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

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ABSTRACT

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

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1. Introduction

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

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

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

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

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

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

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

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

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

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

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

2. Methods

2.1. Study area

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

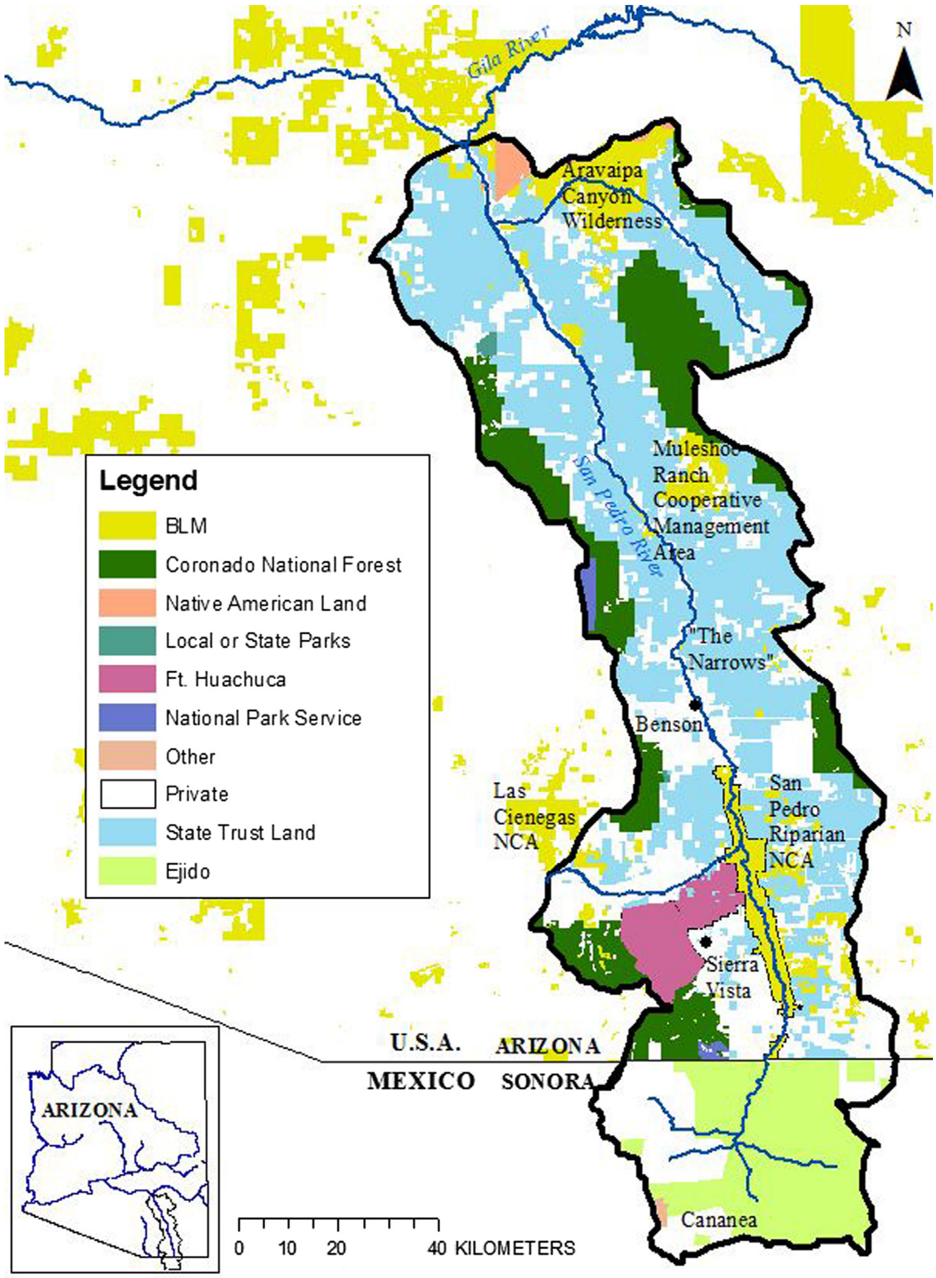

Fig. 1. Land ownership within the San Pedro River watershed, including BLM conservation areas plus BLM land outside the watershed.

2.2. *Ecosystem services, models, and data*

Through discussions with nearly 30 stakeholders including academics, agency scientists, and resource managers, many involved in long-term research and management through the Upper San Pedro Partnership, we identified four broad categories of ecosystem services of interest in the San Pedro: carbon sequestration and storage, water supply, biodiversity, and other cultural services. Carbon, water, and viewshed models are included in both ARIES and InVEST, so quantification of these services and comparison of results are the focus of this analysis. InVEST and ARIES have different underlying modeling philosophies and approaches and do not output identical ecosystem services metrics, making direct comparison of results across all services difficult (Table 1). We also quantified habitat quality using InVEST and open space proximity and recreational value with ARIES, but discuss these results elsewhere (Bagstad et al., 2012) as these models lacked counterparts for comparison between the tools.

For the water-supply models, we used precipitation data from 2002, a representative dry year in southeast Arizona, and 2007, a representative wet year, to evaluate a range of annual water-supply outcomes in this semiarid environment with highly variable seasonal and annual precipitation. We obtained many of the spatial data needed to populate the models from the EPA San Pedro Data Browser (Kepner et al., 2003), state and federal agencies, and other research groups. The full data needs for InVEST and ARIES are provided in their respective modeling references (Tallis et al., 2013; Bagstad et al., 2011). Assumptions and specific data sources used for the InVEST and ARIES model runs on the San Pedro are detailed in Appendix A of Bagstad et al. (2011, 2012), respectively, and in Supplemental online material to this paper. We applied economic values to results for carbon and water

Table 1
Input data requirements, modeling approach, and outputs for ARIES and InVEST Tier 1 carbon, water, and viewshed models.

Model	Requirements	Approach	Outputs
ARIES carbon	Spatial data for influences on regional carbon dynamics, including anthropogenic greenhouse gas emissions, vegetation, soils, climate	Models carbon sequestration and potential stored carbon release probabilistically, compares these against emissions to estimate regional carbon balance	Spatially explicit carbon sequestration and stored carbon release (tonnes C/ha/year) and uncertainty; outputs can be valued using social cost of carbon estimates
InVEST carbon	Land-cover data; table linking land-cover type to carbon storage	Models sequestration as a function of land-cover change over time	Spatially explicit carbon storage (tonnes C/ha) when land-cover data are available for only one time period, or sequestration if multiple years of land-cover data are available (tonnes C/ha/year); outputs can be valued using social cost of carbon estimates
ARIES water supply	Spatial data influencing water supply and use, including precipitation, water demand, land cover, vegetation, soil, climatic data, hydrography, digital elevation model (DEM)	Models annual evapotranspiration and infiltration probabilistically and combines these results with flow models spatially linking water sources (e.g., precipitation) to users	Spatially explicit water supply (mm/year) and uncertainty, showing areas from which users derive their water, or ecosystems providing water to specific users; outputs can be valued using market price, replacement cost, or willingness to pay estimates for water
InVEST water supply	Land cover, soil depth, annual precipitation, plant available water content, potential evapotranspiration, watershed boundary, DEM; tabular data linking land cover to water demand, evapotranspiration, maximum root depth	Models annual water yield using average annual precipitation and the Budyko curve, subtracting evapotranspiration from combined infiltration and runoff; can estimate water demand by assigning consumptive water-use values to each land-cover type	Spatially explicit water yield and demand (mm/year); outputs can be valued using market price, replacement cost, or willingness to pay estimates for water
ARIES viewsheds	Features that influence the quality of potentially valuable views, features that may degrade these views (i.e., visual blight), locations of users (e.g., housing or recreation sites), DEM	Probabilistically models “sources” of high quality views, “sink” features that degrade views, user locations, and flows that connect users to natural features showing actual use via lines of sight	Spatially explicit esthetic values (in relative units) and their uncertainty, showing areas from which users derive the greatest benefit
InVEST viewsheds	Population density, location of visual blight, DEM	Line of sight model quantifies visibility of undesirable features to viewers	Population with views of blight features, number of blight features visible at each point on the landscape

elsewhere (Bagstad et al., 2012). While value information can aid in decision making, for the purposes of comparing model results it simply scales the model outputs by a common factor, so we do not present valuation results in this paper.

2.3. Scenarios

An important goal of this project was to evaluate the effectiveness of ecosystem service modeling tools in addressing managerially relevant scenarios. InVEST and ARIES rely on diverse input data; for any spatial data that are model inputs, inserting a scenario-relevant alternative data layer (e.g., for land use, population density, or precipitation) yields a second set of results that can be compared to baseline conditions. We chose to model urban growth and a restoration management option. These two scenario types vary in the spatial extent, nature, and degree of impacts on ecosystem services, and test the tools’ ability to accommodate managerially relevant scenarios.

Traditionally quantified economic benefits such as increased employment and municipal tax base are often used to justify the negative environmental and social impacts that can accompany urban growth. Consideration of ecosystem services as an opportunity cost of urban growth can more fully show the costs and benefits of urban expansion. Urban growth is a diffuse process of widespread landscape change. It is encountered in a wide variety of contexts and has notable environmental and social consequences (Burchell et al., 2005; Kroll et al., 2012), making the capacity to quantify its impacts important for ecosystem service modelers and modeling systems (Norman et al., 2012). We compared urban-growth scenarios using year 2000 baseline plus “open” and “constrained” development scenarios for 2020, which were developed by Steinitz et al. (2003) based on the different population-growth projections and development policies. These scenarios assume expansion in desert scrub (10–17%) and urban (179–507%) land-cover types and reductions in agriculture (13–85%) and grasslands (17–21%).

Restoration projects such as mesquite management fall under the SPRNCA’s mandate “to protect, enhance, and maintain the riparian area and the aquatic, wildlife, archeological, paleontological, scientific, cultural, educational, and recreational resources of the public lands

Table 2
InVEST and ARIES results: carbon sequestration and storage.

Scenario	InVEST carbon storage (tonnes) (change over a 20-year period)	InVEST carbon sequestration (tonnes/year)	ARIES carbon sequestration (tonnes/year) (change)
2000 housing baseline	53,019,000		526,200
2020 open development	49,660,000 (−3,359,000)	−167,950	410,900 (−115,300)
2020 constrained development	50,817,000 (−2,202,000)	−110,100	416,600 (−109,600)
Pre-mesquite management (SPRNCA only)	1,557,000		14,152
Post-mesquite management (SPRNCA only)	1,523,000 (−34,000)	−1700	14,004 (−148)

surrounding the San Pedro River in Cochise County, Arizona" (16 U.S.C. 460xx). In real-world terms, however, restoration decisions hinge on the prioritization of scarce resources and the cost of and public response to alternative options. Ecosystem services provide a quantifiable metric for comparison with other costs and benefits. We identified 922 ha adjacent to roughly 11 river kilometers with perennial streamflow with potential for the conversion of mesquite shrubland into native grasslands to evaluate the ecosystem service effects of mesquite management. This scenario is representative of a discrete land-management decision that could impact ecosystem services – in this case for grassland conservation and restoration, though development or resource extraction could be similarly modeled.

3. Results

In this section we describe quantitative changes in ecosystem services modeled for carbon, water, and viewsheds using InVEST and ARIES. We first present results for each service, then compare changes in ecosystem services for the scenarios. Due to problems with integrating multiple land-cover datasets into the models, we were only able to map results in Mexico using the InVEST carbon and viewshed models, and were only able to map values in the Lower (northernmost) San Pedro using the ARIES models. However, since the land-use/cover changes for the scenarios occurred in the U.S. portion of the Upper San Pedro only, our comparative results using the InVEST and ARIES models remain unbiased by the fact that we could not run some of the models across the entire watershed. We can thus directly compare scenario changes between the two tools, even though ARIES and InVEST mapped ecosystem services across different spatial extents.

3.1. Carbon sequestration and storage

We modeled carbon sequestration and storage using ARIES and InVEST for all scenarios. The InVEST carbon model showed a loss in carbon storage under the urban-growth scenarios, with greater carbon-storage loss under the open development scenario (3.4 million tonnes lost over a 20-year period) than the constrained scenario (2.2 million tonnes lost, Table 2, Fig. 2). It also showed a small loss of carbon storage (34 thousand tonnes) under the mesquite-management scenario. When converted to annual values (i.e., dividing the total change by 20 years), InVEST results indicate a loss of 168 thousand tonnes/year of carbon storage under the open development scenario and 110 thousand tonnes/year under the constrained development scenario. ARIES results indicate relatively similar lost carbon sequestration under the urban-growth scenarios – a loss of 115 thousand and 110 thousand tonnes/year, respectively, under the open and constrained development scenarios. A relatively small change in carbon sequestration was quantified under the mesquite management scenario (loss of 148 tonnes of sequestration/year).

3.2. Water supply

We modeled water yield/supply using InVEST and ARIES for all scenarios. Both the models treat groundwater and groundwater flows in a simplistic manner. ARIES spatially links surface-water users to areas of surface-water provision. Since nearly all water use in the San Pedro River watershed is from groundwater and we lack information about groundwater use and flows, we could not model *actual* flows of water to users. Instead, we quantified precipitation, infiltration, and evapotranspiration independent of flows. InVEST simplifies water movement by combining the movement of groundwater and surface water, assuming that groundwater follows the same flow path as surface water and reaches a stream where it is eventually discharged as base flow. In the San Pedro River watershed this process is very slow, with water taking an average of 1100 years to move from recharge zones to the river (MacNish et al., 2009). InVEST water-yield models have been tested in other groundwater-dominated systems, where they were deemed to perform acceptably provided that the results could be calibrated to time-series streamflow data (Mendoza et al., 2011, their box 4.1).

The InVEST water-yield model showed annual water-yield increases in the Upper San Pedro watershed of 8–12% for the open development scenario and 4-5% for the constrained development scenario in comparison with the baseline, based on the representative wet- and dry-year precipitation (Table 3, Fig. 3). This increase in water yield results from reduced infiltration and faster runoff, which are a function of increased impervious surfaces with urban growth and have been well documented through both field observations and disciplinary models (e.g., Kennedy et al., 2013). This is generally an undesirable effect, as faster runoff causes problems with erosion, water quality, aquatic habitat, and groundwater recharge, though we did not quantify these impacts.

ARIES results are not directly comparable to those obtained using InVEST. In this application, ARIES quantified *theoretical* changes in water yield, independent of actual hydrologic flows, which it calculates as the reduction in infiltration and evapotranspiration under the urban-growth scenarios. ARIES quantified a decrease in theoretical (flow-independent) infiltration and evapotranspiration of 2.3% under the constrained development scenario and 2.7% under the open development scenario, compared to the baseline. Although the sign of the change is opposite to the InVEST results (which quantified increased water yield), they quantify the same type of change – reduced infiltration and evapotranspiration in the case of ARIES and increased water yield due to the reduced infiltration and evapotranspiration in the case of InVEST. In both the models, the predicted changes result largely from reduced infiltration, an undesirable change in a groundwater-driven system.

Using InVEST, we found an increase in annual water yield of 0.3–0.8% for the mesquite management scenario. This result was expected given the lower evapotranspiration typical of grasslands relative to mesquite, as demonstrated by Nie et al. (2012) using similar scenarios as modeled using the Soil and Water Assessment Tool (SWAT, Arnold and Fohrer, 2005). As modeled by ARIES, mesquite management similarly reduced annual evapotranspiration within the SPRNCA by 0.3%. The detailed interactions between

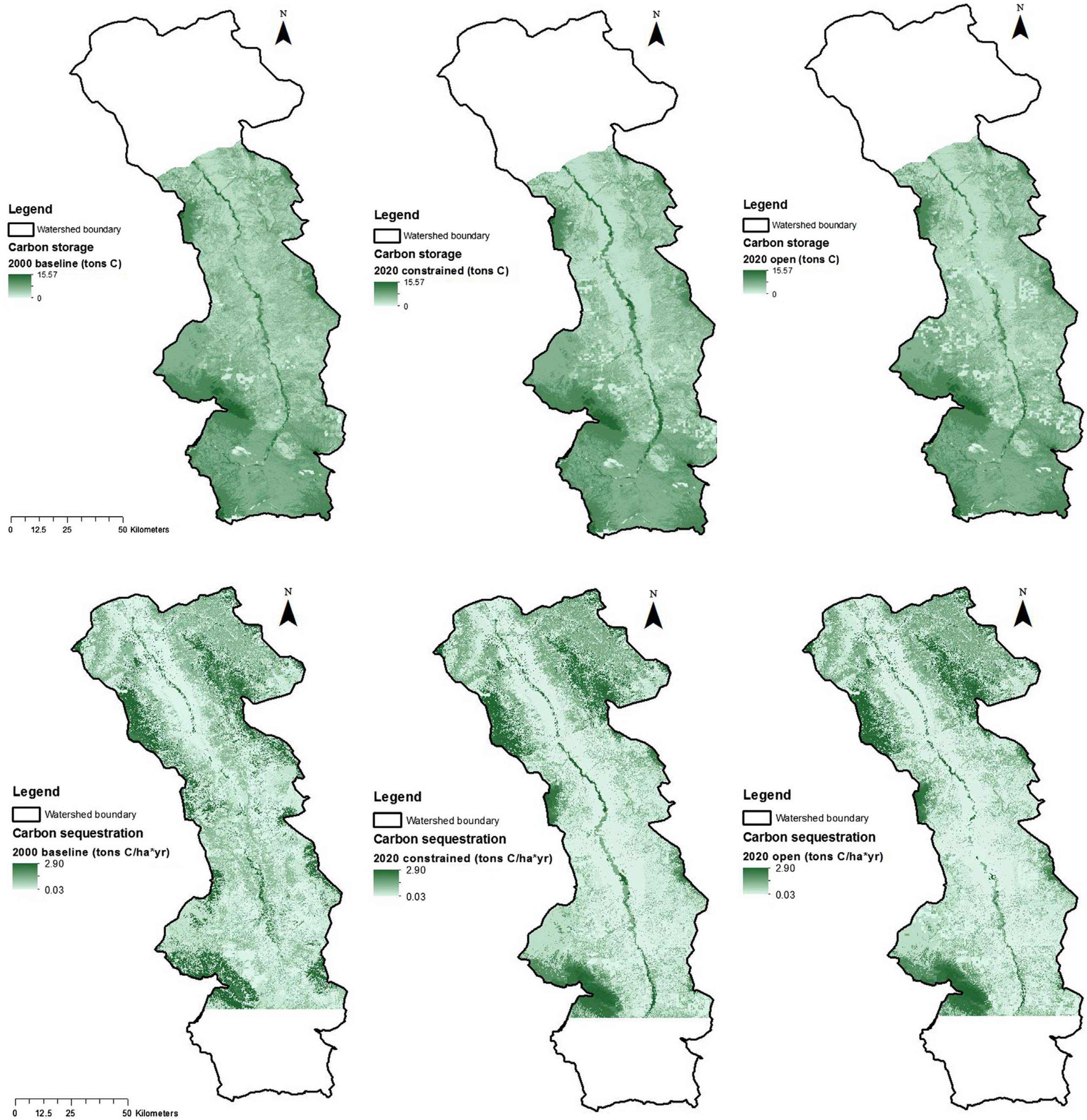

Fig. 2. InVEST (top) and ARIES (bottom) baseline and urban growth carbon sequestration results.

evaporation, transpiration, infiltration, and energy balance for grasslands and shrublands in semiarid watersheds are not completely understood but have important implications for both carbon and water budgets (Moran et al., 2009). Both InVEST and ARIES simplify the system to such a degree that their results are difficult to precisely interpret, although our finding that grasslands promote greater surface and groundwater flows and lower evapotranspiration, benefitting nearby riparian ecosystems, is theoretically consistent with field studies and disciplinary hydrologic models.

3.3. Viewsheds

We modeled viewsheds using InVEST and ARIES only for the urban-growth scenarios, as we lacked information on how changes in mesquite and grassland cover translate into improved or diminished viewshed quality. The InVEST viewshed model quantified a substantial increase in the number of visible developed pixels (i.e., visual blight) across the landscape, with an 89% increase in the constrained development scenario and a 275% increase in the open development scenario (Table 4, Fig. 4). However, these results tell only part of the story, as they do not comprehensive account for the locations of viewers, visual blight, and visually valued views. Using ARIES, we mapped the theoretical source (i.e., view-source quality, independent of the location of users) and actual use (dependent on user presence and ecosystem service flows via lines of sight) for viewsheds. We found a decrease in theoretical viewshed quality of 0.04–0.1%, as land-cover types with greater visual appeal were replaced by development. We also found an increase in actual viewshed use of 240–555%, with greater changes occurring in the open than the constrained development scenario because of the higher population growth associated with the former. These results indicate slight declines in

Table 3
InVEST and ARIES results: water supply.

Scenario	InVEST water yield, 1000 m^3		ARIES theoretical evapotranspiration and infiltration, 1000 m^3 (change)
	2002 – dry year (change)	2007 – wet year (change)	
2000 housing baseline	507,627	987,713	235,407
2020 open development	568,469 (+60,842)	1,063,809 (+76,096)	229,176 (−6,231)
2020 constrained development	533,537 (+25,910)	1,024,104 (+36,391)	230,067 (−5,340)
Pre-mesquite management (SPRNCA only)	9859	25,264	5561
Post-mesquite management (SPRNCA only)	9935 (+76)	25,338 (+74)	5545 (−16)

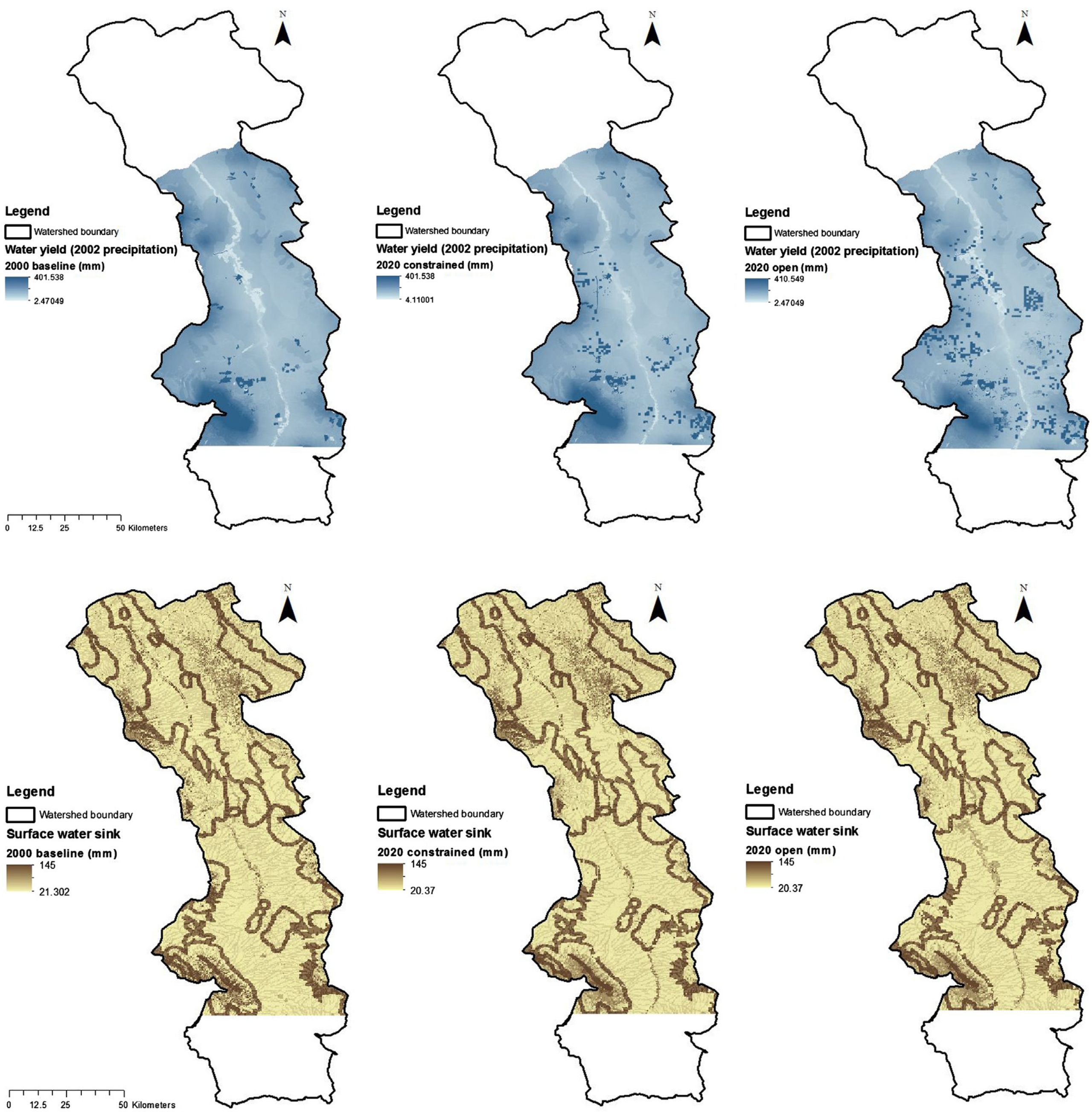

Fig. 3. InVEST (top) and ARIES (bottom) baseline and urban growth water yield results.

the provision of high-quality views as natural ecosystems are replaced by development. They also show a large increase in actual use as many new low-density developments are spread across the landscape with the views of visually valued objects such as mountains or riparian vegetation.

3.4. Scenario analysis: urban growth

Our results show a reduction in carbon sequestration and storage (both ARIES and InVEST), theoretical surface water "sinks" (i.e., evapotranspiration and infiltration, ARIES), and theoretical

Table 4
InVEST and ARIES results: viewsheds.

Scenario	InVEST total visible visual blight points (change)	ARIES viewsheds, relative value	
		Theoretical source (change)	Actual use (change)
2000 housing baseline	739,306,212	1,026,000	142,200
2020 open development	2,771,447,794 (+274.9%)	1,025,000 (−0.1%)	931,000 (+554.7%)
2020 constrained development	1,397,092,583 (+89.0%)	1,026,000 (−0.04%)	483,900 (+240.3%)

viewshed quality (ARIES) in both the urban growth scenarios in relation to our baseline, with greater changes occurring in the open development scenario (Table 5). Increases in water yield in association with urbanization are well documented, and proportionately larger increases are typically observed during smaller rainfall events or drier years when infiltration and interception losses comprise a larger percent of the volume of precipitation (Kennedy et al., 2013). They also show gains in water yield (InVEST), in the number of developed pixels visible on the landscape (InVEST) and actual viewshed use (ARIES). The hydrologic changes correspond to faster runoff and reduced infiltration in a groundwater-driven system, and carry additional undesirable ecological and hydrologic effects that were not quantified using ARIES or InVEST.

3.5. Scenario analysis: mesquite management

For the mesquite-management scenario, we quantified a reduction in carbon sequestration and storage (ARIES and InVEST), a decrease in evapotranspiration (ARIES), and an increase in water yield (InVEST; Table 6), indicating a tradeoff between reduced carbon sequestration and storage but increased water yield for the riparian ecosystem.

4. Discussion

4.1. Quantifying ecosystem service tradeoffs

Although this project was intended as a proof-of-concept for ecosystem service modeling tools and was not expressly intended to guide specific management decisions, it does offer insight into the use of ecosystem service modeling tools in decision making. Before undertaking this project, stakeholders on the San Pedro held preconceived ideas about the likely gains and losses in ecosystem services for the scenarios explored in this study. Our results map and quantify some of these tradeoffs. For the urban-growth scenarios, we quantified losses in carbon sequestration and viewshed quality, gains in the number of beneficiaries, which are likely to increase viewshed values, and increased water yield (an undesirable effect, since it corresponds to reduced infiltration and additional ecological and hydrologic impacts). For the mesquite-management scenario, we quantified losses in carbon sequestration and storage but gains in water yield. Bagstad et al. (2012) also quantified changes in habitat quality, open space proximity, and recreational value for urban growth, mesquite management, and water augmentation scenarios that can inform decision making in the San Pedro River watershed.

The ARIES viewshed results illustrate a case of how landscape quality can decline while at the same time becoming more valuable as ecosystem-service use increases with more beneficiaries present on the landscape, in both the urbanization scenarios. This shows how rising demand for ecosystem services can lead to increases in their value, even as ecosystems are being degraded. It is thus important that rising ecosystem-service values not always be equated to improvements in ecosystem quality.

4.2. Comparability between tools and outputs

While the predicted magnitude of change in ecosystem services was not always comparable when using InVEST and ARIES, the sign of the change was typically equivalent (or had equivalent biophysical meaning for the water supply results), and for this case study a decision maker would reach similar conclusions about scenario-based ecosystem-service impacts using either tool.

For the most directly comparable outputs – carbon sequestration – ARIES and InVEST results were more similar under widespread landscape change scenarios (urban growth) than under the mesquite management scenario, which took place over a relatively limited spatial extent. It is possible that the parameter estimates used for carbon sequestration in grasslands and shrublands were more divergent between the two models, since a single land-cover transition is more sensitive to parameter estimation error than multiple land-cover transitions. Although untested, it is also possible that analyses aggregated across a broad spatial extent provide more room for divergent areas of high and low values quantified using different models to average out, whereas model results aggregated across a more limited spatial extent are naturally more likely to diverge when different modeling methods are used.

ARIES and InVEST generally use different ecosystem service metrics based on the alternative modeling approaches or philosophies. The issue of selecting appropriate ecosystem service metrics is a broad one faced by researchers in this field (Boyd and Krupnick, 2009). While the concept of using ecological endpoints or “final ecosystem goods and services” (FEGS, Boyd and Banzhaf, 2007; Nahlik et al., 2012) has gained support as a way to conceptualize metrics that can be measured or modeled to better support valuation – particularly for navigating the issue of double counting – in other cases the quantification of “intermediate services” will likely remain important (Braat and de Groot, 2012).

InVEST uses published production function information encoded within deterministic models, and while it does account for ecosystem service flows in some models (e.g., hydrology, viewsheds), it does not systematically present results in terms of service provision, use, and flows (e.g., Syrbe and Walz, 2012; Bagstad et al., 2013). InVEST′s Tier 1 models are largely populated by linking land cover to service provision via tables of coefficients (e.g., carbon storage, evapotranspiration coefficient, or nutrient filtering capacity) for each land-cover type; data for the coefficient tables are typically derived from published field experiments. ARIES uses probabilistic models in addition to deterministic ones and generally defines ecosystem service metrics within a paradigm of ecosystem service flow quantification. This yields maps of actual ecosystem service provision and use rather than just potential provision in the absence of human beneficiaries (Bagstad et al., 2013). ARIES models often use remotely sensed or modeled spatial datasets for Bayesian network training or calibration. It is thus not surprising that these approaches yield divergent results. Both approaches have scientific validity, and further comparative applications, perhaps in concert with more robust biophysical modeling, are needed to identify the conditions under which each more accurately quantifies ecosystem services.

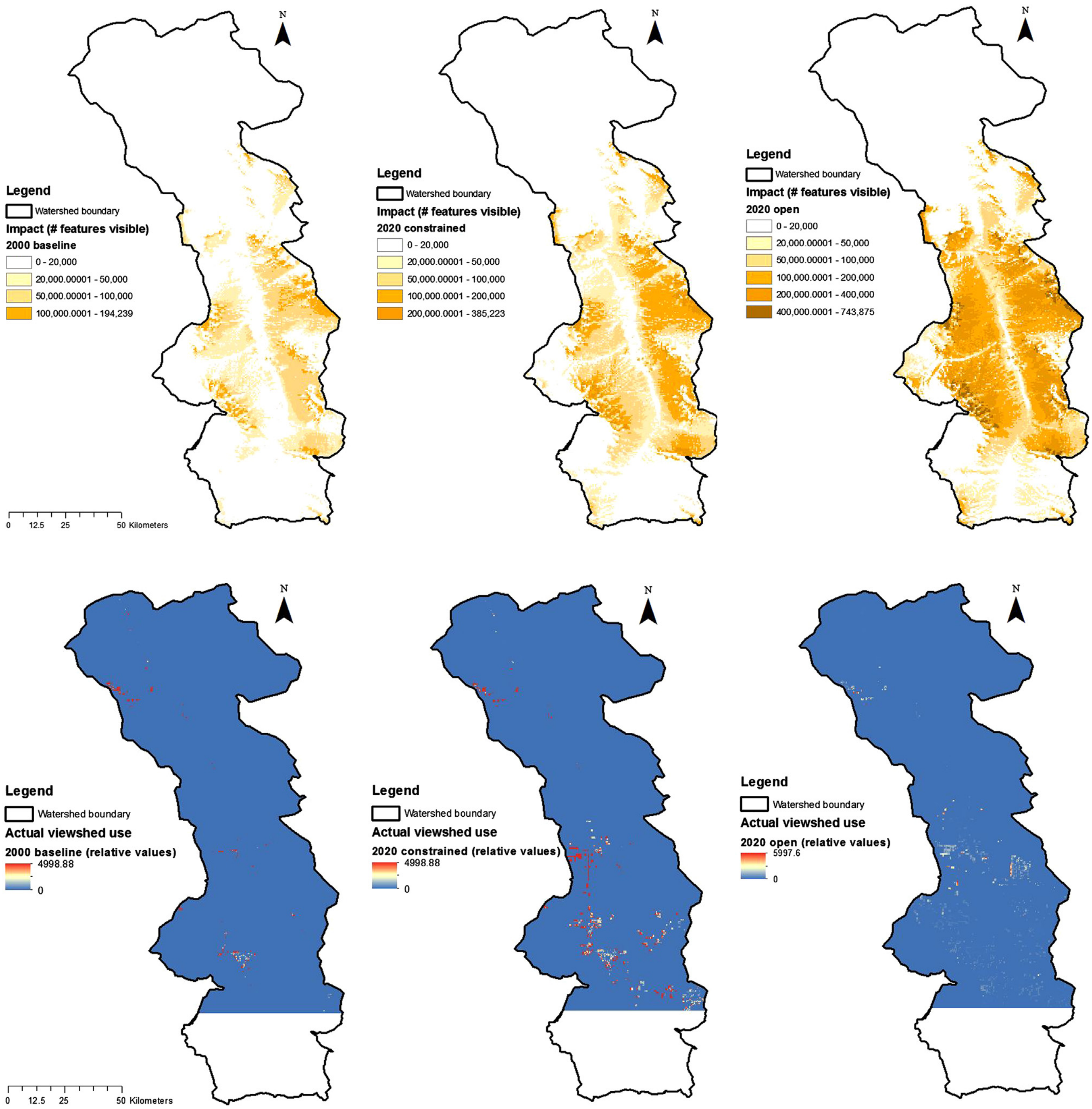

Fig. 4. InVEST (top) and ARIES (bottom) baseline and urban growth viewshed results.

Table 5
InVEST and ARIES results: urban growth.

Service	2020 open change (%)	2020 constrained change (%)
Carbon sequestration (tonnes C/year, InVEST)	−167,950 (−6.3%)	−110,100 (−4.2%)
Carbon sequestration (tonnes C/year, ARIES)	−115,300 (−21.9%)	−109,600 (−20.8%)
Water yield (1000 m^3 water, dry year; InVEST)	+60,842 (12.0%)	+25,910 (5.1%)
Water yield (1000 m^3 water, wet year; InVEST)	+76,096 (7.7%)	+36,391 (3.7%)
Theoretical surface-water sink (1000 m^3 water; ARIES)	−6231 (−2.7%)	−5340 (−2.3%)
Viewshed (million developed pixels visible; InVEST)	+2032.1 (274.9%)	+657.8 (89.0%)
Viewshed theoretical source (relative values; ARIES)	−1000 (−0.1%)	−400 (−0.04%)
Viewshed actual use (relative values; ARIES)	+788,800 (554.7%)	+341,700 (240.3%)

Managers consistently report that they need some idea about the uncertainty associated with model results. ARIES provides uncertainty estimates, generated automatically as a result of using Bayesian network modeling, Monte Carlo simulation, and variance propagation, associated with results and maps spatial flows of ecosystem services by evaluating provision, use, and flow

Table 6
InVEST and ARIES results: mesquite management.

Service	Change (%)
Carbon sequestration (tonnes C/year; InVEST)	−1700 (−2.2%)
Carbon sequestration (tonnes C/year; ARIES)	−148 (−1.1%)
Water yield (m^3 water, dry year; InVEST)	+76,000 (0.8%)
Water yield (m^3 water, wet year; InVEST)	+74,000 (0.3%)
Theoretical surface-water sink (m^3 water; ARIES)	−16,000 (−0.3%)

characteristics for each service. The current generation of InVEST models does not address uncertainty. Kareiva et al. (2011) recommend using a range of values for relevant ecological coefficients needed to parameterize the InVEST models, thus producing a range of values in the model results and some measure of uncertainty. Ideally such sensitivity analyses would explore and account for potential parameter correlations (Elston, 1992). We did not conduct such a sensitivity analysis for this study, and doing so would have increased the time required to apply the tool.

4.3. Feasibility for routine use

The widespread adoption of ecosystem service models will require a greater understanding of their time requirements and performance relative to each other and discipline-specific models under diverse geographic and decision contexts. This application to the San Pedro River watershed provides an initial comparative analysis between the InVEST and ARIES modeling systems, but its conclusions should be revisited in follow-up studies across diverse contexts.

Both the tools were time consuming to apply for the San Pedro. The InVEST application, including data development, model customization, runtime, and analysis for carbon, water, viewshed, and habitat quality models required about 275 h to complete. The ARIES carbon, water, viewshed, open space proximity, and recreation models required about 800 h to complete, with analyses performed by a relatively experienced analyst with a background in GIS and ecosystem services modeling. Individual ARIES models were roughly equally time consuming to construct, run, and test, while the InVEST carbon and water yield models, which require the compilation of biophysical metrics corresponding to LULC data, were more time consuming to parameterize, run, and test than the habitat quality and viewshed models, which rely largely on expert opinion. In briefings with BLM, staff indicated that to facilitate their uptake for agency-wide decision making, tools would need to be able to be applied in a fraction of these time requirements.

InVEST′s Tier 1 models are feasible for use by resource managers given adequate supporting data, GIS software licenses, and a moderate level of GIS expertise. Underlying data are the largest obstacle to widespread adoption of InVEST: assembling the needed spatial data and parameterizing underlying data tables can be time consuming and risks error if done poorly, though it only has to be done once for a given area. A data archive to support InVEST modeling, including preprocessed data and model coefficient values, would greatly reduce the time required for analysis, and could make routine application of InVEST much less time consuming (hence more practical, Bagstad et al., this volume), though some marine data layers are available for download from the InVEST website. InVEST′s Tier 2 models, when available, promise improved accounting for processes that influence ecosystem service provision at a cost of being more data intensive, hence potentially less feasible for routine use.

Once the ARIES web and stand-alone software tools are completed, conducting ecosystem services assessments within past case-study regions will be increasingly feasible. The development and testing of data and models was time consuming in this application of ARIES, since new data and models generally were required for all services. A large number of global and national (U.S.) data layers are now accessible to the ARIES models via Web Coverage Service/Web Feature Service (WCS/WFS), reducing the data preparation needs for future ARIES models. Additionally, improvements to the ARIES modeling language have reduced the time required to develop new ARIES case studies relative to the start of this project. The release of ARIES's global models will enable ecosystem services mapping across a much broader geographic range.

Ecosystem service tools are designed to be relatively easy to apply, to facilitate tradeoff quantification between multiple services, and to link to human beneficiaries. However, these efficiencies come at a cost and discipline-specific biophysical models may be more appropriate for individual services when feasible. Examples include hydrologic models such as SWAT (Arnold and Fohrer, 2005), Variable Infiltration Capacity Model (VIC, Nijssen et al., 1997), Kinematic Runoff and Erosion Model (KINEROS2, Semmens et al., 2008) or Hydrologic Engineering Center′s River Analysis System (HEC-RAS, Brunner, 2010) and carbon modeling efforts such as the USGS LandCarbon project (Zhu et al., 2010). Where resources and expertise are available, discipline-specific models may more accurately quantify individual ecosystem services. However, when such modeling is not possible the simpler models in ecosystem service tools represent a viable alternative. In regions with adequate data availability, the relatively simple deterministic models found in ecosystem services tools (including both InVEST and ARIES) may be more appropriate, while in areas with scarce data and greater uncertainty probabilistic approaches such as those included in ARIES may be more appropriate (Vigerstol and Aukema, 2011). Future versions of both InVEST and ARIES intend to link ecosystem services provision and use concepts with accepted biophysical models, which would be a major step forward for ecosystem service modeling.

Further testing of InVEST and ARIES in common contexts alongside disciplinary models is a next step to understanding where different approaches provide results of sufficient quality to inform decision making within real-world resource constraints. Although the ARIES and InVEST results for this study were time consuming to obtain and were at times incommensurable, they illustrate the strengths and weaknesses of these two major ecosystem services modeling platforms in a semiarid environment. Future comparative applications will be beneficial in providing guidance to scientists and decision makers on when and where these ecosystem service modeling approaches are best applied.

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Disclosure statement: The lead author (K.J. Bagstad), who led the InVEST and ARIES modeling work on the San Pedro, has worked as a co-developer of the ARIES tool since 2007.

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.2013.07.007.

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