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# A comparative assessment of decision-support tools for ecosystem services quantification and valuation

Kenneth J. Bagstad [a,*], Darius J. Semmens [a], Sissel Waage [b], Robert Winthrop [c]

[a] U.S. Geological Survey, Geosciences & Environmental Change Science Center, Denver, CO, USA
[b] BSR, San Francisco, CA, USA
[c] Socioeconomics Program, USDI—Bureau of Land Management, Washington, DC, USA

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ABSTRACT

To enter widespread use, ecosystem service assessments need to be quantifiable, replicable, credible, flexible, and affordable. With recent growth in the field of ecosystem services, a variety of decision-support tools has emerged to support more systematic ecosystem services assessment. Despite the growing complexity of the tool landscape, thorough reviews of tools for identifying, assessing, modeling and in some cases monetarily valuing ecosystem services have generally been lacking. In this study, we describe 17 ecosystem services tools and rate their performance against eight evaluative criteria that gauge their readiness for widespread application in public- and private-sector decision making. We describe each of the tools′ intended uses, services modeled, analytical approaches, data requirements, and outputs, as well time requirements to run seven tools in a first comparative concurrent application of multiple tools to a common location – the San Pedro River watershed in southeast Arizona, USA, and northern Sonora, Mexico. Based on this work, we offer conclusions about these tools′ current 'readiness' for widespread application within both public- and private-sector decision making processes. Finally, we describe potential pathways forward to reduce the resource requirements for running ecosystem services models, which are essential to facilitate their more widespread use in environmental decision making.

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* Corresponding author. Tel.: +1 303 236 1330.
*E-mail address:* kjbagstad@usgs.gov (K.J. Bagstad).

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## 1. Introduction

A large and rapidly growing body of research seeks to identify, characterize, and value ecosystem goods and services – the benefits that ecosystems provide to people (Millennium Ecosystem Assessment (MA), 2005). However, the development of decision-support tools (hereafter tools) that integrate ecology, economics, and geography to support decision making is a more recent phenomenon (Ruhl et al., 2007; Daily et al., 2009). Current tools range from simple spreadsheet models to complex software packages. Unlike *ad hoc* methods for quantifying ecosystem services (e.g., Egoh et al., 2012; Martinez-Harms and Balvanera, 2012), this new generation of analytical tools is intended to enable replicable and quantifiable ecosystem services analyses. Assuming that tools are well-documented and tested, they can add credibility and trust to the decision process, increasing stakeholder confidence in their use. If they are flexible enough for use in diverse decision contexts and can be affordably applied, they could reasonably be incorporated into public- and private-sector environmental decision making on a routine basis.

Numerous groups of tool developers are now developing new approaches for integrating ecosystem services into both public- and private-sector decision-making processes. While aspirations to aid decision makers are cross-cutting, the tools vary greatly. Some are designed to be generalizable to any location in the world while others are place-specific. The tools differ in their approaches to economic valuation, spatial and temporal representation of services, and incorporation of existing biophysical models.

Despite the proliferation of tools, there has been little systematic review and evaluation of ecosystem services tools, in order to determine tool strengths, weaknesses, and applicability to various settings and concurrently apply multiple tools to a common study area. The scope of most other reviews has been limited, providing detailed descriptions of 2–3 tools and references to another 2–4 tools (Nelson and Daily, 2010; Vigerstol and Aukema, 2011). Aside from the rapid evolution of ecosystem service tools, a major reason why thorough reviews have been difficult to complete has been the challenge in circumscribing what constitutes an ecosystem service tool amidst the variety of emerging tools for conservation, land-use planning, and hydrologic and ecological modeling. Additional reviews have addressed some of these other types of tools, as well as one-off modeling approaches not intended to for broader applicability (Institute for European Environmental Policy (IEEP) et al., 2009; Ambrose-Oji and Pagella, 2012; Egoh et al., 2012; Martinez-Harms and Balvanera, 2012; Smart et al., 2012).

Indeed, a broad tradeoff exists between using new ecosystem service tools, many of which are intended to be transferrable to new geographic and decision contexts, versus using existing mapping or modeling approaches that are locally known and trusted by decision makers but require the addition of an ecosystem services component. Emerging ecosystem service tools offer the potential for “standardizing” assessments to facilitate testing and comparison across broad geographic contexts, and provided that models are clearly documented, user-friendly, and easily parameterized, they may facilitate widespread adoption of ecosystem services for decision making. However, these models are often less well known to decision makers, so they face the critical step of achieving stakeholder trust and buy-in. Other well-accepted models may already have such buy-in, but lack an ecosystem services component. Such tools, then, must seek to add components that accurately quantify ecosystem services. The lack of comparability between such locally adapted models may have the added disadvantage of limiting the comparability of their results and their use within common decision frameworks. This tradeoff is also partly related to scale: while some generalized models may be highly effective at the national to regional level, they may be ineffective at the local level if they cannot incorporate accurate, high-resolution data while accounting for local influences on ecosystem service supply, demand, and value. In such cases locally developed models may better account for fine-scale analysis (Smart et al., 2012). However, an improved understanding of generalized models was generally preferred by the U.S.-based public-sector resource management agencies and multinational corporations involved in this review. These entities, which are making decisions across a broad range of geographies, agreed that uniform processes and protocols would be easier to use; however, for localized decision making, adaptation and use of local models might be a preferred strategy (Smart et al., 2012).

While the relative value of these two approaches is a worthwhile debate in the field of ecosystem service modeling, the intent of this review is to qualitatively catalog and evaluate methods that are already generalizable or are intended by their developers to become so. In exploring this part of the tool landscape, it is beyond the scope of the paper to address the adaptability of other biophysical models to ecosystem services and whether that approach or the use of generalizable ecosystem service models is a more appropriate course of action.

This paper is based on a study that was undertaken in 2010 through 2011, which was spurred by the growing demand for more comprehensive analyses of the ecological and socioeconomic consequences of land-management decisions, particularly within the U.S. government′s policy direction for environmental and natural resource management (President′s Council of Advisors on Science and Technology (PCAST), 2011; Council on Environmental Quality (CEQ), 2013). In response, the U.S. Department of Interior-Bureau of Land Management (BLM) launched a pilot project with the U.S. Geological Survey (USGS) to assess the usefulness and feasibility of ecosystem services valuation as an input into decision-making. The BLM manages nearly 100 million hectares of land 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 (Bureau of Land Management (BLM), 2005).

BLM’s goals for the comparative tools assessment were to (1) determine which, if any, methods for valuing ecosystem services are ripe for operational use across the agency, and (2) evaluate the utility of ecosystem service valuation for its resource management decision processes. The first phase of this effort used a study area – the San Pedro River watershed in southeast Arizona and northern Sonora, Mexico (hereafter San Pedro) – that had a legacy of biophysical research to draw upon and a variety of ecological stressors relevant to federal resource management.

The BLM-USGS initiative was coupled with comparative application of additional ecosystem service tools and analysis of their relevance to the private sector – through engaging the same technical specialist to conduct the assessment, which was concurrently coordinated by Business for Social Responsibility (BSR), an independent nongovernment organization (NGO) focused on sustainability issues and their application to the private sector. The BSR initiative asked of all tools where a hypothetical residential development within the San Pedro should be sited to minimize impacts on the provision and flows of ecosystem services (Waage et al., 2011). Based on this comparative application, we summarize the findings from these two linked studies in this article through a review of ecosystem services software and modeling tools.

To our knowledge this is the first effort to evaluate multiple ecosystem service tools and their applicability to environmental decision making across both public- and private-sector contexts. Our analysis includes both (1) place-specific tools – customized for application in a particular geographic context but that could be applied elsewhere – and (2) generalizable tools intended to be applicable in diverse contexts when locally appropriate input data are available.

Quantified biophysical and monetary analysis of ecosystem service values for the San Pedro are presented elsewhere (Waage et al., 2011; Bagstad et al., 2012, in this volume). In this article, we catalog and describe 17 existing tools, evaluating them in terms of eight evaluative criteria used to gauge their utility in public- and private-sector decision making. In addition, we describe the time required to complete an assessment for seven of these tools, which were applied to the case study on the San Pedro.

## 2. Study context

### 2.1. Tools review

Through literature reviews and discussions with 77 colleagues across the academic, public, private, and NGO sectors (see supporting online material for a full list of project participants), we identified 17 tools that assess, quantify, model, value, and/or map ecosystem services (Table 1), excluding *ad hoc* ecosystem service mapping efforts (Egoh et al., 2012; Martinez-Harms and Balvanera, 2012). Numerous "ecosystem-based management tools" exist; for example, the Ecosystem-Based Management (EBM) Tools database contained 183 tools as of November 2012 (Ecosystem-Based Management Tools Database, 2012). We limited this review, however, to tools with an explicit focus on multiple ecosystem services, rather than those ecological, hydrologic, or other biophysical process models that lack a central focus on ecosystem services. We thus, for example, exclude tools for conservation planning or optimization (e.g., C-Plan, Pressey et al., 2005; NatureServe Vista, NatureServ, 2013), integrated models not explicitly linked to ecosystem services (e.g., Landscapes Toolkit (LsT, Bohnet et al., 2011)), and hydrologic process models (e.g., Soil and Water Assessment Tool (SWAT, Arnold and Fohrer, 2005)). We also excluded from our review one-time applications that are not readily under development for new locations (e.g., Maes et al., 2012, Advanced Terrestrial Ecosystem Analysis and Modelling (ATEAM, Schroter et al., 2005)), and tools intended for single landscape types, whose outputs could not inform change analyses (e.g., CITYGreen, American Forests, 2002). Finally, we included three valuation databases that include functionality for users to construct valuation portfolios – the Natural Assets Information System (NAIS), Ecosystem Valuation Toolkit, and Benefit Transfer and Use Estimating Model Toolkit. We exclude from our review those valuation databases that simply provide users with a location to search through non-market valuation studies.

We, or in some cases the tool developers themselves, applied seven of these tools to the San Pedro, including: Artificial Intelligence for Ecosystem Services (ARIES), EcoAIM, EcoMetrix, Ecosystem Services Review (ESR), ESValue, Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), and the Benefit Transfer and Use Estimating Model Toolkit. For the remaining ten tools that we were unable to run in the pilot study – due to budget and time limitations or because they were under development and unable to be independently run at the time of this assessment – we interviewed the tool developers in order to understand their tool's intended use, approach, and level of development. We include descriptions of these tools in this article. We do not, however, include further discussion of primary valuation (various techniques for non-market valuation of ecosystem services) or secondary valuation (various types of benefit transfers), as these are described in detail elsewhere (Farber et al., 2006; Wilson and Hoehn, 2006; Bagstad et al., 2012).

### 2.2. Evaluative criteria to support tool selection

Based on discussions with 77 stakeholders and scientists involved in the BLM and BSR projects, including academic and agency scientists and private-sector practitioners conducting ecosystem services analysis, we developed and reviewed a set of eight evaluative criteria that describe important tool characteristics which decision-makers asserted would be key elements of selecting analytical ecosystem services tools (see supporting online material for a full list of project participants). These criteria qualitatively gauge each tool's ability to support ecosystem service assessments that are quantifiable, replicable, credible, flexible, and affordable. We applied these criteria to each tool in order to assess its relative strengths and weaknesses. The evaluative criteria include

1. *Quantification and uncertainty.* Quantified outputs are essential for measuring ecosystem service tradeoffs, though qualitative tools may be useful in initial screening, scoping, or coarse-grain ranking processes. Reporting a single value can inspire false confidence in the certainty of results, so uncertainty estimates are a valuable addition to the set of model outputs. Although any model can produce a range of output values when the user supplies multiple possible input values (Kareiva et al., 2011), yielding some information about uncertainty, some models more explicitly account for uncertainty using approaches like Monte Carlo simulation or Bayesian network modeling.
2. *Time requirements.* As the time required to apply a tool decreases, it becomes increasingly practical for widespread use.
3. *Capacity for independent application.* Tools that are in the public domain, or for which a software license can be purchased to allow the tool to be independently applicable, were a strong preference of a range of agency stakeholders involved in the BLM pilot study as well as private-sector decision-makers in the BSR component of the study. This contrasts with tools that require contracting with academic or consulting groups for each application of the tool.
4. *Level of development and documentation.* Ideally tools would be sufficiently developed to run reliably, use validated models, produce replicable results, and to have their methods, assumptions and key algorithms, strengths and limitations, and application sites well documented in user manuals and/or peer-reviewed journal articles, which may also include validation exercises. Tools that are well-developed and documented have greater transparency and credibility, and are thus more likely to engender trust with decision makers and the public.
5. *Scalability.* Tools may be applicable from parcel to global scales. Tools that are applicable across multiple spatial scales are attractive to managers because it is easier to learn one tool than many; however, no tool is likely to handle analyses at all scales well, which may necessitate use of multiple tools.
6. *Generalizability.* To support widespread use, tools would ideally be broadly applicable across a variety of ecoregional and socioeconomic settings while providing some degree of customizability to account for differing local conditions. Most tools are either place-specific, reducing transferability but accounting for locally important processes, or broadly generalizable, sacrificing local detail for transferability. Some tools currently use place-specific case studies but are intended to be more generalizable in future releases.
7. *Nonmonetary and cultural perspectives.* Stakeholders consulted asserted that it would be ideal if tools could provide information that incorporates multiple valuation systems (monetary and non-monetary) and cultural perspectives (including indigenous people's and other spiritual and cultural values).
8. *Affordability, insights, integration with existing environmental assessment.* Tools for quantifying and valuing ecosystem

**Table 1**
A survey of ecosystem services tools.

| Tool, URL, and references | Brief description | Tested for the San Pedro? | Rationale for choice to test for the San Pedro |
|---|---|---|---|
| Ecosystem Services Review (ESR), http://www.wri.org/ (World Resources Institute (WRI), 2012) | Publicly available, spreadsheet-based process to qualitatively assess ecosystem services impacts | Yes | A well-documented approach to quickly describe ecosystem services and impacts qualitatively |
| Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), http://www.naturalcapitalproject.org, (Kareiva et al., 2011; Tallis et al., 2013) | Open source ecosystem service mapping and valuation models accessed through ArcGIS | Yes | Well-documented; can be independently applied and tested; amenable to widespread use |
| Artificial Intelligence for Ecosystem Services (ARIES), http://www.ariesonline.org (Bagstad et al., 2011; Villa et al., 2011) | Open source modeling framework to map ecosystem service flows; online interface and stand-alone web tools under development | Yes | Data and models available for several western U.S. states; global model and online interface under development would enable widespread use |
| LUCI (formerly Polyscape), http://www.polyscape.org (Jackson et al., 2013) | Open source GIS toolbox to map areas providing services and potential gain or loss of services under management scenarios | No | Tool not developed by the time of the pilot study |
| Multiscale Integrated Models of Ecosystem Services (MIMES), http://www.afordablefutures.org | Open source dynamic modeling system for mapping and valuing ecosystem services | No | Requires commercial modeling software; model construction currently requires contracting with development group |
| EcoServ (Feng et al., 2011) | Web-accessible tool to model ecosystem services | No | Still in development; initial case studies not available for Southwest |
| Co$ting Nature, http://www1.policysupport.org/cgi-bin/ecoengine/start.cgi?project=costingnature | Web-accessible tool to map ecosystem services and conservation priority areas | No | Tool not developed by the time of the pilot study |
| Social Values for Ecosystem Services (SolVES), http://solves.cr.usgs.gov (Sherrouse et al., 2011) | ArcGIS toolbar for mapping social values for ecosystem services based on survey data or value transfer | No | No survey data available; conditions at study site too different from past studies to support value transfer |
| Envision, http://envision.bioe.orst.edu (Guzy et al., 2008) | Integrated urban growth-ecosystem services modeling system; has used external models, including InVEST, or created new ecosystem service models as appropriate | No | Has not yet been applied in the Southwest; infeasible to run for new sites without a substantial external research effort |
| Ecosystem Portfolio Model (EPM), http://geography.wr.usgs.gov (Labiosa et al., 2013) | Web-accessible tool to model economic, environmental, and quality of life impacts of alternative land-use choices | No | Developed for adjacent Santa Cruz River watershed but; infeasible to run for new sites without a substantial external research effort |
| InFOREST, http://inforest.frec.vt.edu/ | Web-accessible tool to quantify ecosystem services in Virginia | No | Has only been developed for Virginia |
| EcoAIM (Waage et al., 2011) | Proprietary tool for mapping ecosystem services and stakeholder preferences | Yes | Demonstration completed by Exponent (Waage et al., 2011) |
| ESValue (Waage et al., 2011) | Proprietary tool for mapping stakeholder preferences for ecosystem services | Yes | Demonstration completed by Entrix (Waage et al., 2011) |
| EcoMetrix, http://www.parametrix.com (Parametrix, 2010) | Proprietary tool for measuring ecosystem services at site scales using field surveys | Yes | Demonstration completed by Parametrix (Waage et al., 2011) |
| Natural Assets Information System (NAIS), http://www.sig-gis.com (Troy and Wilson, 2006) | Proprietary valuation database paired with GIS mapping of land-cover types for point transfer | No | Proprietary method; limited primary valuation studies to support application to study site |
| Ecosystem Valuation Toolkit, http://www.esvaluation.org (Ecosystem Valuation Toolkit, 2012) | Subscription-based valuation database paired with GIS mapping of land-cover types for point transfer | No | Tool not developed by the time of the pilot study |
| Benefit Transfer and Use Estimating Model Toolkit, http://www.defenders.org (Loomis et al., 2008) | Publicly available spreadsheets, use function transfer to value changes in ecosystem services in the U.S. | Yes | Well-documented; can be independently applied and tested; amenable to widespread use |

services are more desirable if they can cost-effectively provide additional information that conforms with established management and planning processes.

We did not include each tool's biophysical and socioeconomic complexity as an evaluative criterion. Although complexity is an important issue in ecosystem service modeling (Seppelt et al., 2011), and assessments based on proxy information such as land cover have been shown to sacrifice accuracy (Eigenbrod et al., 2010), complex models can lead to a false sense of confidence in model quality, which can make erring on the side of simplicity more defensible. While a model's purpose should typically dictate its needed level of complexity, the most complex models do not always perform better than less complex models (Fultona et al., 2004; Raicka et al., 2006), nor do they necessarily add value to decision making (Tallis and Polasky, 2011).

## 3. Findings: analytical and modeling approaches

This section offers an overview of each of the 17 tools' performance against the evaluative criteria (Table 2) followed by detailed descriptions of all tools′ analytical and modeling approaches, their intended uses, ecosystem services modeled, modeling and valuation approaches, data requirements, and outputs. Descriptions for models that lack full documentation are necessarily less complete, so we do not list the services modeled by these approaches. Finally we describe the time requirements for application of seven tools to a common study area – the San Pedro.

### 3.1. Aspatial ecosystem services impact screening: ESR

The ESR (World Resources Institute (WRI), 2012) is a structured process to identify ecosystem services impacts, dependencies, and

**Table 2**
Description of all ecosystem service tools against key evaluative criteria.

| Tool | Quantifiable, approach to uncertainty | Time requirements | Capacity for independent application | Level of development & documentation | Scalability | Generalizability | Nonmonetary & cultural perspectives | Affordability, insights, integration with existing environmental assessment |
|---|---|---|---|---|---|---|---|---|
| ESR | Qualitative | Low, depending on stakeholder involvement in the survey process | Yes | Fully developed and documented | Multiple scales | High | No valuation component | Most useful as a low-cost screening tool |
| InVEST | Quantitative, uncertainty through varying inputs | Moderate to high, depending on data availability to support modeling | Yes | "Tier 1" models fully developed and documented; "Tier 2" documented but not yet released | Watershed or landscape scale | High, though limited by availability of underlying data | Biophysical values, can be monetized | Spatially explicit ecosystem service tradeoff maps; currently relatively time consuming to parameterize |
| ARIES | Quantitative, uncertainty through Bayesian networks and Monte Carlo simulation | High to develop new case studies, low for preexisting case studies | Yes, through web explorer or stand-alone software tool | Fully documented; case studies complete but global models and web tool under development | Watershed or landscape scale | Low until global models are completed | Biophysical values, can be monetized | Spatially explicit ecosystem service tradeoff, flow, and uncertainty maps; currently time consuming for new applications |
| LUCI | Quantitative, currently does not report uncertainty | Moderate; tool is designed for simplicity and transparency, ideally with stakeholder engagement | Yes, though website is under development and more detailed user guidance is presumably forthcoming | Initial documentation and case study complete; follow-up case studies in development | Site to watershed or landscape scale | Relatively high; a stakeholder engagement process is intended to aid in "localizing" the data and models | Currently illustrates tradeoffs between services but does not include valuation | Spatially explicit ecosystem service tradeoff maps; designed to be relatively intuitive to use and interpret |
| MIMES | Quantitative, uncertainty through varying inputs (automated) | High to develop and apply new case studies | Yes, assuming user has access to SIMILE modeling software | Some models complete but not documented | Multiple scales | Low until global or national models are completed | Monetary valuation via input–output analysis | Dynamic modeling and valuation using input–output analysis; currently time consuming to develop and run |
| EcoServ | Quantitative, uncertainty through varying inputs | High to develop new case studies, low for existing case studies | Yes, pending release of web explorer | Under development, not yet documented | Site to landscape scale | Low until global or national models are completed | Biophysical values, can be monetized | In development, will offer spatially explicit maps of ecosystem service tradeoffs |
| Co$ting Nature | Quantitative | Low | Yes | Partially documented | Landscape scale | High | Outputs indexed, bundled ecosystem service values | Rapid analysis of indexed, bundled services based on global data, along with conservation priority maps |
| SolVES | Quantitative, no explicit handling of uncertainty | High if primary surveys are required, low if function transfer approach is used | Yes, assuming user has access to ArcGIS | Fully developed and documented | Watershed or landscape scale | Low until value transfer can be shown to successfully estimate values at new sites | Nonmonetary preferences (rankings) of relative values for stakeholders | Provides maps of social values for ecosystem services; time consuming for new studies but lower-cost for value transfer |
| Envision | Quantitative | High to develop new case studies | Yes | Developed and documented for Pacific Northwest case study sites | Landscape scale | Place-specific | Allows nonmonetary tradeoff comparison, also supports monetary valuation | Cost-effective in regions where developed; time consuming for new applications |
| EPM | Quantitative | High to develop new case studies, low for existing case studies | Yes, through web browser | Developed and documented for three case study sites | Watershed or landscape scale | Place-specific | Ecological, economic, and quality of life attributes could support nonmonetary valuation | Cost-effective in regions where developed; time consuming for new applications |
| InFOREST | Quantitative | Low, accessed through online interface | Yes, through web browser | Developed and documented only for Virginia | Site to landscape scale | Currently place-specific | Designed as a credit calculator, no economic valuation | Cost-effective in regions where developed; time consuming for new applications |
| EcoAIM | Quantitative | Relatively low for basic mapping, greater for nonmonetary valuation | No | Public documentation unavailable | Watershed or landscape scale | High | Incorporates stakeholder preferences via modified risk analysis approach | Spatially explicit ecosystem service tradeoff maps; relatively time consuming to run |

**Table 2** (*continued* )

| Tool | Quantifiable, approach to uncertainty | Time requirements | Capacity for independent application | Level of development & documentation | Scalability | Generalizability | Nonmonetary & cultural perspectives | Affordability, insights, integration with existing environmental assessment |
|---|---|---|---|---|---|---|---|---|
| ESValue | Quantitative, uncertainty through Monte Carlo simulation | Relatively high to support consultant-stakeholder valuation process | No | Public documentation unavailable | Watershed or landscape scale | High | Nonmonetary preferences via ranked analysis of tradeoffs by stakeholders | Stakeholder-based relative ecosystem service value assessment; relatively time consuming |
| EcoMetrix | Quantitative | Relatively low to support field visits and data analysis | No | Public documentation unavailable | Site scale | High, where ecological production functions are available | Designed as a credit calculator, no economic valuation | One method for site-scale ecosystem services assessment |
| NAIS | Quantitative, reports range of values | Variable depending on stakeholder involvement in developing the study | No | Developed but public documentation unavailable | Watershed or landscape scale | High, within limits of point transfer | Dollar values only | Point transfer for "ballpark numbers," building awareness of values |
| Ecosystem Valuation Toolkit | Quantitative, reports range of values | Assumed to be relatively low | Yes | Under development | Watershed or landscape scale | High, within limits of point transfer | Dollar values only | Point transfer for "ballpark numbers," building awareness of values |
| Benefit Transfer and Use Estimating Model Toolkit | Quantitative, uncertainty through varying inputs | Low | Yes | Fully developed and documented | Site to landscape scale | High | Dollar values only | Low cost approach to monetary valuation |

stakeholders. Although it is a qualitative tool – based on a structured set of questions laid out in a spreadsheet – we include it in this review due to its ability to function as a low-cost scoping tool that can provide an entry point to ecosystem service mapping, modeling, or valuation. The ESR is a free, downloadable spreadsheet describing 27 ecosystem services derived from the Millennium Assessment (Millennium Ecosystem Assessment (MA), 2005) ecosystem services typology. It is focused on private-sector ecosystem services assessment – walking users through a process of identifying business dependencies, risks, and opportunities related to ecosystem services.

### 3.2. *Independently applicable, generalizable, landscape-scale modeling: ARIES, Co$ting Nature, EcoServ, InVEST, LUCI, MIMES, SolVES*

The majority of ecosystem service tools seek to quantify services and their tradeoffs at a landscape scale in order to support scenario analysis using simplified underlying biophysical models or "ecological production functions" (Daily et al., 2009). These tools differ in their modeling approaches, generalizability, and whether they are in the public domain or proprietary.

InVEST and ARIES are perhaps the best known of the generalizable, public-domain tools (Vigerstol and Aukema, 2011). Both use a variety of spatial data as model inputs and encode ecological production functions in deterministic models (InVEST and ARIES) and probabilistic models (ARIES). For provisioning and regulating services, both tools produce maps displaying results in biophysical units, to which per-unit monetary values can be applied; for cultural services and some accompanying models (e.g., InVEST biodiversity and habitat risk) outputs are in relative rankings. InVEST's underlying deterministic models have been more extensively vetted in the peer-reviewed literature, and may be more appropriate for use in contexts where ecological processes are well understood. ARIES' probabilistic models, which are encoded as Bayesian belief networks, may be more appropriate under conditions of data scarcity (Vigerstol and Aukema, 2011).

The current InVEST release includes nine marine and seven freshwater and terrestrial ecosystem service models (wave energy, wind energy, coastal vulnerability, erosion protection, marine fish aquaculture, esthetic quality, fisheries and recreation overlap, habitat risk assessment, marine water quality, biodiversity, carbon storage and sequestration, hydroelectric power production, nutrient retention, sediment retention, timber, and crop pollination (Tallis et al., 2013)). InVEST's Tier 1 models run within ArcGIS (Environmental Systems Research Institute (ESRI), 2013) or as stand-alone executable programs, use land cover and other spatial data to quantify service provision via coefficient tables for each land-cover type (e.g., for carbon storage, evapotranspiration, or nutrient filtering capacity); data for the coefficient tables are typically derived from field experiments. InVEST's Tier 2 models have been described but not yet released as part of a software package. Tier 2 InVEST models have the ability to encode more complex and potentially more realistic underlying processes but are more data- and time-intensive to apply (Kareiva et al., 2011).

The current ARIES release includes eight ecosystem services – carbon sequestration and storage, riverine and coastal flood regulation, freshwater supply, sediment regulation, subsistence fisheries, recreation, esthetic viewsheds, and open-space proximity values, with additional service models in active development. ARIES uses artificial intelligence techniques to pair locally appropriate ecosystem service models with spatial data based on a set of encoded decision rules, quantifying ecosystem service flows and their uncertainty within a web browser or stand-alone software tool environment (Villa et al., 2011). ARIES uses agent-based models to quantify the flow of ecosystem services between ecosystems providing the service and their human beneficiaries, enabling quantification of actual service provision and use, as opposed to theoretical service provision as estimated by many other ecosystem service tools (Bagstad et al., in press).

Four additional tools – Co$ting Nature, EcoServ, LUCI, and Multiscale Integrated Models of Ecosystem Services (MIMES) – are also spatially explicit, public-domain tools that biophysically model ecosystem services but have not yet been as widely documented and applied as InVEST and ARIES. MIMES is a system dynamics model designed to account for temporal dynamics and feedback loops, incorporate existing ecological process models into ecosystem service modeling, and economically value ecosystem services via input–output analysis (http://www.afordablefutures.org). MIMES was developed using Simile, a commercial coding and simulation software package (Simulistics, 2013). Input data include varied spatial datasets depending on the services of interest to the user as well as information that a user applies to parameterize the model′s equations. MIMES outputs include spatially explicit time series of ecosystem service values.

LUCI, formerly known as Polyscape (Jackson et al., 2013), is designed to use simple algorithms and outputs to transparently communicate ecosystem service tradeoffs in settings with stakeholders and decision makers. It is a GIS toolbox that currently includes models for agriculture, flood regulation, carbon sequestration, sediment regulation, and habitat connectivity, and quantifies tradeoffs between those five services. LUCI is designed for applications ranging from the farm field through the watershed to landscape scale, with the upper limits on analysis extent depending on the tradeoff between computational time and the need for presenting near-real-time results in public forums. LUCI′s inputs include commonly available datasets such as elevation, slope, hydrography, and land cover, which can be modified by stakeholders to improve accuracy at high spatial resolution. Its outputs show parts of the landscape that currently provide ecosystem services and areas where management interventions could enhance or degrade services. Initial test applications for LUCI have been conducted in the U.K., New Zealand, Ghana, and Greece.

EcoServ is a web-based tool under development in the U.S. and Canadian Prairie Pothole region, with the intent to eventually develop additional case studies then nationally or globally generalized models. EcoServ links external ecosystem process models and spatial data and will make these accessible to the public via a web tool (Feng et al., 2011). It accounts for temporal climate variability and can provide output maps of service provision under scenarios for climate and land-use change. EcoServ does not explicitly use production functions in modeling ecosystem services, and instead relies on a series of external models to proxy a service of interest. EcoServ does not economically value ecosystem services, although model outputs could be used in external valuation efforts.

Co$ting Nature is a web-based tool that jointly maps ecosystem services and conservation priorities (Mulligan et al., 2010). It uses pre-loaded global datasets at 1 $km^2$ or 1 ha resolution to quantify water yield, carbon storage, nature-based tourism, and natural hazard mitigation for baseline conditions and climate or land-use change scenarios. Co$ting Nature estimates and aggregates these values into a “bundled services index” (i.e., with values ranging from 0 to 1) for potential and realized services, by accounting for ecosystem service provision, beneficiary locations, and flows. While it thus does not support mapping of individual services, their tradeoffs, or valuation, Co$ting Nature can be used to compare overall service generation with biodiversity and conservation priorities, and can be rapidly applied in terrestrial environments globally.

Unlike the previous tools that use biophysical models to quantify ecosystem services, the Social Values for Ecosystem Services (SolVES) tool (Sherrouse et al., 2011) is intended to quantify and map the perceived social values for ecosystem services calculated from a combination of spatial and non-spatial responses to public attitude and preference surveys. The values that are quantified depend on the values typology provided with the survey, which has typically been based on a “forest values typology” (Brown and Reed, 2000). This typology largely corresponds to MA cultural services (esthetic, recreation, spiritual, education, and cultural heritage) and non-use values (option, existence, and bequest value), and has been modified for use in diverse settings ranging from forests to coastal ecosystems. SolVES uses responses to a value-allocation exercise in the survey to calculate a quantitative 10-point “Value Index.” Respondent-mapped locations associated with each value type are then used to calculate the relationship between values and physical attributes of the landscape (environmental data layers such as elevation, distance to water, land-cover type, etc.). These relationships and “landscape metric” data can be used to transfer values to sites where primary survey work has not been completed. Input data also include demographic and attitudinal information about the respondents, which can be used to explore differences in values across different groups of respondents.

A final landscape-scale tool, the UNEP-WCMC Ecosystem Services Toolkit, identifies ecosystem service impacts and stakeholders for five services: climate regulation, water services, harvested wild goods, cultivated goods, and nature-based tourism and recreation (UNEP-WCMC, 2011). It uses field measurements, semi-structured interviews, expert consultations, and published data to quantify ecosystem services. Given the lack of further published information about this toolkit, we are unable to describe its performance against the evaluative criteria in this study.

### 3.3. Independently applicable, place-specific, landscape-scale modeling: Envision, EPM, InFOREST

Three additional public-domain tools – Envision, Ecosystem Portfolio Model (EPM), and InFOREST – are distinctly place-specific, accounting for detailed locally important ecological processes and human preferences underlying ecosystem services but sacrificing generalizability. Though these models can be adapted for application in new areas, this is an expensive and time-consuming process that is likely impractical in most cases; however they may provide substantial insight in regions where they have already been developed.

Envision is designed to explore how development policies affect land-use agent behavior and drive development patterns (i.e., leading to alternative urban-development scenarios), which yield changes in various landscape metrics, which can include ecosystem services such as nutrient regulation, water provisioning, carbon sequestration, food and fiber production, shoreline protection, and pollination (Guzy et al., 2008). Envision is a modular, open-source modeling framework that can incorporate external ecosystem service models such as InVEST. Submodels quantify social preferences for economic development, landscape metrics, land value, and population growth to link spatial data with sets of policies that achieve certain mixes of economic and environmental goals. Accompanying economic valuation is conducted using market prices or avoided/replacement cost methods. Envision has largely been applied in the U.S. Pacific Northwest, though international applications in Colombia and New Zealand are under development.

The EPM models ecological, economic, and quality-of-life values, offering insight into the effects of land-use change (including development, conservation, and restoration choices) on these values (Hogan et al., 2012; Labiosa et al., 2013). Some values are monetized, like the property premium provided by open space; for criteria that are difficult to value monetarily, like biodiversity, alternative user preferences can be compared using a multi-attribute utility approach. EPM case studies have been completed in Miami-Dade County, Florida, Puget Sound, Washington, and the Santa Cruz River watershed, Arizona. When an application is complete, EPM functions as a web-based tool, requiring the user to simply choose their area of interest, select weights for valuation of each criterion, and compare results in the online viewer.

The InFOREST model (http://inforest.frec.vt.edu/) is a web-based assessment tool for quantifying carbon, watershed nutrient and sediment loading, and biodiversity. The user enters the online interface, chooses the area of interest, and (if desired) enters land cover and agricultural practices information. InFOREST is designed as an ecosystem service credit calculator; thus it does not include economic valuation as a goal. It incorporates a series of existing carbon and hydrologic models and habitat metrics. InFOREST has currently been developed for application only in the state of Virginia.

### 3.4. Proprietary, generalizable, landscape-scale modeling: EcoAIM, ESValue

Two tools – EcoAIM and ESValue – have been developed by private-sector consultants to map and value ecosystem services at the landscape scale (Waage et al., 2011). EcoAIM is designed "to (1) inventory ecological services and help in making decisions regarding development, transactions, and ecological restoration, (2) develop specific estimates of ecosystem services in a geographically relevant context, and (3) offer the means for evaluating tradeoffs of ecosystem services resulting from different land or resource management decisions" (Waage et al., 2011). EcoAIM uses a series of publicly available spatial datasets combined with a weighting or aggregation function to derive spatially explicit scores for ecosystem services of interest. EcoAIM can also integrate stakeholder preferences in considering ecosystem service impacts, using a modified risk-analysis approach.

ESValue combines expert and literature-derived data to develop ecosystem service production functions (Waage et al., 2011). ESValue specifies the relative values that society, managers, and stakeholders place on ecosystem services, as developed during a stakeholder-engagement process. The ESValue tool thus facilitates the comparison of what can be produced (i.e., the production function) with what participants want to be produced (i.e., the valuation function) to evaluate tradeoffs between natural resource management strategies.

### 3.5. Site-scale modeling: EcoMetrix, LUCI

The above-described tools are generally designed to operate at the landscape scale, making them useful for modeling watersheds or large parcels, but are generally not intended for site-scale analyses (i.e., for areas less than $\sim$50 ha), in part due to their reliance on spatially explicit data that typically have a lower-bound resolution on the order of $30 \times 30$ m. Site-scale ecosystem service information, evaluating changes on parcels as small as several hectares or less, could be used to select between restoration or development alternatives at fine spatial scales after appropriate macro-level locations for these activities have been identified using a landscape-scale tool. As noted previously, LUCI is one landscape-scale tool also intended for use at the site scale, assuming data are available at an adequate spatial resolution for site-scale analysis.

EcoMetrix, a proprietary tool designed for site-scale ecosystem services assessment, combines field-based measurements with spreadsheet-encoded production functions to quantify site-scale changes in ecosystem services using non-monetary, service-specific metrics (Parametrix, 2010). Its primary use has been to estimate the generation of environmental credits for market-based trading under restoration or degradation scenarios.

### 3.6. Monetary valuation: Benefit Transfer and use Estimating Model toolkit, Ecosystem Valuation Toolkit, NAIS

Most of the modeling tools described above can estimate monetary values by supplying a per-unit market, social, avoided, or replacement cost (e.g., social cost per ton of carbon or avoided cost of dredging a ton of sediment). The tools described in this section use value transfer to estimate monetary values for ecosystem services, independently of or in conjunction with other modeling tools.

Natural Assets Information System (NAIS) and the Ecosystem Valuation Toolkit are valuation databases that combine a library of economic valuation studies with GIS analysis of land cover, which can be used for economic valuation via point transfer (Troy and Wilson, 2006; Ecosystem Valuation Toolkit, 2012). Spatially explicit land-cover data, classified using a locally relevant land-use/cover typology, are used as input data, and are then matched to appropriate valuation studies. Outputs include per-hectare summaries of ecosystem service values for each relevant land-cover type. The Ecosystem Valuation Toolkit can be independently applied through a subscription, while application of NAIS occurs through contracting with its developers.

The Benefit Transfer and Use Estimating Model Toolkit, by contrast, uses function transfer (Loomis, 1992), with transfer functions encoded in a set of public-domain spreadsheets (Loomis et al., 2008). The toolkit includes transfer functions for recreation, property premiums, and willingness to pay for threatened and endangered species recovery. The user enters values for the independent variables required by a given transfer function (e.g., open-space characteristics or open-water area), and the spreadsheet calculates economic value per household or recreation day.

### 3.7. Application of selected tools to the San Pedro

We – or in the case of the proprietary tools EcoAIM, EcoMetrix, and ESValue, their tool developers – applied seven tools to the San Pedro to determine the time requirements of adapting these tools to a new study area. The San Pedro, a tributary of the Gila River, flows north from northern Sonora into southeast Arizona. It is a region of high ecological significance – one of the last free-flowing perennial rivers in the U.S. Southwest and a major migratory bird flyway – but faces serious pressures from urbanization and attendant groundwater depletion (Stromberg and Tellman, 2009). The study area includes the BLM′s San Pedro Riparian National Conservation Area, which has been a focal point for conservation and scientific activity in recent decades. We quantified services identified as important by a group of 27 local resource managers and scientists including water, carbon sequestration and storage, biodiversity, recreation, and esthetic values.

We evaluated the responsiveness of ecosystem services tools to four locally relevant scenario sets, ranging from landscape-scale change to local-scale change on the order of several hundred hectares. We applied the InVEST and ARIES tools to mesquite management, water augmentation, watershed-scale urban growth scenarios, and local-scale housing development scenarios (Bagstad et al., 2012, in this volume). The developers of the EcoAIM, EcoMetrix, and ESValue tools applied these to local-scale housing development scenarios (Waage et al., 2011). We also used the ESR and Benefit Transfer and Use Estimating Model Toolkit, though these tools are aspatial and in the case of the ESR produced qualitative results. Although the Benefit Transfer and Use Estimating Model Toolkit is designed to support rapid monetary valuation using function transfer, its valuation functions were not well suited to valuing the specific ecosystems within the San Pedro (Bagstad et al., 2012).

Even given their current very distinct analytical approaches and ecosystem service metrics, in the comparative application of ARIES and InVEST to the San Pedro the two tools came to similar conclusions about the ecosystem services impacts from a variety of scenarios (Bagstad et al., in this volume). However, even after this application, further model testing and development would be desirable.

In the application of five spatially explicit modeling tools – InVEST, ARIES, EcoAIM, EcoMetrix, and ESValue – their results were too incomparable to draw direct quantitative comparisons, particularly about whether the tools "agreed" on the relative impacts of development at alternative sites (Waage et al., 2011). Unsurprisingly, the ESR, a screening tool, and the Benefit Transfer and Use Estimating Model Toolkit, a spreadsheet-based value transfer tool, could be completed much more quickly than the spatially explicit models (Table 3). Of the remaining models, EcoAIM, which calculates a weighted average of publicly available GIS layers relevant to the service of interest, and EcoMetrix, the site-scale ecosystem services scoring tool, could be completed more quickly than the remaining three tools. However, public-domain models such as InVEST and ARIES could be run with substantially lower resource requirements if a wider array of input data and contextually appropriate models were available to the user, as discussed further in Section 4.4.

## 4. Conclusions

### 4.1. General findings

The tools evaluated in this study differed greatly in their performance against the evaluative criteria (Table 2). Beyond the key distinction between their ease of generalizability, different approaches will be more appropriate in distinct geographic and decision contexts, highlighting the need for further comparative analysis of available tools in diverse settings (e.g., Bagstad et al., in this volume).

Assuming that a tool is flexible enough to quantify ecosystem services in diverse contexts and that its results are credible – transparent, well-documented, and validated where possible – a key trait that will enhance or limit its widespread adoption is the time required to apply it relative to the depth and quality of information it adds to the decision-making process (Table 3).

Some complementarity exists between tools, which suggests that certain tools could be used together to fill different ecosystem service assessment needs, provided that the tool outputs are compatible (e.g., that model outputs can easily support valuation; Fig. 1). For example, the ESR can serve as a "front-end" screening tool to evaluate ecosystem services of importance, either in the absence of local stakeholders who can provide informed input, or in collaboration with stakeholders as a way to structure their input. Co$ting Nature can similarly act as a low-cost, spatially explicit screening tool for identifying potential ecosystem service hotspots, though it cannot disaggregate services for tradeoff analysis and valuation. Such preliminary assessments could then be used as a broader analytical 'frame' within which to conduct more granular analyses from mapping and modeling tools that quantify landscape-scale ecosystem services tradeoffs using biophysical models (e.g., ARIES, EcoAIM, Envision, EPM, InVEST, InFOREST, LUCI, MIMES) and/or surveys to elicit social values (SolVES). If needed, EcoMetrix or LUCI can be used for site-scale modeling to compare tradeoffs at fine spatial scales. For some applications and ecosystem services, valuation can be completed by simply applying a per-unit social, market, avoided, or replacement cost to results of biophysically modeled services. In other cases, it may be more appropriate to value model outputs using

**Table 3**
Estimated time to complete ecosystem services assessments using alternative methods for the San Pedro case study.

| Tool (services quantified) | Estimated person-hours | | Information provided | Additional comments |
|---|---|---|---|---|
| | Pilot study[a] | With improved data archive[b] | | |
| Benefit Transfer and Use Estimating Model Toolkit (recreation) | 10 | 10 | Aspatial valuation | |
| Ecosystem Services Review (27 ecosystem services) | 10 | 10 | Qualitative review | Time to completion could be several times greater if a large number of stakeholders are involved |
| InVEST (carbon, water, viewsheds, habitat quality) | 275 | 80 | Spatially explicit outputs | Time to complete could be drastically reduced with system for sharing data and underlying model assumptions |
| ARIES (carbon, water, viewsheds, open space proximity, recreation) | 800 | 80 | Spatially explicit outputs, uncertainty, flow data | Model customization and debugging was extremely time consuming but will be less so for future applications. Spatial data management system reduces data input needs in future applications |
| EcoMetrix (carbon, water, esthetic, recreation, cultural heritage, biodiversity) | 85 | 85 | Relative service scores by site | Time for field data collection, data entry, and analysis |
| EcoAIM (biodiversity) | 25 | 25 | Spatially explicit weighted average values | Time to prepare GIS data and run overlays |
| ESValue (multicriteria analysis of 22 ecosystem services) | 400 | 400 | Relative preferences for alternative services | Stakeholder engagement the most time consuming step |

[a] A common analyst conducted analyses using the Benefits Transfer and Use Estimating Model Toolkit, Ecosystem Services Review, InVEST, and ARIES. This was not possible for the three proprietary tools – EcoMetrix, EcoAIM, and ESValue. In all cases the analyst was experienced in ecosystem service modeling and valuation, with graduate-level training.

[b] Such an improved data archive – including spatial and aspatial data to populate the InVEST and ARIES models, and descriptions of contexts under which such data are applicable – could substantially reduce the time requirements needed to apply these models, and could also likely benefit the application of proprietary tools.

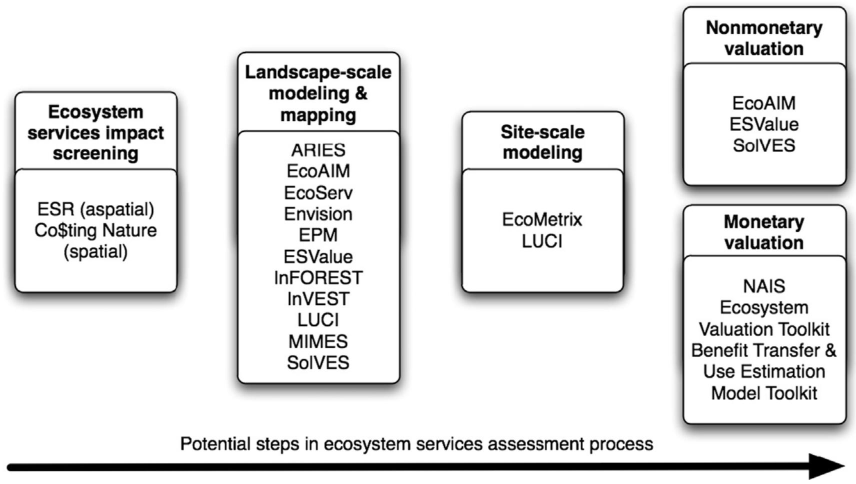


**Fig. 1.** Potential steps in ecosystem services assessment process.

multicriteria analysis tools (e.g., EcoAIM, ESValue) or monetary valuation using NAIS, the Ecosystem Valuation Toolkit, or the Benefit Transfer and Use Estimating Model Toolkit.

### *4.2. Feasibility for widespread use*

While any of these tools can be used given adequate resources, they differ in their appropriateness for widespread use in public- or private-sector settings, where rapid but reliable assessments in diverse geographic contexts are desirable (Tables 1–3). Based on this review and the application of seven tools to the San Pedro in Arizona, and following discussions with a diverse group of public- and private-sector decision makers, who deemed as desirable tools that are quantifiable, replicable, credible, flexible, and affordable, we summarize the current readiness of these tools below.

With the exception of low-cost screening tools, most of these decision makers felt that the time and cost requirements to run quantitative ecosystem service models remain too high for these tools to be used in widespread decision making (Table 3). This is particularly true as their added value relative to existing environmental assessments remains to be shown in practice, even after multiple applications (Waage et al., 2012). For example, qualitative reviews of ecosystem services or application of spreadsheet models took only about 10 h, while application of spatially explicit modeling tools required hundreds of hours of work by an experienced analyst. Whether or not these assessments yielded new insights relative to ‘business as usual’ is the key next question.

Based on the criteria defined above for tools considered in this study, we conclude the following about their readiness for widespread use in public- and private-sector decision making. We present use feasibility rather than specifically favoring one or more tools due to the diversity of decision contexts, user needs, ongoing evolution of tools, and need for more comparative testing:

- *Feasible for immediate widespread use*: ESR, Benefit Transfer and Use Estimating Model Toolkit, Co$ting Nature.
- *Potentially feasible for widespread use given development of supporting databases for spatial and ecological data*: InVEST.
- *Potentially feasible for widespread use given improved guidance on tool use and feasibility of conducting a full stakeholder engagement process*: LUCI.
- *Potentially feasible for widespread use given future development of global models or expanded underlying datasets*: ARIES, EcoServ, SolVES.
- *Proprietary tools, feasible for use in high-profile cases where contracting with consultants or developers, or paying for a subscription is possible*: EcoAIM, EcoMetrix, Ecosystem Valuation Toolkit, ESValue, NAIS.
- *Public-domain tools that are place-specific, require a long lead time to develop, and/or require contracting with universities or consultants. If models have been previously developed for an area of interest they could be immediately applied*: Envision, EPM, InFOREST, MIMES.

Additional multi-tool reviews and comparative quantitative testing are thus desirable for two important reasons: to better understand the tools′ time requirements and use feasibility in more diverse geographic and decision contexts, and to track the development of new tools and expanded capabilities of existing tools.

### *4.3. Implications for public- and private-sector resource management*

At present, few tools have been pilot tested in agency or corporate settings, particularly in comparative assessments. In addition, none of these tools readily mesh with key existing corporate processes and, with the exception of low-cost screening tools, require considerable effort to apply, which serves as an impediment to immediate, widespread, off-the-shelf business application (Waage et al., 2011). All of the tools would require supplemental effort for corporate applications, either in terms of assistance with interpreting findings within a corporate setting or customization to fit particular corporate decision-making contexts. Public- and private-sector managers similarly need clarity on how, when, and why to apply tools to particular decision contexts (Waage et al., 2011).

Quantifying, mapping, and valuing ecosystem services does offer the public and private sector alike a promising way to communicate resource management tradeoffs, particularly for development or extractive resource use that could degrade ecosystem services. However, depending on the decision context, ecosystem service analysis may be more or less useful, which will in part be contingent upon what additional new insights an ecosystem services approach offers relative to the “business as usual” approach to conducting environmental impact assessments.

In a public-sector setting, such as for the BLM, analysis of ecosystem services or other nonmarket values is likely to be most useful when: (1) a proposed action is likely to have a significant direct or indirect effect (ecological, esthetic, historic, cultural, economic, social, or health), and the quality or magnitude of the effect can be clarified by considering such values, (2) the alternative actions to be considered present a strong contrast between extractive and non-extractive uses of land and resources, or (3) the magnitude of the proposed change is large (BLM, 2013).

### 4.4. Lowering barriers to ecosystem service model parameterization and application

Although the San Pedro was chosen as a study area due to its large body of past research, much of this scientific knowledge was not useful for parameterizing the ecosystem service models, as it did not overlap with many of the models' input data needs. Even for areas with rich ecological understanding, this knowledge is not always of the type needed to support ecosystem service modeling, mapping, and valuation (Norgaard, 2010). Looking forward, if ecosystem services approaches are to be widely adopted and applied, such data challenges will have to be addressed. In the process, it will be essential to foster collaboration between ecosystem service modelers and disciplinary researchers in order to integrate past work into ecosystem service models and develop new research methods and identify indicators to quantify ecosystem service production functions. Participation of resource managers – the end users of these tools – can help inform tool developers about which metrics are likely to be most helpful in various decision contexts.

Some of these issues may be resolved in the next generation of the ecosystem services analytical models. For example, tool developers indicated through discussions that, future versions of ARIES, EcoServ, Envision, InVEST, and other models intend to link more completely to existing, peer-reviewed ecological and biophysical process models. This would be a major step forward for ecosystem service modeling, but requires substantial work on model semantics, inputs, and outputs to build linkages between models.

Although modelers typically recognize the need for more data, such data also need to be better organized and accessible to model users when they seek to choose and parameterize a model. Although an ambitious goal, semantic meta modeling offers a path forward in improving ecosystem service quantification in an era of "big data" (Fox and Hendler, 2009; Villa, 2010). Ecosystem service practitioners would benefit from a system of data sharing for (1) spatial data, (2) ecological studies to parameterize ecosystem service models, and (3) economic studies to support valuation. The time spent on this pilot would have been substantially reduced if such resources were available, and they would also reduce the likelihood that practitioners will overlook important data sources. Strategic investment in such systems could be supported by Federal agencies, philanthropic foundations, or industry groups to support public- and private-sector ecosystem service-based decision making. Although in some cases higher quality local data may exist and stakeholders may trust locally collected data over "pre-wired" data, for many other cases well-documented data obtained from credible sources could give modeling efforts a large head start.

While U.S. agencies like the USGS and Natural Resources Conservation Service (NRCS) house abundant public data on land cover, hydrology, and geology, no single site contained all the spatial data needed to run ecosystem services models. Collecting, storing, and pre-processing relevant spatial data in a single location could save future users substantial time and effort. In this regard, spatial data management through Web Coverage Service and Web Feature Service (WCS/WFS) that can call on annotated spatial data to support multiple ecosystem service models could be scaled up to support multiple tools. Emerging environmental data sharing, remote sensing, and visualization tools and practices can also support next-generation ecosystem service modeling (Eye on Earth, 2012; LifeWatch, 2012; Geographic Ecosystem Monitoring and Assessment Service Project, 2013). These sources could enhance the quality and credibility of ecosystem service assessments if they can improve the currency, spatial resolution, and quality of model input and calibration data.

Ecosystem service valuation databases have been developed in the past but have too rarely received funding for maintenance and expansion (McComb et al., 2006; Curtice et al., 2012). The Benefit Transfer and Use Estimating Model Toolkit is free, NAIS is a proprietary database and is not available for public access, and the Ecosystem Valuation Toolkit uses a tiered subscription ranging from free for contributors to an annual fee based on applied use. Other databases lack functions to guide users through the process of constructing a valuation portfolio for their area of interest, but provide useful repositories of nonmarket valuation studies. Such databases that have been relatively well maintained in recent years include the Environmental Valuation Reference Inventory (EVRI) database (Environmental Valuation Reference Inventory (EVRI), 2011), Marine Ecosystem Services Database (Marine Ecosystem Services Partnership, 2013), and the TEEB Valuation Database (van der Ploeg and de Groot, 2010).

Just as databases cataloging economic studies can support valuation, databases of ecological studies are needed to support modeling efforts. As we better understand the data needs for ecosystem service models, it would be valuable to develop databases for the ecological parameters that underlie such models. For instance, the Tier 1 InVEST models link ecosystem service provision to land use/cover via tables. Having accurate values for use in these tables (e.g., for carbon storage, rooting depth, nutrient loading, and evapotranspiration coefficients by land-use/cover type) is critical to running the models and obtaining credible results. For other modeling systems, such ecological information is needed to identify appropriate contexts to apply specific ecological production functions. The U.S. Environmental Protection Agency is beginning work on an "ecological production function library" that could help fill this need for future ecosystem service modelers.

Although systems modeling may remain the goal of more accurately representing complex processes in quantifying ecosystem services (Seppelt et al., 2011), the potential gains in accuracy associated with this approach must be weighed against the increased complexity and reduced generalizability in a time where ecosystem service assessments are increasingly seen as important inputs to decision making (Tallis and Polasky, 2011). Simpler models may also generate greater transparency and trust among users, as may incorporation of local data and models (Smart et al., 2012). Modeling approaches such as LUCI have intentionally considered this issue through simplifying ecosystem service model outputs to improve their intuitiveness (Jackson et al., 2013). Comparative studies of simplified and complex models, which can help us understand the potential gains when accounting for complexity, are increasingly common in ecological and hydrologic modeling (Perrin et al., 2001; Fultona et al., 2004; Raicka et al., 2006; Irmak et al., 2008). They have been less well explored in ecosystem service modeling (but see Tallis and Polasky, 2011), and will be an important area of future research as decision makers seek to identify tools that can be used in a variety of settings while providing accurate and useful information.

As ecosystem service tools continue to develop, additional case studies may suggest means to better integrate with internal public- and private-sector decision processes, allowing the ecosystem service concept to better deliver on its promise of supporting more sustainable decision making (Daily et al., 2009). In an evolving tool landscape, public- and private-sector actors must develop an understanding not only of using ecosystem services concepts and tools, but also of costs and resources needed to develop and maintain the tools, train staff, and integrate these into planning, operations, and governance.

## Disclosure statement

The lead author (K.J. Bagstad), who led comparative analysis of ecosystem service tools, has worked as a co-developer of the ARIES tool since 2007.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.ecoser.2013.07.004.

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