Title: Towards a threat assessment framework for ecosystem services

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Abstract: How can we tell if the ecosystem services upon which we rely are at risk of being lost, potentially permanently? Ecosystem services underpin human wellbeing, but we lack a consistent approach for categorizing the extent to which they are threatened. We present an assessment framework for assessing the degree to which the adequate and sustainable provision of a given ecosystem service is threatened. Our framework combines information on the states and trends of both ecosystem service supply and demand, with reference to two critical thresholds: demand exceeding supply, and ecosystem service 'extinction'. This framework can provide a basis for global, national and regional assessments of threat to ecosystem services, and accompany existing assessments of threat to species and ecosystems.

Ecosystem services under threat

Rapid change to the biosphere, geosphere and atmosphere threatens humanity's life support system [1] and erodes many of the ecosystem services (see Glossary) upon which we depend [2-4]. Identifying and ameliorating threats to ecosystem services is central to avoiding potentially irreversible losses. But which services should we be most concerned about, and where?

The last twenty years have seen rapid growth in our understanding of the critical importance of ecosystems for human wellbeing. The Millennium Ecosystem Assessment (MEA) [4], established an understanding of ecosystem services and how human activities affect them [5], and concluded that sixty percent of the ecosystem services were degraded or being used unsustainably. A more recent analysis reports substantial losses of ecosystem services globally [2]. In response to these and other concerns, the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) was established in 2012 to synthesise scientific evidence on the state of biodiversity and ecosystem services and provide policy-relevant knowledge for decision-makers [6].

The risk of extinction of individual species, and collapse of ecosystems, is tracked and classified IUCN Red List classification systems (Box 1). These systems provide understanding of the scale and urgency of threats to species and ecosystems, and guide plans to avert and alleviate these threats. There is, however, no standard set of criteria for pinpointing when and to what degree adequate provision of an ecosystem service in a given area is at risk, or how immediate the risk of complete loss of the service is. We therefore lack a consistent basis for prioritising investment in abating threats to ecosystem services or promoting their recovery. Such a standardised framework would create a necessary link between the science of ecosystem assessment, and the policy imperative to safeguard ecosystem service provision.

Growing recognition of the importance and complexity of ecosystem services has helped drive advances in our ability approaches to measure, map and chart their dynamics [2, 7]. Increasingly sophisticated approaches for assessing the state of ecosystem services, particularly their supply, are being developed [8-17]. These developments lay the foundation for the development of a structured, consistent classification system designed to determine the degree to which adequate provision of a service is at risk, or might become so in the future.

We present a framework for assessing and classifying risk to the adequate provision of an ecosystem service in a defined region. Our framework considers the supply of a service by natural capital, demand for that service by people, and recent or projected trends in these two factors. It therefore extends the 'risk register' approach proposed by Mace and colleagues for natural capital [13] to incorporate trends in service demand. As the need to prioritise investment in safeguarding ecosystem services becomes more urgent, a framework for assessing when and where ecosystem services are imperilled is timely.

Assessing supply and demand

Ecosystem services encompass a wide variety of benefits to people from nature, which exist within, and are influenced by, complex social-ecological systems [18]. They include physical goods such as crops or fibre (provisioning services); processes including climate and flood regulation (regulating services); and physical, emotional, and spiritual benefits from nature (cultural services) [4].

Because each ecosystem service represents a distinct interaction between people and ecosystems through which human wellbeing is enhanced, service provision depends equally on the structure and function of ecosystems, and upon human needs, values, preferences, assets, and institutions [6]. For example, benefits to people from flood regulation are conditional on both the presence of ecosystems that can absorb and slow flood waters [11] as well as human populations and infrastructure in areas of flood risk that will then benefit from reduced flooding [19].

We therefore argue that the absolute level of service provision is not the appropriate metric for evaluating threat. Instead, the level of risk to adequate ecosystem service provision – *whether supply meets demand* – must be evaluated [20]. This creates challenges for designing a consistent and practicable framework to assess threat to ecosystem services. It means that any threat assessment framework must evaluate both ecosystem service supply (the potential for natural capital to generate a benefit for people [17]) and demand (the level of service provision desired or required by people [21]).

Defining threat in the context of ecosystem services

For species or ecosystems, Red List threat assessment approaches consider the risk of ‘extinction’ or ‘collapse’, respectively (See Box 1). Such approaches are designed to communicate the risk of permanent loss of species or of ecosystem integrity, in order to prioritize conservation actions. The concept of threat to adequate provision of an ecosystem service, however, differs in several key ways due to the need to consider both supply of the resource and demand for it, across multiple spatial scales.

First, the relevant threat will often be the loss of service provision to a group of regionally-circumscribed beneficiaries, rather than global loss of an ecosystem service. A system intended for ecosystem services must be designed at the outset for application at multiple scales.

Second, it is not only the complete loss of ecosystem service provision that can have important effects on human wellbeing. An impact on beneficiaries of a service is characterized by supply being insufficient to meet demand (undersupply). A threat categorisation framework therefore needs to reflect risks related to both the undersupply of an ecosystem service, and complete cessation of supply (in our framework, either *Dormancy* or *Functional Extinction* of the service; see below).

In contrast to the extinction of a species, the loss of an ecosystem service can sometimes be at least partially reversed through the restoration of ecosystems [22, 23]; in other cases, reversal may be impossible. As such, a framework should recognize and distinguish between reversible and irreversible ecosystem service loss.

The framework

Assessing threats to ecosystem services

An overview of the framework we propose is presented in Figure 1. The category into which a given service in a given assessment context falls is determined by the current ratio of supply to demand, in combination with recent or anticipated trends in both supply and demand (Fig. 1).

Least Concern and *Vulnerable* classifications both apply to services for which demand does not currently exceed supply. The key distinction between the two relates to anticipated changes in supply and demand. A service can be Least Concern even if its provision is declining, if that decline is caused or accompanied by a proportional decline in demand (Fig. 1). A well-supplied service for which demand is low is oversupplied, and so even reductions in supply might not be of concern—unless they are rapid, sustained, or approach a tipping point, in which case a Vulnerable classification is warranted (Fig. 1).

If supply of a service has already declined such that supply no longer meets demand, then one of three higher threat levels applies. If supply falls short of demand but the ratio is stable, then the service is classified as *Stable but Undersupplied*; if the ratio is stable but supply (and demand) continues to decline, it is classed as *Endangered*. Finally, if a service is undersupplied, and the supply:demand ratio is continuing to decline, then a higher threat category of *Critically Endangered* applies. The distinction among these categories of undersupply differs from more familiar threat categorisation approaches such as those used for species, because of the need to reflect two undesirable states (undersupply and loss) as well as the risk of moving from a category of undersupply to one of loss.

If declines in the ratio of supply to demand are prolonged or severe, then ultimately, the level of supply relative to demand will become negligible and the service is effectively lost. Our categorization system reflects two forms of ecosystem service loss. If supply potentially can be recovered, then the service is *Dormant*. However, for some services, might not be possible to repair an ecosystem so that service levels meet demand —the service is unrecoverable, and *Functionally Extinct* (Fig. 1). The latter is akin to functional extinction of a service, such as might occur in the case of severe land degradation and loss of soil productivity, permanent land cover replacement, or persistent drying of a waterbody.

Consequences of ecosystem services loss for beneficiaries

Unlike the extinction of a species, the equivalent version of ‘extinction’ of a service in a region is not final. Some ecosystem services are potentially recoverable, and some are substitutable, at least temporarily and at small scales [24, 25]. Five consequences for beneficiaries of a service becoming Dormant or Functionally Extinct are therefore possible, and an example of each of these is illustrated in Figure 2: 1) Ongoing human wellbeing implications due to persistent unmet demand; 2) demand is met through flows of ecosystem services from other regions [26], 3) demand is met through substitution by technology or built infrastructure or other means; 4) demand declines or ceases due to changes in human preferences; or 5) the demand ceases through emigration or other kinds of loss of those demanding the service. Thus, the precise nature of the undersupplied or functionally extinct ecosystem service will influence decisions about whether and how to respond, for example by attempting to recover and restore a dormant service or facilitating ecosystem service substitution.

Applying the framework

What spatial extent?

Defining a precise assessment region within which a particular ecosystem service should be assessed is challenging. First, ecosystem service provision depends on the characteristics of, and interactions between, ecosystems and socioeconomic systems [6, 27]. Second, the spatial scale relevant to the supply of a particular ecosystem service can vary from global (e.g. climate regulation) to local (e.g. aesthetic value). Third, ecosystem services can flow to meet demand at distant locations [8], resulting in mismatches between appropriate assessment regions for ecosystem service supply and demand [28]. For example, global trade has expanded cities' demand for food and timber provision to much larger supply regions [29, 30].

Landscape-scale assessments that incorporate areas of ecosystem service supply and demand, especially landscapes that correspond with ecoregional, watershed, or jurisdictional boundaries (e.g. nations) are often appropriate [31, 32]. However, multi-scale assessments are often a useful approach [33] because they can include different services acting across scales and their interactions [10]. The most appropriate spatial extent or extents will vary depending on the purpose of the assessment, and so for most services the threat category into which they fall will be specific to the particular assessment exercise.

In most cases, ecosystem services are produced within social-ecological systems that defined by biophysical boundaries, beneficiaries, and jurisdictions. For example, assessments often evaluate multiple ecosystem services within single watersheds that encompass similar agricultural landscapes, ecosystems, human actors, and institutional boundaries (e.g. [34]). Assessments focussed on such systems in which common drivers of supply and demand are identified across multiple ecosystem services can help determine how to most efficiently alleviate threats to adequate and sustainable supply.

Alternatively, because stakeholder groups use or value ecosystem services differently [35, 36], identification of a specific beneficiary group or groups [37] could be an important early step in an assessment, with specific spatial or temporal extents for each service determined based on how these groups interact with their environment. For example, fishers are likely to perceive coastal ecosystem services differently than urban dwellers, and the boundaries of an assessment for each group might, at least initially, differ [38]. In some cases, perceptions of ecosystem services associated with a given ecosystem, for example, could even be in conflict

[27]. Assessments that explicitly recognize different stakeholder groups might be more likely to identify the social relationships, institutions, and governance structures that are important for effectively choosing actions to conserve [39, 40] and ensure equitable access to ecosystem services [41].

Estimating state and trend of supply and demand

Application of our framework relies on quantifying not just the current state of ecosystem service supply and demand, but also anticipated trends in these variables over time. Simultaneous assessment of the state and trends of both ecosystem service supply and demand (in the same units) has rarely been attempted (although see [12, 28]), and remains particularly challenging. Research on ecosystem services has focussed on supply, but is increasingly incorporating both supply and demand [9, 20, 42]. While examining trends is more challenging than simply determining current state, estimates from historical data [43-45] or projections of climate or land use change and spatially-explicit human population projections are increasingly being developed and can be applied to estimate trends in ecosystem service supply and demand [34, 46, 47].

Importantly, future trends might often be expected to differ markedly from recent past trends, such as when assessments are linked to evaluating impacts of alternative future development scenarios. Similar to Red List threat assessment systems, our approach allows for assessments to draw from recent or projected changes, as appropriate. Factors such as ecosystem service reliability and accessibility vary markedly among services and regions [48], and a robust forecast of changes in trends in either supply or demand must account for these factors.

Where data are inadequate to inform detailed assessment, estimates can, at least initially, rely on expert opinion [49]. As information about supply and demand improves, these estimates can be evaluated and updated. Such iterative approaches for information-poor environments are standard practice in the assessment of threatened species and ecosystems [50].

Challenges and prospects

Our framework is similar in structure, use, information requirements, benefits, risks and limitations to Red List-type systems of threat assessment. It formalises and makes explicit assumptions about the state and the trend of both supply and demand of ecosystem services. Measuring or estimating all four of these parameters is a substantial challenge; we currently lack these data for most ecosystem services in most places [27]. Service provision is dynamic through time and space, and there are challenges in identifying both the appropriate extent and resolution at which threats to ecosystem services should be assessed. A widely agreed-upon classification of ecosystem services remains elusive [51]. Nevertheless, there are clear avenues for further development of the practical application of our framework, and for testing its assumptions, such as the degree to which the risk categories relate to an increasingly high risk of loss of an ecosystem service [52, 53].

There are substantial challenges in applying a classification approach to the elements of dynamic and interconnected systems (see *Outstanding Questions* Box 3). Supply and demand can be interlinked; waning supply might increase or decrease [38] demand. For example, some harvested species increase in value when they become rarer, while others decrease in value and are substituted. Changes in supply or demand are also likely to be driven in part by changes in the supply of and demand for other, related services.

That some ecosystem services can potentially be recovered, either by restoring supply or altering demand, adds important complexity to our framework. One avenue for recovery is the restoration of degraded ecosystems so that they can once again supply a previously-dormant service. For example, a degraded river ecosystem could be restored so that it can once again provide potable water. Alternatively, people could shift the place from which they draw water through improved access to a nearby water body that is still within the assessment region to meet demand. Judgment about the feasibility and desirability of such alternative pathways for ecosystem service recovery will be value-laden and investment-dependent. Assessing the likely paths to recovery and their feasibility is not an explicit part of our proposed framework, but it could be expanded to encompass such a step depending on the specific goals of the assessment and available data for the region in question.

Concluding Remarks

While knowledge of ecosystem services is far from perfect, decisions continue to be made that affect their provision, potentially irreversibly. In contrast with threatened species or ecosystems, ecosystem service provision is either incompletely or obliquely considered in environmental impact assessment, state of the environment reporting, and conservation planning. We suggest that this is partly due to the lack of a formal approach for identifying which ecosystem services are under threat, and where. Such an approach would render environmental reporting and assessment more complete and commensurate with societal values. While such classification systems are necessarily simplifications of complex phenomena, they play an important role in focussing thinking about responses to environmental change.

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Glossary

Accessibility: the ability of beneficiaries to access and thereby receive benefits from the supply of an ecosystem service; the extent to which a service flows to beneficiaries.

Biodiversity: the variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems. Defined here following the 1993 Convention on Biological Diversity (CBD) meaning of ‘biological diversity’, which equates to ‘biodiversity’ (http//www.cbd.int/convention/articles).

Ecosystem service: defined broadly, the biophysical and social conditions and processes by which people, directly or indirectly, obtain benefits from ecosystems that sustain and fulfill human life [4].

Ecosystem service demand: the level of service provision desired or required by people. Demand is influenced by human needs, values, institutions, built capital, and technology [21].

Ecosystem service supply: the capacity of ecological functions or biophysical elements in an ecosystem to provide a given ecosystem service that is used by human beneficiaries [12]. As such, ecosystem service supply for the purpose of this framework refers to the result of the combination of potential supply (as per [17]) and flow to beneficiaries.

Landscape: a heterogeneous area comprising interacting ecosystems that are repeated in similar form throughout, including both natural and anthropogenic land cover, across which humans interact with their environment [54].

Human wellbeing: the condition of living well. It has multiple constituents, including basic material for a good life, freedom of choice and action, health, good social relations, and security. These constituents, as perceived by people, are situation-dependent, reflecting local geography, culture, and ecological circumstances.

Natural capital: the stock of natural systems and processes from which ecosystem services are derived.

Red List: the IUCN Red List Categories and Criteria, which is a system for classifying species at high risk of global extinction [55]; and the IUCN Red List of Ecosystems Categories and Criteria, an analogous system for ecosystems [56].

Risk: the chance that the level of ecosystem service supply will be inadequate to meet demand or will cease completely within a set time horizon.

Social-ecological system: a complex and adaptive system of biophysical and social factors that interact in a dynamic manner.

Substitution: the situation whereby one ecosystem service is replaced by another, or by a technological solution.

Box 1. Summary of approaches for classifying threat to species and ecosystems under the IUCN Red List Categories and Criteria.

Red List of Threatened Species [57]

Threat: Global extinction (the last individual has died)

Categories: Data Deficient; Least Concern; Near Threatened; Vulnerable; Endangered; Critically Endangered; Extinct in the Wild; Extinct

Criteria: Species are assessed against up to five quantitative criteria (A-E) for assigning species to a risk category relating to states and/or projected trends in distribution, extent of occurrence, area of occupancy, and/or recent or projected trends in population size and composition.

Red List of Threatened Ecosystems [56]

Threat: Ecosystem collapse (a transformation of identity, a loss of defining features, and a replacement by a different ecosystem type)

Categories: Data Deficient; Least Concern; Near Threatened; Vulnerable; Endangered; Critically Endangered; Collapsed

Criteria: Ecosystems are assessed against up to five rule-based criteria (A-E) for assigning ecosystems to a risk category, relating to state and/or trend of distribution, degradation, disruption of biotic processes and interactions, and quantitative (modelled) estimates of risk of collapse.

Box 2 – Examples of threat classification for ecosystem services

Studies that explicitly measure or estimate both the state and trend of supply and demand for ecosystem services remain rare, but here we draw from two published examples to demonstrate how our classification system can be applied, drawing upon combinations of measured and expert-elicited data.

Provisioning service: Water in Leipzig-Halle, Germany

In a rare evaluation of both state and trend in ecosystem service supply and demand, Kroll and colleagues [28] quantified the supply of and demand for water (measured as mean annual percolation rate in $m^3\ ha^{-1}$) across the Leipzig-Halle region of eastern Germany. They estimated both supply and demand (from households, industry, mining and agriculture), and identified areas of over- and under-supply, for 1990, 2000 and 2007. Application of our categorization system to the patterns of supply and demand their analysis revealed would classify the provisioning service of energy in 1990 as undersupplied. The service remained undersupplied in 2000 and 2007, but the ratio of supply to demand increased. Based on this trend, water provision as an ecosystem service in the region is *Stable but Undersupplied* (undersupplied, but the ratio of supply to demand not expected to decrease).

Regulating service: Air purification in Barcelona, Spain

Baro and colleagues [9] compared the supply of air purification services (removal of PM_{10}, NO_2 and O_3 in $kg\ ha^{-1}\ y^{-1}$) with demand (based on air quality guidelines) for five European cities. Based on EU air quality reference standards, all five cities had adequate supply of PM_{10} and O_3 regulation, making these services either *Least Concern* or *Vulnerable* depending on trends in supply and demand. However, NO_2 regulation was undersupplied in all but one city (Stockholm), placing it within the range of *Stable but Undersupplied* to *Critically Endangered*, based on the states of supply and demand alone. Without information on trends, further classification is not possible. However, either a repeat of the evaluation, as per Kroll and colleagues [28] in the previous example, or an expert elicitation of likely future trends, would allow a finer-resolution classification.

Fig. 1. The proposed threat categorization framework for ecosystem services. Description of the criteria for the each of the seven proposed threat categories plus a Data Deficient category, showing the critical thresholds where services transition from secure to at risk, at risk to undersupplied, and undersupplied to lost.

Fig. 2. Examples of alternative consequences of ecosystem service loss for beneficiaries. Some consequences warrant more urgent attention than others; for example, mass environmentally-driven emigration is perhaps more critical than the impact of a change in human preferences. The loss or substitution of an ecosystem service can also have implications for other the provision of other services. For instance, whilst the storm protection service is still provided in Los Angeles via shoreline hardening, the loss of the natural coastline will have repercussions for carbon sequestration, waste assimilation and fisheries production. [58-64]

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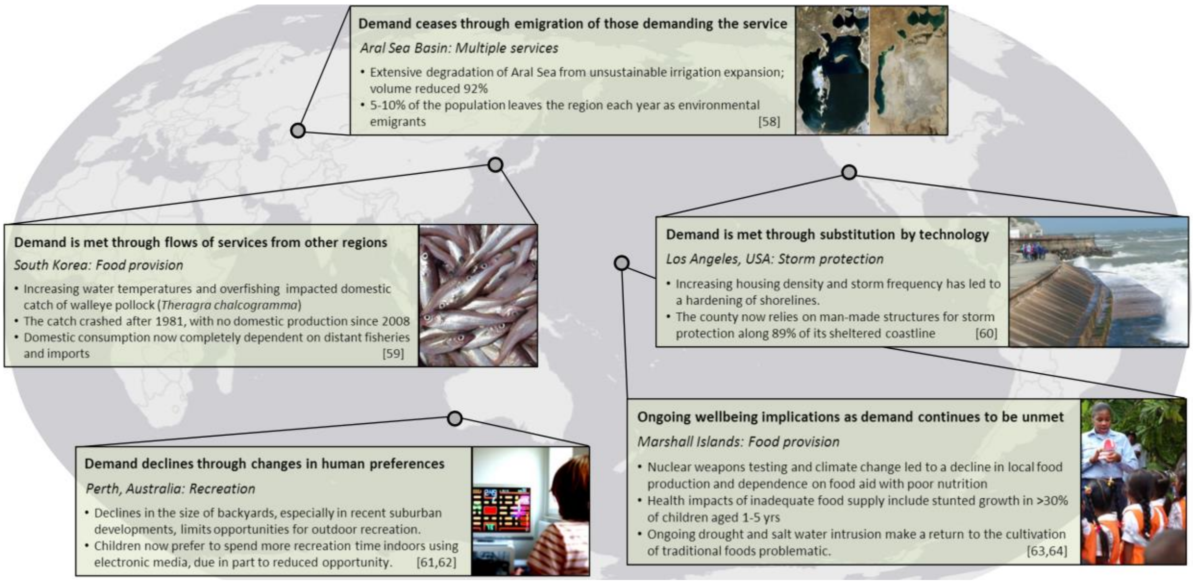
Category	Definition	Threshold
Functionally extinct	Service no longer supplied in the region and is practically unrecoverable	Lost
Dormant	Service no longer supplied in the region but is potentially recoverable	
Critically Endangered	Current levels of demand exceed supply and the ratio of supply to demand declining or expected to decline	Undersupplied
Endangered	Current levels of demand exceed supply; ratio of supply to demand is stable but supply is declining	
Stable Undersupply	Current levels of demand currently exceed supply; neither supply, nor ratio of supply to demand, declining	
Vulnerable	Ratio of supply to demand is declining or expected to decline such that supply is likely to be insufficient to meet demand within a set time horizon	At risk
Least Concern	Supply currently meets or exceeds demand, and does not meet the criteria for Vulnerable	Secure
Data Deficient	Inadequate information is available about either or both of supply and demand to assess the level of threat	n/a


Demand ceases through emigration of those demanding the service
Aral Sea Basin: Multiple services
• Extensive degradation of Aral Sea from unsustainable irrigation expansion; volume reduced 92%
• 5-10% of the population leaves the region each year as environmental emigrants [58]
Demand is met through flows of services from other regions
South Korea: Food provision
• Increasing water temperatures and overfishing impacted domestic catch of walleye pollock (Theragra chalcogramma)
• The catch crashed after 1981, with no domestic production since 2008
• Domestic consumption now completely dependent on distant fisheries and imports [59]
Demand is met through substitution by technology
Los Angeles, USA: Storm protection
• Increasing housing density and storm frequency has led to a hardening of shorelines.
• The county now relies on man-made structures for storm protection along 89% of its sheltered coastline [60]
Demand declines through changes in human preferences
Perth, Australia: Recreation
• Declines in the size of backyards, especially in recent suburban developments, limits opportunities for outdoor recreation.
• Children now prefer to spend more recreation time indoors using electronic media, due in part to reduced opportunity. [61,62]
Ongoing wellbeing implications as demand continues to be unmet
Marshall Islands: Food provision
• Nuclear weapons testing and climate change led to a decline in local food production and dependence on food aid with poor nutrition
• Health impacts of inadequate food supply include stunted growth in >30% of children aged 1-5 yrs
• Ongoing drought and salt water intrusion make a return to the cultivation of traditional foods problematic. [63,64]

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