A comparative assessment of tools for quantification and valuation of ecosystem services

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Abstract

With recent growth in the field of ecosystem services, a variety of tools have emerged to quantify, model, map, and value ecosystem services. Despite the growing complexity of the tool landscape, minimal comparative analysis of these tools has occurred. In this study, we compare 16 ecosystem services tools and rate their performance against eight evaluative criteria that influence their usability. We also provide a more detailed review of seven tools applied at a common location – the San Pedro River watershed in southeast Arizona and northern Sonora, Mexico. For these tools, we describe their modeling approach, inputs, outputs, and assumptions for carbon sequestration and storage, water supply, biodiversity, and aesthetic and recreational value – key stakeholder-recognized ecosystem services for the San Pedro. We summarize the current readiness of these tools to address ecosystem services in public- and private-sector decision making. We find a degree of complementarity between some tools and note that resource requirements to run the tools and interpret outputs to guide public and private-sector decisions are typically too high for use in everyday decision making. However, we also describe opportunities to reduce the resource requirements for running ecosystem services models, primarily through better archives of the spatial, ecological, and economic data needed to support ecosystem services modeling.

Introduction

A large and rapidly growing body of research seeks to identify, measure, and value ecosystem goods and services – the benefits that ecosystems provide to people (1). However, the development of methods and tools that integrate ecology, economics, and geography to support decision making is a much more recent phenomenon (2, 3). Numerous groups of 'tool developers' are now simultaneously working to bridge ecosystem services science with decision-making processes for public and private sector settings.

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 remain place-specific. The tools also differ in

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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 comparative work to understand their strengths, weaknesses, and applicability to various settings. The scope of other comparative studies has been limited, providing detailed descriptions of 2-3 tools and references for 2-4 others (4, 5). While both of these papers describe the strengths and weaknesses of alternative approaches, neither does so in a structured way, nor do they provide comparative results.

Spurred by the growing demand for more comprehensive analyses of the ecological and socioeconomic 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) to assess the usefulness and feasibility of ecosystem service valuation as an input into decision-making. Ecosystem services have gained a more prominent role in the U.S. government's policy direction for environmental and natural resource management (6, 7). BLM sought to determine which, if any, methods for valuing ecosystem services are ripe for operational use across the agency, and to evaluate the utility of ecosystem service valuation for its resource management decision processes. The first phase of this effort, sponsored by BLM's Socioeconomics Program, chose an area that had a history of ecological research to draw from and a variety of ecological stressors highly relevant to federal resource management. We used multiple tools to quantify ecosystem service changes under scenarios involving urban growth, mesquite management/grassland restoration, and water augmentation for the San Pedro River watershed in southeast Arizona and northern Sonora, Mexico.[1] We quantified services identified by stakeholders as locally important, including water, carbon sequestration and storage, biodiversity and biodiversity-dependent ecosystem services such as recreation, and cultural values.

In a closely linked initiative—through engaging the same technical specialist to conduct the assessment—BSR (formerly Business for Social Responsibility, an independent NGO) undertook an evaluation of ecosystem services tools that could be relevant to corporate decision-making processes. The BSR initiative asked of all tools where a hypothetical residential development within the San Pedro River watershed should be sited to minimize ecosystem services impacts (8). This paper summarizes findings from these two linked studies.

Significantly, this paper offers the first comprehensive review of ecosystem services assessment and valuation approaches and modeling tools, greatly expanding on past comparative studies (4, 5). We catalog and describe existing tools, compare the inputs, assumptions, and outputs for approaches used in these pilot studies, and conclude by evaluating the tools against eight evaluative criteria used to gage their utility in public- and private-sector decision making (see methods). We describe full results elsewhere, including quantified biophysical and monetary values of ecosystem services (8-10).

[1] The San Pedro is a region of high ecological significance – one of the last free-flowing rivers in the U.S. Southwest and a major migratory bird flyway – but faces serious pressures from urbanization and attendant groundwater depletion. The study area includes the BLM's San Pedro Riparian National Conservation Area, which has been a focal point for conservation activities and scientific research in recent decades.

Existing tools

Through reviews of the literature and discussions with colleagues across the academic, public, private, and NGO sectors, we identified 16 tools that assess, quantify, model, value, and/or map ecosystem services (Table 1). We or our colleagues were able to apply seven of these tools to the San Pedro watershed – ARIES, EcoAIM, EcoMetrix, ESR, ESValue, InVEST, and the Wildlife Habitat Benefits Estimation Toolkit. For the remaining nine tools that we were unable to run for the pilot study, we conducted phone interviews with the tool developers to understand their tool's intended use, approach, and level of development. We do not include further description 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 great detail elsewhere (9,24,25). For a more detailed description of each tool, see (9).

Results

In this section we compare the inputs, assumptions, and outputs for ARIES, EcoAIM, ESValue, InVEST, and Wildlife Habitat Benefits Estimation Toolkit approaches to modeling each ecosystem service for the San Pedro River watershed (Table S1). We also list other tools capable of addressing that service. The ESR provided qualitative estimates of ecosystem services for the San Pedro and ESValue estimated stakeholder values for ecosystem services tradeoffs, but neither of these approaches quantified ecosystem services for the San Pedro watershed (8). EcoMetrix was applied for all ecosystem services below, using the common approach described under carbon sequestration and storage. EcoAIM was applied only to biodiversity for the San Pedro, but could be applied for all other services using the same methods described under biodiversity.

Carbon sequestration and storage. InVEST, ARIES, and EcoMetrix model carbon sequestration and storage[2]:

- Requirements: ARIES uses spatial data for influences on regional carbon dynamics, including anthropogenic greenhouse gas emissions, vegetation, soils, and climate. InVEST inputs include land-cover data[3] and a table linking land-cover type to carbon storage. For all ecosystem service models, EcoMetrix uses site-specific data collected by field crews.
- Approach: ARIES models carbon sequestration and potential stored carbon release probabilistically, and compares these against emissions to estimate the regional carbon balance. InVEST models sequestration as a function of land-cover change over time, while

[2] EcoServ, Envision, and InFOREST have also been used to quantify carbon sequestration and storage in other applications.

[3] All spatial data to run ARIES models are pre-loaded on the ARIES GeoServer, an open-source software server for handling geospatial data (26). Spatial data for the InVEST models must be supplied by the user, though some marine datasets are available for download from the InVEST website.

EcoMetrix uses field data with a series of literature and expert-derived ecosystem service production functions to quantify a site's capacity to provide climate regulation (16).

- Outputs: ARIES outputs spatially explicit carbon sequestration and stored carbon release (tons C/ha/yr) and associated uncertainty. InVEST outputs spatially explicit carbon storage (tons C/ha) when land-cover data are available for only one time period, or sequestration if multiple years of land-cover data are available (tons C/ha/yr). A social cost of carbon can be applied to InVEST or ARIES results for valuation. EcoMetrix outputs the site's capability to provide a given ecosystem service relative to a reference site, facilitating comparisons between sites or for a single site under a restoration, development, or resource extraction scenario.

Water supply. In the absence of data and resources to calibrate and run traditional hydrologic models, the simplified hydrologic models found in ecosystem service toolkits can be used to evaluate ecosystem services tradeoffs (5). InVEST and ARIES model water yield and demand[4]:

- Requirements: ARIES inputs include spatial data influencing water supply and use. InVEST inputs include land cover, soil depth, annual precipitation, plant available water content, potential evapotranspiration, watershed boundary data, and a digital elevation model (DEM), plus tabular data linking land cover to water demand, evapotranspiration, and maximum root depth.
- Approach: ARIES models annual evapotranspiration and infiltration probabilistically and combines these results with flow models spatially linking water sources (e.g., precipitation) to users. InVEST models annual water yield using average annual precipitation and the Budyko curve, subtracting evapotranspiration from combined infiltration and runoff (12). InVEST can estimate water demand by assigning a consumptive water-use value to each land-cover type to quantify total anthropogenic water demand.
- Outputs: ARIES outputs spatially explicit water supply (mm/yr) with uncertainty, showing areas from which users derive their water, or the ecosystems providing water to specific user groups. InVEST outputs spatially explicit water yield and demand (mm/yr). Outputs from both models can be valued using market price, replacement cost, or willingness to pay estimates for water.
- Other considerations: ARIES can be more easily customized to account for locally-important biophysical processes (e.g., recharge), but uses a highly simplified water routing algorithm relying solely on elevation, hydrography, and probabilistically modeled infiltration and evapotranspiration. It also lacks a groundwater flow model, so results include only surface-water flows and users. InVEST combines surface and subsurface flow, which are known to operate at widely different temporal scales (27), and does not account for locally important recharge processes, such as mountain-front and ephemeral stream recharge. InVEST is designed to provide output at the sub-watershed to watershed scale – "pixel-scale representations of some outputs (are) for calibration and model-checking purposes only" (12).

[4] EcoServ, Envision, and EPM have also been used to quantify water supply in other applications.

Biodiversity. The Wildlife Habitat Benefits Estimation Toolkit can estimate willingness to pay for threatened and endangered species protection, but these values were not relevant to our scenarios for the San Pedro**.** EcoAIM and InVEST model biodiversity[5]:

- Inputs: EcoAIM and InVEST use land-cover data with estimates of habitat quality for each land-cover type and maps of drivers of landscape change such as grazing or roads. InVEST also requires information on the degree of change caused by each of these drivers. EcoAIM requires service-specific metrics, which for biodiversity include species richness and protection, habitat quality/vulnerability, wildlife corridors, and vegetation-cover types. The Wildlife Habitat Benefits Estimation Toolkit uses data on the change in endangered species population size and type of species to value changes in the species' population.
- Approach: InVEST links user-supplied land-cover data with estimates of habitat quality for each land-cover type, maps of drivers of landscape change such as grazing or roads, and the degree of change caused by each of these drivers. EcoAIM estimates biodiversity and other ecosystem services using a series of weighted metrics (8). The Wildlife Habitat Benefits Estimation Toolkit uses a transfer function embedded in an Excel spreadsheet to estimate value.
- Outputs: InVEST and EcoAIM output spatially explicit estimates of habitat quality or biodiversity on a relative scale. The Wildlife Habitat Benefits Estimation Toolkit estimates the total economic value of threatened and endangered species.

Aesthetic and recreational values. ARIES includes viewshed, open-space proximity, and recreation models that quantify the contribution of nature toward aesthetic values, typically measured using hedonic pricing for real estate, and regions that are potentially valuable for specific recreational activities (e.g., bird watching, hunting). The InVEST viewshed model shows the relative visual impact of potential development sites and the population with views of each feature. InVEST recreation models have been described (13), but these are not available as part of the current InVEST toolkit. The Wildlife Habitat Benefits Estimation Toolkit can quantify values associated with open space proximity and recreational visitation, but these values were not suited to our scenarios for the San Pedro[6].

- Inputs: ARIES uses information on features that influence the quality of natural areas in providing valuable views, high-quality open space, or recreational opportunities, plus features that may degrade these values and the locations of users (e.g., housing). InVEST's viewshed model inputs include population and visual blight data plus a DEM. The Wildlife Habitat Benefits Estimation Toolkit uses data on the size and spatial configuration of a housing development, and the size of the open space of interest to estimate the hedonic value of open space.
- Approach: ARIES probabilistically models "sources" of high quality views, open space, recreational value, "sink" features that degrade views or open space access, the locations of users, and flows that connect users to natural features to show actual use and accessibility via

[5] Envision, EPM, and SolVES have also been used to quantify biodiversity values in other applications.
[6] EPM and SolVES have also been used to quantify aesthetic and recreational values in other applications.

lines of sight, distance decay, or transportation networks as appropriate. InVEST's viewshed model uses lines of sight to quantify the visibility of undesirable features to viewers. The Wildlife Habitat Benefits Estimation Toolkit uses a transfer function embedded in an Excel spreadsheet to estimate value.

- Outputs: ARIES outputs spatially explicit aesthetic and recreational values (in relative units) and their uncertainty, highlighting areas from which users derive the greatest benefit. InVEST's viewshed model outputs the relative of visual impact associated with blight features. The Wildlife Habitat Benefits Estimation Toolkit estimates the total property premium from open space.

Discussion

General findings. We successfully quantified ecosystem service trade-offs for a variety of management scenarios using the above-described tools (8-10). A key trait of all decision-making tools is the time required to apply them relative to the depth and quality of information they add to the decision-making process (Table S2). For many of the tools, time requirements could be substantially reduced if they were better developed and supported by high-quality spatial, ecological, and economic data archives. Such data would permit more rapid model parameterization, reduce the likelihood that practitioners will overlook important data sources, and potentially facilitate adoption of these tools by public and private-sector resource managers.

The tools evaluated in this study differed greatly in their performance against the eight evaluative criteria described in the methods section (Table S3). No tool performed well in all cases, suggesting that different tools will be most appropriate in different situations and highlighting the value of a rigorous comparison of available tools. For instance, deterministic models may be more appropriate in data-rich environments while probabilistic approaches may have greater utility in data-poor settings (5).

Some complementarity exists between tools, which suggests that some tools could be used together to fill different ecosystem service assessment needs (Figure 1). For example, the ESR or UNEP-WCMC Ecosystem Services Toolkit 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 local stakeholders as a way to structure their input. This preliminary assessment could then be used as a broader analytical 'frame' with which to conduct more granular analyses from mapping and modeling tools that quantify landscape-scale ecosystem services tradeoffs (e.g., ARIES, EcoAIM, Envision, EPM, InVEST, InFOREST, MIMES, SolVES). If needed, EcoMetrix can be used for site-scale modeling to compare tradeoffs at fine spatial scales. Finally, model outputs can be valued using multicriteria analysis tools (e.g., EcoAIM, ESValue) or monetary valuation using NAIS, SERVES, or the Wildlife Habitat Benefits Estimation Toolkit.

Parameterizing Ecosystem Service Models. Although the San Pedro was chosen as a study site because of its large body of past research, much of this scientific knowledge was not useful for parameterizing the ecosystem service models. Even for areas with rich ecological understanding, this knowledge is not

always the type needed to support ecosystem service modeling, mapping, and valuation (28). Better collaboration between ecosystem service modelers and disciplinary researchers can help to integrate past work into ecosystem service models and develop new research to quantify ecosystem service production functions. Future versions of ARIES, EcoServ, Envision, InVEST, and other models are intended to link more effectively to existing, peer-reviewed ecological process models. This would be a major step forward for ecosystem service modeling, but requires careful consideration of the semantics of model inputs and outputs for linked models.

Use feasibility. While any of these tools can be used given adequate resources, they differ in their appropriateness for widespread internal use in public or private sector settings (Tables S1-3). We summarize the current readiness of these tools below. Given the rapid state of evolution in the field, new tools may appear on the landscape and the capabilities of existing tools may change, so periodic tools review would be desirable.

- *Feasible for immediate widespread use*: ESR, UNEP-WCMC Ecosystem Services Toolkit, Wildlife Habitat Benefits Estimation Toolkit.
- *Potentially feasible for widespread use given development of supporting databases for spatial data and literature*: function transfer, InVEST, point transfer, application of past primary valuation studies.
- *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, ESValue, NAIS, SERVES.
- *Open-source tools that are place-specific, require a long lead time to develop, and require contracting with universities or consultants. If models have been previously developed for an area of interest they could be immediately applied*: EPM, Envision, InFOREST, MIMES.

Public land management outcomes. Before undertaking this modeling exercise, stakeholders held preconceived ideas of how scenarios would increase or decrease provision and use of certain ecosystem services on the San Pedro. Our results, which are broadly consistent with these perceptions, map and quantify these tradeoffs and provide monetized values for many but not all services (9,10). Quantifying, mapping, and valuing ecosystem services thus offers public land management agencies a promising way to communicate resource management tradeoffs, particularly for development or extractive resource use that could degrade ecosystem services. However, time requirements to run ecosystem service models are still too high for these tools to be used in regular decision making, and further work is needed to determine the types of outputs that can be most helpful in the planning process.

Ecosystem services need not be analyzed for every decision. For BLM, analysis of ecosystem services or other nonmarket values be useful when: 1) a proposed action is likely to have a significant direct or indirect effect, 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 (29).

Corporate management outcomes. Several key trends are driving corporate interest in ecosystem services, including:

1. There is increasing awareness within national governments that (a) nature has value that is seldom fully considered in decision-making; (b) ecosystem services are under increasing pressure; and (c) further natural capital-centric investment is needed. As a result, governments around the world are exploring how to apply ecosystem services in public policy (30).

2. Investor awareness and uptake regarding ecosystem services is growing as the trendsetting International Finance Corporation (IFC) has named ecosystem services in its Performance Standard 6, as part of risk management. This means that ecosystem services will now be routinely addressed in environmental and social impact assessments for IFC projects as well as those supported by the 70 Equator Banks and European Export Credit Agencies (31).

As a result of these developments, some companies have named ecosystem services in policies or initiatives. In addition, there is pilot testing of various tools and protocols, though these are seldom publicly discussed. These activities are informing internal discussions on the relevance of and business case for action, which tends to focus on (1) minimizing risk, (2) increasing competitiveness, and/or (3) stabilizing supply chains. At present, however, discussions associated with implications of ecosystem services concepts remains largely an 'insider' discussion, as few in business are aware of ecosystem services or their potential 'value add.' In addition, there is an overall tone of caution and urging for gradual forward movement to understand the value added and associated implications. In particular, there is concern about accounting for ecosystem services in contexts where there are diverse stakeholder groups, a wide range of values, and/or poor data.

As the idea spreads that environmental impacts should be considered in terms of ecosystems and social impacts, the emerging set of ecosystem service assessment tools may offer relevant insights to corporate decision-making processes. This is particularly true for dependencies on natural resource-based inputs that most businesses have not traditionally considered. The challenge is that at present, few tools have been pilot tested in corporate settings, particularly in comparative assessments. In addition, none of these tools readily mesh with key existing corporate processes and thus do not appear to be ready for immediate, widespread, off-the-shelf business application without considerable effort. All the tools would require supplemental effort for corporate applications, either assistance with interpreting findings within a corporate setting or customization to fit particular corporate decision-making contexts. Business managers need clarity on how, when, and why to apply tools to particular business activities and issues.

Conclusions and recommendations for future work. The promise of using ecosystem service assessment tools to support decision making rests on being able to systematically measure impacts in ways that are credible, replicable, and quantifiable. Ecosystem service impacts can often be described qualitatively without the use of valuation methods or models. However, the challenge is to quantify

changes in ecosystem services measured in biophysical or monetary units or weighted preferences for baseline conditions and a range of potential management scenarios. Maps of impacts, tradeoffs, and values can facilitate clearer communication to decision makers and the public and can be a valuable addition to the decision process.

Given the complexity inherent in modeling and valuing ecosystem services and the desire to incorporate them into decision-making processes, it makes sense to estimate and convey uncertainty in model outputs and valuation results. Reporting a single value can inspire false confidence in the certainty of results. Many primary valuation studies report a range of values, and function transfers report standard errors for regression coefficients. ARIES reports uncertainty associated with Bayesian network models and can use Monte Carlo simulation. Future releases of InVEST may also include Monte Carlo simulation to generate uncertainty estimates, and ESValue currently uses Monte Carlo simulation to estimate and report uncertainty. It would be highly useful for model developers to know which uncertainty metrics are most valuable to decision makers, and how uncertainty is or can be used in decision making.

A system of data sharing for: 1) spatial data, 2) ecological studies to parameterize ecosystem service models, and 3) economic studies to support valuation would immensely aid in the ecosystem service valuation process. The time spent on this pilot would have been substantially reduced if such resources were available. Such systems could be supported by Federal agencies, philanthropic foundations, or industry groups to support public and private sector ecosystem service-based decision making.

While agencies like USGS and 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, the ARIES approach to spatial data management – a GeoServer that can call on annotated spatial data to support multiple ecosystem service models – could be scaled up and converted to a web service capable of supporting multiple tools.

Ecosystem service valuation databases have been developed in the past but have too rarely received funding for maintenance and expansion (32). NAIS is a proprietary database and is not available for public access, and a subscription service is planned to provide access to SERVES. The Environmental Valuation Reference Inventory (EVRI) database (33) has been relatively well-maintained but EVRI searches conducted for this pilot revealed that the database is missing a number of key valuation studies for the Western United States. A recent release of EVRI also eliminated the ability to search for studies by U.S. state, making it more cumbersome to use for U.S.-based studies.

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 major 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 use specific ecological production functions.

Given the speed of evolution in the science of ecosystem services, a periodic review of tools for public and private-sector decision-making would be highly desirable. This could take the form of more focused case studies exploring particular nuances of new tools and methods, rather than the broad tools survey undertaken for this initial study. In this vein, BLM is beginning a Phase 2 study that will build upon the lessons learned in this pilot and explore the utility of ecosystem service tools to new ecological, socioeconomic, and decision contexts. Similar case studies across the public and private sector can help keep decision makers abreast of developments in ecosystem services science while building links between developing tools and key public and private sector decision processes.

Methods

Study area. The San Pedro River watershed in southeast Arizona and northern Sonora contains the BLM-managed San Pedro Riparian National Conservation Area (SPRNCA), and has been studied extensively by academic, agency, non-profit, and private sector members of the Upper San Pedro Partnership (34-36). The combination of intense conservation interest in the biologically significant Upper San Pedro and the threat of groundwater decline due to pumping from urban growth, particularly near Sierra Vista and Benson, has led to the development of a decision support system (DSS) designed for use by local watershed groups (37). Our work is the first effort to quantify ecosystem services tradeoffs for the San Pedro (8-10).

Scenarios. We evaluated the responsiveness of ecosystem services tools to four different scenario sets: urban growth, mesquite management, and water augmentation using InVEST and ARIES and housing development using EcoAIM, EcoMetrix, ESValue, InVEST and ARIES (8-10). First, we compared urban-growth scenarios for the year 2000 baseline plus year 2020 “open” and “constrained” scenarios (38). Second, given mesquite encroachment onto desert scrub and grassland ecosystems that has taken place in recent decades (39), there is interest in using fire and/or mechanical removal for mesquite control and grassland restoration. We estimated ecosystem service changes for pre- and post-mesquite management on nearly 930 ha of land within the SPRNCA. Third, the Bureau of Reclamation’s proposed extension of the Central Arizona Project from Tucson to Sierra Vista provides the basis for a family of scenarios (40). We used alternative scenarios for riparian condition representing groundwater rise (41,42) to quantify changes in ecosystem service provision. Finally, as part of BSR’s pilot study, tool developers independently quantified ecosystem services impacts for a set of alternative 200-ha housing development sites (8). We also used the ESR and Wildlife Habitat Benefits Estimation Toolkit, though these tools were aspatial, produced qualitative results (in the case of the ESR), or were poorly suited to valuing the ecosystems and changes from scenarios on the San Pedro (9,10).

Evaluative Criteria. We applied a set of eight evaluative criteria to each method or tool to judge its relative utility in quantifying ecosystem services:

1. Does this method or tool assess ecosystem services directly or just ecological processes?
2. What are the time requirements to use the method or tool?
3. Is the tool or method open source or proprietary (in other words, would it require hiring of consultants, or could agency or corporate environmental compliance staff use it if properly trained)?
4. What is the current level of development and documentation of the tool?
5. What is the scalability (in other words, applicability at varying spatial scales) associated with this tool or method?
6. What is the generalizability (in other words, ease of application at sites in different ecosystems, socioeconomic settings, or regions of the country) associated with this tool or method?
7. How is the tool or method able to incorporate multiple valuation systems (monetary/nonmonetary) and cultural perspectives (including Native American/Tribal values)?
8. How well does the tool "mesh" – cost effectively and yielding new analytical insights – with existing corporate environmental assessment and performance approaches?

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References

1. Millennium Ecosystem Assessment (2005) *Millennium Ecosystem Assessment: Living beyond our means - Natural assets and human well-being* (World Resources Institute, Washington, DC).

2. Ruhl JB, Kraft SE, Lant CL (2007) *The law and policy of ecosystem services* (Island Press, Washington, DC).

3. Daily GC, Polasky S, Goldstein J, Kareiva PM, Mooney HA, Pejchar L, Ricketts TH, Salzman J, Shallenberger R (2009) Ecosystem services in decision making: Time to deliver. *Front Ecol Environ* 7: 21-28.

4. Nelson EJ, Daily GC (2010) Modelling ecosystem services in terrestrial ecosystems. *Faculty of 1000 Biology Reports* 2: 53.

5. Vigerstol KL, Aukema JE (2011) A comparison of tools for modeling freshwater ecosystem services. *J Environ Manage* 92: 2403-2409.

6. Council on Environmental Quality (2009) *Proposed National Objectives, Principles, and Standards for Water and Related Resources Implementation Studies* (Council on Environmental Quality, Washington, DC).

7. President's Council of Advisors on Science and Technology (2011) *Report to the President: Sustaining Environmental Capital: Protecting Society and the Economy* (Executive Office of the President of the United States, Washington, DC).

8. BSR Environmental Services, Tools, and Markets Working Group (2011) *New business decision-making aids in an era of complexity, scrutiny, and uncertainty: Tools for identifying, assessing, and valuing ecosystem services* (BSR, San Francisco, CA).

9. Bagstad KJ, Semmens D, Winthrop R, Jaworski D, Larson J (in review) *Ecosystem services valuation to support decision-making on public lands: A case study for the San Pedro River, Arizona* (USGS Scientific Investigations Report, Reston, VA).

10. Bagstad KJ, Semmens D, Winthrop R (in review) Readiness of tools for ecosystem services valuation: A case study from the semiarid San Pedro River basin, Arizona. In review at *Front Ecol Environ*.

11. Loomis J, Kroeger T, Richardson L, Casey F (2008) A benefit transfer toolkit for fish, wildlife, wetlands, and open space. *Western Economics Forum* 7: 33-43.

12. Tallis HT, Ricketts T, Guerry A, Nelson E, Ennaanay D, Wolny S, Olwero N, Vigerstol K, Pennington D, Mendoza G, Aukema J, Foster J, Forrest J, Cameron D, Arkema K, Lonsdorf E, Kennedy C, Verutes G, Kim C, Guannel G, Papenfus M, Toft J, Marsik M, Bernhartdt J (2011) *InVEST 2.1 beta User's Guide* (The Natural Capital Project, Stanford, CA).

13. Kareiva P, Tallis H, Ricketts TH, Daily GC, Polasky S (2011) *Natural Capital: Theory and practice of mapping ecosystem services* (Oxford University Press: Oxford).

14. Villa F, Ceroni M, Bagstad K, Johnson G, Krivov S (2009) *ARIES (ARtificial Intelligence for Ecosystem Services): a new tool for ecosystem services assessment, planning, and valuation* (11th International BIOECON Conference on Economic instruments to enhance the conservation and sustainable use of biodiversity**,** Venice, Italy) Available at: *http://www.ucl.ac.uk/bioecon/11th_2009/Villa.pdf*.

15. Bagstad KJ, Villa F, Johnson G, Voigt B (2011) *ARIES – Artificial Intelligence for Ecosystem Services: A guide to models and data, version 1.0 Beta* (The ARIES Consortium: Bilbao, Spain).

16. Parametrix (2010) *An introduction to EcoMetrix: Measuring change in ecosystem performance at the site scale* (Parametrix, Portland, OR).

17. Troy A, Wilson MA (2006) Mapping ecosystem services: Practical challenges and opportunities in linking GIS and value transfer. *Ecol Econ* 60: 435-449.

18. Sherrouse BC, Clement JM, Semmens DJ (2011) A GIS application for assessing, mapping, and quantifying the social values of ecosystem services. *Appl Geogr* 31: 748-760.

19. Bolte JP, Hulse DW, Gregory SV, Smith C (2006) Modeling biocomplexity - actors, landscapes, and alternative futures. *Environ Modell Softw* 22: 570-579.

20. Labiosa WB, Bernknopf R, Hearn P, Hogan D, Strong D, Pearlstine L, Mathie AM, Wein AM, Gillen K, Wachter S, (2009) *The South Florida ecosystem portfolio model – A map-based multicriteria ecological, socioeconomic, and community land-use planning tool*. (USGS Scientific Investigations Report 2009-5181, Reston, VA).

21. Feng M, Liu S, Euliss Jr. NH, Young C, Mushet DM (2010) Prototyping an online wetland ecosystem services model using open model sharing standards. *Environ Modell Softw* 26: 458-468.

22. Landsberg F, Ozment S, Stickler M, Henninger N, Treweek J, Venn O, Mock G (2011) *Ecosystem Services Review for Impact Assessment: Introduction and guide to scoping* (World Resources Institute, Washington, DC).

23. UNEP-WCMC (2011) *Measuring and monitoring ecosystem services at the site scale: Introducing a practical toolkit* (UNEP-WCMC: Cambridge, UK).

24. Farber S, Costanza R, Childers D, Erickson J, Gross K, Grove M, Hopkinson C, Kahn J, Pincetl S, Troy A, Warren P, Wilson M (2006) Linking ecology and economics for ecosystem management. *BioScience* 56: 121-133.

25. Wilson M, Hoehn J (2006) Valuing environmental goods and services using benefit transfer: the state of the art and science. *Ecol Econ* 60: 335-342.

26. GeoServer (2011) GeoServer: Accessed February 6, 2012 from: *http://www.geoserver.org*.

27. Mac Nish R, Baird KJ, Maddock III T (2009) Groundwater hydrology of the San Pedro River Basin, *in*: Stromberg, JC, Tellman B, eds., *Ecology and conservation of the San Pedro River* (University of Arizona Press, Tucson, AZ)

28. Norgaard RB (2010) Ecosystem services: From eye-opening metaphor to complexity blinder. *Ecol Econ* 69: 1219-1227.

29. Winthrop, R (2011) Estimating Nonmarket Environmental Values. Draft guidance (ver. 2e), Socioeconomics Program, Bureau of Land Management, Washington, DC.

30. BSR Environmental Services, Tools, and Markets Working Group (2012) *Public policy uptake of ecosystem services concepts: Examining trends from 2009-present* (BSR, San Francisco, CA).

31. International Finance Corporation (IFC) (2012) International Finance Corporation: Accessed February 6, 2012 from: *http://www.ifc.org*.

32. McComb G, Lantz V, Nash K, Rittmaster R (2006) International valuation databases: Overview, methods, and operational issues. *Ecol Econ* 60: 461-472.

33. Environmental Valuation Reference Inventory (EVRI) (2011) EVRI: Accessed January 20, 2011 from: *https://www.evri.ca/Global/HomeAnonymous.aspx*.

34. Moran MS, Emmerich WE, Goodrich DC, Heilman P, Holifield Collins CD, Keefer TO, Nearing MA, Nichols MH, Renard KG, Scott RL, Smith JR, Stone JJ, Unkrich CL, Wong J (2008) Preface to special section on Fifty Years of Research and Data Collection: U.S. Department of Agriculture Walnut Gulch Experimental Watershed. *Water Resour Res* 44: W05S01.

35. Stromberg JC, Lite SJ, Rychener TJ, Levick LR, Dixon MD, Watts, JM (2006) Status of the riparian ecosystem in the Upper San Pedro River: Application of an assessment model. *Environ Monit Assess* 115: 145-173.

36. Colby BG, Orr P (2005) Economic Tradeoffs in Preserving Riparian Habitat. *Nat Resour J* 45: 15.

37. Serrat-Capdevila A, Browning-Aiken A, Lansey K, Finan T, Valdes JB (2009) Increasing social-ecological resilience by placing science at the decision table: The role of the San Pedro Basin (Arizona) Decision-Support System Model. *Ecol Soc* 14: 1.

38. Steinitz C, Arias H, Bassett S, Flaxman M, Goode T, Maddock III T, Mouat D, Peiser R, Shearer A (2003) *Alternative futures for changing landscapes: The Upper San Pedro River Basin in Arizona and Sonora* (Island Press, Washington, DC).

39. Kepner WG, Watts CJ, Edmonds CM, Maingi JK, Marsh SE, Luna G (2000) Landscape approach for detecting and evaluating change in a semiarid environment. *Environ Monit Assess* 64: 179-195.

40. Bureau of Reclamation (2007) *Appraisal report: Augmentation alternatives for the Sierra Vista Sub-watershed, Arizona: Lower Colorado Region* (U.S. Department of Interior Bureau of Reclamation, Denver, CO).

41. Stromberg JC, Lite SJ, Rychener TJ, Levick LR, Dixon MD, Watts JM (2006) Status of the riparian ecosystem in the Upper San Pedro River, Arizona: Application of an assessment model. *Environ Monit Assess* 115: 145-173.

42. Brookshire DS, Goodrich D, Dixon MD, Brand LA, Benedict K, Lansey K, Thacher J, Broadbent CD, Stewart S, McIntosh M, Kang D (2010) After restoration: A framework for preserving semi-arid regions in the Southwest. *Journal of Contemporary Water Research and Education* 144: 60-74.

Figure 1. Potential steps in ecosystem services assessment process.

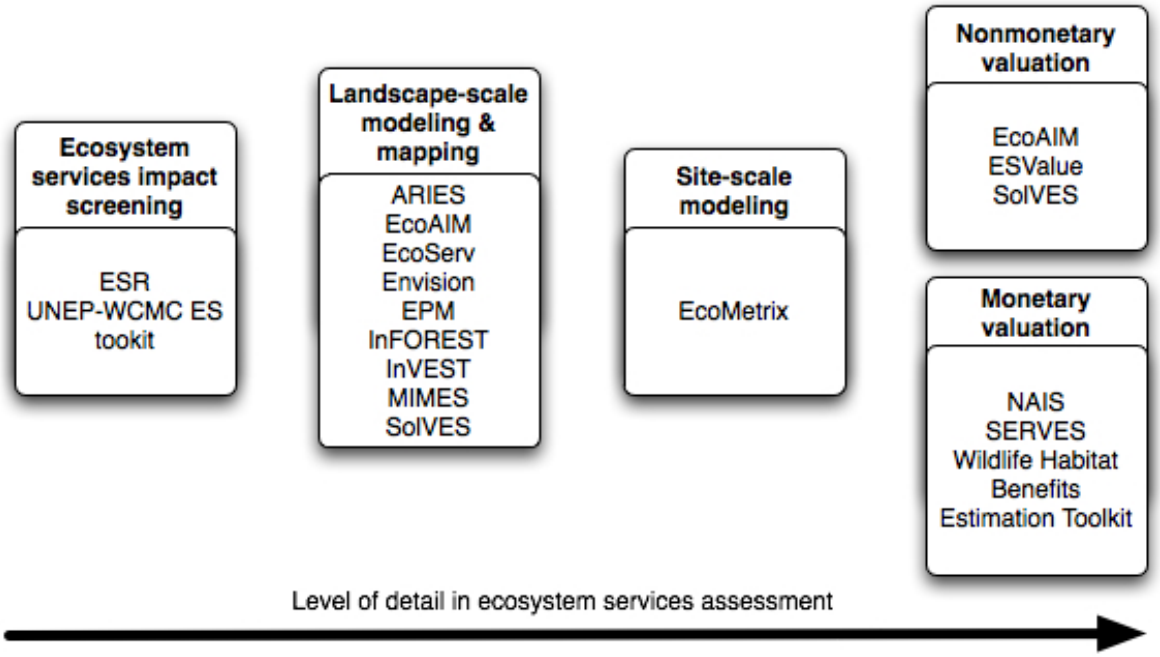

Table 1. A survey of ecosystem services tools.

Tool, URL, and references	Brief description	Tested in this study?	Rationale for choice to test or not test in this study
Wildlife Habitat Benefits Estimation Toolkit, *http://www.defenders.org* (11)	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
Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), *http://www.naturalcapitalproject.org* (12,13)	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* (14,15)	Open source modeling framework to map ecosystem service flows; online interface under development	Yes	Data and models available for several western U.S. states; global model and online interface under development would

			enable widespread use
Multiscale Integrated Models of Ecosystem Services (MIMES), *http://www. affordablefutures .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
EcoMetrix, *http://www.parametrix.com* (16)	Proprietary tool for measuring ecosystem services at site scales using field surveys	Yes	Demonstration for the San Pedro completed by Parametrix (8)
EcoAIM (8)	Proprietary tool for mapping ecosystem services and stakeholder preferences	Yes	Demonstration for the San Pedro completed by Exponent (8)
ESValue (8)	Proprietary tool for mapping stakeholder preferences for ecosystem services	Yes	Demonstration for the San Pedro completed by Entrix (8)
Natural Assets Information System (NAIS), *http://www.sig-gis.com* (17)	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
Simple Effective Resource for Valuing Ecosystem Services (SERVES), *http:// www. eartheconomics. org*	Subscription-based valuation database paired with GIS mapping of land-cover types for point transfer	No	Tool not fully developed by the time of the pilot study
Social Values for Ecosystem Services (SolVES), *http://solves.cr.usgs.gov* (18)	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* (19)	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* (20)	Web-accessible tool to model economic, environmental, and quality of life impacts of alternative land-use choices	No	Being applied for adjacent Santa Cruz River but still under development; infeasible to run for new sites without a substantial external research effort
EcoServ (21)	Web-accessible tool to model ecosystem services	No	Still in development; initial case studies not available for Southwest
InFOREST, *http://www.dof.virginia.gov*	Web-accessible tool to quantify ecosystem services in Virginia	No	Has only been developed for Virginia
Ecosystem Services Review (ESR), *http://www.wri.org/* (22)	Publicly available, spreadsheet-based process to qualitatively assess ecosystem services impacts	Yes	A well-documented approach to quickly describe ecosystem services and impacts qualitatively
UNEP-WCMC Ecosystem Services Toolkit, *http://www.unep-wcmc.org* (23)	Publicly available process to qualitatively assess ecosystem services impacts	No	Full documentation for toolkit has not yet been released

Table S1. Ecosystem services modeling approaches, inputs, outputs, and assumptions.

Model	**Modeling**	**Input data**	**Model**	**Valuation**	**Assumptions**

	approach		outputs		
InVEST (carbon, water supply, biodiversity, viewsheds) (12)	Links carbon pools, habitat quality, biodiversity drivers to land cover type. Can model scenarios as change over time with alternative land cover data. Links water flows and views to users across the landscape.	User-supplied spatial data for land cover and other relevant features (e.g., annual precipitation, population density). Tabular data describing biophysical values (e.g., carbon pools, evapotranspiration coefficients) or relative values (e.g., habitat quality) by land-cover type.	Spatially explicit carbon storage (t C/ha) or sequestration (t C/ha/yr), water yield and use (mm), habitat quality (relative values), visual impacts of blight (relative values).	Apply social cost of carbon ($/t C), market price, replacement cost, or willingness to pay estimates for water ($/unit volume). No valuation for biodiversity or viewsheds.	Tier 1 models simplify carbon sequestration, surface and groundwater relationships.
ARIES (carbon, water supply, open space proximity, viewsheds, recreation) (15)	Bayesian models quantify carbon sequestration, potential stored carbon release, evapotranspiration, infiltration, viewshed, open space, and recreational values. "Sources" of values linked via service-specific flow models to anthropogenic users and "sink" features that deplete service values available to	Pre-loaded spatial datasets on the ARIES GeoServer for climate, vegetation, soils, anthropogenic features that influences supply and demand for each ecosystem service.	Spatially explicit biophysical values (carbon, t C/ha*yr; water, mm); relative values (viewshed, open space proximity, recreation). Uncertainty estimates, service flows, theoretical vs. actual provision	Apply social cost of carbon ($/t C), market price, replacement cost, or willingness to pay estimates for water ($/unit volume). Could apply hedonic pricing to aesthetics results and travel cost or WTP to recreation	Probabilistic models work well under conditions of data scarcity and uncertainty but deterministic models may be more appropriate when these conditions are not met.

	users.		and use.	results.	
EcoAIM (biodiversity)	Weighted average of spatially explicit influences on biodiversity.	Weighted metrics for species richness and protection, habitat quality/vulnerability, wildlife corridors, vegetation cover types.	Spatially explicit weighted biodiversity score (relative values).	No valuation of biodiversity, but other services could be valued monetarily or in multicriteria analysis.	All models in relative units should carefully document underlying assumptions to reduce subjectivity.
EcoMetrix (all services) (16)	Field-collected data (e.g., on vegetation, soils, geomorphology) fed into spreadsheets that encode ecological production functions and estimate relative ecosystem service quantities.	Field-collected data fed into ecosystem service production functions.	Site-level estimates of ecosystem service provision and change under alternative management scenarios (relative values).	Has been used in the past as information in environmental credit calculations.	Based on literature and expert-derived production functions.

Table S2. Estimated time to complete ecosystem services assessments using alternative methods.

Method/Tool	**Est. hours, pilot study**	**Est. hours with improved data archive**	**Information provided**	**Comments**
Synthesis of primary valuation literature	60	20	Locally specific valuation	Time needed for review and synthesis of the literature; could be greater in areas where more studies have been completed.
Value transfer	10	10	Aspatial valuation	Estimate for the Wildlife Habitat Benefits Estimation Toolkit. Time requirements would be substantially greater to build new

				transfer functions.
Ecosystem Services Review	10	10	Qualitative review	Rapid assessment but does not provide quantitative results; time to completion could be several times greater if a large number of stakeholders are involved.
InVEST (4 ecosystem services	275	40	Spatially explicit outputs	Time to complete could be drastically reduced with system for sharing data and underlying model assumptions.
ARIES (4 ecosystem services)	800	40	Spatially explicit outputs, uncertainty, flow data	Model customization and debugging was extremely time consuming but will not be so for future applications. Spatial data management system reduces data input needs in future applications.
EcoMetrix	85	85	Relative service scores by site	Time for field data collection, data entry and analysis.
EcoAIM (biodiversity only)	25	25	Spatially explicit weighted average values	Time to prepare GIS data and run overlays.
ESValue	400	400	Relative preferences for alternative services	Stakeholder engagement the most time consuming step.

Table S3. Description of all ecosystem services tools against key evaluative criteria.

(see attached Excel table)