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Increasing decision relevance of ecosystem service science

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The ecosystem service (ES) community aspires to illuminate how nature contributes to human well-being, and thereby elevate consideration of nature in decision making. So far, however, policy impact of ES research has been limited. To understand why, we identify five key elements of ES research that help inform decisions by connecting the supply of ES to those who benefit from them. Our structured review of the ES literature reveals that only 13% of assessments included the full ES chain from place to value. Only 7% of assessments considered the distribution of ES benefits explicitly across demographic or other beneficiary groups (for example, private landowners versus the broader public), although disaggregation across regions or spatial units was more common (44%). Finally, crucial mediating factors that affect who benefits and how (for example, the vulnerability of beneficiaries or the availability of substitutes for ES) were considered in only 35% of assessments. Our results suggest that increasing the decision relevance of ES research requires more effectively predicting the impacts of specific decisions on the value and distribution of ES across beneficiary groups. Such efforts will need to integrate ecological models with socioeconomic and cultural dimensions of ES more closely than does the current ES literature.

As the connections between human well-being and nature become increasingly evident, it is ever more critical to develop an understanding of these links that is both accessible and applicable to decision makers[1]. Despite surging demand for actionable ecosystem service (ES) science and tools and a burgeoning scientific literature[2], the scale and pace at which ES understanding has translated into action falls short of what is needed to meet global sustainability challenges[3–5]. There remains an urgent need for the ES community to better understand the needs of relevant decision makers and to deliver explicit and pertinent information that meets their demands.

The ES community has made tremendous progress over the past two decades. Since the launch of the Millennium Ecosystem Assessment in 2005, the ES concept has gained traction across the scientific research community and a wide range of public- and private-sector institutions, inspired by its promise to illuminate when, why and how changes to ecosystems affect human well-being[6]. ES understanding now guides endeavours in many capacities, including international goals for conservation and human development, government policy and corporate investments[2,7–9]. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services is working to broaden the inclusion of different knowledge systems, cultures and disciplines in the effort to incorporate understanding of the connections between nature and people in decision making[10].

Yet enormous gaps persist between the desire of the ES research community to inform decisions and the current levels of use of ES information in practice[3–5]. The question remains: how can ES research better meet demand from decision makers? If the goal is to help set humanity on a path towards sustainable development, it is critical that ES assessments reflect key decision-making levers and their consequences in the links between nature and people.

Key elements for decision-relevant ES research

Synthesizing lessons distilled from global efforts to understand and apply ES[3,4,6,11,12], we identify five elements that would enable ES research to effectively inform decisions and help secure both people and nature. As described in the following paragraphs, they are (1) measure both ES supply and benefit, (2) understand the entire ES chain, (3) measure benefits to capture relevant human values, monetary and otherwise, (4) disaggregate benefits among different groups of people and (5) include and assess important mediating factors in the delivery and valuation of benefits.

1. Measure both ES supply and benefit. The supply of ES represents the ecosystem conditions or processes that contribute to the

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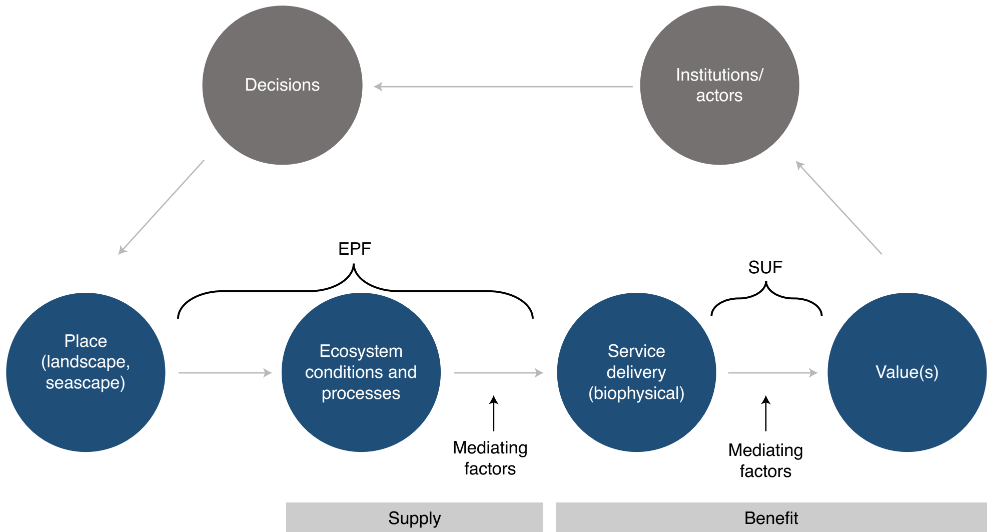


Fig. 1 | Conceptual diagram illustrating how ES information can be integrated into decision-making processes. Here we focus on the pathways connecting the lower components of the diagram, from places to their ecosystem conditions and processes to service delivery (biophysical benefits to people) to the values associated with these benefits. Ecosystem conditions and processes that contribute to the potential delivery of a particular ES constitute the supply of that service; where supply meets the need, use or preference for a service, that supply becomes a benefit[51]. A particular service can provide multiple values and may benefit different groups of people (beneficiary groups) in different ways. Mediating factors, such as the presence of infrastructure or people's differing access to services, affect whether, how and to whom ecosystem conditions and processes deliver benefits. Diagram based on Daily et al.[52].

potential delivery of an ES, such as the amount of sediment retained by wetland vegetation (Fig. 1). To assess the societal importance of this ES supply, studies must also assess the resulting benefits. Benefits are the contributions to human well-being that result from a given ES supply, for example, the increased water quality at the intake of a hydropower plant downstream of a wetland that allows for more efficient energy production. The value of the ES is the magnitude of this benefit measured in monetary, health, energy or other terms. In this example, the ES of sediment retention provided by the wetland can be valued as additional energy produced by the hydropower plant, increased profits for the hydropower company or reduced costs for customers, or an improved quality of life for recipients of the electricity. Where supply and benefit do not scale linearly with each other—as is the case for most services—an analysis that uses supply as a proxy is likely to misidentify where and how people would be impacted by a change in land use or management[13–15].

2. Understand the entire ES chain. Conceptual frameworks for translating ecological conditions into ES values typically include a chain (Fig. 1). The chain can be divided into two main components: an ecological production function (EPF)[16] and a socioeconomic utility function (SUF). EPFs translate the ecosystem conditions and associated processes of a place into measures of supply or—when evaluated in places with existing demand for a service—into biophysical measures of benefit. SUFs translate biophysical measures of benefit into measures of value[17].

Understanding how decisions may change the flow of ES benefits often requires understanding both of these functions. To continue with the hydropower example, the value of sediment retention depends on two linked parts: first, the connection between the amount, quality and configuration of vegetation, the amount of sediment it retains and the resulting water quality downstream (the EPF) and second, the sensitivity of a hydropower facility's production to water quality in terms of sediment loads and the value of energy it produces (the SUF)[18]. ES evaluations that lack the first part may capture the current costs incurred by sediment export to hydropower production but have limited ability to inform how deforestation or restoration choices would alter water quality and therefore hydropower production. However, ES evaluations that lack the second component cannot explicitly link the biophysical supply (here, sediment retention) to its value (in this case, energy production).

3. Measure relevant metrics of benefit. The choice of metric or metrics used to represent benefits has important implications for decisions and their consequences. For example, managing coastal habitats for storm risk reduction on the basis of the monetary value of avoided damages alone would prioritize places with high property values, benefitting wealthier segments of society[19]. Management aimed at protecting the greatest number of people overall could result in entirely different priority areas.

The method used to generate metrics of benefit is equally consequential. A benefits transfer approach often involves applying the per-hectare value of an ecosystem from other studies and then multiplying by the number of hectares of that ecosystem in a new location to generate monetary values,[20] without local EPFs or SUFs. Unless careful attention is paid to the ecological and socioeconomic contexts of the original studies and their applicability to the new context, values generated by benefits transfer may be inaccurate and misleading for decision making.

4. Disaggregate ES benefits among different groups. Accurately accounting for ES benefits depends on assessing the contributions of ES to the needs and values of different groups of people[15,21]. This includes understanding who benefits from ES and how they would benefit under alternative options or scenarios, as decisions are rarely made solely on the basis of calculations of an area's or a service's total societal value. Disaggregating across beneficiaries—rather than calculating a single total value[22]—is critical to making decisions that grow prosperity in an inclusive, equitable way[14,19] and to creating buy-in to decision-making structures built around ES outcomes[23]. These groups can include a government's constituents, different socioeconomic classes, a specific business or other key groups[3,24].

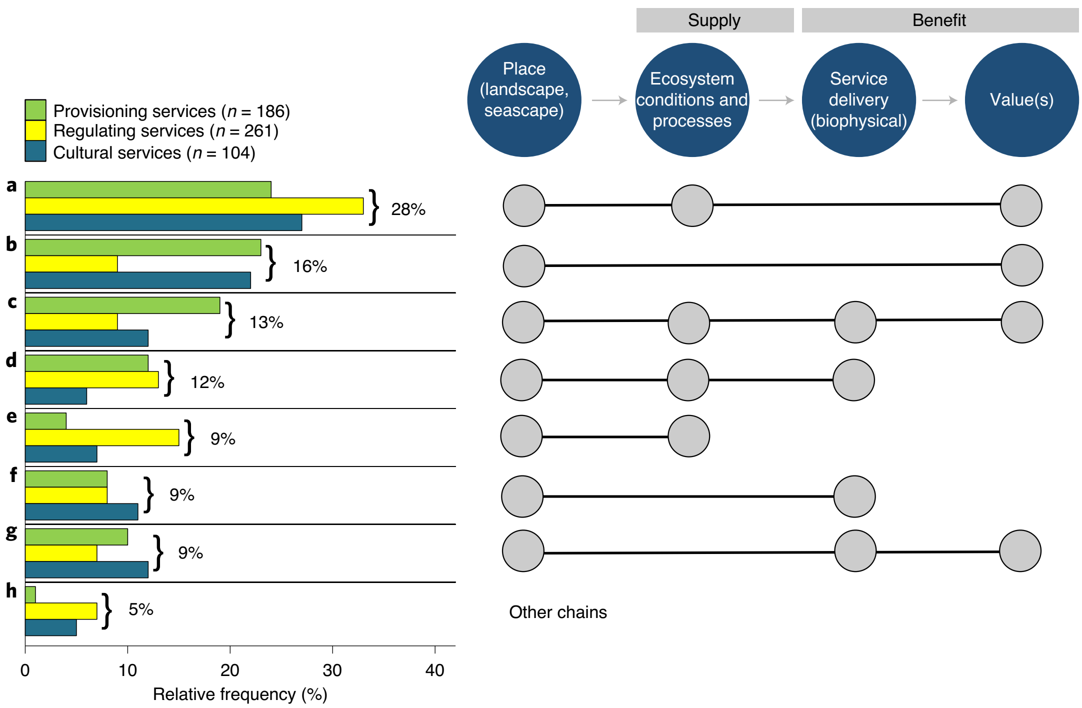


Fig. 2 | Relative frequency of chain types in ES assessments. The bar chart represents the relative frequency of each chain type across assessments of provisioning, regulating and cultural services, ordered from most common (**a**) to least common (**g**). Chain types are illustrated in the right portion of the figure. Percentages shown are the relative frequency of each chain type across all 551 assessments. Grey circles denote components included in each chain type, and histograms give their frequency for provisioning, regulating and cultural ES. All four components of the ES chain were included in just 13% of assessments (**c**). See Results for descriptions of each chain type.

5. Assess mediating factors. Mediating factors are variables that affect whether and how an ecological process delivers benefits to people and the value of those benefits. These can mediate between supply and service delivery, such as the existence of levies, canals or other infrastructure, or between service delivery and value, such as the vulnerability of communities to changes in ES, the availability of substitutes for ES benefits or the ability of beneficiaries to access ES benefits. Accounting for mediating factors is critical to accurately representing ES values for decision making. Consider the value of crop pollination services for nutritional health, which is mediated by individuals' nutritional health status[25]. A person whose diet is rich in nutrients from diverse sources might not suffer health effects from the loss of pollinator-dependent fruits and vegetables, whereas the same loss could put someone with a less robust diet at risk for nutrient deficiencies and associated complications.

Here, we systematically evaluate the preceding five elements by reviewing nearly 500 ES studies randomly drawn from the published literature. Of course, individual ES studies need not address all five elements to contribute to our growing science-policy understanding. However, these elements provide a framework to help connect findings from different studies and can inspire more complete future work. Given the comprehensive nature of the ES field, we include international articles from a wide range of disciplines and journals without filtering (see Methods for additional detail). We examine the degree to which current ES research is addressing each element and the resulting implications for decision making.

Results and discussion

Assessment of ES supply or benefits. Understanding how benefits to people may change under different policies or actions requires tracing a decision's impacts on ecosystem conditions or processes, through to changes in supply and then to benefit (Fig. 1). Ecosystem conditions or processes alone are rarely proxies for ES delivery. Of the 481 primary ES studies we reviewed, fewer than half (46%) linked an ecosystem condition or process to the supply or benefit of a specific ES. An equal fraction of papers (46%) merely indicated that the ecosystem attribute measured had implications for ES in general. The remaining 8% of studies either assigned a total value to ecosystem conditions or processes without attributing that value to any specific service or evaluated governance of ES without assessing supply or benefits. For example, Olsson et al.[26] examined the transition in governance of a marine park that provides multiple important ESs; evaluating the ES supply or benefits was beyond the scope of their study.

Missing components across the ES chain and implications for informing decisions. ES assessments that include an EPF linked to an SUF provide the greatest opportunity for understanding how changes in ecological or socioeconomic conditions will affect ES values to people. When certain components of the ES chain are omitted, this can pose challenges to integration in decision making. The 223 studies that assessed ES supply and/or benefits provided 551 assessments of individual services as some studies investigated multiple services (Supplementary Fig. 1). Among these 551 assessments, we identified several common chain types reflecting various ways studies integrated ES supply and benefit with implications for applying ES to decision making (Fig. 2).

The most common chain type (28% of 551 assessments) estimated value from metrics of supply, without actually considering whether or how much of a service was delivered (Fig. 2a). These assessments frequently used benefits transfer (57%, 90/157) to convert ecological conditions (for example, area of forest or wetland) into monetary value. The frequency of this linkage type is boosted by the fact that papers using this simple benefits transfer approach tend to assess a large number of services, often with a value per unit derived from Costanza et al.[27]. Without accounting for whether and how those ecological conditions actually (instead of potentially) deliver benefits to people, these assessments of value are likely to be substantial overestimates and to have limited accuracy or relevance to decision making[16].

An additional 25% of assessments were essentially descriptive, reporting on the amount or value of ES benefits provided by a place without any intermediate EPF or SUF (Fig. 2b,f). This approach can be used to track changes in potential ES benefits over time or to compare between places. It can motivate conservation, target conservation priorities and support high-level indicators of natural capital over time[28]. However, this simpler approach can only very roughly be used to project changes in benefits that would result from policy implementation or other decisions, unless future changes can be extrapolated from observed trends.

The most complete assessments included links and metrics across the full pathway connecting place to value, using linked EPFs and SUFs. In our sample, only 13% of assessments included this full chain (Fig. 2c). Many of these assessments (41%) use market prices to value provisioning services such as food and timber provision, an unsurprising dominant approach given that the required data are relatively easy to come by. However, studies using the full-chain approach vary widely in geographic location and spatial scale. This approach allows for projecting changes in ES values resulting from changes in both ecological and socioeconomic components of the system. For example, by linking mangrove area to the amount of fish and crabs caught (an EPF), and then linking the amount of fish and crabs caught to payments to fishermen from fishing collectives (an SUF), the assessment by Aburto-Oropeza et al.[29] makes it possible to estimate the value of mangroves to fishermen under current conditions as well as under scenarios involving changes in mangrove area or fish prices.

Assessments that evaluate ES benefits in biophysical terms only via an EPF, without an SUF (Fig. 2d), and those that include an SUF without any EPF (Fig. 2g), accounted for 12% and 9% of linkages, respectively. The former can project changes in service provision with changes to at least some aspects of ecosystem conditions and/or processes. However, without an SUF to account for the relationship between biophysical service delivery and value (whether in terms of number of people affected, monetary value or other metrics), they may not accurately reflect the importance of the service to people and may have limited power to inform decision making[4].

In the latter case, assessments that include SUFs without any EPFs report on the value of a service without accounting for how ecosystem conditions or processes contributed. Without an EPF to account for the relationship between ecological conditions and processes and biophysical service delivery, these assessments are limited in their ability to project how environmental changes could alter those values. Another 9% of assessments, made up largely of provisioning services that measured benefit biophysically (70%), included no metric of service or value (Fig. 2e).

Why are SUFs so rarely incorporated into the full chain? Assessments may stop short of estimating social or economic value because an assessment team lacks the expertise or resources needed to make this link. The lack of an SUF may also result from a disconnect between the output of an EPF and the required inputs to an SUF (Fig. 1). For example, ecological models might link land-use change to changes in sediment and nutrient loads in drinking water, but connecting the impact of these pollutants on health might depend on knowing their daily concentrations, water use by the local population and the dose–response relationship between pollutant concentrations and human health outcomes[30]. Each of the chain types advances our collective understanding and can support specific policy needs, but missing elements could limit their potential application for decision making. Ensuring ES assessments include components necessary for their intended decision context is important for fulfilling the promise of ES science to deliver decision-relevant information. And increasing the frequency of assessments that include the full chain—with both EPFs and SUFs—is a key research priority.

Limited metrics and methods of measuring ES values. Our results reveal important limitations around whether and how ES values are estimated (Fig. 3). Monetary value was the most common metric of benefit among all categories of ES (49% of 551 assessments; Fig. 3a). Biophysical metrics (27% overall) such as tons of carbon were more common for provisioning and regulating services, while self-reported metrics of well-being (17% overall) were more common for cultural services. These differences result from the nature of cultural ES, which often eludes measurement in biophysical or monetary terms[29]. Consideration of non-monetary values relevant to decision makers, such as beneficiary or demand-weighted amount of service, health benefits or job creation (part of 'other'), was rare (7%, 0.5% and <0.01% of assessments, respectively).

Of 268 assessments calculating monetary value (Fig. 3b), 44% used benefits transfer and thus often did not involve any SUF. Regulating and cultural services were most commonly assessed using benefits transfer methods, applying the value of ecosystem conditions or processes as measured in a previous study, typically in a different location. Benefits transfer was also used in 33% of the cases where provisioning services were assigned monetary value. Market price was the second most common method of monetary valuation (32%), used most frequently for provisioning services. Contingent valuation or choice (15%) was relatively common for cultural ES but less so for provisioning and regulating ES. Imputed willingness to pay accounted for 8% of assessments, and the remaining 3% used other methods.

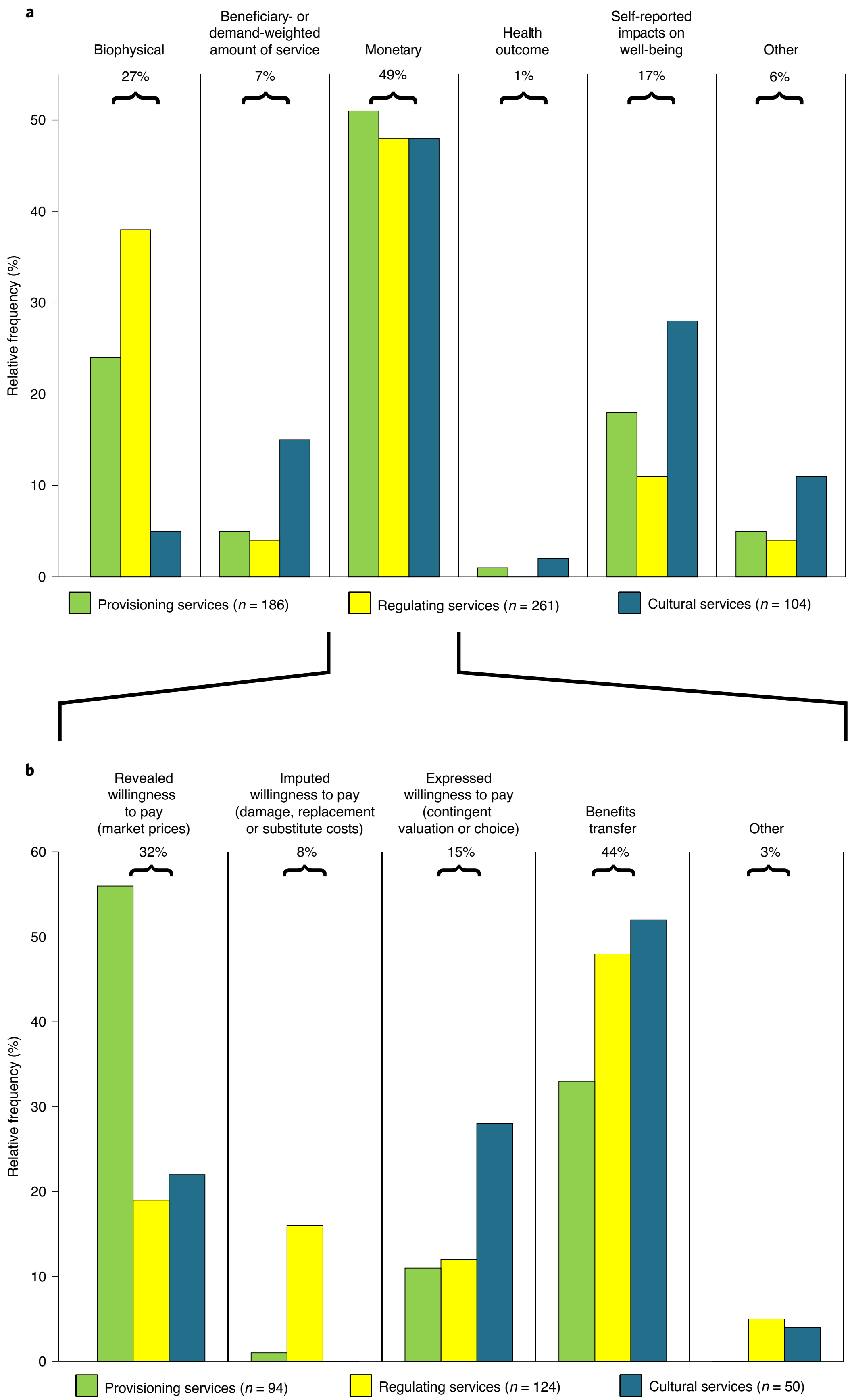
Building decision-relevant SUFs to address a greater range of ES values will also require using a wider range of methods that can account for multiple types of valuation[31,32] and novel data sources that reflect people and their use, need or preference for ES[33,34]. Engaging with relevant work outside the framing of ES and its dominant fields of ecology and economics—such as planetary health, anthropology, indigenous studies, engineering and urban planning—will be important to improving meaningful valuation. Exploring ways to link to shared and relational values, often best elicited through deliberative or narrative approaches[31,32], will also be important.

Rare disaggregation of benefits and consideration of mediating factors. ES metrics were disaggregated in 62% of assessments (Fig. 4). They were most commonly disaggregated spatially (for example, among pixels across a landscape; 31%) or regionally (for example, among counties or provinces; 13%). Disaggregation of ES benefits explicitly across demographic or other beneficiary groups (for example, private landowners versus the broader public) occurred rarely (7%) and most commonly for cultural services

Fig. 3 | Metrics used to quantify ES and methods used for monetary valuation. a,**b**, Bars show the relative frequencies of assessments that used different metrics to evaluate the ES endpoint (supply, service delivery or value, depending on chain type) (**a**) and different methods for calculating monetary value (**b**). Percentages are relative frequencies of each chain type across all assessments and may sum to greater than 100 as multiple metrics may be used for a single chain (for example, both monetary value and self-reported impacts on well-being). ES benefits were most often quantified in monetary terms (49% of assessments); of assessments presenting monetary value, benefits transfer (44%) or market prices (32%) were most commonly used. (See Methods for definitions of each category).

(of which recreation was most commonly assessed, Supplementary Fig. 1). Disaggregation by other factors, such as time or land-use/land-cover type, was present in 23% of studies.

Mediating factors were considered in fewer than 35% of assessments of provisioning and regulating services, although more frequently (60%) for cultural services (Fig. 5). The identity of



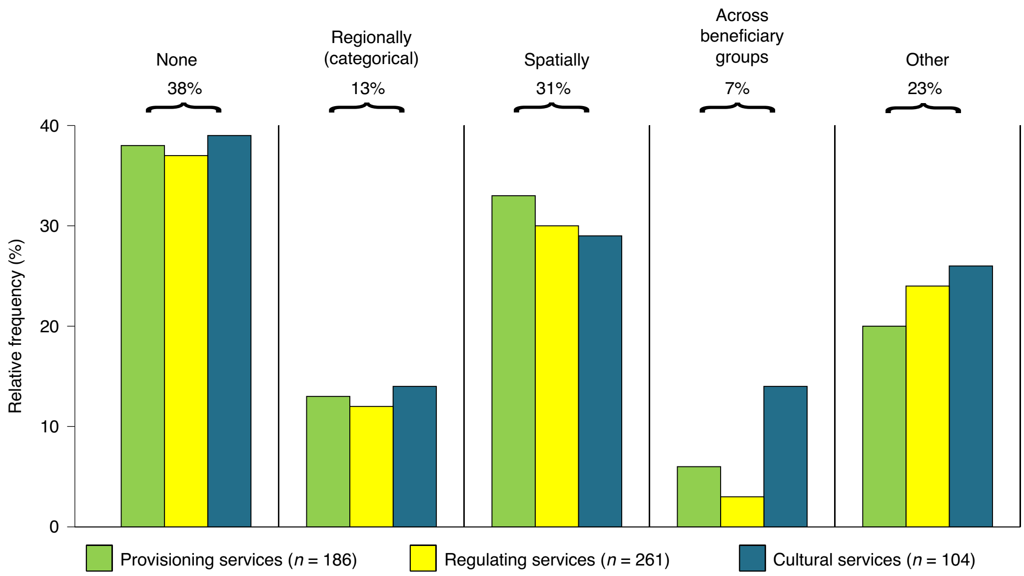


Fig. 4 | Disaggregation of ES benefits along key dimensions. Bars show the relative frequencies of disaggregation of ES by service type. Percentages are relative frequencies of each category across all 551 assessments and may sum to greater than 100 as ES benefits may be disaggregated along multiple dimensions for a single assessment (for example, both spatially within a landscape and by differences across beneficiary groups). ES benefits were most frequently disaggregated spatially (31%) and only rarely by beneficiary group (7%). (See Methods for definitions of each category).

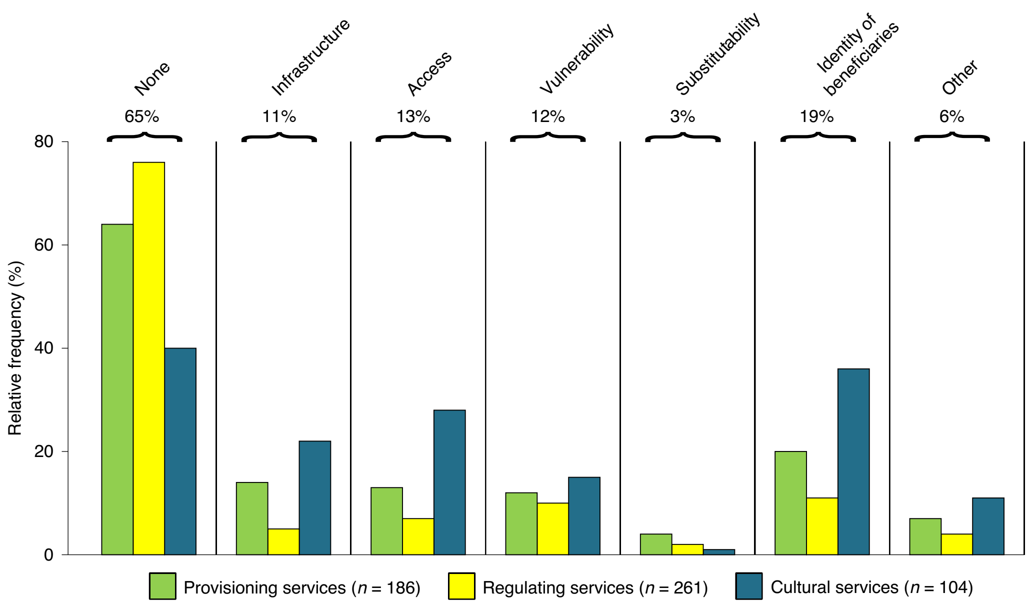


Fig. 5 | Inclusion of mediating factors affecting delivery and value of ES benefits. Bars show the relative frequency with which studies considered different mediating factors within provisioning, regulating and cultural service chains. Percentages are relative frequencies of each category across all 551 assessments and may sum to greater than 100 as multiple mediating factors may be considered for a single chain, and a mediating factor such as infrastructure may also contribute to vulnerability and access. Only 35% of assessments explicitly considered the role of mediating factors with the potential to affect ES benefits. (See Methods for definitions of each category).

beneficiaries (for example, hikers, farmers) was the most commonly considered mediating factor across all service types, although it was considered in fewer than 20% of assessments overall. Mediating factors involving infrastructure (for example, sea walls, levies), access (for example, whether an area permits or prohibits fishing) and vulnerability (for example, households' ability to evacuate in advance of coastal storms) were approximately equally prevalent (included in 11%, 13% and 12% of assessments, respectively) and were most common in studies of cultural ES. Studies rarely (<3% of assessments) considered the substitutability of a service explicitly, such as an alternative fuel source for firewood. Other mediating factors that did not clearly fit into the previous categories were included in only 6% of assessments.

The rare disaggregation of ES benefits among beneficiary groups, combined with limited consideration of mediating factors, prevents any meaningful understanding of how these benefits are distributed or how different groups value them. ES beneficiaries are often diverse and exhibit varying demand for ES, depending on their preferences and values, access to substitutes, vulnerability to environmental hazards and other mediating factors[35]. For example, a hydropower plant and recreational fishers might both benefit from clean water resulting from sediment retention within the same upstream watershed. The hydropower plant might be unaffected by small changes in sediment but require costly changes to plant management in the case of greatly increased sediment loads; recreational fishers may be more sensitive to small declines in water quality from sediment but able to move easily to other rivers if increased sediment reduces fish stocks and aesthetic quality. Given this heterogeneity, the associated value of a change in biophysical ES supply may vary enormously for different groups,[36] even more so than the supply itself. By ignoring this, decision makers risk inequitably distributing ES benefits and exacerbating existing inequalities[37]. Furthermore, decisions that preserve—or even enhance—total ES supply, benefits or number of people benefitting, can still create winners and losers among different beneficiaries[14,38].

In our sample, cultural service assessments (dominated by assessments of recreation) led the other service types in their explicit disaggregation of beneficiary groups and inclusion of mediating factors. For example, Kabisch et al.[39] found that immigrant families in Berlin prefer different green space features than German-born families, so the value of a specific park varies with family background. Assessments of provisioning and regulating services would benefit from an increased use of approaches more often applied in cultural service assessments, such as participatory and deliberative methods[40]. Moving forward, accounting for the preferences of different beneficiary groups and their vulnerability to changes in ES is critical to making decisions that promote an equitable distribution of benefits[41,42].

Improving ES science for decision making. On the basis of the research gaps revealed here, building and linking EPFs and SUFs is an important way to ensure that ES science can better deliver on its promise to effectively link nature with human well-being. Understanding the full ES chain (Fig. 1) provides decision-relevant insights that simple measures of biophysical supply or aggregate monetary values derived from benefits transfer cannot. Making these links is critical to informing societal decisions and actions for nature and people across scales and contexts, from local land-use policies[11] to global goals for sustainable development[9].

Achieving this goal requires direct engagement with policy actors and other decision makers to help define endpoints and outcomes relevant to people in a particular decision context. Moreover, ES scientists and practitioners need to engage meaningfully with individuals, households and communities who are most affected by these decisions to understand the contribution of nature to their well-being. Interdisciplinary teams must work together to develop methods and models that connect relevant endpoints back to the specific ecosystem and socioecological properties and processes that underpin them[3,43–45]. These teams will also need to embrace a broader range of approaches and epistemologies to understand human–nature relationships than has traditionally dominated ES assessments[32].

This research agenda will require a large and coordinated investment of time and expertise from a broad range of collaborating scholars[3,46]. But it will be worth the effort. Evaluating ES without meaningfully linking to people risks turning the ES concept into ‘window dressing’ that simply frames disciplinary studies in new ways. Meeting these challenges will allow ES science to measure effectively and articulate compellingly how ecosystems benefit human well-being and, ultimately, better contribute to transforming decisions at the scale and pace needed to meet global sustainability challenges.

Methods

Literature search. We collected all papers from a search of ISI Web of Science Core Collection using the term ‘(‘ecosystem service*’ OR ‘environmental service*’)’. In addition, we included all papers published in the journal *Ecosystem Services*, which was not indexed in Web of Science as of November 2015. Altogether, we located 12,273 potential papers, from which we randomly selected 1,000 for further analysis. A self-organizing map created from the abstracts of all papers suggested that our random subset was a representative subsample of the literature (Supplementary Appendix A and Supplementary Fig. 3). Our aim was to survey the research efforts of the ES field. We avoided using service-specific search terms (for example, ‘pollination service’ or ‘crop pollination’) to capture the full breadth of services being assessed. Our approach does not capture assessments that do not explicitly use the term ‘ecosystem services’. Our random selection of studies allows us to evaluate where the self-identifying ES research community is directing its focus, rather than to assess the field’s furthest advances or most influential papers.

Of the 1,000 randomly selected papers or book chapters, we were able to locate 955 full-text versions. We eliminated reviews, conceptual frameworks or thought pieces that did not include primary research ($n=426$, or 45%). We also excluded studies that used the terms ‘ecosystem’ or ‘environmental service’ with a different intended meaning (for example, environmental services in hospitals; $n=48$, or 5%). Our final sample size is 481.

Data coding and analysis. For the 481 studies that passed the initial screening, we first recorded whether each study aimed to assess (1) ecosystem conditions or processes; (2) at least one provisioning, regulating or cultural service; and/or (3) some measure of ES benefit or value to people. We used the Millennium Ecosystem Assessment classification[47], excluding supporting services. We also recorded whether papers mentioned a decision context for ES information, as well as a decision maker, institution or governance structure. To ensure consistency across multiple scorers, all participants scored the same set of 12 papers and agreed on the results. Once consensus was reached, remaining papers were scored independently, and results were discussed as a group where there was uncertainty about the score. Papers that aimed to assess at least one specific provisioning, regulating or cultural service (whether supply or benefit) were then scored in greater detail.

For this second round of scoring, we developed a series of service-specific chains representing the conceptual steps involved in EPFs and SUFs for each service (Supplementary Appendix B). To compare among different services, we also categorized sections of the service-specific chains into the four general components shown in Fig. 1: place, ecosystem conditions and processes (affecting potential service provision), service delivery (biophysical benefit to people) and value. For each ES assessed in each paper, we scored which parts of the chain were assessed. In addition, we recorded the ultimate (furthest) measure of the service (biophysical, monetary, human health outcome, beneficiary- or demand-weighted amount of service, self-reported impacts on well-being or other). Biophysical metrics include measures such as tons of sediment retained or board-feet of timber produced. ‘Beneficiary- or demand-weighted amount of service’ includes metrics that combine a biophysical measure with a measure of the number of beneficiaries or amount of demand for that service, such as amount of natural areas accessible per person. ‘Self-reported impacts on well-being’ includes measures of value elicited from beneficiaries, often reported on a relative scale (such as a Likert scale) through surveys or interviews. ‘Other’ includes any metrics that did not clearly fit in the previous categories, often study-specific indicators.

For papers using monetary metrics, we recorded the valuation method used (revealed willingness to pay, imputed willingness to pay, expressed willingness to pay and benefits transfer). ‘Revealed willingness to pay’ includes market prices. ‘Imputed willingness to pay’ includes avoided damages, replacement or substitute costs methods. ‘Expressed willingness to pay’ includes contingent valuation and contingent choice methods. ‘Benefits transfer’ includes assessments that apply monetary values estimated from other contexts.

In addition, we recorded whether the ES benefit was disaggregated and, if so, along which dimensions (spatially explicitly within landscapes, regionally (categorical spatial divisions), by beneficiary group or other). Spatial disaggregation accounts for the relative position of and relationship among units within the study area (for example, as in pixels across a landscape), as compared with regional disaggregation, which considers units only categorically (for example, by political unit). The ‘across beneficiary groups’ category includes studies that differentiated benefits to different groups of people (such as to private landowners versus the broader public). The ‘other’ category includes any other form of disaggregation, such as temporally or by land-use/land-cover type.

Finally, we recorded whether the paper considered mediating factors that could affect ES benefits and, if so, what types (infrastructure, access, vulnerability of beneficiaries, substitutability of benefits, identity of beneficiaries or other). ‘Infrastructure’ includes human-built structures, such as roads or boat launches. ‘Access’ includes any factor affecting access to potential ES benefits, which includes physical access (often through infrastructure) as well as whether access is permitted (for example, is recreational fishing allowed at a particular lake?). ‘Vulnerability of beneficiaries’ includes factors that affect a beneficiary’s vulnerability to loss of ES benefits, such as wealth or health status. ‘Identity of beneficiaries’ includes factors related to identity that might affect the perception or value of potential ES benefits (for example, indigenous community member, farmer, outdoor enthusiast).

To ensure consistency across multiple scorers, we evaluated scorer consistency using both Fleiss' kappa statistic and percentage rater agreement. To validate the consistency of recording across scorers, all nine scorers scored the same ten papers (randomly selected, but without duplicated service types). Interscorer consistency was calculated using Fleiss' kappa statistic [48] for 9 scorers and 72 questions using the R package 'irr' [49]. We calculated a kappa statistic of 0.548, where a score falling between 0.41 and 0.60 indicates moderate agreement[50]. We additionally evaluated percentage rater agreement using the same data set and found an overall agreement of 83%.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data that support the findings of this study are available from the Stanford Digital Repository at https://purl.stanford.edu/pt786dv3952. Source data are provided with this paper.

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Author contributions
All authors were involved in study conceptualization and design, and contributed to review and editing; A.L.V., A.S.-E., R.C.-K., B.E.R., G.M.V., J.D.G., J.A.J., J.R.S., L.J.S., L.L.B., L.M., M.G.E.M. and P.L.H. contributed to data collection; A.S.-E., L.M. and G.M.V. conducted the formal analyses; L.M. led project administration and supervision; A.S.-E. led data management and visualization; and L.M. and T.H.R. led the writing of the original draft.

Competing interests
The authors declare no competing interests.

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Software and code

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Data collection	A simple Python script was used to randomly select papers from the database of potential papers from Web of Science and the journal Ecosystem Services. This script can be made publicly available.
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Study description	We systematically surveyed the ecosystem services (ES) literature, and evaluated how studies addressed 5 key issues: 1) whether both ES supply and benefit are measured, 2) where the entire ES chain is understood, 3) where benefits are measured to capture relevant human values, 4) whether benefits are disaggregated among different groups of people, and 5) whether important mediating factors are assessed and included in valuation of benefits.
Research sample	The research sample includes 481 primary research studies (papers) of ecosystem services, randomly drawn from the ecosystem services literature. Of these 481 papers, 223 papers assessed ecosystem service supply and/or benefit of at least one specific ecosystem service, and included 551 individual assessments in total.
Sampling strategy	We identified 12,273 potential papers that used the term "ecosystem service*" or "environmental service*" from Web of Science and the journal Ecosystem Services. Of these, we randomly selected 1,000 papers and were able to locate the full text version of 955 papers. From these 955 papers, we retained the 481 primary research studies for evaluation.
Data collection	Authors LM and ASE ran the script to randomly select 1,000 papers from the 12,273 potential papers and downloaded the full text versions. LM and ASE completed the first screen to select primary research papers. LM, ASE, JG, PLH and JAJ completed the first round of data collection to assess whether papers evaluated the supply or benefit of specific ecosystem services. ALV, ASE, BCK, BER, JG, JRS, LB, LM and MGM completed the second round of data collection on the specific ecosystem service chains to assess which components were included and how.
Timing and spatial scale	The 12,273 potential papers were identified in November 2015. Data collection on the papers occurred February - May 2016. Spatial scale does not apply in this case, as we were collecting data on research papers.
Data exclusions	From the 1,000 randomly selected papers, we excluded papers that were reviews, conceptual frameworks, thought pieces or otherwise did not include primary research. We also excluded studies that used the term ecosystem service or environmental service with a different intended meaning (e.g., environmental services in hospitals). These criteria were pre-determined in order to focus our study on determining where ecosystem services research efforts were being directed.
Reproducibility	For the first round of data collection, to ensure consistency across multiple scorers, all participants scored the same set of 12 papers and agreed on the results. Once consensus was reached, remaining papers were scored independently, and results were discussed as a group where there was uncertainty about the score. For the second round of data collection, to ensure consistency across multiple scorers, each scorer evaluated the same 10 papers. We then evaluated scorer consistency using both Fleiss' Kappa Statistic and percent rater agreement.
Randomization	Not relevant to this study -- we were evaluating existing studies.
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