REVIEW AND SYNTHESIS

Linking ecosystem characteristics to final ecosystem services for public policy

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Abstract

Governments worldwide are recognising ecosystem services as an approach to address sustainability challenges. Decision-makers need credible and legitimate measurements of ecosystem services to evaluate decisions for trade-offs to make wise choices. Managers lack these measurements because of a data gap linking ecosystem characteristics to final ecosystem services. The dominant method to address the data gap is benefit transfer using ecological data from one location to estimate ecosystem services at other locations with similar land cover. However, benefit transfer is only valid once the data gap is adequately resolved. Disciplinary frames separating ecology from economics and policy have resulted in confusion on concepts and methods preventing progress on the data gap. In this study, we present a 10-step approach to unify concepts, methods and data from the disparate disciplines to offer guidance on overcoming the data gap. We suggest: (1) estimate ecosystem characteristics using biophysical models, (2) identify final ecosystem services using endpoints and (3) connect them using ecological production functions to quantify biophysical trade-offs. The guidance is strategic for public policy because analysts need to be: (1) realistic when setting priorities, (2) attentive to timelines to acquire relevant data, given resources and (3) responsive to the needs of decision-makers.

Keywords

Ecological production functions, ecosystem management, ecosystem services, endpoints, environmental policy, sustainability, trade-offs.

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INTRODUCTION

Governments worldwide are considering using ecosystem services in public policy to advance sustainability goals. As of 2013, 68 countries worked on ecosystem services with activities ranging from convening task forces to implementing new policies (Waage & Kester 2014). Mexico and the United Kingdom (UK) conducted national assessments (Sarukhán *et al.* 2010; United Kingdom National Ecosystem Assessment (UK NEA) 2011), and the European Union (EU) asked Member States to map and assess ecosystem services for accounting systems (European Commission (EC) 2011). China is implementing national policies on ecosystem services, and the United States (US) formally incorporated ecosystem services in a new national forest planning rule (United States Department of Agriculture Forest Service (USDA FS) 2012). Vietnam, Brazil, Costa Rica, Columbia and Peru are creating payment for ecosystem services (PES) programmes at municipal and state levels (Waage & Kester 2014). Recent government activities have created a demand for standardised practices to measure, value and map ecosystem services (Haines-Young & Potschin 2009; Maes *et al.* 2012; Landers & Nahlik 2013; Lü *et al.* 2013; Waage & Kester 2014). To meet

these needs, scientists must first address a data gap: the lack of biophysical measurements linking ecosystem characteristics to final ecosystem services (now referred to as final services) – the things society values directly (Fig. 1). Second, the information must represent legitimate needs presented in terms of trade-offs to aid decision-makers in determining courses of action on multiple services.

In recent years, the number of publications on ecosystem services grew exponentially (Fisher *et al.* 2009; Liu *et al.* 2010; Zhang *et al.* 2010), but progress on the data gap has been slow. Research has centred on management end products like economic values (Liu *et al.* 2010; Zhang *et al.* 2010) and service maps (Seppelt *et al.* 2011; Martínez-Harms & Balvanera 2012), which has advanced categorisation, valuation and mapping techniques (Ouyang *et al.* 2004; Troy & Wilson 2006; Polasky *et al.* 2008; Nelson *et al.* 2009; De Groot *et al.* 2010a; Tallis & Polasky 2011; Ruckelshaus *et al.* 2013). However, there has been minimal improvement on understanding the relationships between ecological mechanisms and ecosystem services to create the realistic end products that managers need (Kremen 2005; Fisher *et al.* 2008; Bennett *et al.* 2009). The dominant method to address the data gap is benefit transfer using species (ecosystem function) values for a particular

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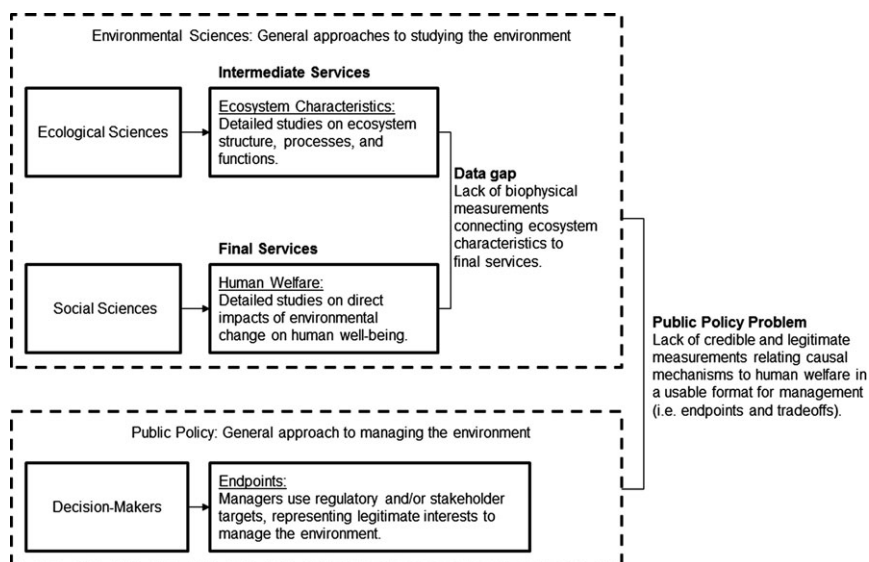*Correspondence: E-mail: zyouyang@rcees.ac.cn*

Figure 1 Ecosystem services bridge the ecological and social sciences relating ecosystem characteristics to human welfare as intermediate and final services. Scientists need to address two problems limiting the use of the ecosystem services approach in public policy: (1) a data gap, which requires conducting primary studies on causal links between ecosystem characteristics and final services, and (2) relevant information for decision-makers, which requires using legitimate interests (i.e. endpoints) and illustrating potential trade-offs of different management actions.

habitat in one location and land cover proxies to estimate ecosystem services at other locations (i.e. policy sites) with similar land cover (Seppelt *et al.* 2011; Martínez-Harms & Balvanera 2012). The problem is current benefit transfer uses secondary data not based on causal relationships between ecosystem characteristics and final services. A valid ecosystem services approach requires adequate resolution of the data gap of which the majority of studies do not address. Second ecosystem services are not presented in a format for management representing legitimate interests and trade-offs so decision-makers can compare management options.

Ecological production functions address these weaknesses by calculating how marginal changes in ecosystem characteristics can lead to changes in final services, which are useful in determining biophysical trade-offs among ecosystem services to select management actions (United States National Research Council (US NRC) 2005; Daily *et al.* 2009; Polasky & Segerson 2009; United States Environmental Protection Agency (US EPA) 2009; The Economics of Ecosystems & Biodiversity (TEEB) 2010; Tallis & Polasky 2011). Ecologists currently are not creating ecological production functions using legitimate final services, which limits the application of the ecosystem services approach. Disciplinary frames separating ecology from economics and policy is a significant barrier causing confusion on concepts and methods. We created a 10-step approach to unify concepts, methods and data from the disparate disciplines. In China, we are testing this approach on an ecological engineering project in Beijing, and a national wetland services monitoring programme. China is the first country to implement national policies on ecosystem services (Lü *et al.* 2013; Waage & Kester 2014), and we believe lessons from China can inform emerging efforts in other nations. In this study, we first present the biophysical measurements that managers need to implement the ecosystem

services approach. Second, we summarise current biophysical methods and their limitations. We attempt to bridge disciplinary thinking to address limitations using: (1) biophysical models to estimate ecosystem characteristics, (2) endpoints to identify final services and (3) ecological production functions to quantify biophysical trade-offs. Lastly, we present a 10-step approach to guide data and modelling choices when measuring ecosystem services for public policy.

Implementing the ecosystem services approach: what do managers need?

An operational definition of ecosystem services that define ecosystem services as the indirect or direct contributions of ecosystems to human well-being (Fisher *et al.* 2009; United States Environmental Protection Agency (US EPA) 2009; De Groot *et al.* 2010b; Tallis & Polasky 2011) is gaining acceptance. A consensus is also growing on classifying these contributions as intermediate or final services. Intermediate services are ecosystem characteristics measured as ecosystem structure, processes and functions that support final services. Final services are components of nature possessing an explicit connection to human well-being that have direct value to society (Boyd & Banzhaf 2007; Fisher *et al.* 2009; Ringold *et al.* 2013). Traditionally, ecologists use ecosystem structure and processes to determine ecosystem functions while economists and decision-makers use endpoints to determine human welfare outcomes from the environment (Boyd 2007). Ecosystem services bridge this divide by relating ecosystem characteristics as intermediate services to human welfare as final services (Fig. 1).

For decision-makers to use the ecosystem services approach, they need credible and legitimate measurements to evaluate potential trade-offs among ecosystem services (Maes *et al.*

2012; Portman 2013). First are credible biophysical measurements linking ecosystem characteristics to final services. Second are legitimate final services represented as legal requirements and/or agreed upon targets (Cook & Spray 2012; Baker *et al.* 2013). Working with managers we selected three biophysical variables to guide efforts on creating credible and legitimate measurements for management: (1) ecosystem characteristic metrics, (2) final service indicators and (3) final services. Final services are the actual, desired values (e.g. legally required level), while final service indicators are the measured, proxy values. Managers felt that this distinction was significant because scientists often monitor final service indicators without referring to policy targets (i.e. final services). The difference between measured results (i.e. final service indicators) and required levels (i.e. final services) are service shortfalls. These variables are similar to those suggested by the US Environmental Protection Agency's work on final services (Landers & Nahlik 2013) and the European Environment Agency's Common International Classification of Ecosystem Services (Haines-Young & Potschin 2013). Lastly, ecosystem service values need to be presented as marginal changes to help managers determine potential trade-offs among ecosystem services to select the best possible action(s) of reducing service shortfalls.

Current biophysical methods

We identified four approaches to measure and evaluate the biophysical supply of ecosystem services: (1) metrics and indicators using primary data, (2) benefit transfer using secondary data and land cover proxies, (3) spatial mapping and (4) modelling systems which combine all three approaches. The four approaches have limitations in addressing management needs, which are impacting the use of ecosystem service measurements in public policy.

Metrics and indicators using primary data
Scientists are developing indicators on ecosystem characteristics and final services, but there are no general criteria on selecting these variables. The first step is selecting the desired ecosystem services then identifying key ecosystem characteristics known to support the selected services. Ecosystem characteristics and ecosystem service indicators have been categorised (Ouyang *et al.* 2004; De Groot 2006; Tallis *et al.* 2012; Van Oudenhoven *et al.* 2012); however, studies often do not separate intermediate and final services (Boyd & Banzhaf 2007). Scientists use primary data to quantify metrics and indicators (Liss *et al.* 2013) and expert opinions to qualitatively connect ecosystem characteristics to ecosystem services (Burkhard *et al.* 2012; Maskell *et al.* 2013). To date, no common set of ecosystem service indicators exist (Boyd & Banzhaf 2007; United States Environmental Protection Agency (US EPA) 2009; Reyers *et al.* 2013), which impacts the interpretation of ecosystem service results (Liss *et al.* 2013).

Ecological production functions offer the most promise in linking ecosystem characteristics and final services; however, few studies employ the production function method because of data limitations and interdisciplinary challenges (Millennium Ecosystem Assessment (MA) 2005; United States National Research Council (US NRC) 2005; Polasky & Segerson 2009; United States Environmental Protection Agency (US EPA) 2009; Liss *et al.* 2013). The classic ecological production function is the bioeconomic model for fisheries that relate habitat changes to fisheries production (Barbier 2007). They have also been developed to relate pollination to crop yields (Ricketts *et al.* 2004) and ecosystem conditions to air quality (Cooter *et al.* 2013). In ecology, there is uncertainty on the term ecological production function since existing regression and process-based models are often incorrectly deemed ecological production functions. Ecologists have developed regression models mathematically resembling production functions, connecting ecosystem structure and processes to functions, such as biodiversity to pollen deposition (Kremen & Ostfeld 2005). However, these regression models are not production functions because outputs are not final services. An important factor contributing to the slow progress on production functions in ecology is disciplinary differences leading to confusion on what are final services. There currently is a lack of consistent understanding on ecosystem characteristic metrics, final service indicators and ecological production functions – a consequence is a data gap on ecosystem services.

Benefit transfer using secondary data and land cover proxies
Benefit transfer is a popular method to estimate ecosystem services at broad geographical scales because it is quick and less costly than primary data collection, but the data gap is impacting the credibility of this method. Benefit transfer is the application of measured values at one place and time (i.e. study site) to infer values at another place and time (i.e. policy site) (Plummer 2009). In theory, scientists use ecosystem service coefficient values (i.e. marginal changes) and spatial variables to transfer values (Troy & Wilson 2006). However, because ecological production functions are unavailable, scientists use species (ecosystem function) values from past studies not intended for ecosystem services (Maes *et al.* 2012), and land cover as ecosystem characteristic proxies to estimate ecosystem services at policy sites with similar land cover to the study sites. Decision-makers often want assessments on multiple services at regional or national scales, but obtaining primary data at these scales is often unfeasible, thus most ecosystem service studies use secondary data (Martínez-Harms & Balvanera 2012). The problem is benefit transfer is only a valid method after the required empirical relationships between ecosystem characteristics and final services are established (Richardson *et al.* 2014).

For benefit transfer to effectively meet the salient needs of decision-makers, the basic requirements must be met, which means first creating a comprehensive database of primary data to derive 'general' ecological production functions using meta-analysis. Many scientific and medical fields recognise meta-analysis as an important tool to 'scale up' results (Rosenberger & Stanley 2006; Stewart 2010). Meta-analytic function transfer uses an ecological production function derived from the results of multiple primary studies (Brander *et al.* 2012). Economists found errors are reduced when transfers are conducted using functions that explicitly account for differences between sites (Rosenberger & Stanley 2006). The data gap undermines the utility of benefit transfer as a means of timely assessing ecosystem services at meaningful scales for policy makers.

Spatial mapping

Scientists have made significant progress on mapping techniques to evaluate the spatial distribution of ecosystem services (Chan *et al.* 2006; Egoh *et al.* 2008; Nelson *et al.* 2009; Raudsepp-Hearne *et al.* 2010; Burkhard *et al.* 2012; Haines-Young *et al.* 2012; La Notte *et al.* 2012; Crossman *et al.* 2013; Onaindia *et al.* 2013; Qiu & Turner 2013); however, the data gap is impacting the use of spatially explicit results. Commonly spatial correlation is used to identify spatial patterns, service ranges and hotspots (Egoh *et al.* 2008; Raudsepp-Hearne *et al.* 2010; Onaindia *et al.* 2013; Qiu & Turner 2013). The analyst then uses this information to determine potential synergies and trade-offs as positive or negative associations among different services (Chan *et al.* 2006; Naidoo *et al.* 2008; Raudsepp-Hearne *et al.* 2010; Onaindia *et al.* 2013; Qiu & Turner 2013). Scientists assess how these synergies and trade-offs may change under variable land covers across varying spatial or temporal scales (Burkhard *et al.* 2012). The trade-offs are interpreted as relative changes in: the composition of service bundles per landscape configuration (Raudsepp-Hearne *et al.* 2010; Haines-Young *et al.* 2012; Qiu & Turner 2013) and services per land cover (Naidoo *et al.* 2008; Nelson *et al.* 2009). Spatially explicit results are helpful to assess the importance of heterogeneity on service flows and scale on service production relative to beneficiaries (Tallis & Polasky 2011). Despite the advancements in spatial mapping, the data gap is impacting the application of spatially explicit results because service maps based only on land cover are vulnerable to considerable errors (Eigenbrod *et al.* 2010; Maes *et al.* 2012; Crossman *et al.* 2013).

Modelling systems

Ecosystem service modelling combines biophysical models with the above approaches to improve the measurement and mapping of ecosystem services (Chan *et al.* 2006; Nelson *et al.* 2009; Logsdon & Chaubey 2013); however, the problem facing modelling systems is the lack of explicit guidance on how to select legitimate final services. Bagstad *et al.* (2013) identified 17 tools that quantify, model and value ecosystem services. The best known, generalisable model is InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) (Crossman *et al.* 2013). InVEST uses ecological production functions and economic valuation methods to create spatially explicit values for 16 services (Tallis & Polasky 2011). InVEST allows users to analyse biophysical and monetary trade-offs among services. The modelling systems are part of the decision-making process where scientists work with stakeholders to tailor analyses to local needs (Ruckelshaus *et al.* 2013). However, none of the modelling systems provide explicit guidance on how to include institutional realities (e.g. regulations, policies) into ecosystem service values, which can limit management adoption (Scarlett & Boyd 2013).

Limitations of current methods

Scientists need to strategically address the data gap considering the needs and timelines of decision-makers while responsibly illustrating the causal links between ecosystem characteristics and final services. Two-thirds of published studies measured ecosystem services using secondary data and land cover with no validation techniques (Seppelt *et al.* 2011). In China, we found that land cover proxies were useful when creating ecosystem service maps and economic values to build awareness, however, experienced limitations when trying to advise policy makers on complex problems. The data gap impacts decision-makers by limiting their ability to set clear goals on intersecting social and environmental problems (Reyers *et al.* 2013). The importance of setting clear and manageable goals to advance public policy is explained well by US President John F. Kennedy (1963) when he stated: 'By defining our goal more clearly, by making it seem more manageable and less remote, we can help all peoples to see it, to draw hope from it, and to move irresistibly towards it'.

We identified several problems limiting the credibility and legitimacy of current ecosystem service methods. First, we found no general criteria on selecting ecosystem characteristic metrics and final service indicators. Second, no clear technical explanation for ecologists on how to apply ecological production functions to determine changes in final services from marginal changes in ecosystem characteristics (i.e. marginality). Third, we were unable to locate any clear steps on how to combine existing ecological methods with production functions to estimate ecosystem services at different spatial and temporal scales. Lastly, most studies were unable to integrate the ecosystem services approach into policy frameworks.

Linking ecosystem characteristics to final ecosystem services

To address the current problems, we synthesised key concepts and methods across ecology, economics and policy, and created a 10-step approach. Three key components underpin our approach: (1) use biophysical models to estimate ecosystem characteristics, (2) use endpoints to identify final services and (3) create ecological production functions to quantify biophysical trade-offs. Below, we present each component, first we introduce its disciplinary origins then we explain how to use the component to advance the ecosystem services approach.

Biophysical models to estimate ecosystem characteristics

Ecologists commonly use biophysical models (empirically based or process-based) to estimate ecosystem characteristics at different spatial and temporal scales. Empirically based models relate management and environmental factors to ecosystem functions through statistical relationships (e.g. Universal Soil Loss Equation). Empirically based models are useful for quick forecasting, but become problematic when investigating thresholds and extrapolating beyond known data and the original model context (Beldring 2002). In ecology, a consensus is emerging that management decisions are best guided by process-based models rooted in causal mechanisms grounded in ecological theory (Cuddington *et al.* 2013). Process-based models are powerful tools to predict: (1) outcomes across a range of spatial and temporal scales, (2) threshold levels and (3) changes in ecosystem functions under different management actions.

A current confusion is how can scientists use existing process-based models to measure ecosystem services? For complex systems like ecosystems, the ecological production

function alone does not afford the same predictive power as process-based models. Yet, existing process-based models are not framed around social variables, making it hard to interpret marginal service changes. We suggest that scientists consider process-based models to estimate key ecosystem characteristics as inputs to ecological production functions. Combining modelling techniques allows scientists to simulate ecological changes across multiple scales, and a means to statistically interpret how those changes may impact social outcomes.

Endpoints to identify final ecosystem services

For most scientists, the main conundrum when measuring ecosystem services is selecting legitimate final services. To date, we lack final services in public policy since policy makers and economists use endpoints. Governments adopted endpoints for a range of environmental issues: endangered species, recreational quality, air and water quality, natural disasters etc. In theory, endpoints should be final services, which regulators define as measurable targets explicitly expressing the actual environmental value to be protected (Suter 2000). However, endpoints in practice are used as: (1) ecological endpoints with no human well-being components (e.g. ecosystem health indicators like indicator species) and (2) human health endpoints (e.g. environmental standards like drinking water quality) that ignore ecosystem functions. Endpoints alone fail to incorporate ecosystem functioning into human choices. The ecosystem services approach attempts to address the endpoint problem; however, guidance is needed to identify appropriate endpoints as final services so managers can use ecosystem service values given current legal frameworks (Fig. 1).

We propose three criteria to select final services using endpoints and/or agreed upon targets: (1) possess explicit social value, (2) direct relevance to management and (3) be a measurable unit of an ecosystem. Legal endpoints offer the most promise as legitimate final services since many governments have regulatory frameworks for pollutant levels, sustainable biotic harvest rates and species and landscape protections. In statutes, biotic endpoints are final services when they have clear social importance, such as halibut population size for a commercial fishery or panda survival rates for heritage values. Management endpoints in environmental plans articulate final services when social objectives have biophysical units like desired acreage of green space for urban recreation or required lake storage for drinking water supply. Scientists can also work with stakeholders to derive final services using pertinent ecological and social data (Ringold *et al.* 2013). For example, ecologists and social scientists can work with managers to link algal biomass to beach closures or dust from wind erosion to landscape aesthetics. Multiple required levels likely exist for any given final service type (e.g. national and state air quality standards), thus scientists should always clearly define who selected the final services.

Ecological production functions

Ecological production functions are regression models that measure the statistical influence of ecosystem characteristics (i.e. explanatory variables: vegetation area, wind speed and sand flux) on final service indicators (i.e. response variables: PM_{10}) for a given place and time via marginal changes (i.e. regression coefficients). Marginal changes are defined as the rate output changes from one additional unit of an input, holding all other inputs constant (Besanko & Braeutigam 2010). In theory, scientists can use marginal changes to determine biophysical trade-offs among services and management options (Polasky & Segerson 2009). The ecological production function is also important for economic valuation because it classifies intermediate and final services. Ecological production functions clarify the economic value of ecosystem characteristics as contributions to final services, which otherwise would go unvalued. If the connections are not distinguished, the value of intermediate services could be 'double counted' when valued in addition to their respective final services (Boyd & Banzhaf 2007). Improving economic valuation is a high priority for policies on PES, mitigation banking, ecological compensation, etc. (Kinzig *et al.* 2011).

The 10-step approach

The 10-step approach unifies the above concepts, methods and data from the disparate disciplines; presented in a stepwise form to clearly illustrate the technical integration of ideas (Fig. 2). Currently, there exists little guidance on how to overcome the identified problems on ecosystem services. Our intent is to offer an approach to guide choices on resource allocations for data collection and model selection, which vary depending on the study objectives and decision context (see Table S1). The guidance is strategic for public policy because analysts need to be: (1) realistic when setting priorities, (2) attentive to timelines to acquire relevant data, given resources and (3) responsive to the needs of decision-makers. The 10-step approach is about building craft not adherence to steps. Its effectiveness will depend on our ability to practice holistic and adaptive thinking (Lee 1993) centred on how ecosystems support human welfare. Below, we summarise the steps in each phase.

Phase I: Identify metrics and indicators (steps 1–4)

Human benefits represented as final services should guide the measurement process. The final service criteria are used to identify legitimate final services using endpoints and/or agreed upon stakeholder targets. The analyst must clearly indicate who selected the final services and the spatial–temporal extent of the assessment. Final services most applicable to public policy, clearly describe their connections to human well-being as management metrics in the given governance context. The biophysical units of final services guide scientists on selecting final service indicators and ecosystem characteristic metrics. The ecosystem characteristic metrics should represent key ecosystem components and management options supporting the final services. The challenge is seeing the connections between social and ecological variables to link final services, final service indicators and ecosystem characteristic metrics (e.g. water quality, total nitrogen and nutrient retention) (Fig. 3).

Phase II. Biophysical measurement (steps 5–10)

From phase I, the selected final service indicators and ecosystem characteristic metrics are the output and input variables
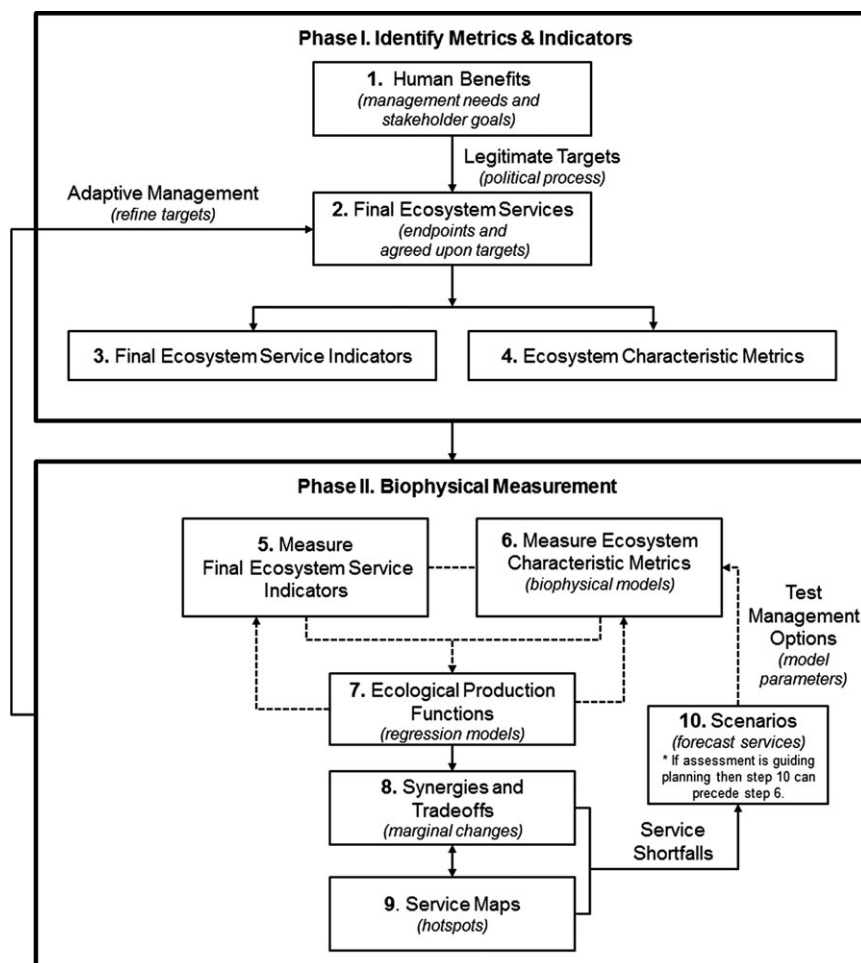
Figure 2 The 10-step approach. Phase I is identifying final services, final service indicators and ecosystem characteristics metrics. Once these variables are selected then scientists can proceed to phase II to measure ecosystem services. Steps 5–7 are repeated until satisfactory ecological production functions are created. Steps 8 and 9 provide information on trade-offs and spatial patterns to understand service shortfalls, which inform scenarios in step 10 that feed model alterations in step 6. The dashed lines are the main modelling steps in phase II.

of the ecological production functions. Available data and field methods are selected to estimate final service indicators and ecosystem characteristic metrics. Depending on the study objectives and scale, scientists should consider biophysical models by identifying applicable process-based or empirically based models. Biophysical models may be unnecessary if scientists can collect all the required primary data for ecological production functions at the scale of interest. If obstacles prevent primary data collection or use of biophysical models then established proxies or secondary data are appropriate when available. Measurement and evaluation is an iterative process (steps 5–10), and every unique combination of ecosystem characteristic metrics and final service indicators results in new production functions. An uncertainty analysis should be conducted, and estimated errors and assumptions reported. Using ecological production functions to relate biophysical model results to final service indicators can help scientists and management interpret the potential causes driving final service outcomes. However, when the analyst interprets marginality, it is important to consider the ecosystem state because a small increase or decrease in structure or function could lead to

large step changes depending on the system's proximity to a threshold.

Marginal changes are used to calculate potential synergies and trade-offs among services and management options. The service results are spatially evaluated using marginal changes and land cover to locate spatial patterns and determine potential beneficiaries. Scientists can use the trade-off results, mapping results and management input to select possible changes to management options to address service shortfalls. The selected changes inform model parameter alterations to run scenarios, and the production functions are used to forecast final service indicators under the scenario conditions.

Applying the approach

We are using the 10 steps to evaluate ecosystem services from the Yongding River Ecological Corridor in Beijing. The Yongding Corridor is currently Beijing's largest ecological engineering project consisting of six new lakes and wetlands. We are assessing five ecosystem services (*endpoints*) selected by the Beijing Water Authority (BWA): (1) water purification
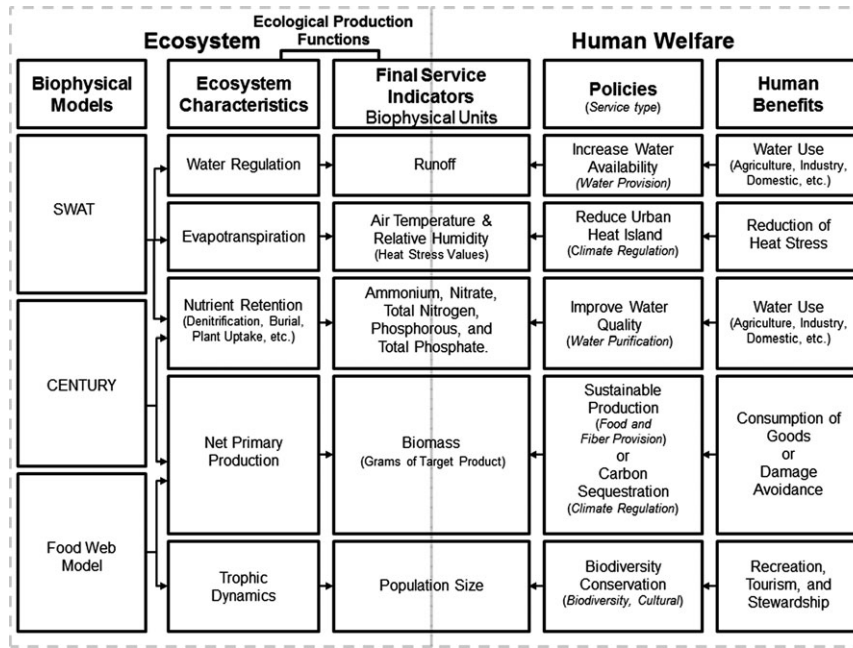
Figure 3 Examples of how to use final service indicators to link biophysical models, ecosystem characteristics, policy targets and human benefits.

(*total nitrogen and total phosphorus water quality standards*), (2) local climate regulation (*human heat stress standard*), (3) water storage (*100 million m³ year⁻¹ for groundwater recharge*), (4) dust control (*PM₁₀ air quality standard*) and (5) aesthetics (*visitor perceptions of scenic beauty*) (Beijing Water Authority (BWA) 2009; Table 1).

In phase I, we identified final services using official BWA planning documents. However, identifying tangible quantities for all services was challenging since BWA goals were a mix of qualitative and quantitative statements. We used government standards and the scientific literature to locate quantities for management then surveyed managers and visitors to evaluate their legitimacy. The use of endpoints and their associated human benefits significantly increased the legitimacy of

our assessment, which has led to management consideration of our results.

In phase II, we are using biophysical models and ecological production functions to: (1) estimate ecosystem services from the new lakes and wetlands on the Yongding River and (2) test management options on reducing service shortfalls. We defined the temporal scale of our analysis as before (2009–2010) and after (2012–2013) addition of the new ecosystems. Next, we selected two spatial scales: the region (BWA desired scale of beneficiaries) and individual lakes/wetlands (scale managers can influence). We used the Variable Infiltration Capacity (VIC) model to evaluate water balance and energy fluxes at varying spatial and temporal scales (Liang & Lettenmaier 1994; Gao *et al.* 2011) because the hydrologic change

Table 1 Final services, final service indicators and data collection methods; example of using endpoints to select final services and final service indicators for five ecosystem services on the Yongding River Ecological Corridor in Beijing, China

No.	ES types	Final services (Endpoints)	Final service indicators	Methods
1	Water purification	Drinking water (mg L⁻¹)* (1) Total nitrogen = 1.0 (2) Total phosphorus = 0.2	(1) Total nitrogen (mg L⁻¹) (2) Total phosphorus (mg L⁻¹)	Monthly water quality samples collected in the field.
2	Local climate regulation	Heat stress values† (1) Sultry = 27–28	(1) Air temperature (°C) (2) Relative Humidity (%)	Hourly air temperature and humidity collected using data loggers.
3	Water storage	Water storage (m³ year⁻¹)* 100 million	Water storage (m³)	Daily water volume simulated using the VIC model.
4	Dust control	Urban residents (μg m⁻³)* (1) PM₁₀ = 150	PM₁₀ (μg m⁻³)	Daily PM₁₀ data from government monitoring stations.
5	Aesthetics	Public perceptions‡ (1) Very beautiful (2) Beautiful	Aesthetic rankings	Monthly visitor surveys conducted in the field.

*Beijing water authority and ministry of environmental protection water and air quality standards.
†Beijing meteorological bureau physical comfort index; physical comfort equation requires air temperature and relative humidity.
‡Visitor survey rankings.

is the main alteration. Empirically based models were also used to estimate the denitrification and wind erosion. The modelled ecosystem characteristics are inputs to ecological production functions. For water purification, for example, we first determined wetland nutrient retention and nutrient loading using field measurements. Next, we created ecological production functions relating wetland area and nutrient loading (i.e. management options) to lake water quality (i.e. management endpoints). Primary data were used to determine wetland nutrient retention and nutrient loading. Biophysical models were used to understand how ecosystem changes were potentially leading to observed final service outcomes: (1) VIC model to simulate seasonal changes in wetland area and (2) denitrification equation to estimate seasonal denitrification rates. Ultimately, we found the wetlands are improving water purification on the Yongding River; however, nutrient loading is greater than the wetland purification capacity, which is causing final service shortfalls. The ecological production functions were critical in helping us determine the potential increase in wetland area and decrease in nutrient loading likely needed to obtain final service levels.

We plan to use the marginal changes to identify potential synergies and trade-offs among the five services from changes in BWA management options like lake and wetland dimensions. For instance, an increase in surface water area and vegetation area may increase local climate regulation via evapotranspiration while decreasing net water storage because of increased water loss. Furthermore, we may expect increases in: (1) dust control due to reductions in bare soil area, (2) water purification from increased nutrient retention and (3) landscape aesthetics because visitors have shown a preference for expansive water bodies for scenic beauty. However, not all ecosystem services are of equal importance to society; a high priority in water-limited Beijing is efficient water storage. Information on potential trade-offs can help managers address priorities in a manner that minimises losses to other services.

Lessons learned

We are starting to apply the 10-step approach, and as of now identified six main challenges to full implementation. First is getting disciplinary scientists to understand an interdisciplinary approach. It takes time and resources to build collective understanding. It took several years to develop this approach working with ecologists, economists, geographers, hydrologists, managers and policy analysts at various institutions in the US and China. Second is identifying legitimate final services, which is the biggest obstacle to creating ecological production functions. Ecologists may feel final services are outside their responsibility; however, ecologists are critical in translating stakeholder goals to measurable biophysical quantities. Framing an assessment around final services can highlight connections; however, if there is no consensus on final services then the likelihood of results being used is low. Third is incomplete knowledge on the study ecosystem, which can prohibit identifying key ecosystem characteristics supporting final services (Groffman *et al.* 2006). Fourth is creating estimates of key ecosystem characteristics for multiple services. Process-based models are complex and improper

parameterisation can lead to large uncertainties in predictions (Peters *et al.* 2006). Process-based models are not always the best option; one has to consider decision timelines and available resources when selecting models (Ruckelshaus *et al.* 2013). Fifth is communicating uncertainties in ecosystem service values. Uncertainty analysis is not routine in ecological studies because existing techniques for estimating uncertainties are neither widely known nor universally effective (Wu *et al.* 2006), which can hinder communicating the reliability of findings (Ruckelshaus *et al.* 2013). Sixth is identifying management options to reduce service shortfalls. Obtaining information on management practices and the feasibility of changing practices will depend on the trust level between scientists and stakeholders.

To date, the most promising aspect of our approach is clarifying the social importance of ecosystem functions because final services guide ecological analysis. Managers of the Yongding Corridor liked how we explained the importance of the underlying hydrology and seasonality on all five services. In China, simple diagrams (Fig. 3) led to productive discussions between managers and scientists on interconnections among ecosystem services by clarifying how ecosystem functions supported multiple endpoints.

Transferability

We are starting to explore the transferability of the 10-step approach to broader geographical scales for national policies on ecosystem services. In China, a major policy initiative is the establishment of ecosystem function zones to improve ecosystem service flows using ecological compensation mechanisms. China has selected 25 key national ecosystem function zones to improve water resource regulation, flood control, soil conservation, sandstorm control, carbon sequestration and biodiversity conservation for national security (Ouyang 2007; Ministry of Environmental Protection & Chinese Academy of Sciences (MEP-CAS) 2008; Ehrlich *et al.* 2012). China is making substantial investments in ecosystem function zones, funding increased from 6 billion RMB ($966 million US dollars) in 2008 to 48.3 billion RMB ($7.78 billion US dollars) in 2013. China is building up its scientific capacity on monitoring ecosystem services to improve environmental policies and regulations (Ouyang *et al.* 2014). The Ministry of Environmental Protection (MEP) and Chinese Academy of Sciences (CAS) are conducting China's first national ecosystem assessment authorised by the State Council of the People's Republic of China (see Appendix S1). A focus area is wetlands because they are the most threatened ecosystems in China. Hence, the Chinese Academy of Forestry Sciences (CAF) and CAS are creating a national wetland services monitoring programme for the State Forestry Administration (SFA). The SFA wants a standardised approach to evaluate wetland targets and compensation schemes to improve wetland management.

The CAF and CAS are pushing to change SFA wetland monitoring practices based on the 10-step approach for the purpose of ecosystem services-based wetland management. First, they are working to establish three indicators: (1) ecosystem characteristics, (2) human drivers and (3) final services. The objective is to create ecological and socioeconomic data

sets to develop ecological production and economic valuation functions for dominant wetland types. Chinese officials and scientists are realising they must invest in the necessary data sets to use meta-analysis and benefit transfer to meet growing demands for wetland service values and trade-off analyses across China. Scientists are testing this approach at lake and wetland sites representing nature reserves and critical ecosystems for water security. Currently, scientists cannot create ecological production functions because they lack primary data, and are working on gathering data on indicators. Scientists are using the 10-step approach to identify indicators, understand ecological production functions and communicate the value of biophysical models to address management problems at specific wetland sites.

When using the 10-step approach, analysts need to be strategic, relating study objectives to the specific decision stage of the particular policy problem. If decision-makers are in the scoping process, scientists may focus on final services to generate educational maps. If managers are planning actions then information on trade-offs may be needed using process-based models and ecological production functions. For large-scale policy efforts with long-time horizons, scientists can interpret the 10 steps as short- and long-term milestones to establish primary studies. In China, scientists were able to use simple ecosystem service maps to help policy makers delineate ecosystem function zones. However, they are realising they need to combine remote sensing, field data and models to advise policy makers in practice on compensation mechanisms to establish ecosystem function zones. Analysts need to make judgments relating the 10 steps to the specifics of the situations they face.

CONCLUSION

A data gap separating ecosystem characteristic metrics and final service indicators is limiting the ecosystem services approach. We designed a 10-step approach to unify concepts, methods and data from ecology, economics and policy to help scientists overcome the data gap. We suggest: (1) estimate ecosystem characteristic metrics using biophysical models, (2) identify final services using endpoints and (3) create ecological production functions to quantify biophysical trade-offs. The guidance is strategic for public policy because analysts need to be: (1) realistic when setting priorities, (2) attentive to timelines to acquire relevant data, given resources and (3) responsive to the needs of decision-makers.

Governments are taking steps to apply the ecosystem services approach to handle intersecting social, economic and environmental problems. In addition to China, the EU, UK, US and United Nations want approaches to measure, map and value ecosystem services at regional to national scales (Landers & Nahlik 2013). Currently, China is taking the most ambitious steps on implementing the ecosystem services approach, but like other nations the public policy problem is limiting effective application. Chinese scientists are using the 10-step approach to understand indicator criteria and ecological production functions to establish primary studies for meta-analytic transfer functions. In the near-term establishing indicators to monitor ecosystem conditions and final services

would be a significant accomplishment for any country. Environmental problems are becoming increasingly complex and important to society, and the ecological sciences are critical to making ecosystem services a viable and useful approach for public policy.

AUTHORSHIP

All authors contributed to the synthesis covering core disciplines in the manuscript: CPW – ecology and ecosystem services, BJ – economics and ecosystem services, APK – ecology and ecosystem services, KNL – social learning and adaptive management and ZO – ecology and ecosystem service policies in China. CPW designed the 10-step approach with consultation from all authors. CPW wrote the first draft of the manuscript, and all authors contributed substantially to revisions.

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