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Biodiversity in the Anthropocene: prospects and policy

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Meeting the ever-increasing needs of the Earth's human population without excessively reducing biological diversity is one of the greatest challenges facing humanity, suggesting that new approaches to biodiversity conservation are required. One idea rapidly gaining momentum—as well as opposition—is to incorporate the values of biodiversity into decision-making using economic methods. Here, we develop several lines of argument for how biodiversity might be valued, building on recent developments in natural science, economics and science-policy processes. Then we provide a synoptic guide to the papers in this special feature, summarizing recent research advances relevant to biodiversity valuation and management. Current evidence suggests that more biodiverse systems have greater stability and resilience, and that by maximizing key components of biodiversity we maximize an ecosystem's long-term value. Moreover, many services and values arising from biodiversity are interdependent, and often poorly captured by standard economic models. We conclude that economic valuation approaches to biodiversity conservation should (i) account for interdependency and (ii) complement rather than replace traditional approaches. To identify possible solutions, we present a framework for understanding the foundational role of hard-to-quantify 'biodiversity services' in sustaining the value of ecosystems to humanity, and then use this framework to highlight new directions for pure and applied research. In most cases, clarifying the links between biodiversity and ecosystem services, and developing effective policy and practice for managing biodiversity, will require a genuinely interdisciplinary approach.

1. Context

Though not yet formally recognized 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 sixth 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 well-being 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 [17], a growing body of natural and social science indicates that biodiverse ecosystems are important for achieving sustainable development [18] and supplying the fundamental services and conditions necessary for human well-being [19].

The imperative of conserving biodiversity spans multiple sectors, from governments and academia to environmental and development non-government organizations (NGOs), to businesses and community groups. Repeated efforts over several decades have included bold international commitments, including the 2020 Aichi targets enshrined in the United Nations Convention of Biological Diversity [20], and the Sustainable Development Goals for 2030 (agreed in 2015) [21]. However, progress to slow biodiversity loss has stalled [22], and it is becoming increasingly clear that neither of these commitments for global biodiversity conservation are likely to be met [8] given projected increases in human population [23] and consequent demands for natural resources [24]. The severity of environmental challenges facing humanity has led many to suggest that a new approach to biodiversity conservation is needed [2,25]. Perhaps the most pragmatic option is to incorporate the value of biodiversity into decision-making using economic methods [26], and yet this idea remains highly controversial [27–29].

In this paper, 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, cost-effective approaches may be used for the purposes of direct conservation planning [30]. 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 [31].

Whenever a decision is made to do one thing instead of another, a choice is made that values the two actions differently and prioritizes 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 prioritization 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 is an expression of value. The problem is that decisions based on non-monetary values cannot be compared to those based on market values and prices, such as agriculture and timber logging. As a result, biodiversity is 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 [32,33]: 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 [34]. This separates intrinsic values (which fall outside the human construct and TEV, and by definition cannot be valued economically) from instrumental values (that contribute to human welfare in some way). Instrumental values are divided into use values (e.g. for food or recreation benefits) and non-use values (e.g. existence value, which includes the satisfaction arising from simply knowing that species and ecosystems continue to exist, or bequest value, which reflects benefits accrued by future generations). There are a range of valuation methods that can be used to estimate instrumental values [35].

Although the TEV framework is widely accepted in some fields, its use as a policy mechanism for biodiversity conservation has been questioned. Some have suggested a more complex set of routes by which the natural environment delivers economic value, in particular ecological resilience [36]. Others propose that it oversimplifies the relationships between people and nature among multiple cultures and knowledge systems [37], with Chan *et al*. [38] identifying a further category of relational values reflecting individual and cultural identity.

These considerations have yet to filter into policy mechanisms in any meaningful way, with most recent valuations of biodiversity focusing on basic monetary values. These are generally derived indirectly from its role in provisioning services (e.g. food and timber) and regulating services (e.g. water and nutrient cycling) [39,40], as well as more directly from cash flows generated by markets such as bio-prospecting and tourism [41]. Its supporters argue that the approach has the advantage of transforming conservation from an imperative that delivers little acknowledged economic return to one in which the value of biodiversity becomes the basis of the development of more sustainable long-term financing. 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.

Opponents of economic valuation have raised a number of challenges. First, it is clear that there are substantial risks associated with this approach as a means to conserve biodiversity [42] because the values derived are likely to be context-dependent

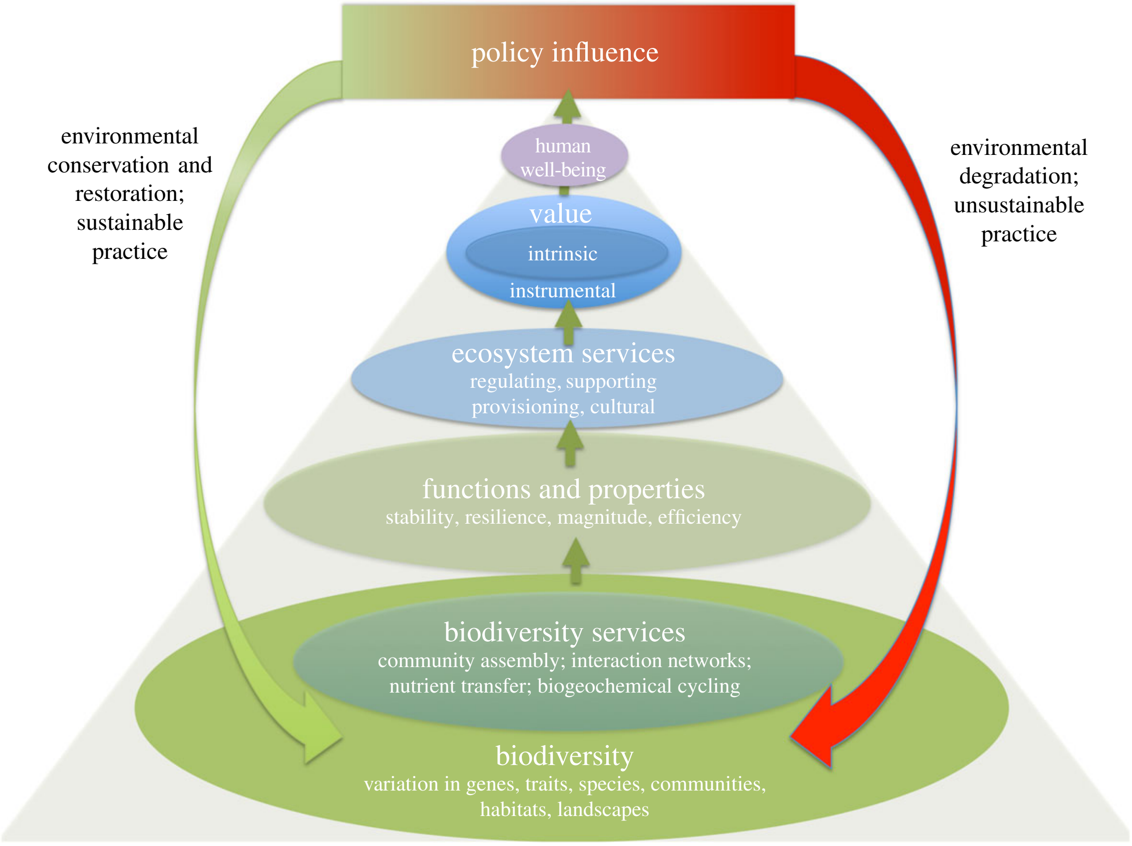

Figure 1. The value of biodiversity to human well-being. Biodiversity is structured by a range of ecological processes including: (i) community assembly (the biotic and abiotic interactions, including environmental filtering, competition and host–parasite interactions, which together determine the distribution of species and their abundance in communities), (ii) interaction networks (the architecture of mutualistic and antagonistic interactions underlying pollination, seed dispersal, predator–prey cycles, 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.

and probably underestimate the true TEV of biodiversity. Furthermore, even where it can be shown that there are significant economic benefits of investing in biodiversity, existing investments fall far short of what is required to effectively safeguard it [20,43,44]. 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 [27]. Others suggest that the whole idea of ecosystem service markets has been oversold [29] and may ultimately undermine conventional environmental protection [28].

Though the concept of putting a monetary price on biodiversity still provokes intense debate, a consensus is emerging that a unified framework, integrating the many different values of biodiversity [45] is essential for meeting environmental goals in the Anthropocene. Rather than focusing on disagreements over whether economic valuations should be undertaken, the debate increasingly centres on how values should be estimated [46] and used in a consistent way in cost–benefit analyses [30] and decision-making [42,47].

3. Recent advances in natural science relevant to biodiversity valuation

Critical to economic approaches is an understanding of the causal links among biodiversity, ecological processes, ecosystem functions and the services derived from these processes and functions (figure 1). To explore these ideas, we introduce and synthesize 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 biodiversity and ecosystem functions and services well enough to measure and predict the effects of anthropogenic activities on the values of biodiversity?

(a) The value of biodiverse ecosystems

Ecosystem processes, functions and services are a product of the activities of the communities of organisms that reside in a given system (figure 1). However, it does not necessarily follow that the inherent diversity of these communities matters.

Indeed, disentangling biodiversity's effects from the myriad factors that govern ecosystem function has been much more difficult than initially perceived [48]. Biodiversity is an extraordinarily complex feature of biological communities involving taxonomic, genetic, phylogenetic, functional, trophic, spatial, temporal, behavioural and many other dimensions of the diversity of life in an ecosystem [49,50]. 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 (often biomass production) over a limited range of spatial and temporal scales, often assuming that species loss was random [51]. Later studies grew in complexity and expanded beyond these limited approaches [52,53]. 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 [12,52], and (ii) the impact of biodiversity loss on ecosystem functioning is comparable in magnitude to other major drivers of global change [13,54].

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 [48] but await further development and testing. Second, empirical studies are still strongly biased towards small-scale temperate grassland experiments focused on the response of bottom-up ecosystem processes to random species loss (but see [55,56]). 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 (e.g. much of the marine environment) and that are experiencing rapid change (e.g. polar ocean ecosystems)?

In this feature, these questions are addressed in a series of theoretical and empirical studies. Turnbull *et al*. [57] 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 also 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, real environments are vastly more heterogeneous than experimental settings, and 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 [58].

New 'real world' support for diversity-stability effects, and corroboration of expectations from niche theory, is presented by Tuck *et al*. [59], who describe findings from the first 10 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 [60]. Tuck *et al*. [59] provide support for the idea that increased species diversity promotes resilience in tropical forests through insurance effects (i.e. spatial and temporal complementarity in ecosystem functioning [61]).

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, biomass production, 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 [62,63]. 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 [64].

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*. [50] 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*. [65] 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 [66,67], or in taxa such as microbes where species limits are poorly defined [68]?

In this feature, Cavanagh *et al*. [66] highlight the dearth of studies exploring the relationship between diversity and ecosystem value in the marine environment, and the tendency to focus on specific ecosystem services (often harvested species). They discuss implications of this for conservation and management strategies and propose a how best to embed the biodiversity–ecosystem services relationship in decision-making. Murphy *et al*. [67] emphasize 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, recent (post-2012) research in the field of biodiversity–ecosystem functions and services has confirmed the pervasiveness of positive biodiversity–productivity–stability relationships in numerous environmental contexts, and across broader spatial and temporal scales [53,56,57]. It is also becoming increasingly clear that interactions within and between lineages and trophic levels are the fundamental architecture of functional and stable ecosystems [55,58,68]. Recent findings highlight the importance of top-down (animal mediated) as well as bottom up (microbe or plant mediated) processes. Moving forward, perhaps the key research challenges in this field are to determine the capacity of biodiversity (measured in multiple ways) to sustain key ecosystem functions and flows of services in the face of interacting global stressors (habitat loss/degradation, climate change, disease, overhunting, etc.), and to use this information to identify tipping points in biome and planetary stability and resilience, as well as effective policy interventions. This will require a truly multidisciplinary approach with relevance across multiple scales. At one level, technical advances are needed to integrate global mechanistic models (e.g. General Ecosystem Models; [69]) with insights and approaches from the fields of ecology, evolutionary biology, climate science and the earth sciences, using datasets sampled widely from the tree of life. Just as importantly, it is vital that research focuses on generating outputs which can be translated into real policies and practices relevant to local contexts. For a list of key future research questions, see the electronic supplementary material, table S1.

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

A major criticism of the valuation approach to conserving biodiversity is that current understanding of the mechanistic links between species and the functioning and resilience of ecosystems is far from complete [70–72]. Without this, we may fail to protect those elements of diversity crucial for ecosystem integrity.

As described above, there is growing consensus that maximizing species richness probably maximizes the productivity and stability of ecosystems under fluctuating environmental conditions [12,15]. 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. productivity) 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 [73], and others may not contribute in a significant way [74–76]. As a result, growing emphasis has been placed on the identity and diversity of traits or evolutionary lineages mediating ecological functions [71,77], with the use of metrics such as 'functional diversity' (FD) or 'phylogenetic diversity' (PD) in studies assessing the impact of anthropogenic activities [78–82].

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 phenotypic and/or behavioural 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 [83–85]. For example, Pigot *et al.* [86] 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.

That species loss is buffered by functional redundancy in very diverse environments is a pervasive idea in ecology [87]. However, 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.* [50] find that large areas of functional morphospace are supported only by 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.* [88] show that large-bodied, pelagic fishes, which account for a major proportion of functional trait space, are highly vulnerable to fishing. These findings, along with other related work (e.g. [62]), 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. This generally arises through intrinsic sensitivity to population pressures, combined with human activities (hunting, harvesting and land-use change) [62,89]. 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 [90,91].

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.* [49] suggest 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 deer as a case study, the authors illustrate the need to consider complex interactions among multiple dimensions of biodiversity to fully comprehend how ecosystems respond to environmental change.

Together, these papers highlight the potential of using functional traits to quantify the values and functions of biodiversity. However, while functional traits offer some promise, they also present pitfalls. Most importantly, we still lack a complete understanding of the causal mechanisms linking many forms of biodiversity loss to impacts on services, particularly at broader scales. One of the core challenges is that there is no simple mapping between species' traits, functions and services. Multiple traits may produce a single function, and 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).

In summary, further research is required in many areas before we can reliably quantify the impacts of anthropogenic activities on the values of biodiversity and develop robust metrics to guide environmental policy. For example, we need to examine the dynamic consequences of species extinction on the delivery of ecological process, and whether the extinction of species from ecological networks will be buffered by niche expansion of the remaining species (electronic supplementary material, table S1). Similarly, more evidence is needed to support the idea that functional traits extracted from present-day snapshots of ecological networks or assemblages can help us predict the resilience of ecosystems in the face of environmental change.

4. Linking biodiversity science to value, human well-being and policy

(a) A framework for understanding the foundational role of 'biodiversity services'

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 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's values, 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 well-being ultimately depends (see also [92]). 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 [93]. 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 may be more vunerable to disease and potentially less able to withstand changing environmental conditions. Tree diversity stabilizes the system yet this diversity does not arise on its own. Instead, it is generated through density-dependent processes such as those mediated by disease and herbivory, e.g. Janzen–Connell effects [94]. Moreover, it is only made possible by the pollination of flowers and dispersal of seeds by numerous specialized 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 human well-being. 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 and have benefits beyond the final ecosystem service with a market value (e.g. pollination, soil formation and nutrient cycling). Ignoring these factors potentially leads to under appreciation and underestimation of biodiversity's values, and could precipitate policy decisions that ultimately compromise human well-being and sustainable development (figure 1). We recognize that myriad factors influence policy decisions, and that it is important to frame the values of biodiversity in ways that resonate most with the different types of decision-maker. Conservation policy-makers, for example, may be more likely to be influenced by intrinsic values associated with protecting rare species, whereas land-use planners may have more direct interests in values associated with particular ecosystem services (e.g. connected to flood risks). However, as decision-making becomes more 'mainstream' and hence largely dictated by wider socio-economic goals and considerations, so arguments about economic value and the role of biodiversity in this broader context become more relevant.

(b) Integrating biodiversity values into decision-making processes

There is widespread recognition of the urgent 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 particularly 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' [95]. 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 [96].

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 [97]. 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 [98]. 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 [37,99]. 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 (https://sustainabledevelopment.un.org/). The goals are important in having been universally adopted 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 synthesized in this 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) (see also [100]). 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 [21]. In doing so, they will bring biodiversity to the heart of the sustainable development agenda.

5. Conclusion

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 (electronic supplementary material, 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 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 well-being, 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 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 and 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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