Biodiversity in the Anthropocene: prospects and policy

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Abstract

Balancing the ever-increasing needs of the Earth's human population with the maintenance of the biological diversity that ultimately supplies those needs is one of the greatest challenges facing humanity. The scale of this challenge has led some to suggest that a new approach to biodiversity conservation is needed. One idea rapidly gaining momentum—as well as opposition—is to incorporate the value of biodiversity into decision-making using economic methods. Here, we develop various lines of argument for how biodiversity might be valued, building on recent developments in natural science, environmental economics and science-policy processes. Then we provide a synoptic guide to the papers in this special feature, which collectively address two key questions: First, in what ways and to what extent are more biodiverse ecosystems demonstrably more valuable? Second, do we understand the links between biological systems and human wellbeing well enough to measure and predict the effects of anthropogenic activities on the values of biodiversity? We conclude that while more biodiverse systems may better sustain the value of ecosystems to humans, there remain significant gaps in our understanding of the causal links between biodiversity and value. This means that economic valuation approaches to addressing biodiversity loss should proceed with caution and complement rather than replace traditional approaches. We also conclude that effective policy and practice around maintaining biodiversity demands a genuinely interdisciplinary approach, and with this in mind present a framework for understanding the foundational role of 'biodiversity services' in sustaining the value of ecosystems to humanity. We use this framework to highlight new directions for pure and applied research.

1. Context

Though not yet formally recognised as such, the term "Anthropocene" is increasingly used to label Earth's current epoch [1, 2]. A major hallmark of this period is the transformation of ecosystems for human use [3], a process leading to the loss of wilderness [4] and multiple impacts on ecosystems from biotic homogenization [5, 6] to the rapid erosion of species richness in the most highly transformed areas of Earth [7]. At global scales, evidence is mounting that humans are precipitating Earth's 6th mass extinction [8-10] and the collapse of its life support systems [11].

As awareness of the scale and rapidity of biodiversity loss has grown, so too has our appreciation of the many ways that biodiversity supports human wellbeing either directly through enhanced ecosystem functions and services [12, 13] or indirectly by increasing the resilience of such functions in the face of environmental change [14-16]. Although the underlying causal mechanisms continue to be explored and a clear consensus is still lacking [17], a growing body of natural and social science indicates that biodiverse ecosystems are important for achieving sustainable development [18] and securing key resilient services underlying future human wellbeing [19].

Our increasing awareness of biodiversity's importance spans multiple sectors, from governments and academia to environmental and development NGOs, to businesses and community groups. Repeated efforts over several decades have included bold international commitments such as the 2020 Aichi targets made by the UN Convention of Biological Diversity and the Sustainable Development Goals for 2030 (agreed in 2015). However, progress to slow biodiversity loss has stalled [20], and it is becoming increasingly clear that neither of these international commitments for global biodiversity conservation are likely to be met [8] given projected increases in human population [21] and consequent demands for natural resources [22]. The scale of environmental challenges facing humanity has led some to suggest that a new approach to biodiversity conservation is needed [23, 24]. Formulating new approaches is easier than implementing them, but one idea rapidly gaining momentum—as well as opposition—is to incorporate the value of biodiversity into decision-making using economic methods [25].

In this article, we focus on biodiversity—defined as the diversity of genes, traits, species, habitats and landscapes in the biosphere—and develop various lines of argument for how it might be valued, building on recent developments in natural science, environmental economics and science-policy processes. Then we provide a synoptic guide to the papers in this special feature and highlight research advances relevant to biodiversity valuation. Finally, we outline key future directions, and discuss how best to integrate the links between biodiversity and ecosystem services into policy. As part of this, we present a framework for understanding the indirect nature of some of these links by highlighting the foundational role of "biodiversity services" in sustaining the value of ecosystems to humanity.

2. Evolving perspectives on valuing biodiversity

Many real world decisions are based on comparing the costs and benefits of alternative actions. The favoured action is the one that delivers most benefit relative to its cost (cost-benefit analysis) or delivers a desired outcome most efficiently (cost-effectiveness analysis). In the case of biodiversity, such economic approaches are rarely used outside the realm of direct conservation planning, where cost-effective approaches may be employed [26]. However, decision-making more often misses out biodiversity completely. In large part this is because biodiversity values are complex and highly contested: there is no common approach to valuing biodiversity and those approaches that do exist are often controversial or only applied in certain very specific contexts [27].

Whenever a decision is made to do one thing instead of another, a choice is made that values the two actions differently and prioritises one over the other. This is itself an implicit statement of value. Therefore, valuation in a broad sense underpins the decision to establish a protected area in one location compared to another, or to protect one set of species before others. The prioritisation may not be couched in terms of the monetary benefits that flow in response to the actions, but an implicit choice has been made that may be an expression of value. The problem is that these decisions are limited to the conservation domain and the values (which are not monetary) cannot be translated to domains where market values and prices are common, such as agriculture, timber logging or other marketable goods and services. The absence of monetary valuation for biodiversity conservation has been approached in various ways, none of which has successfully dealt with the problem that biodiversity is hard to value, and thus often treated as if it has no value, leading to environmentally harmful policy and practice (figure 1).

How might we value biodiversity? In the first place it is important to clearly distinguish between biodiversity and ecosystem services [28, 29]: biodiversity may underpin or regulate ecosystem functions and services, or it may be an ecosystem service itself. A commonly used typology of values, popular with environmental economists, is the Total Economic Value (TEV) framework [30]. This separates intrinsic values (which fall outside the human construct and, by definition, cannot be valued economically) from instrumental values (that contribute to human welfare in some way), which are divided into use values (e.g. for food or recreation benefits) and non-use values (e.g. existence value, which reflects satisfaction from knowing that species and ecosystems continue to exist, or bequest value, which reflects fact that future generations will also benefit). There are a range of economic valuation methods that can be used to estimate instrumental values [31]. The TEV framework has recently been challenged by a more complex set of values revealed through a consideration of the relationships between people and nature among multiple cultures and knowledge systems [32]. Thus, Chan et al. [33] propose adding a further category of relational values to intrinsic and instrumental values.

Despite these developments, most recent valuations of biodiversity focus on its monetary values, generally derived indirectly from its role in provisioning services (e.g. food, timber) and regulating services (e.g. water and nutrient cycling) [34, 35], as well as more directly from cash flows generated by markets such as bio-prospecting and tourism [36]. This approach has the advantage of transforming conservation from an imperative that delivers little economic return to one in which the value of biodiversity becomes the basis for programs that effectively pay for themselves. For example, rather than park guards being paid by wildlife-protection NGOs that are dependent on donor contributions, they would instead be paid through revenues generated from ecotourism, carbon credits, and payments from adjacent farms for the bio-control and pollination services provided by the park. Viewed from this perspective, economic valuation of biodiversity becomes a critical step in conservation, providing a means to identify who benefits from nature, and hence who may be willing to contribute to its conservation.

Though seemingly sensible in theory these approaches face a number of challenges. First, it is clear that there are substantial risks associated with this approach as a means to conserve nature [37] because the values derived are likely to be context-dependent and probably underestimate the true total economic value of biodiversity. Furthermore, even when these values are measurable, existing investments fall far short of what is required to effectively safeguard biodiversity [38-40]. Second, there are substantial disagreements with the principles involved. To many conservation biologists, it is simply inconceivable that conservation should and could pay for itself. Some see such approaches as tantamount to selling out on biodiversity [41]. Others suggest that the whole idea of ecosystem service markets has been oversold [42] and may ultimately undermine conventional environmental protection [43].

Though the concept of putting a monetary price on nature still provokes intense debate, a consensus is emerging that a unified framework, integrating the many different values of nature [44], is essential for meeting environmental goals in the Anthropocene. Rather than focusing on disagreements over whether economic valuations should or should not be undertaken, the debate now centres on *how* values should be estimated [45] and used in decision-making [46, 47] and cost-benefit analyses [48].

3. Recent advances in natural science relevant to biodiversity valuation

Critical to these economic approaches is an understanding of the causal links between biodiversity, ecological processes, ecosystem functions and the services derived from these processes and functions (figure 1). To explore these ideas, we introduce and synthesise articles in this feature within the context of two key questions. First, in what ways and to what extent are more biodiverse ecosystems demonstrably more valuable? Second, do we understand the links between biological systems and human wellbeing well enough to measure and predict the effects of anthropogenic activities on the values of biodiversity?

(a) The value of biodiverse ecosystems

Ecosystem functions, and the goods and services derived from those functions, are partly driven by the mass of organisms that reside in a given system; it does not necessarily follow, however, that the inherent diversity of this mass matters. Indeed, disentangling biodiversity's effects from the myriad factors that govern ecosystem function has been much more difficult than initially perceived [49]. Biodiversity is an extraordinarily complex feature of biological communities involving taxonomic, genetic, phylogenetic, trophic, spatial, temporal, behavioural, and many other dimensions of the diversity of life in an ecosystem [50, 51]. For reasons of empirical tractability, early studies tackled this complexity by focusing on how changes in a single dimension of biodiversity (usually species richness) influenced a single ecosystem function over a limited range of spatial and temporal scales, often assuming that species loss was random [52]. Later studies grew in complexity and expanded beyond these limited approaches [53, 54]. By 2012, the consensus view based on 20 years of research was that (i) experimental reduction in species richness, at any trophic level, negatively impacts both the magnitude and stability of ecosystem functioning [12, 53, 55, 56]; (ii) multi-trophic richness is beneficial for ecosystem services and multi-functionality; and (iii) the impact of biodiversity loss on ecosystem functioning is comparable in magnitude to other major drivers of global change [13, 57].

The implications of these conclusions still remain unclear for two key reasons. First, robust theoretical frameworks for understanding the mechanistic links between diversity and ecosystem functions and services are emerging [49] but await further development and testing. Second, empirical support remains uneven with most evidence derived from small-scale temperate grassland experiments focused on the response of bottom-up ecosystem processes (e.g. biomass over-yielding) to random species loss (but see [58, 59]). It is difficult to know whether the results are relevant to complex processes operating over longer timeframes, larger spatial scales and across trophic levels.

Because of these limitations, critics often conclude that biodiversity experiments cannot illuminate how species loss will affect ecosystem functioning in the real world. In particular, to what extent do the relationships detected also apply to long-lived tropical plant species, microbes, and animal species performing key top-down ecosystem processes such as pollination, seed dispersal and predation? Are they relevant to much less well-studied environments where biodiversity remains poorly quantified and that are experiencing rapid change, such as the marine environment in general and polar ocean ecosystems in particular? And how do they compare to other impacts on functions and services (e.g., warming, greater climate variability, nutrient and other pollution, human appropriation of freshwater, changing fire regimes).

In this Special Feature, these questions are addressed in a series of theoretical and empirical studies. Turnbull et al. [60] propose that niche (coexistence) theory can explain mechanistic links between species richness and key ecosystem functions (i.e. biomass over-yielding, multi-functionality and temporal stability). They also use niche theory to address some of the most prominent criticisms of biodiversity experiments. They suggest that not only are the results of these experiments highly likely to apply in real-world situations, but in many cases the relationships between diversity and ecosystem functioning in the real world will be steeper and/or saturate at higher levels of diversity. For example, although real environments are vastly more heterogeneous than experimental settings, niche theory predicts that a heterogeneous, fluctuating world is likely to require even more species to adequately fill niche space and ensure the sustainability of ecosystem function [56].

New ‘real world’ support for diversity-stability effects is presented by Tuck et al. [61] who describe findings from the first ten years of the Sabah Biodiversity Experiment in Borneo. This large-scale (500 ha) experiment tests the role of the identity, composition and diversity of enrichment-planted long-lived dipterocarps on the functioning and stability of selectively logged lowland rainforests during restoration [62]. Tuck et al. provide support for the idea that increased species diversity promotes resilience in tropical forests through insurance effects (spatial and temporal complementarity in ecosystem functioning [63]), and as such corroborates expectations from niche theory or models [64].

Plants have often been centre stage in the debate about valuing biodiversity because they are clearly linked to high-profile ecosystem functions such as carbon uptake, gaseous exchange, hydrological cycles and climatic moderation. Animals, by contrast, have less direct connection with core ecosystem functioning, but they nonetheless provide a wide range of services integral to ecosystem health and stability, such as nutrient transfer, decomposition and pollination. Moreover, animals are highly susceptible to human activities (e.g. hunting, disturbance, area effects, and so forth), such that the extinction of larger vertebrates is perhaps the dominant signature of the Anthropocene [9, 10]. Despite this, we remain largely ignorant about how much animal diversity matters for ecosystem functioning, services and resilience [65].

In this feature, two articles consider direct and indirect impacts of the loss of vertebrates on dependent species in lower trophic levels. Bregman et al. [51] use the functional structure of avian communities to explore the impact of anthropogenic land-use change on two animal-mediated processes in tropical forests: seed dispersal and insect predation. The results reveal a disproportionate loss of large-bodied frugivorous birds, an effect with important implications for the structure and economic value of tropical forests, given the role these species play in the seed dispersal of larger, longer-lived hardwood species. Similarly, Griffiths et al. [66] find positive effects of dung beetles on seedling recruitment through their role as secondary seed dispersers, suggesting that changes in dung beetle communities caused by anthropogenic activities could have implications for future vegetation composition of tropical forests.

Most empirical support for the idea that species loss impairs ecosystem functioning derives from studies in terrestrial environments where biodiversity is relatively well studied and quantified. In other words, there is an inevitable bias in empirical studies towards systems in which a high proportion of species have been identified and quantified in terms of their functional traits and phylogenetic relationships. Given these biases, can we predict the impact of species loss on ecosystem functions and services in much less well-known ecosystems, such as the marine environment, where many species remain to be described, or in taxa such as microbes where species limits are poorly defined?

In this feature, Cavanagh et al. [67] highlight the dearth of studies exploring the relationship between diversity and ecosystem value in the marine environment, and the tendency to focus on specific ES (often the harvested species). They discuss implications of this for conservation and management strategies and propose a conceptual view that would enable this critical relationship to be embedded in decision-making. Murphy et al. [68] emphasise the importance of a systematic approach to analysing polar ocean ecosystem structure and functioning, with a particular focus on integrating factors such as species interactions and life cycles with an understanding of environmental controls at different spatial and temporal scales. Based on a comparative analysis of several key polar marine ecosystems, they propose a framework for understanding interactions between biodiversity and functioning of pelagic ecosystems, thus providing a much-needed context in which to understand and predict marine ecosystem responses to change.

In summary, new observational and experimental studies in non-grassland systems are beginning to corroborate the conclusions of biodiversity experiments, with many of the biological processes that promote coexistence also generating diversity-function relationships. However, more research is needed that unites the fields of community ecology and biodiversity experiments, and explicitly tests the extent to which findings based on autotrophs generalize across complex ecological networks, spanning multiple trophic levels and involving top-down processes mediated by animals (see electronic supplementary table S1 for key future research questions).

(b) Measuring and predicting effects of anthropogenic activities on the value of biodiversity

A major criticism of the valuation approach to conserving biodiversity is that current understanding of the mechanistic links between species, their ecological functions (i.e. niche traits) and the properties of ecosystems is far from complete

[64, 69, 70]. Without this, we may fail to correctly conserve those elements of diversity crucial for ecosystem integrity.

As described above, there is growing consensus that maximising species richness likely maximises the productivity and stability of ecosystems under fluctuating environmental conditions [12, 71]. Consequently, there is still widespread use of taxonomic diversity (i.e. species richness) as a measure of the functionality and "value" of the ecosystem. However, we also know that species vary in their contributions to ecosystem functions (e.g., biogeochemical processes) or properties (e.g., biomass or stability): some species may perform many roles, some may perform roles more key than others, some species' roles may be redundant [72], and others may not contribute in a significant way [73-75]. As a result, growing emphasis has been placed on the identity and diversity of traits or evolutionary lineages mediating ecological functions [64, 76], with the use of metrics such as "functional diversity" (FD) or "phylogenetic diversity" (PD) in studies assessing the impact of anthropogenic activities [77-81].

The various ways in which species influence ecosystem functions and properties are, in principle, becoming increasingly well understood [13]. However, applying these findings to natural ecosystems is difficult. In particular, we still know little about the traits that lead some species to dominate ecological functions while rendering other species vanishingly rare, and we are only beginning to understand how functional traits are distributed within and across communities and the ecological and evolutionary processes generating these patterns [82-84]. For example, Pigot et al. [85] show that the FD of frugivorous bird assemblages may be a relatively weak predictor of the ecological functions they support, and that additional information on the abundance and intrinsic traits of species (i.e. functional identity) is crucial in determining their relative importance in a community. Because they find that species niches are strongly constrained by their traits and conserved over evolutionary time, they suggest that highly distinct species may nevertheless be less substitutable than those with more redundant traits.

A pervasive idea in ecology is that in very diverse environments, species loss is buffered by functional redundancy [86]. New studies indicate that despite the potential for high functional redundancy in diverse ecosystems, most species tend to be strongly clustered in trait space. Bregman et al. [51] find that large areas of functional morphospace are supported by only small numbers of highly distinctive, large bodied frugivorous birds and that these are the first to disappear following habitat degradation. Similarly, D'Agata et al. [87] show that large bodied, pelagic fish, which account for a major proportion of functional trait space, are naturally highly vulnerable to fishing. These findings, along with other work [88], provide growing evidence for a problem of 'double jeopardy' whereby a handful of highly distinct species, often positioned at higher trophic levels, play disproportionately large roles in the ecosystem but also tend to be rare and prone to local extinction - either naturally or as a result of human activities (hunting, land-use change). The articles in this feature add to a growing consensus that even a small decline of animal diversity can have serious consequences for ecosystem functioning, in particular because those species to disappear first often perform vital functions [89, 90].

Understanding, predicting and ultimately mitigating the effects of anthropogenic pressures will require the use of multiple measures of biodiversity. Building on this theme, Naeem et al. [50] review the literature and highlight that while research has expanded to consider a wider variety of functions, organisms and habitats, most studies continue to examine individual facets of biodiversity in isolation. Using the impacts of herbivory by whitetail deer as a case study, they illustrate the need to consider the complex interactions amongst multiple dimensions of biodiversity in order to fully comprehend how ecosystems respond to environmental change. Together these papers highlight both the opportunities and existing knowledge gaps in using functional traits to quantify the values and functions of biodiversity (table S1).

In summary, we are still lack a complete understanding of the causal mechanisms linking many forms of biodiversity loss to impacts on services. It is clear that there is no simple mapping between species' traits, functions and services. Multiple traits may produce a single function, while multiple functions may produce a single service. Moreover, traits effecting ecosystem functioning may often differ from those influencing the response of species to ecosystem perturbations (e.g. global stressors such as climate change). Much more research is needed to clarify the extent to which these processes are mediated by particular species traits. Future research should also examine the dynamic consequences of species extinction on the delivery of ecological process and determine whether this can be predicted using present day snapshots of network structure, and whether the extinction of species from ecological networks will be buffered by niche expansion of the remaining species (table S1).

4. Linking biodiversity science to value, human wellbeing and policy

While values have always informed environmental policy even if only implicitly, contemporary approaches seek to integrate ecosystem services into different policy contexts, for example through the use of Total Economic Value (TEV). Social scientists, environmental economists and policy makers are familiar with the TEV framework, but they may be less clear on the processes by which value is produced by biodiversity (and sometimes conflate the term 'biodiversity' with final ecosystem products and services). Meanwhile, natural scientists are familiar with frameworks linking ecological processes to ecosystems functions and services, but may be much less clear on the significance of these processes to our understanding of biodiversity value, and the creation of environmental policy.

To address this disconnect, we suggest a framework that explicitly links biodiversity to value-based policy decisions via ecosystem functions and services (figure 1). In this schema, we assume that policy decisions affect biodiversity positively or negatively by their impact on the drivers of biodiversity loss. Biodiversity in turn is viewed as the bedrock on which human wellbeing ultimately depends (see also [91]). Linking biodiversity to direct benefits are ecological processes that are generally not identified as valuable services *per se*, and yet they are integral to the downstream flow of services to humanity. We refer to these ecological processes as 'biodiversity services', and place them at the foundation to all other functions and services provided by the ecosystem (see figure 1 for details).

To understand the concept of biodiversity services, consider the importance of forests to humanity. They produce oxygen, regulate hydrological cycles, moderate climates and store carbon [92]. The loss of tree diversity may appear unimportant to the policy-maker who might assume that these benefits would flow from large stands of a single species. However, such monocultures are easily wiped out by disease and potentially less able to withstand changing environmental conditions. Tree diversity stabilises the system yet this diversity does not arise on its own. Instead, it is generated through density-dependent processes mediated by disease and herbivory, e.g. Janzen-Connell effects [93]. Moreover, it is only made possible by the pollination of flowers and dispersal of seeds by numerous specialised organisms. Although much of the diversity of microbes, pathogens, insects, birds and mammals in the forest system is not directly generating services to humanity, it is supplying something more fundamental by allowing the ecosystem to regenerate in perpetuity, and to withstand and recover from disease and environmental change.

A key message from this framework is that functions, services and values are all interdependent. Economic valuation must take these interdependencies into account, or else risk underestimating biodiversity's role in wellbeing. For example, final ecosystem services with marketable value depend strongly on ecological processes that cannot be directly valued and/or that also produce other services that are much harder to value directly (e.g. pollination and soil formation). Ignoring these factors potentially leads to underestimation of biodiversity's value, and could precipitate policy decisions that ultimately compromise human wellbeing and sustainable development (figure 1).

There is widespread recognition of the need to take account of biodiversity values in decision-making both nationally and internationally. At the international level, three major policy processes and platforms are important: The Convention on Biological Diversity (CBD), the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), and the Sustainable Development Goal (SDG) framework. One of the targets of the CBD's current Strategic Plan for Biodiversity is that by 2020, biodiversity values will have been "integrated into national and local development and poverty reduction strategies and planning processes" [94]. Parties to the CBD are expected to incorporate these targets in their own National Biodiversity Strategies and Action Plans (NBSAPs), and significant effort and resources are invested in supporting NBSAP development and implementation [95].

Meanwhile, IPBES has been designed as an interface between science and policy communities, to enable policy-makers to ask questions and scientists to address these questions based on the current state of knowledge [96]. Acting at unavoidably coarse scales, the IPBES programme nonetheless includes vital support and capacity development to individuals and institutions operating at regional, national and sub-national scales [97]. The success of IPBES will be judged on its ability to bring together diverse and credible knowledge in a way that is transparent, coherent and influential in terms of global policy making [32, 98]. Key challenges for IPBES will be showing how its assessments can help the global community meet the recently agreed SDGs and build on the Aichi Biodiversity targets when they expire in 2020.

Finally, the SDG framework is the pre-eminent commitment on environment and development for the next two decades [99]. The goals are important in having been universally adopted by developed and developing countries alike for delivery nationally as well as internationally. Biodiversity explicitly appears within the framework in the form of Goal 15 (*Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss*). However, it is implicit in Goal 14 (*Conserve and sustainably use the oceans, seas and marine resources for sustainable development*). Moreover, as highlighted by the science synthesised in this Special Feature and illustrated in Figure 1, the conservation and restoration of the ecosystems that harbour biodiversity is fundamental to achieving a wide range of other societal goals embodied within the SDGs including food security (Goal 2), water security (Goal 6), mitigation and adaptation to climate change (Goal 13), and livelihood diversification (Goal 8). The challenge now for scientists and practitioners is to work together to make this case to governments and the various constituencies investing in and overseeing implementation of the SDGs [100]. In doing so they will bring biodiversity to its rightful, foundational place, at the very heart of the sustainable development agenda.

Conclusions

The balance of evidence suggests that more biodiverse ecosystems are more productive, stable and resilient, and that by maximizing species, functional and phylogenetic diversity we maximize an ecosystem's value over the long term. However, we are still a way off from being able to causally and accurately link many forms of biodiversity loss to impacts on ecosystem services. Although many key questions remain (see electronic supplementary table S1), current research points to the prudent approach of conserving as much diversity as possible. However, to do so requires expanding beyond traditional biodiversity metrics (e.g. species richness) to include trait- and phylogeny-based metrics. As data on species traits, food webs, and guild structure grows, for plants, animals, and microorganisms, a more complete understanding of 'biodiversity services' and their contribution to ecosystem services will emerge, and predictions of the *economic*, not just the ecological, consequences of biodiversity loss will improve.

In the meantime, attempts to place an economic value on biodiversity's contribution to ecosystem services must proceed with great caution. They must take the complexity and uncertainty of the underlying science into account and acknowledge the high likelihood that estimates undervalue the total contribution of biodiversity to human wellbeing, especially when considering future generations and the uncertain environmental conditions they will experience. As such, an economic valuation approach to biodiversity conservation should complement rather than replace traditional approaches (especially in poorly studied ecosystems such as the marine environment).

We note, in closing, that an implicit assumption behind the broader rationale of our analysis here, and the following papers in this Special Feature, is that improving scientific understanding of the links between biodiversity and value should result in improved prospects for biodiversity. However, recent analyses [8] show that while indicators of effective responses are improving (e.g. awareness of the value of biodiversity and establishment of protected areas) the state of biodiversity is deteriorating, according to standard metrics. This suggests that a key challenge moving forward is to identify and overcome the myriad social, cultural and political obstacles to effective translation of policy into actions and financial resources that benefit biodiversity. To do this, ecologists and conservation biologists need to engage much more strongly with and draw on the social sciences (e.g., political science, psychology, anthropology) as well as the humanities (e.g. history, philosophy, and aesthetics). This in itself will require focused effort by members of all these disciplines to share knowledge and develop common languages and frameworks [101].

Ultimately, meeting the challenge of understanding and maintaining the value of biodiversity in the Anthropocene demands a genuinely interdisciplinary approach, one that rigorously unites the social sciences, natural sciences and humanities on the one hand, and researchers and practitioners on the other. At a time of planetary collapse, and political divide, such collaboration and cooperation within and between disciplines and sectors has never been more important.

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NS wrote the first draft of this manuscript; all co-authors commented.

Figure 1 The value of biodiversity to human wellbeing. Biodiversity is structured by a range of ecological processes including: (i) *community assembly* (the biotic and abiotic interactions, including environmental filtering, competition, and host-parasite interactions, which together determine the distribution of species and their abundance in communities), (ii) *interaction networks* (the architecture of mutualistic and antagonistic interactions underlying pollination, predator-prey cycles, population control etc.), (iii) *nutrient transfer* (the breakdown of nutrients and transfer across the environment), and (iv) *biogeochemical cycling* (the cycling of chemicals, e.g. C, N, through the biosphere and lithosphere). These processes—which can be termed "biodiversity services"—underpin and determine the stability, resilience, magnitude, and efficiency of the functions and properties of ecosystems. Those functions and properties that benefit people are referred to as 'ecosystem services' and reflect what it is we tend to value about biodiversity. Values are divided into *intrinsic* (which by definition cannot be valued economically) and *instrumental* values (that contribute to human welfare in many and varied direct and indirect ways). When economic valuation is done correctly (i.e. robust assessment and weighting of values), the outcome is green environmental policy (left, green arrow implying positive effects on biodiversity and ecosystems) that leads to environmental conservation, restoration, protection, and sustainable practice. When done incorrectly, it can lead to environmental degradation and unsustainable practice (right, red arrow, implying harmful effects on biodiversity and ecosystems). Two elements of this framework are therefore critical; the natural science underpinning biodiversity's influence over ecosystem functions and properties, and the social science underpinning values and valuations. If incomplete, poorly done, or ignored, policy is more likely to be red than green.

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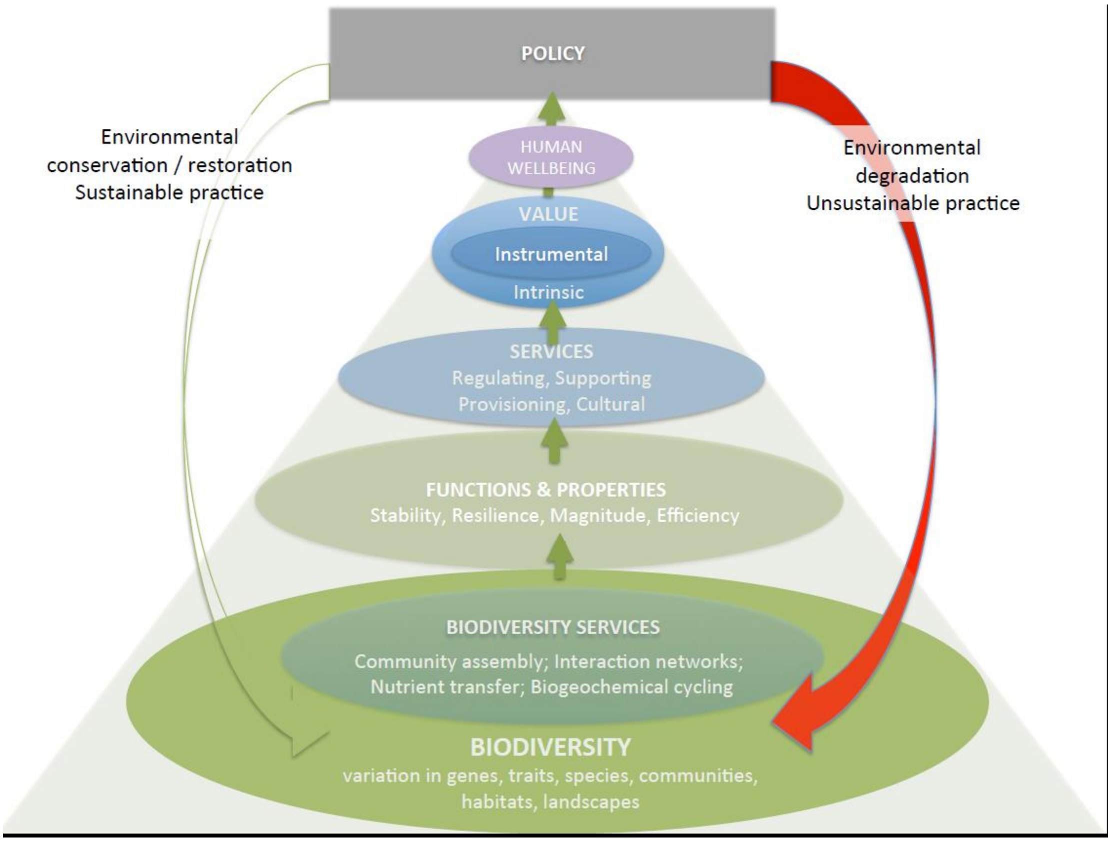
Figure 1


POLICY
HUMAN WELLBEING
VALUE
Instrumental
Intrinsic
SERVICES
Regulating, Supporting
Provisioning, Cultural
FUNCTIONS & PROPERTIES
Stability, Resilience, Magnitude, Efficiency
BIODIVERSITY SERVICES
Community assembly; Interaction networks;
Nutrient transfer; Biogeochemical cycling
BIODIVERSITY
variation in genes, traits, species, communities,
habitats, landscapes
Environmental conservation / restoration
Sustainable practice
Environmental degradation
Unsustainable practice