

Biodiversity in the Anthropocene: prospects and policy

Nathalie Seddon^{1,2,3}, Georgina M. Mace⁴, Shahid Naeem⁵, Joseph A. Tobias⁶, Alex L. Pigot^{4,7}, Rachel Cavanagh⁸, David Mouillot^{9,10}, James Vause¹¹ and Matt Walpole¹¹

5

*¹Biodiversity Institute and ²Edward Grey Institute, Department of Zoology
University of Oxford, UK*

*³International Institute for Environment and Development, 80-86 Gray's Inn Rd,
London WC1X 8NH*

10 *⁴Centre for Biodiversity and Environment Research, University College London, UK*

⁵Columbia University, New York, USA

*⁶Department of Life Sciences, Imperial College London, Silwood Park, Buckhurst
Road, Ascot, Berkshire, SL5 7PY, UK*

⁷Groningen Institute for Evolutionary Life Sciences, University of Groningen,

15 *Groningen, The Netherlands, PO Box 11103, Groningen 9700 CC, The Netherlands*

⁸British Antarctic Survey, Cambridge, UK

⁹MARBEC, UMR CNRS-UM2 9190, Université Montpellier, France

*¹⁰Australian Research Council Centre of Excellence for Coral Reef Studies, James
Cook University, Townsville, QLD 4811 Australia*

20 *¹¹United Nations Environment Programme, World Conservation Monitoring Centre,
Cambridge, UK*

25 **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 to suggestions that a new approach to biodiversity conservation is needed. One
30 idea rapidly gaining momentum—as well as opposition—is to incorporate the value 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,
35 highlighting research advances relevant to biodiversity valuation. We conclude that more biodiverse systems 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. More research is needed to clarify links between biodiversity and value. However, we argue that the functions, services
40 and values arising from biodiversity are interdependent, and that economic valuation approaches to biodiversity conservation should account for this interdependency and complement rather than replace traditional approaches. We stress that effective policy and practice around maintaining biodiversity demands a genuinely interdisciplinary approach. With this in mind we present a
45 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.

50 **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
55 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
60 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 [17], a growing body of natural and social science
65 indicates that biodiverse ecosystems are important for achieving sustainable development [18] and supplying the fundamental services and conditions necessary for human wellbeing [19].

The imperative of conserving biodiversity spans multiple sectors, from governments and academia to environmental and development NGOs, to
70 businesses and community groups. Repeated efforts over several decades have included bold international commitments, including the 2020 Aichi targets enshrined in the UN 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
75 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 [25, 26]. Perhaps the most pragmatic option is to
80 incorporate the value of biodiversity into decision-making using economic methods [27], and yet this idea remains highly controversial [28-30].

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 [31]. 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 [32].

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 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 often treated as if it has no value, leading to environmentally
115 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 [33, 34]: 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
120 environmental economists, is the Total Economic Value (TEV) framework [35].
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
125 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 [36].

Although the TEV framework is widely accepted in some fields, its use as a
130 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 [37]. Others propose
that it oversimplifies the relationships between people and nature among
multiple cultures and knowledge systems [38], with Chan et al. [39] identifying a
135 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, timber) and regulating services (e.g. water and
140 nutrient cycling) [40, 41], as well as more directly from cash flows generated by
markets such as bio-prospecting and tourism [42]. 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
145 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 [43] because the values derived are likely to be context-dependent and probably underestimate the true total economic value 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, 44, 45]. 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 [28]. Others suggest that the whole idea of ecosystem service markets has been oversold [30] and may ultimately undermine conventional environmental protection [29].

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 nature [46] 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 [47] and used in a consistent way in cost-benefit analyses [48] and decision-making [49, 50].

3. Recent advances in natural science relevant to biodiversity valuation

Critical to 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

180 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

185 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
190 [51]. 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 [52, 53]. For reasons of empirical tractability, early studies tackled
this complexity by focusing on how changes in a single dimension of biodiversity
195 (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 [54]. Later studies grew in complexity and
expanded beyond these limited approaches [55, 56]. By 2012, the consensus
view based on 20 years of research was that (a) experimental reduction in
200 species richness, at any trophic level, negatively impacts both the magnitude and
stability of ecosystem functioning [12, 55]; and (b) 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
205 reasons. First, robust theoretical frameworks for understanding the mechanistic
links between diversity and ecosystem functions and services are emerging [51]
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
210 see [58, 59]). Because of these limitations, critics often conclude
that

ecosystem functioning in the real world. In particular, to what extent do the

biodiversity experim

relationships detected also apply to long-lived tropical plant species, microbes, and animal species performing key top-down ecosystem processes such as
215 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
220 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
225 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
230 require even more species to adequately fill niche space and ensure the sustainability of ecosystem function [61].

New 'real world' support for diversity-stability effects, and corroboration of expectations from niche theory, is presented by Tuck et al. [62] who describe findings from the first ten years of the Sabah Biodiversity Experiment in Borneo.
235 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 [63]. Tuck et al. provide support for the idea that increased species diversity promotes resilience in tropical forests through insurance effects (spatial and temporal
240 complementarity in ecosystem functioning [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, biomass production, hydrological cycles and climatic moderation. Animals, by contrast, have less direct connection with core ecosystem
245 functioning, but they nonetheless provide a wide range of services integral to

ecosystem health and stability, such as nutrient transfer, decomposition and pollination [65, 66]. 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].

250 Despite this, we remain largely ignorant about how much animal diversity matters for ecosystem functioning, services and resilience [67].

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. [53] use the functional structure of avian communities to explore the impact of
255 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
260 species. Similarly, Griffiths et al. [68] 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
265 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
270 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 [69, 70], or in taxa such as microbes where species limits are poorly defined [71]?

In this feature, Cavanagh et al. [69] highlight the dearth of studies exploring
275 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. [70]

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, 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 [56, 59, 60]. It is also becoming increasingly clear that interactions within and between lineages and trophic levels are the fundamental architecture of functional and stable ecosystems [58, 61, 71]. 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; [72]) 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 can be translated into real policies and practices relevant to local contexts. For a list of key future research questions, see table S1.

(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 and the functioning and resilience of ecosystems is far from complete [73-75]. Without this, we may fail to protect 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, 76]. 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 [77], and others may not contribute in a significant way [78-80]. As a result, growing emphasis has been placed on the identity and diversity of traits or evolutionary lineages mediating ecological functions [74, 81], with the use of metrics such as “functional diversity” (FD) or “phylogenetic diversity” (PD) in studies assessing the impact of anthropogenic activities [82-86].

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 [87-89]. For example, Pigot et al. [90] 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
345 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 [91]. 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. [53] find
350 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. [92] show that
large bodied, pelagic fish, which account for a major proportion of functional
trait space, are highly vulnerable to fishing. These findings, along with other
355 related work (e.g. [93]), 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,
360 harvesting, land-use change) [65, 94]. 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 [95, 96].

Understanding, predicting and ultimately mitigating the effects of
365 anthropogenic pressures will require the use of multiple measures of
biodiversity. Building on this theme, Naeem et al. [52] 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
370 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, as well as the existing
375 knowledge gaps (table S1). 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.

380 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 functional
385 traits can fulfil their potential as metrics for quantifying the value of biodiversity and guiding 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 (table S1). Similarly, more evidence is
390 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 wellbeing and policy

395

(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
400 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
405 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 [97]). 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 [98]. 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 [99]. 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 human 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 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 value, and could precipitate policy decisions that ultimately compromise human wellbeing and sustainable development (figure 1). We recognise 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" [100]. 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 [101].

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 [102]. 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 [103]. The success of IPBES will be

475 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 [38,
104]. 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.

480 Finally, the SDG framework is the pre-eminent commitment on
environment and development for the next two decades [105]. 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,
485 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 feature and illustrated in figure 1, the conservation and restoration of the
490 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 106]. The challenge now for
scientists and practitioners is to work together to make this case to governments
495 and the various constituencies investing in and overseeing implementation of the
SDGs [21]. In doing so they will bring biodiversity to its rightful, foundational
place, at the very heart of the sustainable development agenda.

Conclusions

500 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
505 many key questions remain (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 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 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 [107].

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.

545 **Acknowledgements**

We thank the Oxford Martin School for supporting the Biodiversity Institute symposium on the “Values and Functions of Biodiversity”, where the idea for this special feature arose. RC was supported by the Integrating Climate and Ecosystem Dynamics (ICED) programme under a NERC International Opportunities Fund Grant NE/I029943/1 with additional NERC core funding to 550 British Antarctic Survey. ALP was funded through a VENI fellowship of the Netherlands Organisation for Scientific Research. Finally, we thank two anonymous referees for their constructive comments on an early draft of this manuscript.

555

Author contributions

NS wrote the first draft of this manuscript; all co-authors contributed to revisions.

560 **References**

1. Zalasiewicz J, Williams, M., Haywood, A., Ellis, M. 2011 The Anthropocene: a new epoch of geological time? *Phil Trans Roy Soc B* **369**, 835-841.
2. Corlett RT. 2015 The Anthropocene concept in ecology and conservation. *Trends Ecol Evol* **30**, 36-41.
- 565 3. McGill BJ, Dornelas M, Gotelli NJ, et al. 2015 Fifteen forms of biodiversity trend in the Anthropocene. *Trends Ecol Evol* **30**, 104-113.
4. Watson JEM, Shanahan DF, Di Marco M, et al. 2016 Catastrophic declines in wilderness areas undermine global environment targets. *Curr Biol* **10.1016/j.cub.2016.08.049**.
- 570 5. Magurran AE, Dornelas M, Moyes F, et al. 2015 Rapid biotic homogenization of marine fish assemblages. *Nature Comms* **6**.
6. Dornelas M, Gotelli NJ, McGill B, et al. 2015 Assemblage time series reveal biodiversity change but not systematic loss. *Science* **344**, 10.1126/science.1248484.
- 575 7. Newbold T, Hudson LN, Hill SLL, et al. 2015 Global effects of land use on local terrestrial biodiversity. *Nature* **520**, 45-50.
8. Tittensor DP, Walpole M, Hill SLL, et al. 2014 A mid-term analysis of progress toward international biodiversity targets. *Science* **346**, 241-244.
9. Ceballos G, Ehrlich PR, Barnosky AD, et al. 2015 Accelerated modern 580 human-induced species losses: Entering the sixth mass extinction. *Science Advances* **1**, e1400253.

10. Payne, Jonathan L., Bush, Andrew M., Heim, Noel A., et al. 2016 Ecological selectivity of the emerging mass extinction in the oceans. *Science* **10.1126/science.aaf2416**.
- 585 11. Steffen W, Richardson K, Rockström J, et al. 2015 Planetary boundaries: Guiding human development on a changing planet. *Science* **10.1126/science.1259855**.
12. Cardinale BJ, Duffy JE, Gonzalez A, et al. 2012 Biodiversity loss and its impact on humanity. *Nature* **486**, 59-67.
- 590 13. Hooper DU, Adair EC, Cardinale BJ, et al. 2012 A global synthesis reveals biodiversity loss as a major driver of ecosystem change. *Nature* **486**, 105-U129.
14. Oliver TH, Heard MS, Isaac NJB, et al. 2015 Biodiversity and Resilience of Ecosystem Functions. *Trends Ecol Evol* **30**, 673-684.
15. Isbell F, Craven D, Connolly J, et al. 2015 Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature* **526**, 574-577.
- 595 16. Duffy JE, Lefcheck JS, Stuart-Smith RD, et al. 2016 Biodiversity enhances reef fish biomass and resistance to climate change. *Proc Natl Acad Sci U S A* **113**, 6230-6235.
17. Balvanera P, Siddique I, Dee L, et al. 2014 Linking biodiversity and ecosystem services: current uncertainties and the necessary next steps. *Bioscience* **10.1093/biosci/bit003**.
- 600 18. Mace GM, Reyers B, Alkemade R, et al. 2014 Approaches to defining a planetary boundary for biodiversity. *Glob Environ Chang* **28**, 289-297.
19. Gilmour JP, Smith LD, Heyward AJ, et al. 2013 Recovery of an Isolated Coral Reef System Following Severe Disturbance. *Science* **340**, 69-71.
- 605 20. CBD. 2014 Resourcing the Aichi Biodiversity Targets. Report of the High-Level Panel on Global Assessment of Resources for Implementing the Strategic Plan for Biodiversity 2011-2020. Montreal, Canada.
21. Waage J, Yap C, Bell S, et al. Governing the UN Sustainable Development Goals: interactions, infrastructures, and institutions. *Lancet Global Health* **3**, e251-e252.
- 610 22. Butchart SHM, Walpole M, Collen B, et al. 2010 Global Biodiversity: Indicators of Recent Declines. *Science* **328**, 1164-1168.
23. Gerland P, Raftery AE, Ševčíková H, et al. 2014 World population stabilization unlikely this century. *Science* **346**, 234-237.
- 615 24. Sulston J, Rumsby M, Green N. 2013 People and the Planet. *Environ Resource Econ* **55**, 469-474.
25. Corlett RT. 2015 The Anthropocene concept in ecology and conservation. *Trends Ecol Evol* **30**, 36-41.
- 620 26. Mace GM. 2014 Whose conservation? *Science* **345**, 1558-1560.
27. Atkinson G, Bateman I, Mourato S. 2012 Recent advances in the valuation of ecosystem services and biodiversity. *Oxford Rev Econ Policy* **28**, 22-47.
28. McCauley DJ. 2006 Selling out on nature. *Nature* **443**, 27-28.
29. Neuteleers S, Engelen B. 2015 Talking money: How market-based valuation can undermine environmental protection. *Ecol Econ* **117**, 253-260.
- 625 30. Silvertown J. 2015 Have Ecosystem Services Been Oversold? *Trends Ecol Evol* **30**, 641-648.
31. Bottrill MC, Joseph LN, Carwardine J, et al. Is conservation triage just smart decision making? *Trends Ecol Evol* **23**, 649-654.
- 630 32. Helm D, Hepburn C. 2014 *Nature in the Balance*, Oxford University Press.

33. Mace GM, Norris K, Fitter AH. 2012 Biodiversity and ecosystem services: a multilayered relationship. *Trends Ecol Evol* **27**, 19-26.
34. Bateman IJ, Harwood AR, Mace GM, et al. 2013 Bringing Ecosystem Services into Economic Decision-Making: Land Use in the United Kingdom. *Science* **341**, 45-50.
35. Pearce D, Atkinson G, Mourato S. 2006 Cost-benefit analysis and the environment: recent developments. *OECD Publishing*.
36. Bateman IJ, Mace GM, Fezzi C, et al. 2010 Economic analysis for ecosystem service assessments. *Environ Res Econ* **10.1007/s10640-010-9418-x**.
37. Admiraal JF, Wossink A, de Groot WT, et al. 2013 More than total economic value: How to combine economic valuation of biodiversity with ecological resilience. *Ecol Econ* **89**, 115-122.
38. Díaz S, Demissew S, Carabias J, et al. 2015 The IPBES Conceptual Framework — connecting nature and people. *Curr Opin Environ Sust* **14**, 1-16.
39. Chan KMA, Balvanera P, Benessaiah K, et al. 2016 Opinion: Why protect nature? Rethinking values and the environment. *Proc Natl Acad Sci U S A* **113**, 1462-1465.
40. Daily GC. 1997 *Nature's services: Societal dependence on natural ecosystems*. Washington, D.C., USA, Island Press; 392 p.
41. Daily GC, Polasky S, Goldstein J, et al. 2009 Ecosystem services in decision making: time to deliver. *Front Ecol Environ* **7**, 21-28.
42. Balmford A, Green JMH, Anderson M, et al. 2015 Walk on the Wild Side: Estimating the Global Magnitude of Visits to Protected Areas. *PLoS Biol* **13**, e1002074.
43. Redford KH, Adams WM. 2009 Payment for ecosystem services and the challenge of saving nature. *Conserv Biol* **23**, 785-787.
44. James AN, Gaston KJ, Balmford A. 1999 Balancing the Earth's accounts. *Nature* **401**, 323-324.
45. Pearce D. 2007 Do we really care about Biodiversity? *Environ Res Econ* **37**, 313-333.
46. Tallis H, Lubchenco J. 2014 A call for inclusive conservation. *Nature* **515**, 27-28.
47. Hicks CC, Cinner Joshua E, Stoeckl N, et al. 2015 Linking ecosystem services and human-values theory. *Conserv Biol* **29**, 1471-1480.
48. Bottrill MC, Joseph LN, Carwardine J, et al. 2008 Is conservation triage just smart decision making? *Trends Ecol Evol* **23**, 649-654.
49. Redford KH, Adams WM. 2009 Payment for Ecosystem Services and the Challenge of Saving Nature. *Conserv Biol* **23**, 785-787.
50. Vira B, Adams WM. 2009 Ecosystem services and conservation strategy: beware the silver bullet. *Cons Letts* **2**, 158-162.
51. Grace JB, Anderson TM, Seabloom EW, et al. 2016 Integrative modelling reveals mechanisms linking productivity and plant species richness. *Nature* **529**, 390-393.
52. Naeem S, Prager C, Weeks B, et al. 2016 Biodiversity as a multidimensional construct: A review, framework, and multidimensional case study of herbivory's impact on plant biodiversity. *Proc Roy Soc B* **This feature**.
53. Bregman T, Lees A, MacGregor H, et al. 2016 Using avian functional traits to assess the impact of land- cover change on ecosystem processes linked to resilience in tropical forests. *Proc Roy Soc B* **This feature**.

- 680 54. Hector A, Schmid B, Beierkuhnlein C, et al. 1999 Plant Diversity and Productivity Experiments in European Grasslands. *Science* **286**, 1123-1127.
55. Naeem S, Duffy JE, Zavaleta E. 2012 The Functions of Biological Diversity in an Age of Extinction. *Science* **336**, 1401-1406.
56. Tilman D, Isbell F, Cowles JM. 2014 Biodiversity and ecosystem
685 functioning. *Ann Rev Ecol Evol System* **45**, 471-493.
57. Tilman D, Reich PB, Isbell F. 2012 Biodiversity impacts ecosystem productivity as much as resources, disturbance, or herbivory. *Proc Natl Acad Sci U S A*, 10394-10397.
58. Schneider FD, Brose U, Rall BC, et al. 2016 Animal diversity and ecosystem
690 functioning in dynamic food webs. *Nature Comms* **7**, 12718.
59. Liang J, Crowther TW, Picard N, et al. 2016 Positive biodiversity-productivity relationship predominant in global forests. *Science* **354**.
60. Turnbull L, Isbell F, Purves DW, et al. 2016 Understanding the value of plant diversity for ecosystem functioning through niche theory. *Proc Roy Soc B*
695 **This feature**.
61. Soliveres S, van der Plas F, Manning P, et al. 2016 Biodiversity at multiple trophic levels is needed for ecosystem multifunctionality. *Nature* **536**, 456-459.
62. Tuck SL, O'Brien M, Phillips C, et al. 2016 Insurance effects of tree diversity in tropical forest restoration: Survival and growth during the first
700 decade of the Sabah Biodiversity Experiment. *Proc Roy Soc B This feature*.
63. Hector A. 2011 The Sabah Biodiversity Experiment: a long-term test of the role of tree diversity in restoring tropical forest structure and functioning. *Phil Trans Roy Soc B* **366**, 3303-3315.
64. Yachi S, Loreau M. 1999 Biodiversity and ecosystem productivity in a
705 fluctuating environment: The insurance hypothesis. *Proc Natl Acad Sci USA* **96**, 1463-1468.
65. Estes JA, Terborgh J, Brashares JS, et al. 2011 Trophic Downgrading of Planet Earth. *Science* **333**, 301-306.
66. Roman J, Estes JA, Morissette L, et al. 2014 Whales as marine ecosystem
710 engineers. *Front Ecol Environ* **12**, 377-385.
67. Bello C, Galetti M, Pizo MA, et al. 2015 Defaunation affects carbon storage in tropical forests. *Science Advances* **1**, e1501105.
68. Griffiths H, Bardgett R, Louzada J, et al. 2016 The value of trophic interactions for ecosystem function: dung beetle communities influence seed
715 burial and seedling recruitment in tropical forests. *Proc Roy Soc B This feature*.
69. Cavanagh RD, Broszeit S, Pilling GM, et al. 2016 Valuing biodiversity and ecosystem services: a useful way to manage and conserve marine resources? *Proc Roy Soc B This feature*.
70. Murphy EJ, Cavanagh RD, Drinkwater KF, et al. 2016 Understanding the structure and functioning of polar pelagic ecosystems to predict the impacts of
720 change. *Proc Roy Soc B This feature*.
71. Bell T, Tylianakis J. 2016 Microbes in the Anthropocene: spillover of agriculturally-selected bacteria and their impact on natural ecosystems. *Proc Roy Soc B This feature*.
- 725 72. Harfoot MBJ, Newbold T, Tittensor DP, et al. 2014 Emergent Global Patterns of Ecosystem Structure and Function from a Mechanistic General Ecosystem Model. *PLoS Biol* **12**, e1001841.

73. Gravel D, Albouy C, Thuiller W. 2016 The meaning of functional trait composition of food webs for ecosystem functioning *Phil Trans R Soc Lond B* **371**, 20150268.
74. Sakschewski B, von Bloh W, Boit A, et al. 2016 Resilience of Amazon forests emerges from plant trait diversity. *Nature Clim Change* **advance online publication**.
75. Srivastava DS, Vellend M. 2005 Biodiversity-ecosystem function research: Is it relevant to conservation? *Ann Rev Ecol Evol System* **36**, 267-294.
76. Isbell F, Craven D, Connolly J, et al. 2015 Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature* **526**, 574-577.
77. Mouillot D, Villéger S, Parravicini V, et al. 2014 Functional over-redundancy and high functional vulnerability in global fish faunas on tropical reefs. *Proc Natl Acad Sci USA* **111**, 13757-13762.
78. Kleijn D, Winfree R, Bartomeus I, et al. 2015 Delivery of crop pollination services is an insufficient argument for wild pollinator conservation. *Nature Comms* **6**.
79. Winfree R, Fox JW, Williams NM, et al. 2015 Abundance of common species, not species richness, drives delivery of a real-world ecosystem service. *Ecol Lett* **18**, 626-635.
80. Fauset S, Johnson MO, Gloor M, et al. 2015 Hyperdominance in Amazonian forest carbon cycling. *Nature Comms* **6**, 10.1038/ncomms7857.
81. Cadotte MW. 2013 Experimental evidence that evolutionarily diverse assemblages result in higher productivity. *Proc Natl Acad Sci USA* **110**, 8996-9000.
82. Flynn DFB, Gogol-Prokurat M, Nogeire T, et al. 2009 Loss of functional diversity under land use intensification across multiple taxa. *Ecol Lett* **12**, 22-33.
83. Banks-Leite C, Pardini R, Tambosi LR, et al. 2014 Using ecological thresholds to evaluate the costs and benefits of set-asides in a biodiversity hotspot. *Science* **345**, 1041-1045.
84. Thuiller W, Pironon S, Psomas A, et al. 2014 The European functional tree of bird life in the face of global change. *Nature Comms* **5**, 10.1038/ncomms4118.
85. Diaz S, Lavorel S, de Bello F, et al. 2007 Incorporating plant functional diversity effects in ecosystem service assessments. *Proc Natl Acad Sci USA* **104**, 20684-20689.
86. D'agata S, Mouillot D, Kulbicki M, et al. Human-Mediated Loss of Phylogenetic and Functional Diversity in Coral Reef Fishes. *Curr Biol* **24**, 555-560.
87. McGill BJ, Enquist BJ, Weiher E, et al. 2006 Rebuilding community ecology from functional traits. *Trends Ecol Evol* **21**, 178-185.
88. Díaz S, Kattge J, Cornelissen JHC, et al. 2016 The global spectrum of plant form and function. . *Nature* **529**, 167-171.
89. Laughlin DC, Joshi C, Bodegom PM, et al. 2012 A predictive model of community assembly that incorporates intraspecific trait variation. *Ecol Lett* **15**, 1291-1299.
90. Pigot AL, Bregman T, Sheard C, et al. 2016 Quantifying species contributions to ecosystem process: a global assessment of functional trait and phylogenetic metrics across seed-dispersal network. *Proc Roy Soc B* **This feature**.
91. Naeem S, Li S. 1997 Biodiversity enhances ecosystem reliability. *Nature* **390**, 507-509.

92. D'agata S, Vigliola L, Graham NAI, et al. 2016 Intrinsic functional vulnerability in species-rich ecosystems: the case of coral reef fishes. *Proc Roy Soc B* **This feature**.
93. Estes JA, Terborgh J, Brashares JS, et al. 2011 Trophic Downgrading of Planet Earth. *Science* **333**, 301-306.
94. Tobias JA, Şekercioğlu ÇH, Vargas FH. 2013 Bird conservation in tropical ecosystems: challenges and opportunities. In *Key Topics in Conservation Biology*, vol. 2. eds D. MacDonald, K. Willis, pp. 258–276. John Wiley & Sons, London.
95. Solan M, Cardinale BJ, Downing AL, et al. 2004 Extinction and Ecosystem Function in the Marine Benthos. *Science* **306**, 1177-1180.
96. Díaz S, Purvis A, Cornelissen JHC, et al. 2013 Functional traits, the phylogeny of function, and ecosystem service vulnerability. *Ecol Evol* **3**, 2958-2975.
97. Naeem S, Chazdon R, Duffy J, et al. 2016 Biodiversity and human well-being: an essential link for sustainable development. *Proc Roy Soc B* **This feature**.
98. MEA. 2005 Millennium Ecosystem Assessment. Ecosystems and Human Well-being: Biodiversity Synthesis. *World Resources Institute*.
99. Bagchi R, Gallery RE, Gripenberg S, et al. 2014 Pathogens and insect herbivores drive rainforest plant diversity and composition. *Nature* **506**, 85-88.
100. CBD. 2010 Strategic Plan for Biodiversity 2011-2020. UNEP/CBD/COP/DEC/X/2, Secretariat of the Convention on Biological Diversity, Montreal, 13 pages.
101. Pisupati B, Prip C. 2015 Interim Assessment of Revised National Biodiversity Strategies and Action Plans (NBSAPs). Cambridge, UK and Fridtjof Nansen institute, Lysaker, Norway, UNEP-WCMC.
102. Larigauderie A, Mooney HA. 2010 A step closer to an IPCC-like mechanism for biodiversity. *Curr Op Environ Sustain* **2**, 9-14.
103. Brooks TM, Lamoreux JF, Soberon J. 2014 IPBES ≠ IPCC. *Trends Ecol Evol* **29**, 543-545.
104. Vohland K, Nadim T. 2015 Ensuring the success of IPBES: between interface, market place and parliament. *Phil Trans Roy Soc B* **370**, 20140012.
105. <https://sustainabledevelopment.un.org/>.
106. Folke C, Biggs R, Norström AV, et al. 2016 Social-ecological resilience and biosphere-based sustainability science. *Ecol Soc* **21**, 41.
107. Bohan DA. 2016 The Quintessence Consortium. Networking our way to better ecosystem service provision. *Trends Ecol Evol* **31**, 10.1016/j.tree.2015.1012.1003.