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Uncertainty assessment in ecosystem services analyses: Seven challenges and practical responses

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ABSTRACT

Ecosystem services (ES) analyses are increasingly used to address societal challenges, but too often are not accompanied by uncertainty assessment. This omission limits the validity of their findings and may undermine the 'science-based' decisions they inform. We summarize and analyze seven commonly perceived challenges to conducting uncertainty assessment that help explain why it often receives superficial treatment in ES studies. We connect these challenges to solutions in relevant scientific literature and guidance documents. Since ES science is based on a multiplicity of disciplines (e.g. ecology, hydrology, economics, environmental modeling, policy sciences), substantial knowledge already exists to identify, quantify, and communicate uncertainties. The integration of these disciplines for solution-oriented modeling has been the focus of the integrated assessment community for many years, and we argue that many insights and best practices from this field can be directly used to improve ES assessments. We also recognize a number of issues that hinder the adoption of uncertainty assessment as part of standard practice. Our synthesis provides a starting point for ES analysts and other applied modelers looking for further guidance on uncertainty assessment and helps scientists and decision-makers to set reasonable expectations for characterizing the level of confidence associated with an ES assessment.

1. Introduction

1.1. Ecosystem service assessments are flourishing, assessments of their uncertainty are not

Ecosystem Service (ES) assessments are becoming increasingly common as scientists and practitioners around the world respond to the demand for ecosystem-based management. These assessments analyze how ES – the benefits people derive from nature – may be affected by future societal or environmental conditions, in order to inform policy and decision-making more broadly. Typical applications include spatial planning, payment for ecosystem services (PES) design, climate adaptation and hazard mitigation, development impacts and permitting, restoration planning, and corporate risk management (Ruckelshaus et al., 2015). These initiatives represent billions of dollars of investment in ES programs (Bennett and Carroll, 2014), and millions of people affected by local, national, and global policies.

Although some ES assessments have a theoretical focus, most studies are conducted with some claim to decision-relevance – for example, in a recent survey, Nahuelhual et al. (2015) report that 82% of ecosystem service mapping studies cite a decision-making purpose. In decision-oriented studies, characterizing uncertainty and assessing the robustness of study conclusions is critical for achieving quality and credibility of the analysis. Beyond credibility, understanding uncertainties associated with ES assessments allows decision-makers to consider hedging opportunities to protect objectives they may value. For example, land trusts may choose different parcels to target for conservation when they understand how future land pressures may differ from historical ones. In general, decision-makers are more likely to meaningfully incorporate scientific information into their decisions if they deem it credible and salient, i.e. with confidence that the scientific approach is sound and that their needs have been adequately translated by the analysts (Cash et al., 2003).

Even when studies have a theoretical focus, assessing uncertainty should be an integral part of the analyses as it allows one to test critical assumptions underlying analytic findings and meet the ethical demands of transparency. Besides decision-makers, failure to assess uncertainties is arguably unfair to any consumers of the analysis – whether they are scientists, potential stakeholders, or the general public (Pappenberger and Beven, 2006; Refsgaard et al., 2007).

Despite the issues outlined above, ES assessments and the decisions they inform do not always rely on best modeling practice. In fact, a

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large body of literature now questions the robustness of ES assessments, in particular with regards to their treatment of uncertainty (Eigenbrod et al., 2010; Seppelt et al., 2011; Hou et al., 2013; Schägner et al., 2013; Schulp et al., 2014). In their review of 153 published regional ES assessments, Seppelt et al. (2011) found that only one third included uncertainty assessment "in even the most basic quantitative way" (p.632), and only 18% attempted to thoroughly test the models by addressing independent validation. These findings are corroborated by more recent literature, which highlights the large uncertainties involved in ecosystem services modeling (e.g. Birkhofer et al., 2015), and suggests that the problem of uncertainty assessment remains inadequately addressed.

1.2. What is uncertainty, and why is it a challenge for the ecosystem service analyst?

Uncertainty is complex and manifests in different ways. In this paper, given our focus on ecosystem services assessment, we focus on *modeling* uncertainty, which we define as "the lack of confidence that a decision-maker has about possible outcomes and/or probabilities of these outcomes" (Refsgaard et al., 2007). We use "uncertainty assessment" as an umbrella term including problem scoping, qualitative treatments of uncertainty, and formal quantitative analysis techniques (including sensitivity analysis and various model verification approaches described in Appendix B1).

The literature on uncertainty includes many definitions and typologies (Matott et al., 2009; Warmink et al., 2010; Hou et al., 2013), with various levels of application for ES assessments. We propose here the typology developed by Walker et al. (2003) as a useful framework to analyze uncertainty in ES studies. It distinguishes between three dimensions of uncertainty: location (i.e. "what is the source of uncertainty?"), level ("how uncertain are we?"), and nature ("are we uncertain because of inherent variability, or lack of scientific knowledge?"). Refsgaard et al. (2007) later replaced level with "type" of uncertainty to more discretely categorize that dimension (i,e. describe uncertainty in terms statistical, scenario, qualitative uncertainty, or recognized ignorance).[1] The typology hints at the complexity and multi-faceted nature of uncertainty and suggests that assessing the relative importance of multiple sources of uncertainty may constitute a significant task for the analyst (see practical implications in Section 3.1).

In addition to the complexity of uncertainty, other factors may contribute to the rarity of uncertainty assessments in ES studies:

1) The diversity of purposes of ES modeling efforts: models are used for prediction, exploratory analysis, communication, or learning (Brugnach et al., 2008), which changes the focus of uncertainty analysis. Within each realm, different applications may require characterizing uncertainty with respect to different types of outputs, e.g. relative ordering (for prioritization), relative performance (for choosing between development plans), or absolute accuracy (for attributing costs and benefits).
2) The diversity of the studies' disciplinary focus: even if most ES studies are multi-disciplinary, there is often a main discipline that may drive the perception and treatment of uncertainty, while it goes undertreated along other disciplinary axes (e.g. one or the other of hydrology or economics may drive ES assessments for Water Funds, see Section 2).
3) The background, technical capacity, and values of the modeling team (especially the team lead), whose own perceptions and experience will influence the treatment of uncertainty
4) The nascent state of the field, which has afforded little time to establish a community of practice with shared and codified standards (Polasky et al., 2015).

These factors are of course non-trivial, but they characterize a situation similar to that of other modeling communities in the past decades.

1.3. Is the ES community alone?

We argue in this paper that a large number of challenges faced by ES analysts have been partially addressed within other scientific disciplines and that the ES community can fruitfully draw from them. Of course, many techniques exist within the natural and social sciences upon which ES assessments are based (e.g. ecology, hydrology, economics, geospatial sciences), and we highlight them where appropriate. However, we draw particular attention to the often unrecognized specialties falling under the terms "integrated environmental modeling," or "integrated assessment," which we take to broadly encompass several related disciplines such as "impact assessment", "policy analysis" and others (see Laniak et al. (2013) for a definition of these and related terms). Importantly, these disciplines hold keys not only to technical challenges faced by ES modelers, but also to less-appreciated challenges such as bridging between multiple disciplines and decision-makers.

Integrated assessment can be defined as the "integration of knowledge from different disciplines with the goal to contribute to understanding and solving complex societal problems, that arise from the interaction between humans and the environment, and to contribute in this way to establishing the foundation for sustainable development" (Jakeman et al., 2008). In addition to environmental sciences, decision making and policy analysis are often part of the integrated assessment, with an explicit focus on the entire modeling process and its ability to usefully inform decisions. ES assessment can be seen as a particular case of integrated assessment, meaning that insights on uncertainty from this community of practice can be readily applied for ES assessments.

1.4. Aims of this paper

Our reflections on uncertainty assessments in ES studies echo those from Pappenberger and Beven (2006), who criticize the main reasons why hydrologists fail to conduct uncertainty analysis, but also provide practical guidance. Borrowing their rhetorical framing, we analyze seven common challenges and concerns that scientists and ES practitioners may have about treating uncertainty in ES assessments. These challenges were identified from our own experience, from the literatures on ES and uncertainty assessment, and were discussed with scientists and practitioners attending the 2015 Natural Capital Symposium (natcap2015.wordpress.com), and a related 2016 workshop at the National Center for Socio-Environmental Synthesis (SESYNC workshop "Motivating and Improving Uncertainty Assessment in Ecosystem Services Modeling to Inform Decisions").

This paper is not the first effort to understand, characterize and promote uncertainty analysis in ES assessment specifically (Grêt-Regamey et al., 2013; Hou et al., 2013). However, our goal here is to advance these efforts with a practical mindset, legitimizing some concerns, refuting others, and ultimately orienting readers toward solutions. This synthesis is of highest relevance for ES analysts themselves as well as others working in similar integrated modeling areas, like cost-benefit analysis or integrated environmental assessments. Therefore, this paper makes three contributions:

i) It explicates the challenges faced by ES analysts when tasked to "deal with uncertainty";
ii) It helps leaders and coordinators of ES assessments manage

[1] In this framing the concept of "deep" uncertainty, referred to later, would essentially encompass any type other than statistical, and also encompasses statistical uncertainties in cases where parties to the decision may not agree on the statistical uncertainty, or even objectives of interest.