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Observations, indicators and scenarios of biodiversity and ecosystem services change — a framework to support policy and decision-making

Cornelia B Krug[1,2], Michael E Schaepman[1,2], Lynne J Shannon[3], Jeannine Cavender-Bares[4], William Cheung[5], Peter B McIntyre[6], Jean Paul Metzger[7], Ülo Niinemets[8,9], David O Obura[10], Bernhard Schmid[1,11], Bernardo BN Strassburg[12], Astrid JA Van Teeffelen[13], Olaf LF Weyl[14], Moriaki Yasuhara[15] and Paul W Leadley[16]

Improving understanding of how biodiversity and ecosystems respond to environmental change is necessary to guide policy and management. To this end, the bioDISCOVERY project of the international programme on global change, Future Earth, initiates and supports international networks of scientists to advance research on monitoring and observations, scenarios and models, and assessments of biodiversity and ecosystems. bioDISCOVERY activities seek collective solutions to key research challenges, and provide support for the international science community by participating in the development of global databases. This global working-group approach is essential for directing cutting-edge science toward supporting international policies, addressing urgent environmental issues, and closing research gaps through transdisciplinary integration and mobilisation of the scientific community.

Addresses
[1] URPP Global Change and Biodiversity, University of Zurich, Zurich, Switzerland
[2] Remote Sensing Laboratories, Department of Geography, University of Zurich, Zurich, Switzerland
[3] Marine Research Institute, University of Cape Town, Rondebosch, South Africa
[4] Dept. of Ecology, Evolution and Behavior, University of Minnesota, Saint Paul, MN, USA
[5] Changing Ocean Research Unit, Institute for the Oceans and Fisheries, The University of British Columbia, Vancouver, Canada
[6] Center for Limnology, University of Wisconsin, Madison, WI, USA
[7] Department of Ecology, Institute of Biosciences, University of São Paulo, Rua do Matão, 321, travessa 14, 05508-900 São Paulo, SP, Brazil
[8] Estonian University of Life Sciences, Kreutzwaldi 1, 51014 Tartu, Estonia
[9] Estonian Academy of Sciences, Kohtu 6, 10130 Tallinn, Estonia
[10] CORDIO East Africa, P.O. Box 10135, Mombasa 80101, Kenya
[11] Department of Evolutionary Biology and Environmental Studies, University of Zurich, Zurich, Switzerland
[12] IIS International Institute for Sustainability, Estrada Dona Castorina, 124 – Horto, Rio de Janeiro, Brazil
[13] Institute for Environmental Studies (IVM), Faculty of Science, Vrije Universiteit, Amsterdam, The Netherlands
[14] South African Institute for Aquatic Biodiversity, Grahamstown, South Africa
[15] School of Biological Sciences and Swire Institute of Marine Science, the University of Hong Kong, Hong Kong Special Administrative Region
[16] Laboratoire d'Ecologie, Systématique et Evolution, UMR 8079, University Paris-Saclay/CNRS/AgroParisTech, Orsay, France

Corresponding author: Krug, Cornelia B (cornelia.krug@geo.uzh.ch)

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Introduction

It is well documented that biodiversity at all levels — that is, genes, species, communities and habitats — is being heavily impacted by global-scale changes including habitat degradation and loss, overexploitation, invasive species, pollution, and climate change [1]; and that pressures on biodiversity from these drivers are likely to increase in the future. Several factors impede the use of observations and models of biodiversity to inform decision making at local to international scales that seeks to slow the loss of biodiversity. First, it is difficult to monitor changes in biodiversity in a consistent manner across multiple scales, to transform observations into informative indicators, and to attribute these changes to direct and indirect drivers [2,3]. Second, projections of future biodiversity dynamics are underused to support proactive policy and management, in part because of high uncertainty and weak coupling with ecosystem services and socio-economic development [4–6]. Third, a multitude of barriers — one of the foremost being the lack of structured and sustained dialog between scientists and decision makers — hamper the translation of scientific findings into policy and ecosystem management guidelines [6]. Each of these challenges could be overcome by using the momentum arising from release of new global assessments to fuel greater dialog with the policy community [7].

Since its inception more than a decade ago, the bioDISCOVERY project, in collaboration with a wide range of partners, has helped mobilise the scientific community to address these issues. bioDISCOVERY is an international research project, now part of the Future Earth international research platform,[1] that strives to foster collaborative interdisciplinary activities on biodiversity and ecosystem science. This scientific network seeks to integrate observations, indicators, and scenarios to support policy and decision-making for global environmental management. bioDISCOVERY builds upon a component of the former DIVERSITAS programme (see Box 1).

bioDISCOVERY is actively responding to recent changes in the international science-policy landscape, particularly the launch of the international science-policy platform on biodiversity and ecosystem services, IPBES[2] [8,9•,10•], and the 2030 Agenda for Sustainable Development and its Sustainable Development Goals (SDGs[3] [11]). These priorities are served by the mission to improve the understanding of biodiversity and ecosystem responses to global environmental change, and to support decision-making and policy setting on various levels and scales. bioDISCOVERY is built on the recognition that integrated observation and modelling approaches are the underpinning of global assessments of biodiversity change. Thus, bioDISCOVERY activities are centred around three components: first, *monitoring and observations*, second, *models and scenarios*, and third, *supporting assessment bodies* (Figure 1).

This paper outlines how these three components of bioDISCOVERY as well as associated activities (Figure 2) can help improve understanding of biodiversity and ecosystem response to global environmental change, and how they contribute to closing knowledge gaps. We highlight how the use of observations and models provide new insights into biodiversity and ecosystem responses, including feedbacks among the drivers of change. Indicators and scenarios can then assist in identifying policy and management decisions that ensure the conservation and sustainable use of biodiversity and ecosystems globally.

Box 1 bioDISCOVERY

bioDISCOVERY is an international research programme fostering collaborative interdisciplinary activities on biodiversity and ecosystem science. Using a network approach, we promote the use of observations, indicators, models and scenarios to support policy and decision-making for informed global environmental management.

The mission of bioDISCOVERY is to stimulate and advance interdisciplinary collaborative research on feedbacks between global change drivers and the biodiversity, functioning and services of natural ecosystems. This science supports decision-making and policies that ensure the conservation and sustainable use of biodiversity worldwide. Synthesis and catalysing work forms the backbone of bioDISCOVERY activities, which are centred around three components: Monitoring & Observations, Models & Scenarios and Supporting Assessment Bodies.

bioDISCOVERY was established in 2006 under the auspices of DIVERSITAS, the international programme on biodiversity science. Initially, the project was to cover the 'origins and maintenance of biodiversity', but it was soon recognised that the scope was too ambitious, and two closely related projects arose — bioGENESIS, which was to provide an evolutionary framework for biodiversity science [66], and bioDISCOVERY, focused on assessing, monitoring and predicting biodiversity change [67]. bioDISCOVERY brought together interdisciplinary groups of scientists from the fields of biodiversity science, ecology, evolutionary biology and land system science to collaborate in activities under three foci, first, strengthening biodiversity assessments, second, improving observation and understanding biodiversity change, and third, improving biodiversity projections. Efforts brought about key contributions to the Convention on Biological Diversity [4,60,61] and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) [38,54], led to the establishment of the GEO Biodiversity Observation Network (GEO BON) [2], and significantly advanced science underpinning observations and predictions of biodiversity change [22,34••].

In 2015, bioDISCOVERY transitioned to Future Earth, the international platform for research for global sustainability (www.futureearth.org) as part of the integration of DIVERSITAS programs into Future Earth; the project office moved to the University of Zurich in 2017. Future Earth is built on the legacy of the four ICSU global environmental change programmes, DIVERSITAS, IGBP, IHOPE and WCRC, and was created with the objective of strengthening links between science, policy and society, and to address the grand challenges of sustainable development [70]. bioDISCOVERY now has the opportunity to mobilise a wider range of disciplines and partners in order to achieve its goals.

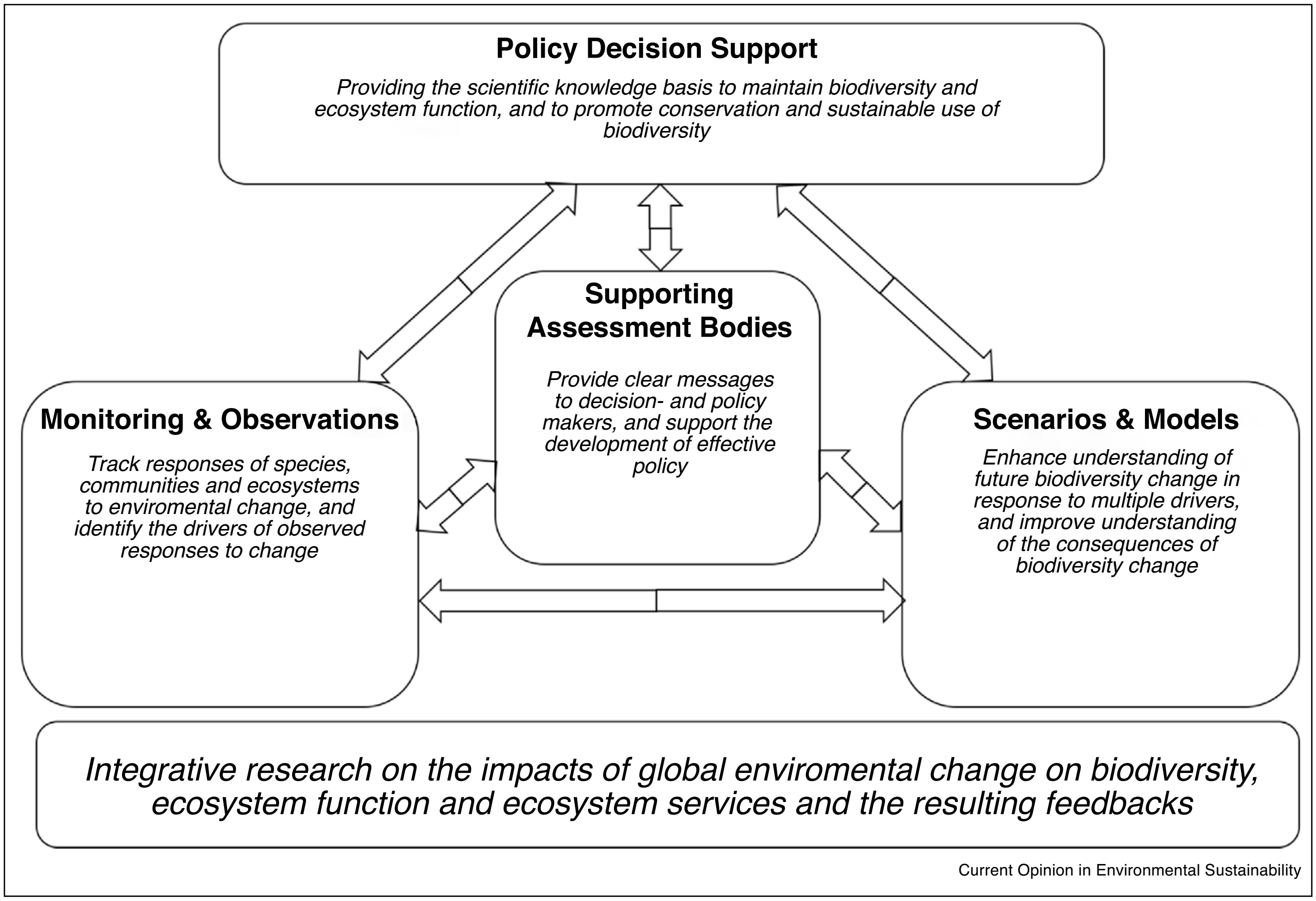
Observations and indicators

Time series of observations track the responses of species, communities, and ecosystems to environmental change, provide insight into the mechanisms underpinning observed responses to global change, and contribute to improving models and scenarios of biodiversity and ecosystems.

Earth observations provide measures of taxonomic, functional and structural diversity (or their proxies) at various spatial and temporal scales [12•,13]. Remote sensing allows assessment of ecosystem properties that underpin the supply of ecosystem services [14,15]. Increasingly, physical metrics from remote sensing allow reliable proxies for ecosystem properties with minimal requirements

[1] Future Earth is the international platform for research for global sustainability science (www.futureearth.org).
[2] www.ipbes.net
[3] www.sustainabledevelopment.un.org

Figure 1



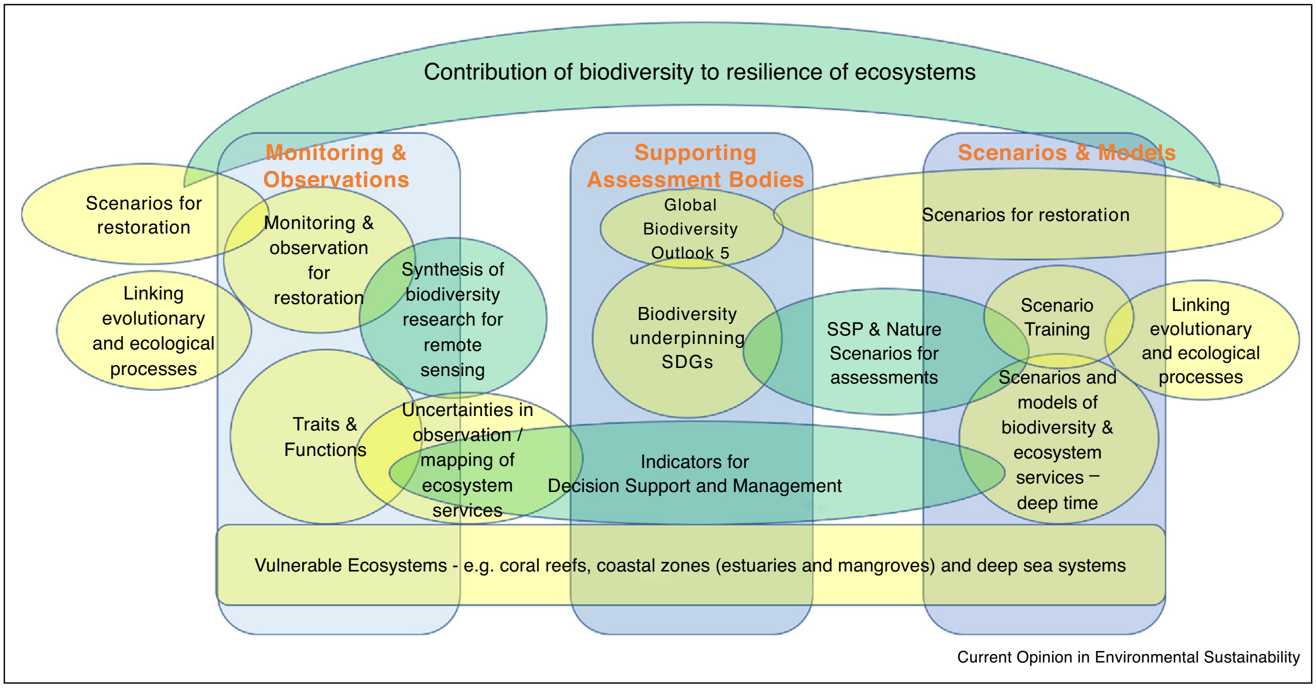
bioDISCOVERY framework. Structure of the bioDISCOVERY science plan with its three components and their relationship to policy and decision support. Integrative research forms the basis for activities in the components. Arrows indicate the flow of information.

for local validation [16]. Thus, remote sensing can help to close gaps in biodiversity observation data collected on the ground [17,18], and provide global spatial assessments of select traits [19]. Recent work provides the precursors for a coherent set of Essential Biodiversity Variables (EBVs) derived from satellite remote sensing [20], which can be matched with field observations of key variables at sites worldwide. For instance, combining observations of nutrient and carbon fluxes with remote sensing allows inferences about ecosystem functioning at continental to global scale [21], and parallel inferences about spatiotemporal variation of ecosystem service provisioning [15].

Knowledge of (functional) traits of species assists in further explaining variability in ecosystem function [21]. Traits are the outcome of evolutionary and community assembly processes [22], and are thus a better predictor of ecosystem dynamics and functioning than species identity [23] 1. Functional or trait diversity in plants (both inter-specific and intraspecific variation in traits) can predict collective contributions to ecosystem functioning better than taxonomic diversity [24]. Knowledge about the relationship between environment and traits allows us to build new models that predict future vegetation based on plant functional traits [25]. Such knowledge may further help to identify species that, based on their traits, are particularly sensitive to environmental change (either positively or negatively [26•]).

Experiments, which are fundamental complements to observational studies, help to clarify the cause-effect relationships associated with specific drivers, which the observational studies can only hint at. By manipulating key environmental drivers, their impacts on biodiversity and ecosystems can be assessed directly. Experiments not only provide a way to distinguish between cause and effect in observed relationships, but also allow us to investigate future conditions that cannot be observed currently [27•]. Furthermore, they link general theory and complex natural situations by isolating causal mechanisms [28], although this reductionist approach is most helpful when experimental conditions are realistic depictions of current or potential future environmental conditions [29]. To be able to link ecosystem function to

Figure 2



bioDISCOVERY activities. Key components of bioDISCOVERY including monitoring and observations, supporting assessment bodies, as well as scenarios and models. Colours indicate the status of the given activity (green = higher maturity and ongoing activity; yellow = envisaged activities).

ecosystem services, it is necessary to describe specific mechanistic connections, and to place small-scale ecosystem function assessments in the context of large-scale patterns of ecosystem services (e.g. [30–33]). Given that data to inform cross-scale, mechanistic models are often inadequate, there is a need for strategic collection of this data and strategic design of observations and experiments to guide predictions of species' and ecosystem responses to global environmental change [34••].

Within the *Observation and Indicators* component of bioDISCOVERY, the focus of activities continues to be the 'nuts and bolts' of improving science approaches by combining observation sets, in particular remote sensing, and *in situ* measurements of biodiversity, functional traits and ecosystem functions, and linking these approaches by models to provide an integrated understanding of biodiversity and ecosystem change at multiple scales. For example, remotely sensed data can be used to improve the accuracy and performance of species distribution models [13,17].

Observations of biodiversity and ecosystem responses to environmental change help to identify *indicators* to monitor change and responses to change. Indicators have been shown to be useful in comparing different ecosystems [35] and are valuable tools of communication because they are both simple and informative [36]. A successful implementation of policy requires robust data and a diverse set of indicators [37]. However, data are often lacking to inform indicators and adequately assess biodiversity trends. In particular, a new generation of indicators that consider less-studied taxonomic groups, and are standardised across regions to allow for global comparisons and measure change over multiple time points, are needed to support policy and decision-making [38]. There is also a lack of indicators of ecosystem functioning [39]. As these research gaps are filled, bioDISCOVERY is poised to synthesising information from multiple indicators into coherent messages that can inform decision-making.

Building on comparative indicators of marine ecosystem condition [40], we see particular opportunities for advancing freshwater and marine indicators. Such efforts can complement IPBES and GEO-BON (Group on Earth Observations — Biodiversity Observation Network) processes nicely. Moreover, synthetic indicators can guide management decisions by accounting for the delivery of land-based and air-based stressors to water bodies along with direct human impacts (see [41]).

Our activities (see Figure 2) foster and advance the use of remote sensing to document changes in biodiversity, ecosystem functioning and ecosystem services. Combining remote sensing, local field monitoring, and broad survey networks will elucidate uncertainties in quantification of these response variables in space and time.

Experiments will be used to understand cause-effect relationships that underpin changes in biodiversity and ecosystem dynamics. Linking *in situ* observations and experiments will also provide insight into the role of micro-evolution in shaping species' response to environmental change. Our understanding of the links between environmental conditions, species traits (and their variation) and ecosystem properties and function is still incomplete [21], and further progress will require a combination of observation and experiments. Using a trait-based approach, remote sensing will be able to predict functional biodiversity change at larger scales [42••].

Models and scenarios

Projections of future ecosystem and biodiversity change are limited by incomplete understanding of the underlying processes, insufficiency of available modelling tools, and a lack of data to validate and parameterise models [43]. Computational ecology is a key emerging field that can provide projections of biodiversity change [44], yet current models exclude many important biological processes that shape species' responses to environmental change [34••]. There is a need for modelling approaches that integrate biodiversity composition and ecosystem function, and account for the interactions between the two [45]. This approach will facilitate testing for interactions between composition and function, and projecting biodiversity and ecosystem futures more realistically [45].

Existing global change scenarios are often dominated by climatic shifts, whereas ecological dynamics are not well integrated into most modelling frameworks [46••]. For example, a number of important ecological processes are entirely absent from Integrated Assessment Models [47]. To improve projections of biodiversity and ecosystem change, we need models that account for a broad range of global-change drivers to explore the future of biodiversity [47]. Furthermore, multi-model comparison approaches have highlighted the benefit of incorporating information from model ensembles based on different assumptions and driver interactions (e.g. [48]). Further work is needed to improve model projections and reveal sources of uncertainty [49], thereby providing a more robust basis for decision-making [50]. For example, uncertainties in future projections can stem from input parameter variability, scenario uncertainty, or model uncertainty [51]. In this context, paleo-ecological evidence is not only useful and important to quantify the relationship between climate change and ecosystem response, but also can be used to test the ability of models (in particular dynamic global vegetation models) to simulate ecosystem processes [43].

Biodiversity and ecosystem services are shaped by local, regional and global change drivers and responses, hence scenarios used in IPBES and other syntheses need to integrate across multiple scales [46••]; and responses will have to be implemented at local scales [52]. There is particular need to develop more local-scale scenarios that can leverage mechanistic understanding from observations and experiments. For example, Teh *et al.* have synthesised projection from well-parameterised local models to understand patterns of change in Canada's coastal marine ecosystems [53].

Taken together, the *Models and Scenarios* activities within bioDISCOVERY (see Figure 2) promise to enhance understanding of past and future biodiversity changes in response to diverse natural and anthropogenic drivers, and their consequences for ecosystem functioning and services. Our approach will generate improved predictions of environmental change, and allow exploration of how different policy scenarios might mediate losses of biodiversity, ecosystem function, and ecosystem services. The development of 'nature visions', linking targets for biodiversity conservation with sustainable development targets, allow better representation of socio-ecological systems. It also informs decision-making in human-modified systems [54]. In particular, future work will focus on assessing the impact of a suite of socio-economic pathways (SSPs) on biodiversity and ecosystem services, how policy options for conservation and restoration of biodiversity may mediate SSP outcomes, and the feasibility of achieving Aichi Target 15 and climate mitigation through large-scale restoration efforts. To this end, Metzger *et al.* [55] have proposed a framework for scenario-based restoration planning. We also intend to expand the time horizon for scenarios — using 'deep time' to understand sources of uncertainty and improve future predictions.

Supporting assessment bodies

Policy and decision-making support

Setting environmental policies and making management decisions can be informed by scenarios and models [6,56] derived from robust input data [37], but appropriate indicator frameworks [57,58•,59] are then needed to measure both the positive and negative impacts on biodiversity and ecosystem function. The more rigorous the models, inputs, and scenarios, the clearer and stronger will be the messages conveyed by the scientific community to decision-makers. Spatial scale is at the crux of this challenge; observations, models, and indicators all need to address the interface between local management and global policy. If well integrated, there can be abundant synergies with IPBES, IPCC, and sustainable development agendas.

Efforts of the bioDISCOVERY scientific community have brought about key contributions to the Convention on Biological Diversity, in particular into the Global Biodiversity Outlook 3 [4] and 4 [60,61], but also the visioning process for the 2020 Aichi Targets [62]. Contributions to the Intergovernmental Science-Policy

Figure 3

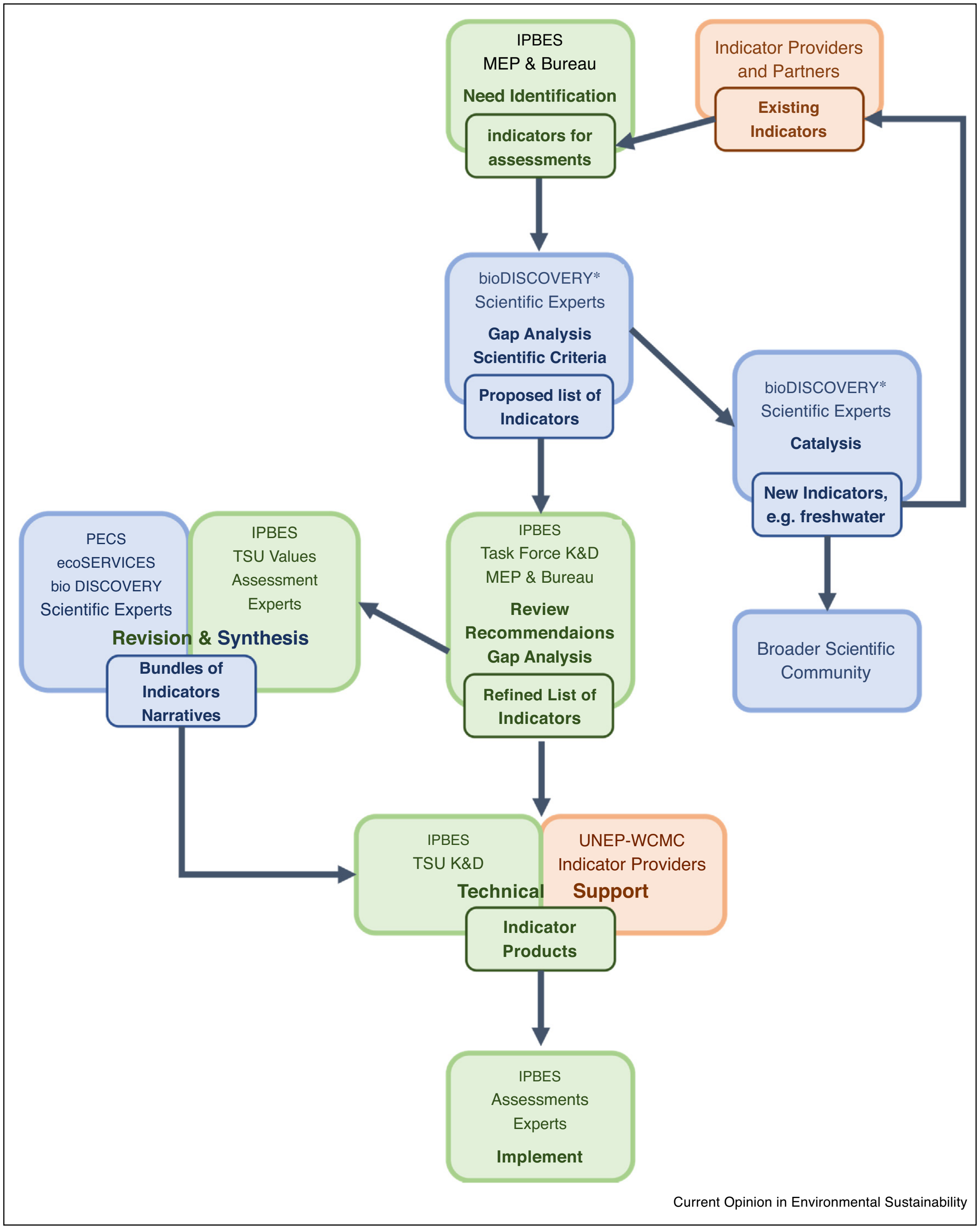


illustration of the iterative science-policy process. Illustration of the science-policy process, using as example the process leading to the development of indicators for use in IPBES assessments. The process begins with need that is being identified (in this case, indicators for use in assessments). bioDISCOVERY convened the scientific community to mobilise new indicators, and to assess already existing indicators. This lead to the development of new indicators for freshwater systems. The IBPES Task Force on Knowledge and Data and the MEP and Bureau then reviewed the list of indicators identified by the scientific experts, and made recommendations on their use. Indicators accepted for the IPBES process where than processed by the IPBES TSU on Knowledge and Data and UNEP-WCMC to provide products for use in assessments. In a parallel stream, the scientific community, under the guidance of the IPBES TSU on Values, and in collaboration with IPBES experts, was tasked to develop bundles of indicators and narratives for inclusion in IPBES assessments. Blue indicates the scientific community, green the various IPBES bodies, red other partners involved in the process. * bioDISCOVERY acted as a convener, the meetings and workshops included participants from

Platform on Biodiversity and Ecosystem Services (IPBES) have focussed on knowledge generation for use in the various assessments, for example the synthesis of information for indicators [38] (Figure 3), and supporting the work of the IPBES Technical Support Unit and expert group on scenarios [54]. Activities also led to the establishment of the GEO BON [63], which significantly advances observations and predictions of biodiversity change [22,34••].

In the future, case studies on vulnerable coastal marine and freshwater ecosystems will serve as a focus for integrating the components of bioDISCOVERY, yielding lessons and insights into the challenges of integrating observations, mechanistic models, and future scenarios. Coral reefs in particular are degrading rapidly under a multitude of anthropogenic threats. They are not only 'running the climate gauntlet' [29], but are also stressed from changes in community structure due to overfishing [64], species invasions [65] and pollution [66]. At the same time, reefs and other coastal ecosystems provide a wide range of ecosystem services [29] that are vital for sustaining human livelihoods and food security. Working with global reef observations collated regionally and globally through the Global Coral Reef Monitoring Network focused on the use of Essential Ocean Variables (Bax *et al.*, in review; Miloslavich *et al.* in review) and Essential Biodiversity Variables [3] relevant to coral reefs, bioDISCOVERY will help develop and model indicators to inform the urgent policy action that is needed [67]. We are launching parallel efforts in the world's freshwaters, integrating large-scale observations of shifting quantity and quality of water with improved global assessments of fishery and biodiversity patterns.

Another integrative activity that connects all bioDISCOVERY priorities, and cross-cuts across terrestrial, freshwater and marine realms, will focus on the resilience and adaptive capacity of biodiversity and ecosystems to global environmental change. We currently have a limited understanding of the impacts of disturbances on the stability of ecosystems [68], but biodiversity and its variation from intraspecific and interspecific to across landscape variation play crucial roles in the long-term resilience of ecosystem functions and services [69]. Anthropogenic activities change the suite of traits and species interactions that shape ecosystem functioning, potentially eroding system resilience [39]. Our work on the links between biodiversity, ecosystem functioning, and ecosystem services will help to elucidate the role of biodiversity in buffering ecosystems against ongoing global change.

Conclusions

We have outlined bioDISCOVERY's vision and priorities for integrating detailed results (observations and modelling) with synthetic analyses (indicators and scenarios) to support environmental policy-setting and decision-making on global and local scales. This research network approach focuses on global capacity building through collaborations among early-career researchers, established experts, and end-users. In addition to fostering syntheses of biodiversity research across diverse communities, we have identified compelling opportunities for bioDISCOVERY to contribute to scenario training programmes.

bioDISCOVERY's success in the activities outlined above relies on the participation of researchers across many disciplines and spanning terrestrial, marine and freshwater habitats. Our ultimate goal is to develop innovative perspectives on biodiversity and ecosystem services based on high-quality data, methods and models, and present them for use at the science-policy interface.

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(Figure 3 Legend Continued) other Future Earth Global Research Projects. IPBES: Intergovernmental science-policy platform for biodiversity and ecosystem service, MEP: Multidisciplinary expert panel, K&D: Knowledge and Data, TSU: Technical Support Unit, PECS: Programme on Ecosystem Change and Society, UNEP-WCMC: United Nations Environmental Programme World Conservation Monitoring Centre.

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