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Modelling ecosystem services in terrestrial systems

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Abstract

Over the past few decades, a multi-disciplinary research community has documented the goods and services provided by ecosystems in specific sites scattered across the world. This research community has now begun to focus on creating methods and tools for mapping and valuing the ecosystem services produced on any landscape in the world. We describe some of these methods and tools and how they calculate and express ecosystem service provision and value on landscapes. We also describe methods for predicting landscape change. These predictions can be used by multi-ecosystem service models to assess potential changes and trade-offs in ecosystem service provision and values into the future.

Introduction and context

Ecosystem services are the processes and conditions that are mediated by ecosystems and their biodiversity and that sustain and enhance human life [1-3]. Ecosystem services include processes that support the production of consumable goods (e.g., food and timber), processes that support and regulate life (e.g., storm surge protection [4,5], crop pollination [6,7], and carbon sequestration [8]), conditions that enhance life (e.g., recreational, aesthetic, and spiritual values [9,10]), and conditions that preserve valuable options (e.g., undiscovered medicinal benefits from plants [11]). Like built and human capital, the natural capital that underpins ecosystem service production is an essential input into our economies and livelihoods.

However, the value that natural capital, when compared with other forms of productive capital, contributes to our economies and well-being is often poorly understood and scarcely monitored. As a result, the ecosystem services generated by it are typically undervalued by markets and therefore are susceptible to degradation and depletion [12]. Correcting for this market failure requires two advances in analytical capabilities. First, we need to understand how changes in land use/land cover (LULC), land management, ecosystem and climatic dynamics, and human populations on a landscape translate into changes in ecosystem service provision, the use of services, and the value of use [13]. Second, based on this understanding, we need to design and implement policy interventions that will improve aggregate social welfare on the landscape, where social welfare includes both ecosystem service values and marketed economic returns [14-20]. This policy step requires a thorough understanding of the human preferences for the goods and services that nature provides and the types of incentives that ecosystem service providers (primarily land owners and managers) and potential beneficiaries will respond to. In this review, we discuss some recent advances in the modelling of terrestrial ecosystem service provision, the use of services, and value of use (see [21] and cross-reference to Kai Chan and Mary Ruckelshaus' F1000 report for a discussion of marine ecosystem service models [22]).

Modelling foundations

There are plenty of models that track one or two terrestrial ecosystem processes (for examples, see [23-33]). With them, measuring the impact of landscape pattern on the provision, use, and value of multiple ecosystem services requires running each service model. And if the potential impacts of landscape change scenarios are being investigated, then this process has to be replicated for each scenario as well [34]. In most cases, such a task is impractical given the complexity of the single-process models, their various analytical scales, and their tendency not to place ecosystem processes and conditions into human use and value contexts, the link that transforms processes and conditions into services. The Millennium Ecosystem Assessment (MA) [35] was one of the few efforts to use individual models to measure the potential impact of projected LULC change on the provision of multiple ecosystem services (see [36-38] for a similar large-scale example). Specifically, the MA research team created four scenarios of global population, economic, and technology change over time. The MA modellers then used already-published models to allocate the global LULC changes necessary to satisfy each scenario's demand for living space, food, and energy subject to scenario-specific regional and global constraints and expected climate change. Finally, the MA research team used already-published, single-process models to determine each scenario's impact on the global environment, including the provision of ecosystem services.

The MA's reliance on complicated biophysical and economic models in its scenario analysis and the MA's global focus has limited wider replication of its ecosystem service modelling methodology, experimentation with alternative scenarios, and discussion of scenario results at local levels [39]. These limitations have fuelled a quest to create multi-ecosystem service modelling systems that can build on the MA's foundation of scientifically rigorous ecosystem service modelling but that are more user-friendly, flexible, and transparent and that can be applied at scales relevant to local policy-makers and concerned citizens. The hope is that these emerging modelling systems will increase ecosystem service-based policy-making and broaden the range of participants in ecosystem service conservation planning.

Major recent advances

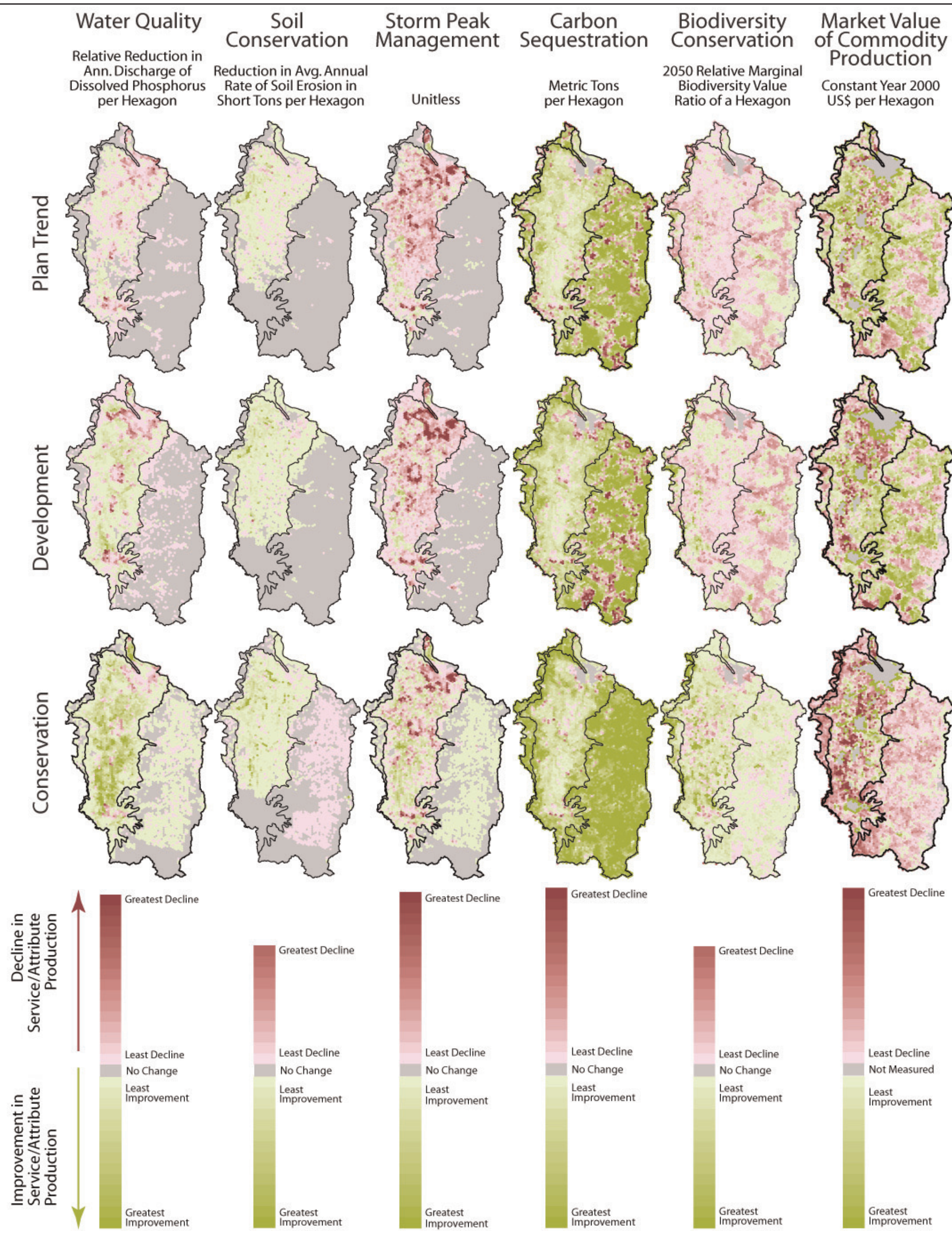
Models designed to link terrestrial ecosystem service provision, the values associated with the provision, and the trade-offs across services at the landscape-level are emerging rapidly. Published examples include EcoMetrix, Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) [40,41], and Artificial Intelligence for Ecosystem Services (ARIES) [42].

EcoMetrix (Parametrix, Inc., Auburn, WA, USA) is one of a growing number of propriety software systems that are designed to help local governments design and implement ecosystem service conservation programs, including payment for ecosystem service programs. However, propriety software systems limit experimentation and wider participation in ecosystem service modelling. In contrast, InVEST and ARIES are examples of open-source software systems that allow for wide-scale user input and experimentation.

Both InVEST and ARIES estimate the biophysical provision of multiple ecosystem services across a landscape, can translate this provision into maps of service use (who and where people are benefiting from service provision) and monetary value (the value that people receive from the use of the service), and can predict trends in service provision and values on the landscape. The main difference between these two models, and across the ecosystem service modelling literature in general, lies in the ecosystem service provision calculation and valuation methodology. InVEST determines ecosystem service provision and value at a point on the landscape by using ecological and economic production functions, where LULC and related management and biophysical data at the point and elsewhere on the landscape are inputs (Figure 1). By contrast, ARIES uses a benefit transfer approach. Under this methodology, each point on the landscape is assigned ecosystem service provision and value largely according to its LULC, where the ecosystem service provision and values associated with the LULC are culled from other site-based studies. The more the LULC being valued on the study landscape is similar in type, function, and landscape context to the other studies providing its value, the more precise the benefits transfer approach is.

For several reasons, we believe that the production function approach produces more accurate and policy-relevant results. First, production functions, if appropriately calibrated, can register and value ecosystem service changes due to subtle changes in ecosystem processes, ecosystem conditions, or human access at some point on the landscape. In contrast, a database of LULC values used in a benefits transfer approach may not be rich enough to register small changes in conditions at a point if the change on the landscape does not involve LULC conversion. Second, the change in ecosystem service provision and value at one point on the landscape given change elsewhere on the landscape can be explained with production functions, assuming that they are explained by conditions at other points on the landscape. In contrast, provision and value at a certain point on the landscape tend to be insensitive to change at other locations under the benefits transfer approach. The major drawback of using production functions to calculate service provision

Figure 1. Maps of change in ecosystem service provision and biodiversity conservation from 1990 to 2050 for the three land use/land cover (LULC) change scenarios in the Willamette Basin, Oregon, USA, as determined with InVEST [59]



Comparing multiple outputs across different LULC scenarios demonstrates the extent of the synergies or trade-offs among services and biodiversity (here biodiversity is treated as a separate attribute that forms the basis for all services). In this application of InVEST, the authors found little evidence of trade-offs between ecosystem services and biodiversity conservation: scenarios that enhance biodiversity conservation also enhance the provision of ecosystem services. The next step in this analysis is to convert all biophysical supply on the service maps, apart from biodiversity, into maps of human use metrics and monetary values. InVEST, Integrated Valuation of Ecosystem Services and Trade-offs. Image originally published in Nelson *et al.* [58], *Front Ecol Environ* 2009.

and value is that they require more data and expertise to apply than the benefits transfer approach, and this sometimes makes benefits transfer a tempting methodology choice. Further investment in the production function methodology is based on an optimistic assumption that through research and practice, researchers can develop tools that are sufficiently general to be applied anywhere in the globe but that are sufficiently flexible to be tailored to local conditions.

We know of two other open-source multi-ecosystem service modelling and measuring methodologies under development. The Economics of Ecosystems and Biodiversity (TEEB) is a recent European Commission-based initiative to measure and model the provision and value of ecosystem services [43]. A suite of interconnected ecosystem service modules, collectively referred to as Multiscale Integrated Models of Ecosystem Services (MIMES), have been written for use with Simile (Simulistics Ltd., Edinburgh, UK), an object-based modelling and simulation software. Although the MIMES modules are available on the web [44], model documentation and related publications are not available.

Multi-ecosystem service models are particularly useful to policy-makers if they can help illustrate potential trade-offs between economic development and ecosystem service provision in the future. Such analyses require predictions of future LULC and land management patterns. There are many approaches for predicting future LULC and land management patterns. For example, in the EnVISION/Evoland modelling system, simulated 'agents' (e.g., households, firms, local leaders, and government agencies) make LULC and land management change decisions on a landscape over time such that their preferences are maximized subject to land-use policy constraints [45,46]. In an alternative approach to agent modelling, real-life agents on the landscape are surveyed on their LULC decision-making and how their decision process would change in response to new policies. Future LULC maps are then created by allocating future LULC demand according to survey results ([47] and unpublished data from Swetnam *et al.*,).

The primary challenge in agent-based modelling is accurately capturing all of the landscape change forces that affect LULC and land management decision-making; the failure to account for one or more forces of change can lead to LULC and land management change predictions that do not appear to be reasonable. Statistical techniques that use observed LULC and land management changes from the past to predict future changes, such as econometric models and cellular modelling methods [48-51], ostensibly capture all of the forces of change that were present on the landscape in the past. However, this means that if policy, biophysical, or economic conditions are expected to change significantly on the studied landscape or if the modeller wishes to simulate the impact of a land-use policy or other landscape dynamic that did not exist in the past, then statistical models used to predict future LULC and land management patterns will have to be modified to appropriately incorporate novel landscape dynamics. Such modifications can be difficult to implement [52].

Finally, algorithms that spatially allocate expected LULC change at the regional or global level according to land-use suitability maps have been developed. In these approaches, allocation of expected LULC change is guided by spatially-explicit data that indicate which areas across a region or globe are more suitable for which types of land use. Suitability is generally determined by the economic principle that land will be put to the use that generates the best net economic returns [53,54]. This approach differs from agent-based modelling and statistical techniques in that it does not model individual agent decision-making on the landscape or try to extrapolate past behavior into the future but instead assumes that landscape change is driven by basic principles that have been observed repeatedly. This approach is best applied in cases in which the modeller is most interested in predicting change at very large scales and the accuracy of predicting change at finer spatial grains is not paramount.

Future directions

Nascent multi-ecosystem service models such as InVEST and ARIES need to be rigorously validated and verified against observed data [41]. Furthermore, ecological processes are stochastic, scale-dependent, and often non-linear, and may exhibit threshold effects [55]. The emerging multi-ecosystem service models need to do a much better job at considering and representing such dynamics.

Multi-ecosystem service models will need to become more consistent in their use of valuation metrics. First, the value metric used needs to be landscape- and policy-relevant. For example, the pollution retention service provided by a landscape will be one value if we consider the regulated water treatment costs avoided and another if we consider the human mortality and morbidity avoided. In landscapes where water pollution is strictly controlled and regulated, avoided treatment costs are more appropriate for policy analysis. In contrast, in landscapes where the potable water supply is limited, the value of human mortality and morbidity avoided due to landscape and land management design may be more policy-relevant. Second, the modelling systems need to do a better job of defining what values are *not* included in monetary estimates. Non-monetized services can be just as important to people on the landscape as monetized services, and if the provision of non-monetized services is not significantly highlighted, there is a risk that these sources of value will be ignored during policy-making.

Ecosystem service modelling is just beginning to be applied in the policy arena. For example, the state of New Jersey, USA, used ARIES to map its provision of ecosystem services and their values [56]. InVEST is being used to create maps of priority areas for environmental conservation in China and Indonesia, to design self-sustaining water funds for watershed protection in Colombia and Ecuador, and to advise land-based carbon sequestration investments with other ecosystem service co-benefits in the state of Hawaii [57]. A consortium of organizations organized by a research team from Cambridge University is using various ecosystem service models to advise the Tanzanian government on the best use of international conservation funds. We are certain that ecosystem service conservation and the methods of tools used to guide it will increasingly play a larger role in environmental policy around the world.

Abbreviations

ARIES, Artificial Intelligence for Ecosystem Services; InVEST, Integrated Valuation of Ecosystem Services and Trade-offs; LULC, land use/land cover; MA, Millennium Ecosystem Assessment; MIMES, Multiscale Integrated Models of Ecosystem Services.

Competing interests

The authors declare that they have no competing interests.

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