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REVIEW PAPER

The use of geographic information systems to map and assess ecosystem services

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Abstract In recent years, geographic information systems (GIS) have become a powerful tool for mapping and assessing the provision of ecosystem services within a landscape. GIS can help land managers and conservationists visualize spatial and temporal patterns and changes in ecosystem services and estimate the potential impact from projected changes in land use or management or climatic conditions on the provision of these services. The end-goal of ecosystem service assessment is usually to estimate marginal values of ecosystem services to inform decisions where trade-offs in ecosystem service provision will affect human well-being. Because our ability to estimate the provision of ecosystem services underlies our ability to estimate their societal values, the theoretical bases of GIS approaches and models for assessing ecosystem services need to be well understood before they are employed for decision-making purposes. This paper reviews GIS approaches and software developed for the assessment of ecosystem services and highlights their strengths and weaknesses in the context of different end uses.

Keywords GIS · Decision making · Ecosystem services · Geographic information systems · Mapping · Modeling

Introduction

Several modern scientists have described society's critical dependence on natural goods and processes (e.g. Leopold 1949; Odum 1975; Westman 1977). However, the benefits that

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people obtain from ecosystems became more widely studied following two key publications by Daily (1997) and Costanza et al. (1997), which alluded to these benefits as ecosystem services. In 2005, the Millenium Ecosystem Assessment (MEA), a comprehensive report on the consequences of ecosystem change for human well-being, further promoted and defined the concept of ecosystem services. The MEA grouped ecosystem services into four categories: (1) provisioning services, such as food, water, timber, and fiber; (2) regulating services that affect climate, floods, disease, wastes, and water quality; (3) cultural services that provide recreational, aesthetic, and spiritual benefits; and (4) supporting services such as soil formation, photosynthesis, and nutrient cycling (MEA 2005). These four categories of services contribute to the multiple dimensions of human well-being, including basic materials for living, health, security, social relations and freedom of choice and action (Alkire 2002). The authors of the MEA concluded that humans have changed ecosystems more rapidly and extensively in the last 50 years than in any similar time period in human history, degrading 15 of the 24 ecosystem services investigated (MEA 2005). Repercussions for human well-being from this degradation have been well-documented in some contexts, but the complex relationship between changes in ecosystem services and the multiple dimensions of human well-being has largely proven challenging to evaluate (Raudsepp-Hearne et al. 2010a).

Humans have degraded ecosystems in part because of incentives to convert natural lands to uses that are privately profitable, and the public and private benefits from natural capital and its flow of related ecosystem services have rarely entered into the decision-making equation (Daily et al. 2009). Proponents of the ecosystem service concept argue that demonstrating the value (economic and otherwise) of ecosystem services will allow people a better opportunity to make decisions about the environment that maximize human well-being in the long term. Researchers are therefore interested in developing methods for quantifying the provision and value of ecosystem services so this information can be incorporated into planning and decision-making at different scales and in different sectors (Hein et al. 2006; Kemkes et al. 2010).

Current and reliable information is needed for a better understanding of how ecosystems provide services and how changes to ecosystems impact service provision (Troy and Wilson 2006). Because ecosystems are heterogeneous and the provision of ecosystem services varies across space and time, geographic information systems (GIS) provide a powerful tool for visualizing and analyzing the provision of ecosystem services within a landscape (Baral et al. 2009). In addition, the proliferation of freely available satellite imagery and associated databases allows for a GIS-analysis of ecosystem services in areas of the world where few other forms of data are available. GIS can be used to visualize how ecosystem services are distributed across a landscape, to compare the distributions of multiple ecosystem services with drivers of change and other social-ecological parameters, and to model how changes in land use or land cover, land management, ecosystem and climatic conditions, and human populations affect ecosystem service provision and the value and use of services (Kareiva et al. 2011).

It is important to distinguish between the mapping or modeling of ecosystem processes, structure, and composition, and ecosystem services. Ecosystem processes, also often referred to as ecosystem functions (Jax 2005), are the complex interactions among biotic and abiotic elements of an ecosystem that lead to a concrete result and are often described in terms of rates such as change or production per unit time (e.g. nutrient cycle, water cycle, energy cycle, photosynthesis) (Wallace 2007). Although the MEA considers some ecosystem processes to be regulating or supporting ecosystem services, in this paper we use Wallace's (2007) interpretation of ecosystem processes as being a means to an end, a process that must be managed to provide an ecosystem service, rather than the ecosystem service itself. Ecosystem composition, or the identity and abundance of abiotic and biotic elements such as species, water, air, energy, land, and manmade features in a system and ecosystem structure, or the distribution and arrangement of the elements, are the result of ecosystem processes and are the aspects of ecosystems that may be valued by humans (Noss 1990; Wallace 2007). Ecosystem processes, structure, and composition only describe the supply side of ecosystem services; an ecosystem process does not produce an ecosystem service and an ecosystem element or the spatial arrangement of elements is not considered an ecosystem service until a person is benefitting from it (Chan et al. 2006). For example, if a patch of native habitat in an agricultural landscape houses native bee populations but the bees are not within foraging distance of a crop that requires pollination, the pollination process does not produce the ecosystem service of food (Tallis and Polasky 2009).

There has been extensive research on mapping and modeling ecosystem processes, structure, and composition and for reasons of practicality, indicators of these have all been used to estimate ecosystem services, as appropriate data and models are often not available. Because ecosystems are one of the primary landscape units that provide ecosystem services, prior to mapping ecosystem services it is often important to understand the actual distribution of ecosystems, or their on-the-ground occurrences as represented by primary data such as atlas data or a region-wide survey (Eigenbrod et al. 2010; Rolf et al. 2012). Despite its importance, primary data can be expensive and difficult to obtain, and less than 40 % of studies base their results on primary data (Seppelt et al. 2011). Secondary data consisting of spatial units such as land cover classes and watersheds are more often used as proxies for ecosystems (Eigenbrod et al. 2010). Although maps based on proxy data are helpful for depicting broad-scale patterns in ecosystem services, because the maps do not fit actual data well they are less useful for identifying priority areas that provide multiple ecosystem services (Eigenbrod et al. 2010). Scientists are encouraged to report the shortcomings of their approaches to ecosystem service mapping so that decision makers are more aware of the benefits and drawbacks to using a given approach for depicting the provision of ecosystem services (Seppelt et al. 2011). Improvements in remote sensing may also provide better primary data for mapping the distributions of ecosystems (see Ayanu et al. 2012 for a review of remote sensing applications in ecosystem service quantification). There is no one-size-fits-all approach to mapping or estimating ecosystem services, as services may be more or less related to individual ecosystems (i.e. many are provided by heterogeneous landscapes) and are often defined in unique ways across particular contexts.

New models are attempting to incorporate both the provision and associated benefits and values to humans of ecosystem services into their design, and hold much promise for supporting complex decisions around landscape management and conservation (Kareiva et al. 2011, and see Table 1 for a list of ecosystem service-specific models reviewed in this paper). This paper reviews the different ways that GIS has been used to estimate ecosystem services and their values, and how information generated by these different approaches may be more or less useful for feeding into different types of decisions. Approaches to estimating ecosystem service values using GIS include: (1) the development of ‘static’ estimates, or data-driven values that present a snapshot of current or past ecosystem services across a landscape; (2) the development of ecosystem service models that can be used to analyze how changes in landscapes impact the provision of ecosystem services and benefits; and (3) the development of models and approaches that emphasize social preferences and priority-setting for ecosystem service management.

Table 1 Characteristics of GIS models for mapping and assessing ecosystem services

Tool	Type of model	Access	Appropriate scale for use[a]	Time[b]	Stakeholder involvement
InVEST	Production function	Open	Landscape to watershed	160–260 h	Desirable
ARIES	Benefits transfer	Open	Landscape to watershed	200–300 h	Desirable
ESValue	Prioritization	Proprietary	Site-level to landscape	200 h	Required
EcoAIM	Prioritization	Open	Site-level to watershed	25 h for one variable	Required
EcoMetrix	Benefits transfer	Proprietary	Site-level	1 h/acre	No
NAIS	Benefits transfer	Proprietary	Site-level to watershed	N/A	Desirable
SolvES	Prioritization	Open	Landscape	N/A	Required

[a] Landscapes generally refer to broad spatial scales such as states, forest districts and river basins and are usually considered to be larger than watersheds, which range from 100 to 10,000 km^2 in size (O'Neill et al. 1997; Steel et al. 2010)

[b] Time to develop and parameterize a case study as applied by Waage et al. 2011

Using GIS to analyze the current or past distribution of ecosystem services

Many studies have presented GIS analyses of ecosystem service distributions at a variety of scales since the 1990s. Indicators of ecosystem services are chosen and mapped in order to understand where ecosystem services are located on a landscape, to identify the location of 'hotspots' where high provision of individual or multiple ecosystem services occurs, and to compare the distributions of multiple ecosystem services to better understand trade-offs and synergies (Chan et al. 2006; Beier et al. 2008; Naidoo et al. 2008; Egoh et al. 2009; Swallow et al. 2009; Willemen et al. 2009; Raudsepp-Hearne et al. 2010b). We call these mapped indicators of ecosystem services "static" distributions (i.e. data-derived estimates, as opposed to models). Mapped service estimates are derived from land cover or other ecosystem proxies (e.g. forest cover, see Costanza et al. 1997), indicators of ecosystem service use (e.g. number of deer killed in a year by hunters, see Raudsepp-Hearne et al. 2010b), data related to the condition or supply of a service (e.g. water quality data), and ecosystem service equations that link production values to their potential use or benefit to human populations (e.g. Chan et al. 2006), among others. Each service indicator is mapped at a chosen spatial resolution, using boundaries that are arbitrary (e.g. raster grid), ecological (e.g. watershed), or social (e.g. census units).

Scientists have struggled to quantify ecosystem services using consistent, comparable approaches. Ecosystem services have been quantified at different spatial and temporal scales, in relation to their supply or production, demand and consumption, and using an array of indicators or metrics. The metrics used to quantify the supply or production of ecosystem services have not always been relevant to human well-being. In some cases, this is a result of the data available for ecosystem service quantification, which is not always in a form that is relevant to human well-being (e.g. remote sensing data can be used to quantify net primary production in grasslands, but may not be able to account for how much is actually consumed or used by humans). The need for spatially explicit data for use in GIS analyses further narrows data choices. In other cases, scientists estimate ecosystem services for the purposes of exploring scientific theory, and the beneficiaries of the services are not of primary importance or even identified. The variety of indicators used to develop current and historical maps of ecosystem services in GIS suggest that their contextual relevance and the end-goal of the exercise may be more important than consistency in their use.

Assigning values to the benefits from ecosystem services has focused mainly on producing estimates of Total Economic Value (TEV) for the provision of ecosystem services, often estimated by assigning monetary values to specific land covers using GIS (e.g. Costanza et al. (1997)). Like estimates of current ecosystem service provision, TEV is also a static value, which is useful in large-scale trade-off decisions, or for communication purposes about the value of ecosystems. More recently, studies have attempted to use GIS in conjunction with social science methodologies to assign non-monetary values (also static) to ecosystem service benefits. This has been accomplished through participatory mapping exercises (e.g. Bryan et al. 2011), where ecosystem service beneficiaries rate areas that are important or valuable to them in terms of ecosystem service provision and benefits.

Static information on spatial trade-offs or synergies among multiple ecosystem services and biodiversity, or comparisons of supply versus demand for individual ecosystem services across space can be a useful input into specific decisions (e.g. see van Jaarsveld et al. 2005, where current supply and demand for water were mapped across southern Africa, highlighting to policy-makers where water shortages are occurring and interventions are needed). An understanding of demand can be important because a change in the supply of an ecosystem service does not necessarily mean there will be an associated change in social benefits from the service (Wainger and Mazzotta 2011). Demand can be affected by people's willingness to adapt or find substitutes for the lost or reduced ecosystem service (Wainger and Mazzotta 2011). In some contexts, space-for-time substitutions have been used to infer how land use choices and management may impact ecosystem services (Raudsepp-Hearne et al. 2010b). For decision-making purposes, a principal benefit of GIS mapping of current and past distributions of ecosystem services is the ability to use context-specific data and indicators, which may be more accurate and relevant than values obtained from generic models.

While these 'static' estimations of ecosystem service spatial distributions can contribute to a baseline understanding of what ecosystem services are present in a system and where they are, they are less useful for understanding changes in ecosystem services and benefits and impacts from management decisions. Marginal values of ecosystem services, or the estimated rate of change in value of an ecosystem service compared with changes from current levels of the service (Costanza et al. 1997) are more desirable in most decision-making contexts because policy and economic decisions are made in terms of the marginal values of an ecosystem service. For example, decision makers want to know how the supply of ecosystem services will change given alternative development plans or policies. When the supply of services provided by forests (e.g. fuel wood) is more abundant than demand, consumers' willingness to pay for one more unit of the service is small, but when the service becomes scarce people are willing to pay a higher price (Fisher et al. 2008). It is this marginal value that is more important in decision-making contexts than the total value of global forests (Fisher et al. 2008).

Modeling ecosystem services dynamically with GIS

Ecological production function approach

The ecological production function is the feasible output of ecosystem services that are provided by an ecosystem (Tallis and Polasky 2009). In the context of GIS, applications that use the ecological production function model how changes in ecosystem processes, composition, and structure across space and time change the provision of and distribution of ecosystem services. Modeling ecosystem service provision from ecological production functions is the approach for assessing ecosystem services most suited to decision support, as it allows for the development of scenarios and predictions of how land use and management decisions might affect ecosystem services and their benefits. 'Static' maps of ecosystem services described above can inform decision-makers about what is in a system, but cannot help to determine how change will affect ecosystem service provision. If the production functions are appropriately modeled, this approach can account for changes in the provision of ecosystem services due to subtle changes in ecosystem processes, ecosystem conditions, or human access (Nelson and Daily 2010). However, understanding of how land cover and other variables translate into the production of ecosystem services is still very patchy (Tallis and Kareiva 2006). In some cases, the distribution of many ecosystem services may be so idiosyncratic to particular social-ecological systems that we may be unable to estimate them accurately from generic production functions and models.

Most applications of the ecological production function approach have been conducted for a single ecosystem service at a time or for a specific social-ecological context (e.g. Wilson and Carpenter 1999; Barbier 2000; Kaiser and Roumasset 2002; Ricketts et al. 2004; and see Barbier 2007 and Pagiola et al. 2004 for reviews). Some of these studies attempt to model both the services and their benefits to humans (e.g. Barbier et al. 2008), although most production function models focus solely on the condition of the ecological function. A challenge for decision-makers is how to model the impacts of decisions or land use changes on multiple ecosystem services. Improving the ability to model multiple ecosystem services is important because many services are interrelated and incentives that encourage increased consumption of one service may adversely impact other services (Kinzig et al. 2011). Running individual models for specific ecosystem services is both time and data intensive, and does not provide an obvious method to integrate findings across services.

Several programs have been developed recently to model multiple ecosystem services in a variety of systems. InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) (Natural Capital Project 2011) is an open-source GIS tool that has been developed by several partners for estimating ecosystem service values using the ecological production function approach. InVEST consists of a suite of GIS models that predict the provision and economic value of ecosystem services using land use/land cover maps and related biophysical, economic, and institutional data (Natural Capital Project 2011). In most of the models, an ecological production function is defined for the ecosystem service, and multiple input variables for each land cover type are used to model the level of provision of that service for each raster unit. The value of ecosystem services is determined by combining supply-side models about provision with the likely level of ecosystem-service demand (Tallis and Polasky 2009). For example, riparian vegetation can provide the service of reducing siltation of reservoirs. To estimate the value of avoided siltation in reservoirs, the modeler can ask how much vegetation is upstream of a reservoir (the supply-side aspect of the model) and estimate the value of the service by estimating the costs saved by avoiding dredging and other maintenance costs (the demand-side aspect of the model). Ecosystem processes and services that can be modeled by InVEST so far include: wave energy, coastal vulnerability, coastal protection, marine fish aquaculture, marine aesthetic quality, fisheries and recreation, marine habitat, terrestrial biodiversity, carbon storage and sequestration, reservoir hydropower production, water purification/nutrient retention, sediment retention, timber production and crop pollination.

InVEST has possibly been the most widely used GIS software tool for mapping ecosystem services, and has been applied in decision-support processes in a diversity of geographic contexts (Nelson and Daily 2010). To inform this article, we conducted an online survey of the use of GIS approaches to assessing ecosystem services (Electronic Supplementary Material), and InVEST was the only pre-packaged model that more than one respondent had used (11 out of 85 people that completed the survey had used InVEST). Strengths of InVEST, as identified by survey respondents, included ease of use, simplicity, good selection of important ecosystem services, peer-reviewed methodology and multi-functionality. A further strength is the growing community of users that share information within a supported InVEST forum, as well as support offered from the developer team. Weaknesses identified by survey respondents including the modeling capabilities of freshwater services, the biodiversity model, the potential for oversimplification, and lack of sufficient explanation of the models in the user guide.

InVEST can be run at different spatial scales and extents, which is important for its applicability to a variety of decision-making contexts. However, spatial relationships among landscape components are oversimplified in the models. For example, within a land use category, patches of that land cover are considered to be the same, no matter what their size or location in relation to other land covers. The quality of land cover data also has a large impact on the results of the model. Both data sources and locally-relevant parameters for the models can be hard to find in specific contexts, requiring the use of global datasets that may or may not be accurate at smaller scales. The models have yet to be tested thoroughly across many ecological systems, and validating InVEST results will be needed before high confidence in the tool will be possible. However, of the survey respondents that had been able to ground-truth InVEST results to any extent ($n = 3$), the results matched well with other sources of information.

In general, the ecological production function approach requires a lot of data, expertise, time, and funding to implement. It will not always be possible to model the ecosystem services that are most relevant to a given decision in a specific location, if the ecological production functions are not developed or the data is not available for that location. Tools such as InVEST will be critical for meeting the needs of decision-makers and researchers who do not have the resources to develop context-specific models for multiple ecosystem services. However, it will be important to make sure that the models are used appropriately and the information generated is credible and relevant. The quality of available data and having local expertise to parameterize and check models will also be limiting factors.

Benefits-transfer approach

In the benefits-transfer, or value-transfer, approach, to modeling ecosystem services, research results on the value of ecosystem services in one setting are applied to another setting for which little information is available (Wilson and Hoehn 2006). For example, Costanza et al. (1997) used the benefits-transfer approach to map ecosystem service values for the whole planet by applying value estimates for a given ecosystem type in specific locations to all hectares of that ecosystem type. Benefits-transfer has been applied to many ecosystems statically in order to determine the Total Economic Value (TEV) of ecosystem services, but recently the approach has been incorporated into models in order to predict how changes in systems will affect benefits for humans. In our survey of use of GIS applications for ecosystem services, no one had used the programs mentioned in this section.

An open-source GIS application that has recently been developed for applying the benefits-transfer approach is ARIES (ARtificial Intelligence for Ecosystem Services), developed by the University of Vermont's Ecoinformatics "Collaboratory," Conservation International, Earth Economics, and experts at Wageningen University (Waage et al. 2008; Ecoinformatics Collaboratory 2011). ARIES is an application that builds models of ecosystem service provision, use and spatial flow in an area (Villa et al. 2009). Like InVEST, ARIES is able to accommodate a scale-explicit approach to mapping ecosystem services since the provision and usage of services occurs at different spatial and temporal scales. The program uses probabilistic models (spatial Bayesian networks) to map the ecological and socioeconomic factors contributing to the provision and use of ecosystem services (Villa et al. 2009). After each ecosystem service is modeled independently, it is linked to other services. Unlike InVEST, the basis for ecosystem services valuation is the quantification of the actual flow of benefits and not of the processes that bring them into existence (Villa et al. 2009). For example, it creates Bayesian network models of provision, source, and sink (depletion of a benefit along its path to the beneficiary) and the flow analysis is then used to determine what areas are critical to the delivery of the service (Villa et al. 2009). ARIES uses web-accessible technology (as opposed to users requiring their own GIS software) and stores many global datasets relevant to their models. Users define the ecosystem service beneficiaries/benefits of interest, draw or provide GIS maps of their system boundaries, and can supplement or replace the ARIES datasets with more locally relevant data for model runs. ARIES is currently being pilot tested in case studies in western Washington, California, Vermont, Dominican Republic, and Mexico (Voigt 2010; Ecoinformatics Collaboratory 2011) although none of these studies have been described in the scientific literature yet. An independent review of ecosystem service models in the context of decision-making found that ARIES required substantially more time and expertise to parameterize the models than InVEST (Waage et al. 2011). The same review found that ARIES and InVEST produced similar results in a test-case ecosystem service assessment. The strengths of the approach taken by ARIES developers will become clearer as the model is further tested and refined, and becomes more widely accessed.

Two proprietary GIS software programs that have been developed by consulting firms using the benefits-transfer approach include EcoMetrix (Parametrix 2011a) and the Natural Assets Information System (Troy and Wilson 2006). EcoMetrix is intended for use by landowners to characterize the ecosystem services and processes on a site and analyze changes from baseline to future conditions (Parametrix 2011a). For example, it was used to evaluate the relative level of ecosystem services provided by four streambank restoration projects by assigning weighted values for six indicators of stream function and then mapping these values to show the amount of "lift" or increases in ecosystem services compared to the unrestored states of the area (Parametrix 2011b). Fieldwork is necessary to complement computer modeling, and this approach is only suitable at small scales or in conjunction with other tools at larger scales (Waage et al. 2011).

The Natural Assets Information System (NAIS) is a decision-support system framework that consists of a GIS database and query engine that is used to create ecosystem service values for a habitat type. The consulting firm that developed the framework, the Spatial Informatics Group (SIG), works with clients to determine the appropriate geographic units for representing ecosystem service value flows, such as watersheds, parcels, jurisdictions, and zip codes (Spatial Informatics Group 2009). SIG does GIS overlay analysis between the land or aquatic cover type layer and the polygon layer that summarizes the ecosystem service values. They then produce a map showing total value flows by area by geographic unit and cover type (Spatial Informatics Group 2009). The NAIS framework has been most often applied to land use planning situations at relatively small scales, including Maury Island, a small island in Puget Sound, Washington; Elgin Air Force Base, Florida; and three California counties, although it has been used to map the ecosystem service values for larger areas such as the commonwealth of Massachusetts (Troy and Wilson 2006). This approach can be useful for scenario planning; for example, the Maury Island study estimated and mapped the ecosystem service values by parcel for the island under current and future conditions under a proposed zoning change (Troy and Wilson 2006).

The benefits-transfer approach is advantageous because users can get system-specific information for a given area relatively cheaply and quickly through literature reviews. However, the reliability of the benefits-transfer approach has been debated in the economics literature because of its drawbacks, largely related to errors that occur in the transfer process because of differences between the characteristics of the site to which values are being transferred and the site used to generate the values (Brouwer 2000). For example, in seven studies that empirically tested the validity of the benefits-transfer approach applied to environmental goods such as fishing, water quality improvements, recreation, and biodiversity on agricultural land, transfer error was generally in the range of 1–75 % but was as high as 475 % in one case (Brouwer 2000). In comparison, meta-analytical studies that have included a variety of valuation techniques, including benefit transfer and production function valuation methods, have found average transfer errors of 74 % for studies valuing wetlands (Brander et al. 2006) and 186 % for studies valuing coral reefs (Brander et al. 2007). The acceptable level of transfer error may be context specific, depending on the risk tolerance of decision-makers, available data, and the characteristics of the ecosystem studied.

When transferring results from one location to another great care must be taken to closely match the methods used to value one setting to the new location (Tallis and Polasky 2009), and economic valuation studies do not exist for many systems. In addition, assuming that every hectare of a given habitat type is of equal value doesn't enable analyses of how ecosystem service provision and value changes under new conditions, weakening its usefulness for management (Nelson et al. 2009). Despite these limitations, proponents of the benefit transfer approach assert that it is better than the status quo approach of assigning no value to ecosystem services (Troy and Wilson 2006). This approach may be more appropriate for ecosystem services that provide economic benefits relatively independent of location and its social-cultural context (Turner et al. 1998). For example, carbon sequestration in terrestrial and aquatic ecosystems provides the global social value of delaying the impacts of global climate change regardless of where the sequestration occurs (Turner et al. 1998).

Approaches that emphasize social preferences and priority setting for ecosystem service management

Several new ecosystem service approaches go beyond ecological modeling and place a greater emphasis on integrating human preferences and priorities into ecosystem service tools. ESValue (developed by Cardno ENTRIX—www.entrix.com) integrates existing information and expert opinion with stakeholder values to identify key site-specific ecological effects and resulting change in economic value for different management strategies. Expert ecological input is used to identify and weight project variables that determine the degree of ecosystem change and stakeholder preferences associated with ecosystem services in an area are then incorporated. EcoAIM (Ecological Asset Inventory and Management) is a GIS optimization model that balances ecosystem service variables with a risk-analysis basis, including metric weightings of stakeholder preferences. The U.S. Geological Survey (USGS) offers the SolVES program (Social Value for Ecosystem Services), an ecosystem service model developed by several scientists designed to assess, map and quantify the perceived social values for ecosystems, such as aesthetics, biodiversity and recreation (Sherrouse et al. 2011).

These tools have not been widely used or tested (we cannot describe these models in any detail as very little has been written about them). EcoAIM was the only other model that had been used by our survey respondents aside from InVEST, and the respondent wrote that that the results were validated and the model performed well. EcoAIM and ESValue were tested by Business for Social Responsibility (BSR), which found ESValue methods very time-consuming and EcoAIM a relatively quick tool (although they only tested biodiversity) (Waage et al. 2011). The goals of these models are very different from the goals associated with InVEST, ARIES and other models mentioned above, making it difficult to compare them. The predominance of ecological and economic values being developed in ecosystem service assessments needs to be balanced with other types of values representing the benefits that people get from ecosystems (Chan et al. 2012), and these tools provide important approaches for developing more holistic understanding of services within their particular contexts.

Discussion

GIS have proven to be useful for mapping and assessing the value of ecosystem services in different contexts. GIS have been used to map ecosystem services across space using indicators, the ecological production function approach, in which detailed information is used to map the services and underlying processes affecting those services in an area and the benefits-transfer approach, in which ecosystem service values from one area are transferred to the same ecosystems in other areas. GIS have also been used to define priorities for ecosystem service management, inputting stakeholder values and priorities into spatial models. There are now several ecosystem service models available for general use, most of which have not been extensively tested. Lack of knowledge of the processes that contribute to ecosystem service provision and the distribution of benefits is the major challenge for scientists and practitioners. This lack of knowledge has resulted in the majority of ecosystem service assessments focusing on discrete periods of time for which data is available and on static ecological, social and economic values associated with the benefits to society from ecosystem services. We believe that there is great potential for using recently developed ecosystem service models to understand ecosystem services in a dynamic context, although they are not refined enough yet to support most decision-making.

Decision-makers are eager to apply ecosystem service tools and approaches to model ecosystem change within their particular problem contexts. For the most part, finite resources allocated to ecosystem service assessments will dictate that context-specific research into how ecosystem services are produced on a given landscape will not be feasible. For this reason, pre-packaged models that can assess the provision and value of multiple ecosystem services in different landscapes have high potential value to decision-makers. However, caution should be applied to the use and interpretation of models developed for broad use. The programs that have been developed, such as InVEST and ARIES, need to be validated and verified against observed data, especially in systems that are very different from those in which the models were developed (e.g. drylands) (Nelson and Daily 2010). The models also need to better consider and represent the stochastic, scale-dependent, and non-linear nature of ecological processes, and threshold effects (Nelson and Daily 2010). The developers of InVEST have acknowledged that including changes in climate, technology, market prices, human population, and feedback effects is the essential next step in the development of InVEST (Nelson et al. 2009). All current ecosystem service models should be considered works in progress, as researchers attempt to fill in the many gaps within ecosystem service science. Table 1 provides an overview comparison of the GIS models mentioned in this paper.

It is difficult to generalize about which tools provide the most credible results. The models should only be used when the ecosystem service definitions, indicators and model parameters are relevant to a particular question and context (which often may not be the case). The choice of tool will be context dependent, and some research energy should be applied to helping decision-makers sort through available methods and tools for considering ecosystem services. Decision-makers are interested in tools that model the spatial distribution of ecosystem services and their benefits, how this will change under different scenarios, and how these changes will impact a diversity of stakeholders with different values and priorities. None of the models mentioned in this paper is able to address all of these issues, but there is potential for using some of the models in combination. Waage et al. (2011) suggest how some of the tools can be used in conjunction to develop complementary information and provide a more complete assessment of ecosystem services and their beneficiaries (Fig. 1). Decision-making processes for considering ecosystem services within a particular problem-context are also important, such as World Resources Institute's Ecosystem Services Review (www.wri.org/project/ecosystem-services-review). Alternatively, because of the limitations of software packages and the context-specific needs of locations, some practitioners with advanced GIS skills may create their own models using GIS rather than use an existing platform. In our survey, 12 out of 85 respondents created their own models using GIS. The amount of time and expertise required for building models, or even gathering data for and parameterizing existing models should not be underestimated.

Conclusion

While GIS can be a powerful tool for mapping and assessing ecosystem services, it may be most effective when implemented as part of a multi-criteria decision-making framework such as structured decision-making that integrates technical information with value-driven decisions and accounts for uncertainty. Some ecosystem services related to aesthetics or cultural values cannot be quantified or modeled in GIS, yet these services should still be accounted for by decision makers and stakeholders. In the future, greater inclusion of social scientists in assessment teams as part of the decision-making framework could also aid in the interpretation of models and implementation of approaches that enhance effective decision-making and aid in conflict resolution. Social scientists can also improve our understanding of social issues that influence the depletion of ecosystem services, such as economic incentives, policies, inequalities in wealth distribution, and social conventions.

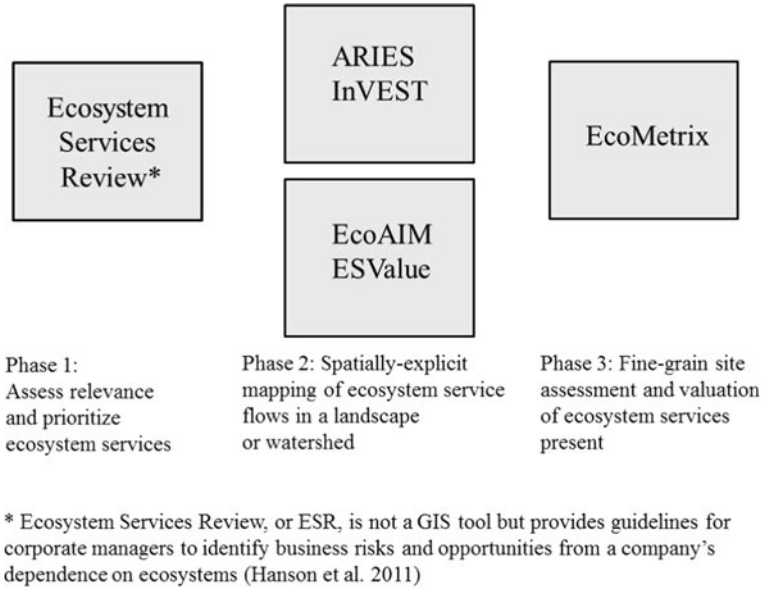

Fig. 1 One proposed method for integrating several decision-making and GIS tools for conducting a complete assessment of ecosystem services. Adapted from Waage et al. (2011)

Technically, GIS models could be improved by better evaluating the opportunity costs of alternative land uses. In addition, scientists now understand that ecosystems display nonlinear dynamics and drivers or stressors may cause rapid shifts in ecosystem processes, structure, and composition, affecting the provision of ecosystem services. As our knowledge of the thresholds at which ecosystems may shift to new states improves, this information should be incorporated into GIS platforms that model ecosystem services dynamically.

Ecosystem services will likely continue to be depleted without widespread changes in economic incentives, policies, poverty levels, and cultural norms that favor short-term economic profits or the use of resources in poverty-stricken areas for short-term survival over the preservation of natural capital for humans' long-term welfare. One of the primary advantages of the ecosystem services concept is that the benefits that humans derive from nature are increasingly acknowledged in land use and management decisions. Improving our technical knowledge of the provision and value of ecosystem services is a worthwhile goal that is necessary for supporting and implementing informed and forward-thinking management and policy changes, and GIS is a powerful tool that can help scientists achieve that goal.

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