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Benefit relevant indicators: Ecosystem services measures that link ecological and social outcomes

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ABSTRACT

There is a growing movement in government, environmental non-governmental organizations and the private sector to include ecosystem services in decision making. Adding ecosystem services into assessments implies measuring how much a change in ecological conditions affects people, social benefit, or value to society. Despite consensus around the general merit of accounting for ecosystem services, systematic guidance on what to measure and how is lacking. Current ecosystem services assessments often resort to biophysical proxies (e.g., area of wetland in a floodplain) or even disregard services that seem difficult to measure. Valuation, an important tool for assessing trade-offs and comparing outcomes, is also frequently omitted due to lack of data on social preferences, lack of expertise with valuation methods, or mistrust of valuation methods for non-market services.

To address these shortcomings, we propose the use of a new type of indicator that explicitly reflects an ecosystem's capacity to provide benefits to society, ensuring that ecosystem services assessments measure outcomes that are demonstrably and directly relevant to human welfare. We call these *Benefit-relevant indicators* (BRIs) and describe a process for developing them using causal chains that link management decisions through ecological responses to effects on human well-being. BRIs identify what is valued and by whom, but stop short of valuation. A BRI for the ability of wetlands to ameliorate flooding would connect measures of the quantity and quality of wetland in a floodplain, as affected by wetlands management decisions, to the number of people or properties downstream that are vulnerable to flooding. BRIs can support monetary or non-monetary valuation, but are particularly useful when valuation will not be conducted; in such cases they serve as stand-alone measures of "what is valued" by particular beneficiaries. BRIs are valid measures of ecosystem services in that they are directly linked to human well-being. Flexibility in the development of BRIs helps to ensure that they are broadly applicable across practitioner and stakeholder communities and decision contexts.

1. Introduction

Ecosystem services are generally defined as goods and services that are of value to people, provided wholly or in part by ecosystems (NESP, 2016; MEA, 2005). Incorporating ecosystem services into decision-making is expected to improve how decisions are made and communicated to the public (National Research Council, 2005; PCAST, 2011). Inclusion of ecosystem services is growing within a wide range of decision-making contexts (Ruckelshaus et al., 2015; Olander and Maltby 2014), in part due to the recognition that a failure to do so may lead to

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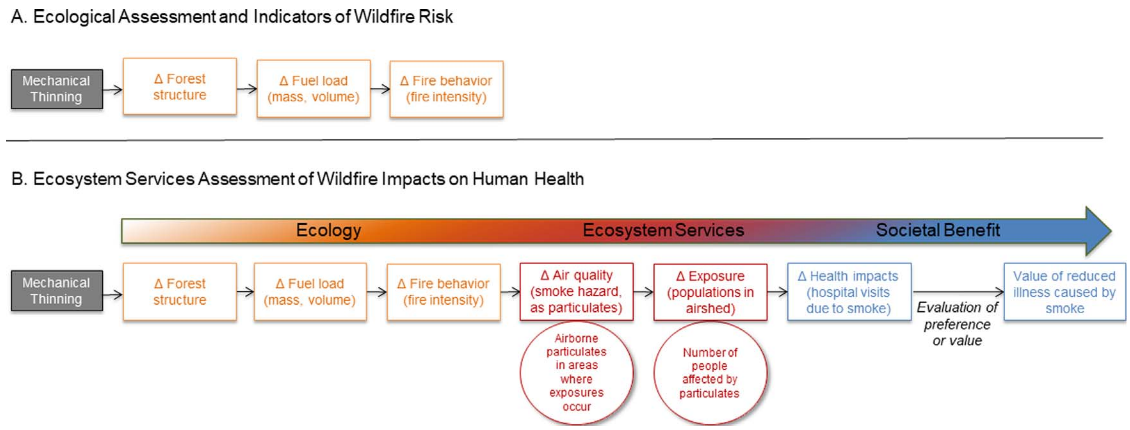

Fig. 1. Ecological and ecosystem services assessments and indicators are not the same. For example, resource managers wishing to assess mechanical thinning of forests to reduce the intensity of fire may undertake an ecological assessment (orange text) to consider changes in the fuel load, which affects fire intensity as well as other biophysical features. In contrast, an ecosystem services assessment would extend the assessment to outcomes that matter to people (red text), which could then be extended to specific benefits to people (blue text) such as reducing the incidence of smoke and poor air quality which can reduce exposure and adverse health outcomes for nearby residents (Rittmaster et al., 2006; Kochi et al., 2010). Thus, the ecosystem service of interest is a change in airborne particulates that is near populations that could be exposed or, even better, a change in the number of people exposed to this change in air quality. These are the BRIs that can provide quantifiable measures of an ecosystem service that is valuable to people and affects human welfare.

substantial unattributed losses in the benefits ecosystems provide to people (MEA, 2005). This growth is reflected in multiple contexts. One hundred and twenty-six countries are now members of the Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2016), which provides scientific information in response to requests from policy makers (https://www.ipbes.net/). Forty-three companies in the financial sector have signed the Natural Capital Declaration "to integrate natural capital considerations into loans, equity, fixed income and insurance products, as well as in accounting, disclosure and reporting frameworks" (Natural Capital Declaration, 2012; Natural Capital Coalition, 2016). In addition, approximately two hundred organizations have joined the Natural Capital Coalition, which supports the development of methods for natural and social capital valuation in business (http://naturalcapitalcoalition.org/).

The US federal government has also moved forward to integrate ecosystem services information into decision-making. New principles and requirements for federal investments in water resources were issued by the White House Council on Environmental Quality in 2013 and the Forest Planning Rule was issued by the U.S. Forest Service in 2012; both request explicit consideration of ecosystem services (CEQ, 2013; USFS, 2012). In addition, the Executive Offices of the President committed to issue new guidance related to federal decision making and ecosystem services that will apply broadly across the government (Council on Climate Preparedness and Resilience, 2014; EOP, 2015).

Despite consensus around the general concept of ecosystem services and the need to consider them in decision-making, those applying ecosystem service analysis to support decisions typically lack systematic guidance on what to measure and how (Boyd et al., 2016). A lack of standards for ecosystem service measures, together with a lack of a common methods and vocabulary acts as a barrier to those wishing to apply ecosystem service frameworks (Polasky et al., 2015). At present, there is even confusion and inconsistency over what is meant by "ecosystem service" indicators (Bauer and Johnston, 2013; Boyd and Krupnick, 2013; Boyd et al., 2016; Johnston et al., 2012). In particular, the assumption is often made that biophysical measures provided by ecological assessments or studies are the same as ecosystem service indicators – they can be, but usually are not, because they often do not reflect what people actually value (Boyd et al., 2016). Existing efforts to better define and identify ecosystem services measures (e.g., using final and intermediate services; Boyd and Krupnick, 2013; Fisher et al., 2009; Johnston and Russell, 2011) provide some insight, but fall short of clear guidance for what to measure when seeking useful stand-alone indicators of ecosystem services.

Assessments of ecosystem services require both (a) biophysical measures related to ecosystems; these reflect underlying changes in biophysical structure and function driven by alternative management decisions or environmental change (e.g., climate change) and (b) social or economic measures of preference or value; these reflect the impact of ecosystem services on human welfare. What is less clear is the hand-off between the biophysical measures and valuation–the link between the biophysical measure and a measure of what that biophysical entity means to (or how it affects) people. This is particularly important when valuation in monetary or non-monetary terms is not feasible or acceptable, but some measure of what is valued by people is needed for decision making. Benefit-relevant indicators (BRIs), as we describe them in this article, fill this gap. BRIs are indicators that are directly relevant for social welfare and thus are useful inputs into decision making, while also being well suited for subsequent valuation or other social science analyses (Olander et al., 2015, 2017). We illustrate this concept using a variety of generic examples. The concept of BRIs is designed to be broadly applicable to myriad context and scales over which ecosystem services analyses are applied.

2. Benefit-relevant indicators

Ecological features and processes are essential for the provision of ecosystem services but are not the same as services (Palmer and Filoso, 2009; Tallis et al., 2011). Until there is some person somewhere who benefits from a given element or process of an ecosystem, that element or process is not a service (see Fig. 1). BRIs are indicators explicitly constructed to reflect an ecosystem's capacity to provide benefits to society. BRIs support ecosystem services assessments by measuring outcomes that are demonstrably and directly relevant to human welfare (Olander et al., 2015, 2017). Use of BRIs will enhance the quality and consistency of ecosystem services assessment, fostering greater connectivity between ecological and social implications and outcomes.

BRIs are measures that capture the connection between ecological change and social outcome by considering what is valued by people, whether there is demand for the service, how much it is used (for use values) or enjoyed (for non-use value), and whether the site provides the access necessary for people to benefit from the service, among other considerations (Olander et al., 2015). The relationship between BRIs and ecosystem services is related to, but often not same as, the relationship between BRIs and what have been called "final or intermediate ecosystem goods and services" (FEGs) (Boyd and Banzhaf, 2007). Some things that are not FEGs may qualify as BRIs, as more fully elaborated in Supplemental Online 1.

Despite the name "benefit" relevant indicators, BRIs can also be measures of a disservice that results in lower rather than higher benefits. For example, wolves can create a disservice to ranchers who lose livestock to predation. In other cases, BRIs can provide positive benefits up to a certain quantity, above which benefits may become negative. For example, many wildlife species (for example, geese) are valued for recreational (e.g., hunting, viewing) and existence purposes up to a certain density, but at higher densities may be viewed as pests (e.g., due to damage caused to crops and landscaping; cf. Rollins and Briggs, 1996). Hence, some BRIs will not have an unambiguously positive or negative impact on human welfare and may have positive impacts for some groups in society, but negative impacts for other groups.

The general concept of BRIs will be familiar to those conversant with economic valuation or benefit-cost analyses that include non-market values because BRIs typically form the foundation of these methods, although the term BRI is rarely used within valuation (Freeman et al., 2014; USEPA, 2014; NMFS, 2007; US BLM, 2013). However, BRIs need not be accompanied by valuation—they can be informative as stand-alone indicators of what is valued. By accounting for ecological, social and institutional context, BRIs can be used directly in decision-making processes in addition to being an input into a formal valuation process in which preferences are quantified through monetary or non-monetary methods. BRIs serve a particularly important function when they represent less tangible *non-use* values that can be difficult to quantify and are often excluded from assessments. For example, various types of indicators can be used to quantify aspects of threatened or endangered species that have been linked to non-use values held by various groups in particular circumstances (e.g., species distribution, abundance, population viability, survival probability, official status or designation; cf. Wallmo and Lew, 2011; Zhao et al., 2013); these indicators can be used to inform decisions directly even when valuation will not be conducted (although valuation, when feasible, can provide information on social welfare implications not provided by BRIs alone). BRIs can also be interpreted as arising from relational values that characterize the various ways that nature gives meaning and value to people (Chan et al., 2016; Tadaki et al., 2016).

2.1. BRIs reflect changes in ecological conditions in units relevant to beneficiaries

An indicator becomes benefit *relevant* when it is cast in units that resonate with stakeholders as something that affects their welfare proximally. Table 1 provides a few illustrative examples of measures that would and would not be considered BRIs. For example, "numbers of catchable fish" is more relevant to fishers than other measures such as dissolved oxygen content in the water or an index of biotic integrity—even though water quality might directly influence fish populations. Similarly, in the causal chain connecting a change in forest management to changes in the risks of wildfire, the BRI emerges when fire behavior is translated into units directly relevant to human health (Fig. 1b). As a simple rule of thumb, if members of the beneficiary groups affected by an ecological change (e.g., those whose health is affected by airborne particulates) cannot easily understand why an indicator is relevant to their welfare, it is unlikely that the indicator is an effective BRI. Because of this, engagement with the public and stakeholder groups via participatory processes can be an important part of BRI identification.

BRIs do reflect changes in ecological condition and so they must build on good indicators of the ecological changes. For example, marsh, reef, or mangrove habitat are all known to dampen incoming waves and, in so doing, protect coastal areas from erosion and inundation (Narayan et al., 2016; Koch et al., 2009). For this service, habitat area is not the most relevant ecological metric; multiple studies have shown that the leading offshore habitat edge plays a disproportionate role in dampening waves compared with more interior acres of habitat. In this case, contiguity of offshore habitat edge is the appropriate ecological indicator to reflect a step on the causal chain for a coastal protection ecosystem services assessment.

2.2. BRIs capture physical and institutional constraints on the flows of services

Since a BRI must capture only those ecological components and processes that can be enjoyed or used by people for some benefit, identifying BRIs requires information on limits to people's ability to access (physically or otherwise) a benefit (Tallis and Polasky, 2009). These may take the form of physical constraints or constraints imposed by institutions or policies. For example, for the service of timber production, the amount of available timber alone is not a sufficient BRI. Physical infrastructure such as roads or features such as steep terrain may limit tree harvests in some areas. Separately, legal restrictions may limit physical access to areas with trees (e.g., protected areas) or regulate harvest rates or areas (e.g., through riparian buffer restrictions). A BRI must reflect these constraints so that the flow of services is not over-estimated. In this case, a BRI would be the density and size of harvestable trees accessible to forest managers.

2.3. The best BRIs indicate the intensity of human use or enjoyment

BRIs that capture biophysical outcomes that are closely tied to human use, enjoyment, or appreciation are most useful. The strength of indicators can be distinguished on the basis of their distance or proximity to social outcomes. This is often a matter of degree. For example, knowing whether the waters affected by wetland restoration (Fig. 2b) are the most popular fishing areas in the state given their accessibility (averaging 100 people per day during the season) or are highly prized for their beauty but somewhat isolated and used by fewer people (10 people per day during the season) would provide insight into the relative values possibly associated with changes to those areas. Data on fish mortality and reproduction can be a sufficient BRI, but number of fish caught would provide information about the intensity of fishing,

Table 1
Examples of what would and would *not* qualify as a BRI.

Ecosystem Service	Not BRI	BRI
Existence or abundance of wolves	People donating to general conservation organizations[a]	Numbers of wolves × number of people holding existence value for wolves
Ecological production of commercially harvested fish	Fish abundance	Amount of fish landed commercially by Native Americans
Flood regulation	Flood frequency	Number of vulnerable people (e.g., elderly) in areas with flood risk reduced by management action
Water quality regulation	Nitrogen concentration (proxy measure)	"Swimmable days" x number of people with ready access to the swim sites

[a] Donating to conservation organizations is not a BRI because (1) there is no direct link between conservation donations and wolf populations—individuals may donate for reasons other than values for wolves—and (2) wolf existence is a public good—each individual can in principle obtain this benefit without paying for it—so individuals will free-ride on payments made by others, and free riders will thus not be accounted for by only considering donations.

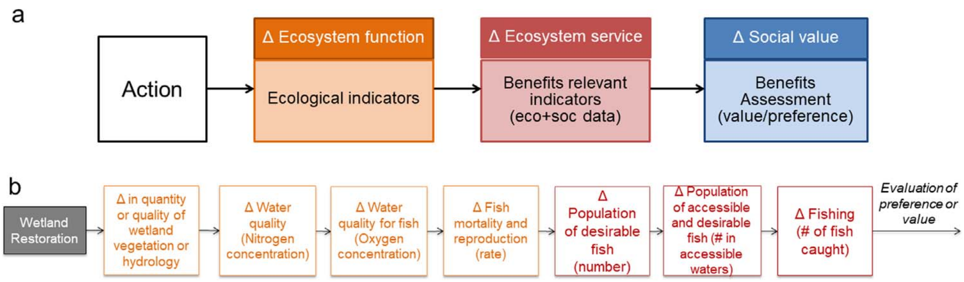

Fig. 2. An ecosystem service causal chain (a) shows how an action, stressor, policy or project moves through an ecosystem to affect benefits to people. Use of a causal chain to identify the BRIs is illustrated using a (b) wetland restoration example to show the causal relationships between the restoration action, ecological changes (orange text), ecosystem services and BRIs (red), and the value these services have to people (blue). The change in fish abundance in waters used by anglers is a BRI. The change in the number of fish caught is a better and preferable BRI if it can be estimated or measured. Only one of these BRIs would be used to avoid double counting. BRIs that capture intermediate outcomes "earlier" in the causal chain are less desirable than BRIs that capture outcomes "later" in the causal chain, because the earlier BRIs increase the number of links to be established to firmly anchor the measure to benefits. For example, the extent of wetland restoration is not a BRI, unless a tight relationship has already been firmly established between the area of wetland restored and fish abundance.

making that measure a better BRI. As another example, a good BRI for the health impacts of smoke from fire would explicitly capture exposure (how many and which people?) and hazard (how bad is the air?).

Even for non-use values like the existence of a of an old-growth forest, a historical or culturally important place, or a particular species like an endangered tortoise, measures need to represent the elements that impart value to people, including the presence, quantity, quality and sustainability of these places, habitats, or species. Many of these non-use values are similar to those described by some authors as "intrinsic" (see Supplemental Online 2).

2.4. Causal chains can be used to identify BRIs that link ecological outcomes to benefits for an identifiable group of people

The best approach for identifying and selecting BRIs for assessment is to use causal chains. A causal chain in an ecosystem services assessment combines information on ecological outcomes with information on how those outcomes affect people to determine impacts on human well-being (Fig. 2). The idea is to go beyond a focus on ecological outcomes and their associated ecological indicators to consider ecosystem services and benefits. A BRI reflects the relevant links in a causal chain ending with the potential benefit of a service to an identifiable group of people. A BRI should also be specific enough to reflect the ecosystem condition that is causally and proximally tied to the human benefit.

Causal chains can be linked together into conceptual models that are useful in evaluating how a management action or policy is expected to propagate through the ecosystem to effect changes in the provision of ecosystem services and benefits to various segments of society (NESP, 2016). These models answer the questions: How does a policy, management decision, or program action affect ecological conditions? How do changes in ecological conditions lead to changes in the delivery of ecosystem services (defined as ecological changes that directly influence people)? How do those changes in the delivery of ecosystem services affect benefits or costs to individuals or groups? Understanding the benefits and costs of changes in services to people requires some understanding of, or engagement with, affected stakeholders and the general public. Conceptual diagrams and causal chains are used to identify the general types of ecosystem services and social outcomes relevant to a decision, thereby informing subsequent development of BRIs to provide the best measures of these services. Using this approach can improve how decision makers define problems and formulate solutions (Wainger and Mazzotta, 2011).

3. Using causal chains to identify BRIs

Developing conceptual diagrams from causal chains is a critical step to ensure that ecosystem services assessments are comprehensive and transparent and to ensure that indicators selected for assessment reflect outcomes directly relevant to human beneficiaries. In the process of conceptualizing, it is critical to ask: Have all significant effects of a policy, management decision, or program on ecological conditions been included? Have the changes in ecological conditions that lead to changes in the delivery of affected ecosystem services been included? Have the effects on individuals or groups from changes in the delivery of ecosystem services been included? Have all significant impacts that people care about been included in the diagram (even if they will not all be included in the final analysis)? Answering these questions to the extent possible should result in a conceptual map that shows management actions affecting multiple aspects of an ecosystem, with each potentially having impacts on social benefits.

An initial expansive diagram is useful for considering and illustrating all possible impacts to valued services, and can help practitioners identify indicators that best reflect how ecological change will affect social outcomes. To provide an example, we continue the forestry example with understory thinning (Fig. 3). In developing such a diagram, it might be tempting to refer to a designated or "master list" of services or indicators to help ensure the assessment is complete. This may be a useful starting point but is often misleading because such lists do not capture site-specific information that is critical (see Supplemental Online 3).

Constructing a conceptual diagram is a staged process in causal analysis. The process of constructing a conceptual diagram often starts with a simple mapping process to stimulate discussion of the scope of the assessment or problem definition. Indicators are then added to the map to make the concepts measurable. Ultimately, the diagram might be implemented as data-driven models that are used to estimate changes in services expected to result from management or policy actions.

4. Quantifying BRIs

Following development of conceptual causal chains, a quantitative assessment will likely be focused on those effects most important to the decision—often those expected to have the largest impacts on human welfare. Assessors can use some key guiding questions to help determine which services should be included and which BRIs need to be quantified. First, is an impact on an ecosystem service (the change in the BRI) likely to be large *and* strongly driven by the proposed activity? All impacts on ecosystem services should be considered for quantification, not only those targeted by the proposed activity. Second, will the expected changes to the ecosystem service (as measured by a BRI) matter to many people or to groups of special concern? Answering this question implies consideration to how many people and which groups will be affected by or will care about likely changes in a service. Such consideration should account for physical or institutional (e.g., legal) access to services and can provide information regarding intensity of use. Such information is captured by the best BRIs.

A large body of literature explains how to quantify changes in ecological conditions (e.g., US EPA, 2014, 2016; Toevs et al., 2011; Bortone, 2005) but there is much less written about quantifying services. The former is focused on how to measure ecological processes or features (e.g., net primary productivity) rather than on benefit-relevant endpoints that are the focus of ecosystem service assessments. Direct

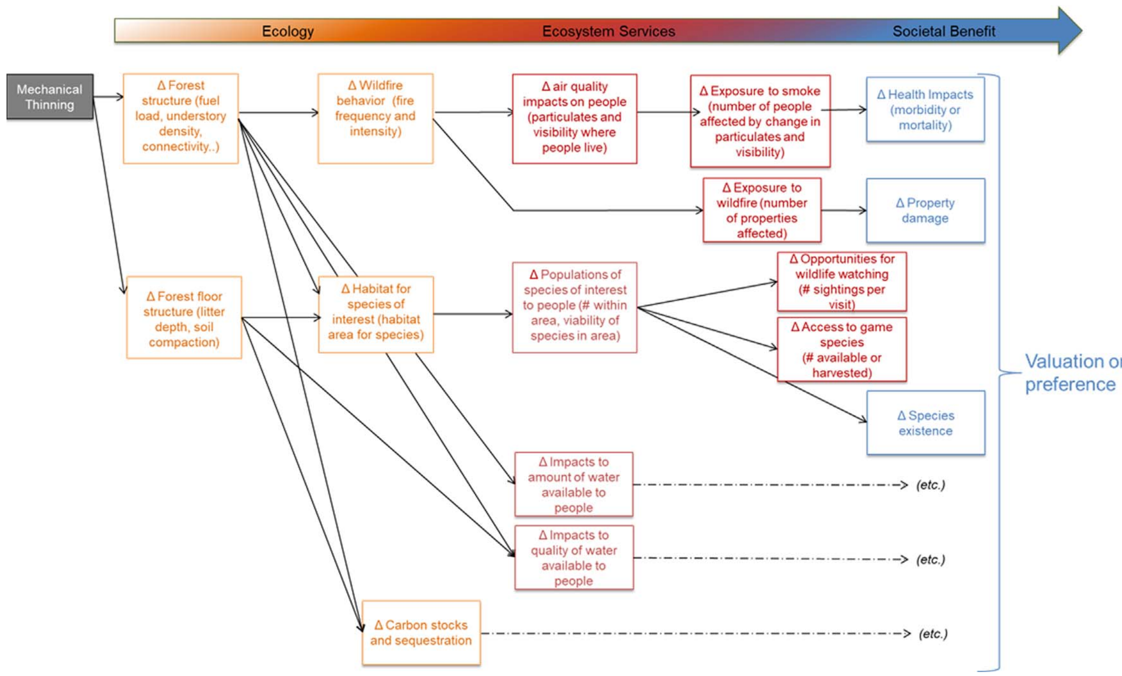

Fig. 3. Expansive causal assessments are useful to understand the multiple ways in which an action influences ecological systems (orange), services or BRIs (red), and societal benefits (blue). The line between the ecological changes, BRIs and social benefits are not always sharp and there can be overlaps; sometimes an ecological change (e.g., species population) can be a BRI, and sometimes BRIs (e.g., opportunities for wildlife watching) can represent social benefits. This illustration is simplified. Understory thinning affects forest structure, which changes not only the intensity of fires, but also species habitat, risk of pest and pathogen outbreaks, and forest carbon storage. Each of these ecological changes can be followed along individual causal chain branches of the conceptual map to one or more ecosystem services and anticipated human benefits, for which BRIs can be identified. To ensure a transparent process, these initial conceptual diagrams should be expansive and comprehensive, including all likely changes, even those that are likely to be difficult to measure or model or that are likely to have only a small effect, if it could be important to people. Later this expansive model can be winnowed down to those outcomes most likely to be large and/or important to human well-being.

measurement of BRIs should be used to assess or monitor the ecosystem services outcomes of an action that has already taken place, while predictions or estimates of changes in BRIs can be used to assess proposed projects, actions and policies.

The process of quantifying ecosystem services involves converting the conceptual model depicted as a causal chain into an operational empirical model to estimate a change in a BRI as a function of an action, i.e., developing a formal relationship between an action (policy, project, management) and its effect on the production of services. The methods that can be used differ in the time, resources, and capacity required (Fig. 4). A narrative description of changes in ecosystem services could take the least time and resources and can provide a context for creating well-defined measurement scales. However, narrative information is not easily reproducible, testable, or useable in valuation or decision analysis methods in the same ways as information expressed using a well-defined measurement scale. Given these limitations, BRIs cannot be purely narrative; instead quantitative data (which includes categorical, ordinal (rank) or continuous data) are required.

A BRI's scale of measurement must be defined with sufficient clarity and precision to be applied by different users and to different decision contexts with consistent results (e.g., they must be repeatable). Numerical measurement scales, whether continuous (e.g., board feet of merchantable timber available from a specified land parcel) or discrete (e.g., numbers of deer taken by recreational hunters during a specified period of time from a specified geographic region), are obvious candidates. Sometimes descriptive narrative information can be converted to well-defined categorical or qualitative data. A relevant categorical BRI might include the presence or absence of a resource valued for its simple existence, such as the presence/absence of a particular listed species in a specific geographic area during a specific period of time, as determined by an agreed-on detection method. Other types of categories might reflect key thresholds or officially defined categories—for example, whether a population is considered endangered or threatened according to established guidelines. Thresholds between categories need to be defined clearly to provide reliable results. Scales such as "low," "medium," and "high" fail to meet this standard of clarity, unless such terms are clearly linked to well-defined thresholds. Categorical measures of BRIs must be defined using a scale that is unambiguous, measurable, and replicable (Clemen and Reilly, 2001; Hazen, 2000; Schultz et al., 2012). Quantitative measures of ecosystem services will make the services easier to evaluate intuitively and to incorporate into formal analysis, making the services more likely to be fully considered in decisions. Quantification of BRIs can be conducted using a range of methods, but all require understanding what resources and what people are affected, and would benefit from a consideration of uncertainty.

4.1. Methods for quantifying BRIs influence their accuracy

Various methods may be used to quantify BRIs, depending on the level of accuracy required. Informal and formal methods of expert elicitation (e.g., Bayesian belief networks) can be used to generate models and estimate measures of BRIs, including estimates of uncertainty (e.g., Landuyt et al., 2013; Kuhnert et al., 2011). Existing models or well-established relationships may be drawn from the literature, or new models may be developed to capitalize on available data (e.g., Richardson et al., 2014; Watson Keri et al., 2016; Johnson et al., 2016). For example, in the wetland restoration example (Fig. 2), a study of fish mortality and reproduction that collected data on the effects of wetland restoration in a similar region could be used to estimate the proposed project's effect on services. (See Peterson et al., 2003; Powers et al., 2003 for a similar example on reefs and fish.) Likewise, the health effects of smoke from fires (Fig. 1) might be estimated using a concatenation of several sources of data and models (fire intensity from a fire behavior model, smoke production from fire intensity, a plume model for the airshed, and so on) (e.g., Rittmaster et al., 2006).

The accuracy of BRI quantification and/or forecasting is likely

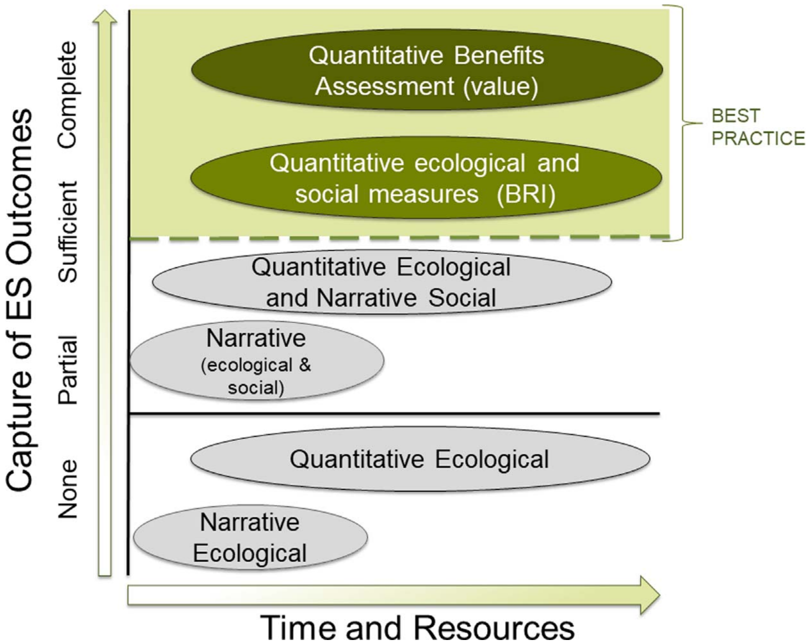

Fig. 4. Approaches for capturing of ecosystem services (ES) outcomes in assessments and decision making.

improved when models are based on data generated within the study region based on experiments using the management actions being evaluated and explicitly measuring outcomes in terms of the desired BRI (and any intermediate variables needed to build the model). This is the method of adaptive management, in which management treatments are implemented as experiments (with controls) and outcomes are monitored over time. In this case, the measured outcomes (BRIs) would be used to develop a local model that explicitly translates the management action into its ecosystem services outcomes. Clearly, this approach is ambitious. But because adaptive management is a stated ambition of most resource managers, this aspiration of measuring BRIs to develop a predictive model is entirely consistent with broader aspirations for improved management.

4.2. BRIs require identification of the serviceshed

Quantification of BRIs also requires understanding what resources and what people are affected. By design, BRIs are defined for a particular service that benefits a particular beneficiary group and thus a critical step involves defining the "serviceshed" – the population of people that will be affected (Tallis et al., 2012). A serviceshed captures the area that provides a specific ecosystem service to a specific group of people. The boundaries are defined by the area that supports the biophysical production of the service, by relevant access constraints (physical and institutional) to the service, and by demand for the service within that area (Tallis and Polasky, 2009; Boyd and Banzhaf, 2007). Thus, for example, people who visit or may potentially visit a lake are within the lake's serviceshed, even if they live outside its watershed. If, however, constraints such as inaccessibility or prohibition of fishing in parts of the lake exist, no fishing benefit can be generated where fishing is not allowed, even if fish are very abundant; the BRI might be the change in recreationally important fish accessible to anglers given the constraint. If people value the existence of the lake or species in the lake whether they visit the lake or not, then its condition and continuance is what matters and access is not relevant.

For a locally used service like municipal water supply, the serviceshed can be drawn around those using water within the watershed downstream of the policy or project action. Decision makers need to know not only where these people are, but who they are, how many, and whether they are affected by potential changes in the provision of services (e.g., reduction in flood or fire frequency or intensity). For a service used or appreciated by a broader or spatially distributed group of people, like cultural appreciation of a particular location, the serviceshed would include the area providing the service and its connections to those using or appreciating the service. Servicesheds for non-market services such as these can be more difficult to identify. A serviceshed including all those who value the particular service can be national or even worldwide. Servicesheds for nonuse values in particular can often span very great distances (Johnston et al., 2015; Haefele et al., 2016).

All services do not flow to all people equally, and some decision contexts present a requirement to consider those differences (e.g., Jennings et al., 2016). A serviceshed captures the population that will be affected, and can help decision makers consider where a change in provision of a service may have a large impact on particular populations, including social groups of special concern, such as the elderly, young, or disabled or those who are part of tribal communities or are economically disadvantaged.

Direct engagement and outreach with communities and community groups, along with social media and surveys, can be used to identify and determine the size of affected communities (Reed, 2008; Bright et al., 2003; Wood et al., 2013). In the absence of a primary study or other direct means to identify the distribution of affected individuals (e.g., a survey conducted using a random sample over the potentially relevant area), indirect means, while less accurate, may be used. For example, data from the U.S. census or large-scale surveys like the National Survey on Recreation and the Environment (https://www.srs.fs.usda.gov/trends/nsre-directory/ NSRE, 2016), and perhaps information on what people purchase (e.g., fishing gear or bird identification guides), can help identify and quantify affected people. A considerable economic literature is devoted to determining the "extent of the market" for ecological benefits (or where benefits occur); this literature details a variety of approaches (Bateman et al., 2006; Loomis, 2000; Loomis, 1996).

4.3. Uncertainty varies with the method used to measure BRIs

Quantification of BRIs often involves considerable uncertainty (Hou et al., 2013; Carpenter et al., 2009). The complexity (length) of the causal chain amplifies uncertainty, because information loss occurs at each link of the chain. For example, we are generally more confident about the impact of restoration on nitrogen concentrations than we are about restoration impacts on oxygen content and fish population demography, and still less confident about the effects on numbers of catchable fish (Fig. 2). Similarly, we might expect some uncertainty about human health impacts of smoke from fires (Fig. 1) because of the propagation of model uncertainties about fire behavior, smoke production, plume dispersion in the airshed, and human response to smoke exposure. It is worth underscoring that one advantage of using causal chain diagrams is that they facilitate communication of these uncertainties by being explicit about the links between cause and effect and what is known (or unknown) about these links, and by being explicit about what proxies are being used and making clear the need to determine their relevance to the benefit of interest.

Another source of uncertainty in BRIs arises from the difficulty of measuring impacts in relevant terms. For example, in the case of a commercial fishery we might index "catchable fish" directly from commercial landings. But in other (noncommercial) instances, we might have to be satisfied with estimates of fishing success derived from fishing permits, visitor days, or some other measure imperfectly related to actual numbers of fish caught. An additional complication is that measures such as "fish caught" can be confounded with attributes of the social system – such as fishing expertise or technology. Unless confounding factors such as these are held constant it can be unclear to what extent the measure reflects changes in the ecological system alone (i.e., flow directly from biophysical effects of the action under consideration). Where such confounding is expected to be significant, measures such as fish abundance in areas used for fishing can provide less confounded alternatives. In all cases, the use of proxies for BRIs should be accompanied by an estimate of confidence in the accuracy of the proxy estimate, and a clear description of what the proxy is designed to measure. When choosing the most suitable BRIs for any particular application, analysts often need to balance the direct proximity or relevance of the measure to benefits with the effect of potentially confounding factors and the ability to obtain accurate information.

5. Use of BRIs in intuitive, trade-off and preference analyses

By design, BRIs provide intuitive inputs to ecosystem services analysis and stakeholder deliberations because they have a direct and unambiguous link to social value. BRIs can serve as the starting point for decisions about how to manage ecosystems to enhance social value, whether those decisions are made intuitively or with the aid of formal methods to capture preferences through monetary or non-monetary valuation (Fig. 5).

Table 2
Alternatives matrix for considering ecosystem services in intuitive decision making using an illustrative example.
Source: Adapted from National Ecosystem Services Partnership, *Federal Resource Management and Ecosystem Services Guidebook* (Durham: National Ecosystem Services Partnership, Duke University, 2016), https://nespguidebook.com/assessment-framework/alternative-matrices-and-maps/.

Ecosystem Service Benefit-Relevant Indicator		Policy or Management Alternative		
		Option A	Option B	Option C
BRI 1	Vegetation density in areas upstream of flood prone area with people or property of interest	Decrease 5–10%	Increase 5–10%	Increase 15–30%
BRI 2	Aquifer volume accessible by households	Decrease 5–10 acre feet	Increase 5–10 acre feet	Increase 1–2 acre feet
BRI 3	Amount of fish landed commercially	Little to no change	Little to no change	2–3% increase
BRI 4	Acres of wetland habitat supporting recreationally important bird or fish species	15% decrease	5% increase	10% increase

5.1. Intuitive decision making has limitations but is improved with BRIs

BRIs can be used in intuitive decision making, where preferences, priorities and tradeoffs among conflicting objectives are handled without explicit analysis. Intuitive comparisons require decision makers to use their knowledge of preferences (stakeholder or institutional) implicitly, rather than to assess them explicitly. When such an approach is taken, a basic, helpful step can be to construct an "alternatives matrix" that depicts each policy option's associated (measured or modeled) BRI outcomes (Table 2). An alternatives matrix can include other information in addition to ecosystem services, such as the costs of different alternatives. This approach can help with transparency and communicating what is known about different alternatives and can place ecosystem services on the same footing as other factors important in decisions.

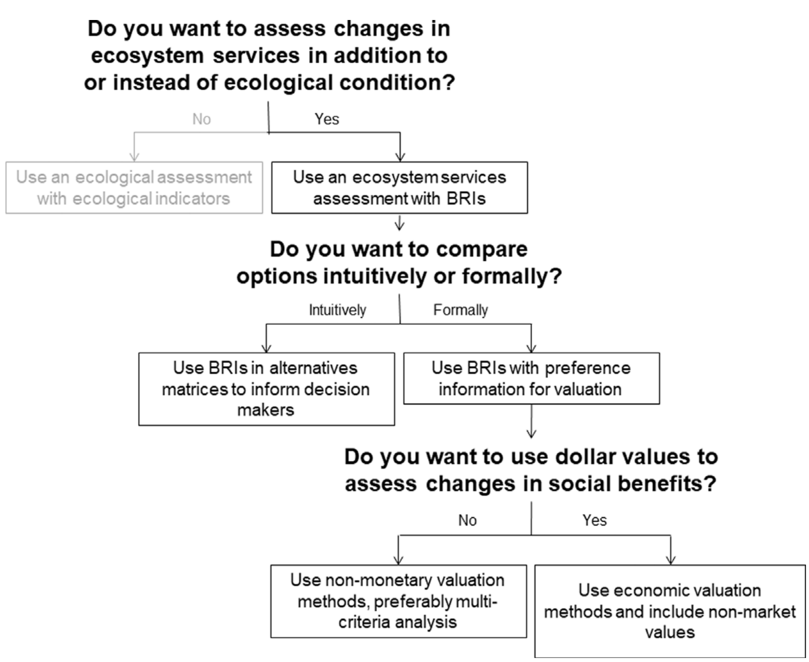

Fig. 5. How benefit-relevant indicators can be used in ecosystem services assessments.

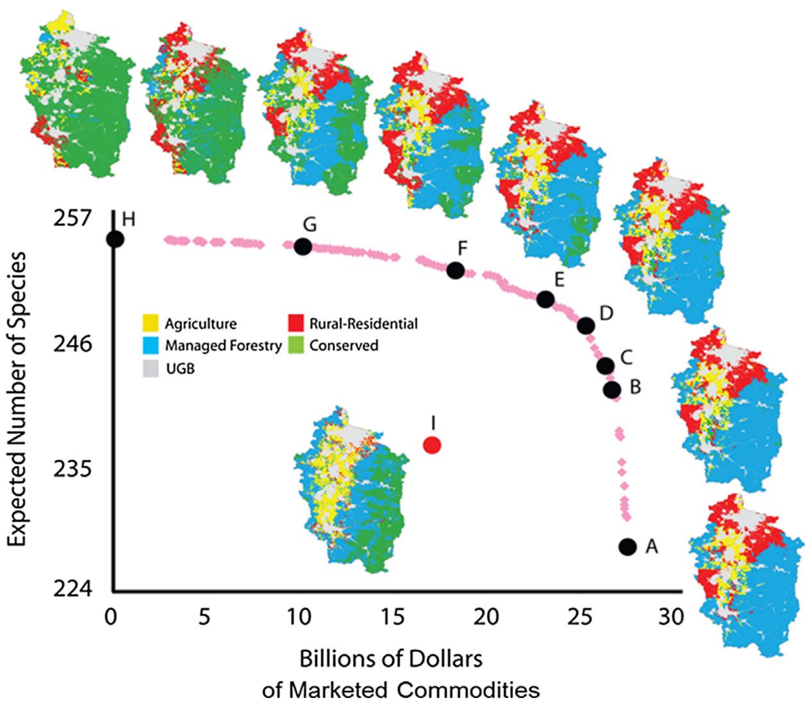

Fig. 6. Schematic plot ("efficiency frontier") showing how marketed commodities and number of species can be used to assess tradeoffs between land use policies and species persistence.
Source: S. Polasky et al. "Where to Put Things? Spatial Land Management to Sustain Biodiversity and Economic Returns," *Biol. Cons* 141(6) (2008):1505–1524.

5.2. Evaluating tradeoffs with BRIs can be useful but does not replace preference analyses

BRIs alone do not depict the importance, weight, or value attached to ecosystem services outcomes. Hence, the insight that BRIs alone can provide into tradeoffs is limited. Consider policies that incentivize different types of land use among agriculture, timber, housing, and conservation areas that affect the value of marketed commodities—agricultural crops, timber harvests, and housing values (all measured in dollars). These policies may also affect the persistence of terrestrial vertebrate species (measured in number of species expected to persist in the basin) and so tradeoffs in ecosystem services are inherent (Fig. 6). It is assumed that species have existence value to the extent that people perceive benefits from the survival of a species, though putting that value in monetary or even non-monetary terms is difficult.

Although some services in this example are reflected in value terms and others in BRIs, trade-offs can still be considered. Clearly, points B–F are superior to point I, which represents the current land use pattern, because they generate both higher conservation benefits in terms of more species and higher value of marketed commodities. But whether C is preferred to D or vice versa (or to any other two points on the efficiency frontier) depends on a value judgment about the relative importance of species conservation versus value of marketed goods (Polasky et al., 2008). Is greater conservation or greater value of commodities preferred? In this case, BRIs help assessors consider the options in intuitive and socially relevant terms, but they do not identify a single best option without further analysis.

An action with positive effects on a greater number of BRIs will not necessarily have greater social value than an action that affects fewer BRIs. In general, the assessor cannot simply count (positively) affected BRIs provided by a system as a proxy for social value. Effects on social welfare depend not only on how many BRIs are affected, but also on the degree of change in each BRI and the relative values of each BRI to all beneficiary groups. Most decision contexts and policy options (environmental or not) involve tradeoffs that, if they are to be evaluated formally rather than intuitively, require application of preference evaluation methods.

5.3. The use of BRIs in preference evaluation improves transparency and defensibility and also clarifies the outcome being valued

An explicit expression of preferences in the form of monetary or non-monetary valuation is needed to make well-informed management decisions if changes in services (in response to management or policy) vary in direction or magnitude, such that tradeoffs are implied. For example, explicit expressions of preferences for affected stakeholder populations are needed if (1) some services increase while others decrease due to the alternative management actions under consideration, (2) different stakeholder populations receive different changes (increases or decreases) in ecosystem services due to alternative actions (e.g., receive different levels of smoke), (3) different stakeholder populations experience or value the same change in a service differently (e.g., experience different health effects of smoke because of factors such as age), (4) different stakeholder populations have different priorities among ecosystem services (e.g., different populations prioritize health consequences differently relative to financial consequences), (5) there is a need to compare ecosystem service benefits or losses to monetary costs (or cost savings) in comparable units. In each of these circumstances tradeoffs will have to be made, among services, among stakeholder groups, or between benefits and costs. Hence, a preference evaluation of some kind will be required to understand net social benefits. Here, *evaluation of preferences* refers to a broad set of analytical methods, including both economic valuation and non-monetary multi-criteria analysis. *Value* is used in the economic sense to imply well-defined, generally monetary, measures of value. *Preference (s)* is used to reflect how individuals order outcomes based on the relative satisfaction or enjoyment (i.e., utility) they provide; outcomes that generate greater utility also generate greater value. Without preference evaluation, the analysis is left only with conclusions regarding quantities of *what is valued* (e.g., additional irrigation water in Fig. 7), without any information on *how much they are valued* (e.g., how much the additional irrigation water contributes to increased farm profits, Fig. 7).

Information or assumptions about social preferences or values are essential for decision makers to draw conclusions about how changes in the provision of ecosystem services will affect social benefits. Even "more is better" conclusions require decision makers to assume a

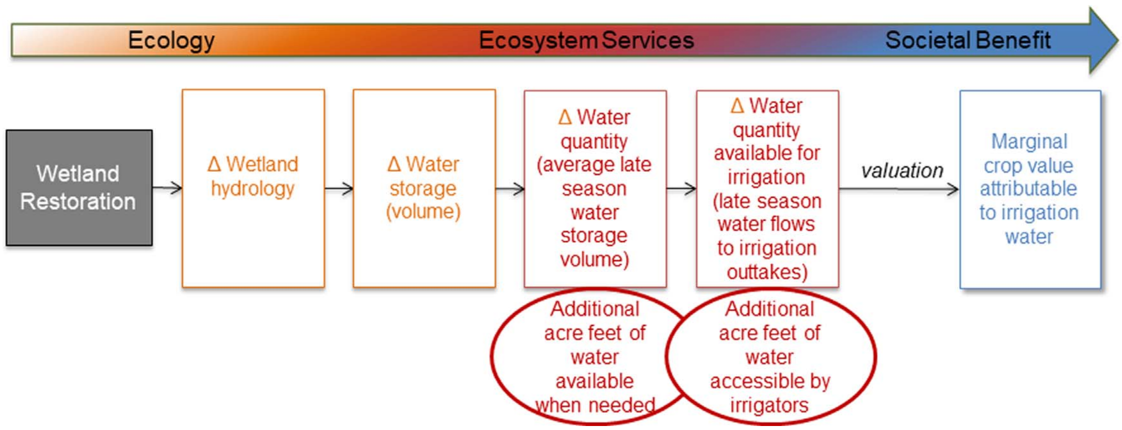

Fig. 7. Valuation links the ecosystem services supply measured as a BRI (red in circles) quantities of what is valued and the social benefit (blue). "Marginal" refers to a small, additional change to an existing quantity. Consequently, marginal crop value would refer to the additional crop value provided by the action under study.

positive relationship between services and social welfare. A policy that influences a greater number of services is not necessarily superior to a policy that influences fewer, and more of a service is not always better.

In principle, it is possible to conduct preference evaluation using BRIs at any point in a causal chain, as long as the relationships between actions and changes in services (i.e., ecological production functions) are known. In some cases, preferences or values are estimated for measures that—although not BRIs in a universal sense—do represent BRIs in a specific context (e.g., a measure of chemical water quality in a context in which that measure has immediate and measurable health implications for people, quantifiable through established models). Regardless of the point on the causal chain at which values or preferences are estimated, BRIs improve the process and, in general, preferences and values can be estimated with greater certainty when the evaluation (e.g., monetary valuation) is conducted for BRIs that are more directly proximate to human welfare (i.e., are further to the right on the causal chain) (Boyd and Krupnick, 2013; Johnston and Russell, 2011). Additionally, the use of vague or poorly defined measures will lead to poorly defined or biased measures of value. Put another way, a measure of value can only be as good as the biophysical measure on which it is based. Johnston et al. (2012) and Schultz et al. (2012) discuss desirable properties of biophysical indicators used for valuation. The most appropriate BRIs for use within any particular valuation model will depend on the type of value being estimated and the type of valuation model being used. The economic literature provides guidance on the choice of specific BRIs for different types of revealed and stated preference valuation, although these works do not necessarily use the "BRI" terminology (Boyd et al., 2016; Johnston et al., 2012, 2017; Ringold et al., 2009, 2011; Schultz et al., 2012; Zhao et al., 2013).

Economic values are meaningful only for a particular quantity of a market or nonmarket commodity (or BRI) relative to a specific baseline. In other words, they are only meaningful when valuing a specific change in the provision of a service. If the change is large (i.e., non-marginal), value estimation must account for the fact that per-unit values for any commodity generally diminish as more of that commodity is obtained (a phenomenon referred to as *diminishing marginal utility*, where utility is the amount of benefit obtained). For example, a recreational angler is generally willing to pay more per fish to increase her catch from 0 to 1 fish than from 99 to 100 fish; the value of a marginal fish depends on how many fish have already been caught (Johnston et al., 2006). In most cases, the change in a BRI cannot be multiplied by a simple "unit value" to arrive at a total value of the change (at least for non-marginal changes); doing so would overlook the fact that marginal values tend to diminish as quantity or quality increases. Similarly, values per unit of area (e.g., per acre) generally cannot be calculated and multiplied by the total affected area. Applying values determined for one scale of change to another scale of change is inappropriate, making it difficult to estimate regional or national values from local values. Patterns such as these are relevant whether monetary or non-monetary valuation methods are applied. Thus, values for any BRI should be determined over the relevant scale of change, rather than being assumed to be linear for any range of effects and invariant across geographic scales. Methods to account for diminishing marginal values (i.e., downward sloping demand) in economic valuation are well established (Freeman et al., 2014). Johnston and Wainger (2015) discuss value scaling for ecosystem services when data are limited and value patterns cannot be estimated directly. In a small number of cases, linear value scaling may be feasible, but this is an exception rather than the rule. An example would be small-scale localized changes in a good valued due to its global consequences (or because it is sold on global markets), such as changes in local greenhouse gas emissions.

While monetary expressions of value are often preferred for policy analysis and expressing all benefits in a common monetary metric allows for analysis of tradeoffs among services and a clear bottom line in terms of net benefits, there are limitations to using monetization to express the value of ecosystem services (Arrow et al., 1996; National Research Council, 2014), Decision makers may be reluctant to monetize some kinds of services (especially cultural, e.g., Winthrop, 2014), or the difficulty or expense of estimating monetary values may be large relative to agency resources (Wainger and Mazzotta, 2011).

When monetization of all or some of the ecosystem services measures in an analysis is inappropriate or too difficult to do well, assessors can use a variety of analytical methods with both monetized and non-monetized components to develop a ranking or rating of alternatives with respect to their contributions to stakeholder preferences for ecosystem services (Maguire, 2014; NESP, 2016; Gregory et al., 2012; Department of Communities and Local Government, 2009). Although multi-attribute utility analysis, or MAUA (a type of multi-criteria analysis) has been criticized as too time-consuming and too dependent on special expertise, it has the advantage of obliging users to think carefully about all the elements of preference evaluation in a systematic way. MAUA assigns relative preferences to different levels of a single BRI and these preferences can differ among stakeholders and among decision contexts. It also assigns different weights or priorities among multiple BRIs in order to create a single combined metric of overall contribution to ecosystem services. Non-monetary methods such as MAUA can be useful for planning processes and can reveal options that produce the highest ecosystem services benefits for a given amount of spending, even when benefits cannot be monetized (Wainger et al., 2010; Arvai and Gregory, 2003; Gregory and Wellman, 2001; Linkov et al., 2004).

6. Conclusions

Incorporating ecosystem services into decision-making can change the way a problem is perceived and the way solutions are formulated because decision makers consider not only changes to ecological conditions but also how these changes can affect people. Yet despite consensus around the general concept of ecosystem services, those seeking to conduct ecosystem service analysis to support decisions often lack systematic guidance on what to measure and how. As a result, decision makers frequently attempt to conduct ecosystem services analysis using biophysical measures or narratives that are poorly suited to the purpose. Common examples include imprecise narrative descriptions of ecosystem services or biophysical measures that lack a clear and identifiable relationship to social benefits. As a result, ecosystem services are often not considered on an equal footing with other costs and benefits when decisions are made.

This article seeks to formalize measurements that are ideally suited to support ecosystem services analysis, defined in terms of Benefit Relevant Indicators (BRIs). BRIs are measurable descriptors of ecosystem services of all types, whether market goods or non-market, including those that support existence values for species and ecosystems. BRIs use well-defined measurement scales; these can be categorical, ordinal or continuous, permitting measurement of qualitative as well as quantitative characteristics that are compatible with valuation and decision analysis methods. BRIs make explicit the connections between ecological conditions and human use and enjoyment using causal chains, which can be implemented as mental models or as formal predictive models, along with serviceshed that clarify the areas and beneficiaries affected. BRIs can be inputs to formal valuation of preferences in either monetary or non-monetary terms. Or, when formal valuation is either not desired or not possible, BRIs themselves can represent ecosystem services in analyses of environmental management decisions. Because BRIs are defined based on social relevance, their use can also increase the transparency and defensibility of subsequent nonmarket valuation.

By moving beyond purely ecological measures and using BRIs in academic and government research and applications, understanding of the connection between ecological change and social outcomes can be improved. This can help to improve the handoff of information between natural and social scientists and enhance the information available to decision makers considering management that alters ecosystem services. This linking of ecological and social outcomes is the foundation for the ongoing transition in both the public and private sector to better incorporate ecosystem services and natural capital into decision-making.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolind.2017.12.001.

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