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Comparing approaches to spatially explicit ecosystem service modeling: A case study from the San Pedro River, Arizona

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ABSTRACT

Although the number of ecosystem service modeling tools has grown in recent years, quantitative comparative studies of these tools have been lacking. In this study, we applied two leading open-source, spatially explicit ecosystem services modeling tools – Artificial Intelligence for Ecosystem Services (ARIES) and Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) – to the San Pedro River watershed in southeast Arizona, USA, and northern Sonora, Mexico. We modeled locally important services that both modeling systems could address – carbon, water, and scenic viewsheds. We then applied managerially relevant scenarios for urban growth and mesquite management to quantify ecosystem service changes. InVEST and ARIES use different modeling approaches and ecosystem services metrics; for carbon, metrics were more similar and results were more easily comparable than for viewsheds or water. However, findings demonstrate similar gains and losses of ecosystem services and conclusions when comparing effects across our scenarios. Results were more closely aligned for landscape-scale urban-growth scenarios and more divergent for a site-scale mesquite-management scenario. Follow-up studies, including testing in different geographic contexts, can improve our understanding of the strengths and weaknesses of these and other ecosystem services modeling tools as they move closer to readiness for supporting day-to-day resource management.

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1. Introduction

Ecosystem service valuation has been a subject of academic interest for decades, but has recently matured to the point where it can inform policymaking (Ruhl et al., 2007; Daily et al., 2009; PCAST, 2011). Recent years have seen a proliferation of software decision-support tools that integrate ecology, economics, and geography for use in spatially explicit planning and conservation (Daily et al., 2009; BSR, 2011; Vigerstol and Aukema, 2011). Despite this proliferation of tools, there has been a dearth of quantitative comparative work to understand their relative strengths, weaknesses, and applicability to various settings. The scope of the few ecosystem services tool reviews to date has been limited, providing detailed descriptions of 2–3 tools and references for 2–4 others (Nelson and Daily, 2010; Vigerstol and Aukema, 2011). While both of these papers describe the strengths and weaknesses of alternative approaches, neither provide comparative results from the application of multiple tools to the same geographic context.

Spurred by growing demand for more sophisticated analysis of the social and economic consequences of land management decisions, the U.S. Department of Interior – Bureau of Land Management (BLM) launched a pilot project with the U.S. Geological Survey (USGS) in early 2010 to assess the usefulness and feasibility of ecosystem service valuation as an input to BLM's resource management decisions (Bagstad et al., 2012).

The BLM manages the largest terrestrial resource portfolio in the United States, including nearly 100 million hectares of land and over 280 million hectares of subsurface mineral estate. These lands stretch across the western U.S. from Alaska's North Slope to the Mexican border. Under its multiple-use mission, BLM's responsibilities range from facilitating the development of oil, gas, coal, solar energy and other commodities to providing many forms of recreation, restoring habitat, and preserving scenic values, archeological heritage, and environmental quality (BLM, 2005). Tradeoffs across disparate management objectives are a constant.

By design the BLM is a relatively decentralized agency, allowing resource management decisions to be informed by knowledge of local conditions. Most of the decisions are made by officials at over 100 field offices, the smallest administrative unit in the agency's organization, typically less than 1 million hectares in area. These include land and resource allocation decisions made through *resource management plans* and project implementation decisions through *environmental impact statements* (EIS) or, for less complex decisions, shorter *environmental assessments*. In addition,

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programmatic decisions establish the criteria for permitting, sitting, and mitigating a class of projects. For example, BLM's Solar Energy Development Programmatic EIS establishes such criteria for industrial-scale solar development across six western states (BLM and DOE, 2012). Ecosystem service metrics are potentially relevant to all of these categories of decisions. At almost any scale, BLM-managed lands form one component of a jurisdictional mosaic that includes private, state and other federally managed lands. Understanding the cross-jurisdictional effects of the agency's decisions is often critical.

Although ecosystem services analysis is appropriate for inclusion in agency planning documents, including those required by the National Environmental Policy Act (NEPA), to date they have been rarely used in this way, with the exception of historically well-quantified non-market values such as recreation (Ruhl et al., 2007). Without tools and standards for measuring, quantifying, and valuing ecosystem services, agencies, the public, and other stakeholders are unlikely to support their incorporation into decision-making processes. The recent emergence of ecosystem service tools offers initial insight into how services could be measured and compared for such decision-making processes.

The USGS-BLM pilot project sought to: (1) review the “landscape” of tools for quantifying, mapping, and valuing ecosystem services and (2) quantify ecosystem services using different tools, where feasible, comparing the utility of model outputs for decision makers for a chosen management unit and for agency-wide application. While BLM commissioned this study and it was set within the context of agency decision making, the results are relevant for a variety of other resource managers interested in bringing ecosystem services into decision-making processes. A parallel project led by BSR (formerly Business for Social Responsibility) also explored the application of ecosystem service tools for private-sector decision making, with a geographic focus on the same case-study site, the San Pedro River in southeast Arizona (BSR, 2011; Bagstad et al., this volume).

We provide a full review of the “tools landscape” elsewhere, describing and evaluating 17 ecosystem services modeling and valuation tools (Bagstad et al., 2012, this volume). In this paper, we present results from two spatially explicit ecosystem services modeling systems designed to quantify tradeoffs between multiple services: Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST, Tallis et al., 2013) and Artificial Intelligence for Ecosystem Services (ARIES, Villa et al., 2011). We limited our quantitative analysis to the InVEST and ARIES tools for four reasons – other tools either: (1) are qualitative or not designed to support spatially explicit, scenario-based analysis; (2) use proprietary software, requiring contracting with consultants and/or raising software licensing issues that our project budget could not support; (3) use place-specific approaches that are not broadly applicable; and/or (4) are at too early a stage of development for the independent application.

InVEST is a freely downloadable ArcGIS toolbox currently containing nine marine and seven freshwater and terrestrial ecosystem service models (Tallis et al., 2013). Additionally, the late 2012 InVEST 2.4 release includes stand-alone versions of some models that can be run outside ArcGIS, though GIS software is still needed to view and edit model inputs and outputs. Along with these simpler (“Tier 0 and 1”) models, a set of more complex (“Tier 2”) models has been described but not yet distributed in a software package (Kareiva et al., 2011). Tier 1 models use spatial land-use/land-cover (LULC) data and other input parameters and coefficient tables linking LULC to ecosystem service provision to populate biophysical models of ecological production functions (Daily et al., 2009) and quantify services. Output maps for different services can be compared, as can baseline and scenario results for multiple ecosystem services. For most of the Tier 1 models, valuation data can be input into the models to derive dollar values based on the biophysically quantified ecosystem services.

ARIES is an open-source modeling framework using artificial intelligence techniques, including machine reasoning and pattern recognition, with a library of ecosystem service models and spatial data to pair locally appropriate data and models, quantifying ecosystem service flows and their uncertainty within a freely accessible web browser and stand-alone software tool (Villa et al., 2011). ARIES quantifies and maps the “source” (supply) and “use” (demand) for ecosystem services using ecological production functions within probabilistic or deterministic models, as appropriate. It then uses a family of agent-based models to quantify the flow of services between ecosystems providing a service and their human beneficiaries, accounting for service-specific flow paths and biophysical features that can deplete ecosystem service flows (“sinks”; Johnson et al., 2012). Ecosystem service flow modeling enables the quantification of actual service provision and use, as opposed to just theoretical or in situ service provision (Bagstad et al., 2013), which has often been quantified by other modeling approaches but provides a less realistic view of ecosystem service dynamics (Syrbe and Walz, 2012). Like InVEST, scenarios can be modeled, ecosystem service tradeoffs compared, and monetary values can be applied to biophysical outputs to derive dollar values for some services.

Nelson and Daily (2010), Vigerstol and Aukema (2011), and Bagstad et al. (this volume) discuss InVEST, ARIES, and other models more generally without presenting comparative results. Further details on the InVEST and ARIES modeling systems are provided in their respective modeling references (Kareiva et al., 2011; Tallis et al., 2013; Villa et al., 2011; Bagstad et al., 2011). This place-specific application of the ARIES and InVEST modeling tools allows us to discuss implications for the San Pedro, to compare the relative strengths and weaknesses of ARIES and InVEST, and to explore the implications of spatially explicit, scenario-based ecosystem services modeling in support of natural resource management.

2. Methods

2.1. Study area

The San Pedro River has its headwaters near Cananea, Sonora, Mexico and flows north into the United States where it eventually meets the Gila River, a major tributary of the Lower Colorado River. Located at the confluence of four major biomes – the Chihuahuan and Sonoran deserts, Rocky Mountains, and Sierra Madre Occidental, this semiarid basin is a region of high biodiversity and conservation interest. However, it faces significant threats from groundwater decline due to pumping for urban growth and attendant water use, particularly near Sierra Vista and Benson, Arizona. These concerns have led to extensive research within the basin across the fields of ecology, hydrology, geomorphology, economics, and increasingly cross-disciplinary research (Moran et al., 2008; Stromberg and Tellman, 2009; Brookshire et al., 2010). The BLM manages the roughly 231 km^2 San Pedro Riparian National Conservation Area (SPRNCA), among other lands in the basin, and The Nature Conservancy, USDA Forest Service, Arizona State Trust Lands, Department of Defense (Fort Huachuca), and National Park Service also manage land on the U.S. side of the border (Fig. 1). After consulting with project partners, we chose to use the entire San Pedro River basin, an area covering approximately 12,000 km^2, as the study area, to better account for ecosystem service flows and values across these different jurisdictional boundaries, though data limitations did not support analysis of all services across the entire watershed.