicators to track and communicate complex systems. CIs are a mathematical combination of a set of indicators that have no common meaningful unit of measurement. They are increasingly used for decision making in a range of sectors such as economics, business statistics, health and academic performance (Munda et al., 2009; Paruolo et al., 2013). In the environmental sector they are often used for global scale assessments (see Table 1) and to guide policy at local to regional scales (Mendoza and Prabhu, 2003; Di Franco et al., 2009; Ochoa-Gaona et al., 2010). CIs enable direct comparison of disparate social and environmental variables and, due to their clear and unidimensional output, can also gain traction with policy-makers and the general public. Their increasing popularity is unlikely to slow; many have suggested that in order to communicate broad trends effectively and influence conservation policy, meaningful CIs will be required (Balmford et al., 2005; Mace and Baillie, 2007). CIs are similar to mathematical or computational models in that they are simplified representations of reality, although whereas models are usually based upon scientific theory and detailed biological or physical dynamics, CIs are often simply an aggregation of variables considered relevant to a system or issue (Nardo et al., 2008). Modelling studies also typically address, and when possible quantify, inherent uncertainties that arise when simplifying real-world complexities (Kokko, 2005). If CIs are to be used more, and more effectively, within conservation, methodological decisions made in their construction, and the consequent uncertainties, should be clearly understood, described and, if possible, represented or treated – just as with any other type of conservation modelling for decision-making (e.g., Regan et al., 2002).

Here, we explore the uncertainties that underlie environmental CI construction, with the aim of putting recognition of uncertainty at the heart of CI construction and use. We develop a framework to capture the full range of types and sources of uncertainty in a systematic fashion, using four prominent environmental CIs as primary case studies (but also draw reference to others) and suggest methods to navigate them. We first discuss the methods that are specific to each individual stage and then address those that deal with multiple sources of uncertainty. Finally, we discuss ways forward to improve the development and use of composite indicators in practice.

2. Characterising uncertainting and understanding trade-offs

In order to characterise uncertainties within CIs it first important to understand how CIs are constructed. Although individual CIs differ, Fig. 1 shows the construction stages for a typical environmental CI. The typical stages of CI construction are:

- Theoretical framework is the overarching conception of the CI and choice of subgroups and categories, which act as the key areas of the system that are of interest to be measured. The theoretical framework can impact technical choices such as weighting and normalization.
- Data selection involves construction and normalization of variables or sub-indicators as well as analysis and choice of underlying data.
- Construction of the CI includes approaches used for aggregation and weighting of sub-indicators, subgroups and categories.
- Post-development communication involves dissemination and communication of results.