



Monitoring biodiversity change through effective global coordination

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The ability to monitor changes in biodiversity, and their societal impact, is critical to conserving species and managing ecosystems. While emerging technologies increase the breadth and reach of data acquisition, monitoring efforts are still spatially and temporally fragmented, and taxonomically biased. Appropriate long-term information remains therefore limited. The Group on Earth Observations Biodiversity Observation Network (GEO BON) aims to provide a general framework for biodiversity monitoring to support decision-makers. Here, we discuss the coordinated observing system adopted by GEO BON, and review challenges and advances in its implementation, focusing on two interconnected core components – the Essential Biodiversity Variables as a standard framework for biodiversity monitoring, and the Biodiversity Observation Networks that support harmonized observation systems – while highlighting their societal relevance.

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Introduction

The agreement on the Aichi Biodiversity Targets by the Parties of the Convention on Biological Diversity (CBD) [1], the Sustainable Development Goals of the UN Agenda 2030 (Resolution 70/1), and the establishment of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) [2] are encouraging responses to the biodiversity crisis [3]. However, for these international efforts to be successful, our ability to assess biodiversity change must drastically improve. The concept of biodiversity itself is complex and multifaceted, embracing several dimensions of life on earth, from genes to species and ecosystems, operating at multiple scales [4,5]. The data currently supporting biodiversity assessments vary spatially, temporally, and/or thematically (e.g. taxons, realms) [6,7**]. This impairs our ability to derive meaningful conclusions about the intensity and drivers of biodiversity change [8], their consequences for the delivery of benefits to society [9], and to assess the effectiveness of conservation measures [7**]. Furthermore, spatial

gaps are particularly problematic when available biodiversity data do not overlap with areas of current and predicted increases in impacts, for example from habitat loss and fragmentation [6,10**].

To address these challenges, the Group on Earth Observations Biodiversity Observation Network (GEO BON) was established in 2008, as a global initiative that aims to improve the acquisition, coordination and delivery of biodiversity observations and related services to users including decision-makers and the scientific community [4]. Ten years later, GEO BON has developed a globally coordinated strategy for the monitoring of biodiversity change based on two fundamental components: an Essential Biodiversity Variables (EBVs) framework [11], and a system of coordinated Biodiversity Observation Networks (BONs) for sustained, operational monitoring.

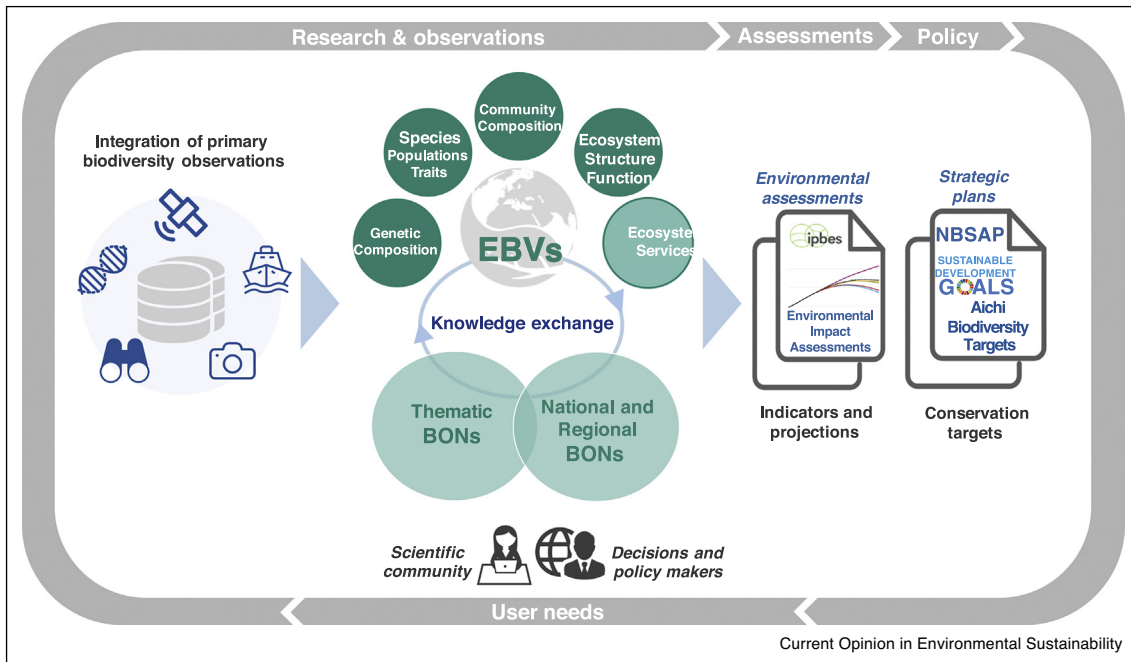
Here, we review progress made in the development of the EBVs and their conceptual framework, discuss the rationale for BONs as a mechanism to measure and interpret EBVs, and the challenges in establishing BONs. Finally, we reiterate the societal relevance of a coordinated biodiversity observation system.

A global observing system for biodiversity

GEO BON, the biodiversity flagship of the Group on Earth Observations (GEO), aims to integrate existing biodiversity monitoring efforts, currently scattered across regions, to build a coordinated and harmonised system of observing systems for biodiversity. The development of this observing system is driven by the needs of users [12], ranging from the scientific community, to local communities, industry and NGOs, to national and sub-national policy makers, and intergovernmental bodies. GEO BON's approach is based on the interconnection between the EBV framework and the BON development process (Figure 1). These two components are connected via capacity building and knowledge exchange mechanisms for tools, techniques, and best practices. As a result, GEO BON's structure has evolved from being originally organized around realms (e.g. marine, terrestrial) and monitoring methods (*in situ*, remote sensing), to a cross-realm and cross-method approach centred on the different levels of organization of biodiversity, and related ecosystem services [13]. This structure is organized around the top-down development of the EBV framework, within working groups, and the bottom-up development of BONs that both test the framework and increase biodiversity observation capacity (Figure 1).

Inspired by the Essential Climate Variables (ECVs) [14], GEO BON put forward the concept of Essential Biodiversity Variables. These are a minimum set of biological state variables, complementary to one another, that are needed to detect biodiversity change [11]. The EBV approach provides guidance to the various biodiversity

Figure 1



Essential Biodiversity Variables require the integration of primary biodiversity observations from multiple sources. GEO BON coordinates and promotes EBV development by facilitating collaboration between biodiversity experts—organised in Working Groups— and Biodiversity Observation Networks. The EBVs, and derived indicators, can then be used for assessments at multiple spatial and temporal scales to support policy and decision making processes.

observation systems and facilitate data sharing across habitats and regions. EBVs are produced by integrating biodiversity observations (primary data), obtained via *in situ* monitoring or remote sensing, in space and time, often through the use of models and other environmental observations and ancillary data [15] (Figure 2). EBVs are organized around six classes (Genetic Composition, Species Populations, Species Traits, Community Composition, Ecosystem Structure, and Ecosystem Function [11]). Variables are prioritized from the many potential biodiversity change variables based on relevance, sensitivity to change, generalizability across realms, scalability, feasibility, and data availability [16]. These criteria make EBVs well-suited to be the building blocks of biodiversity indicators (Figure 2), such as those used to track progress against the international and national targets for biodiversity and sustainability [17,18,19], and within IPBES assessments [20]. EBVs are also important for supporting the development of global and regional change scenarios (Figure 2). Properties such as scalability make them particularly useful for the next generation of multi-scale scenarios [21].

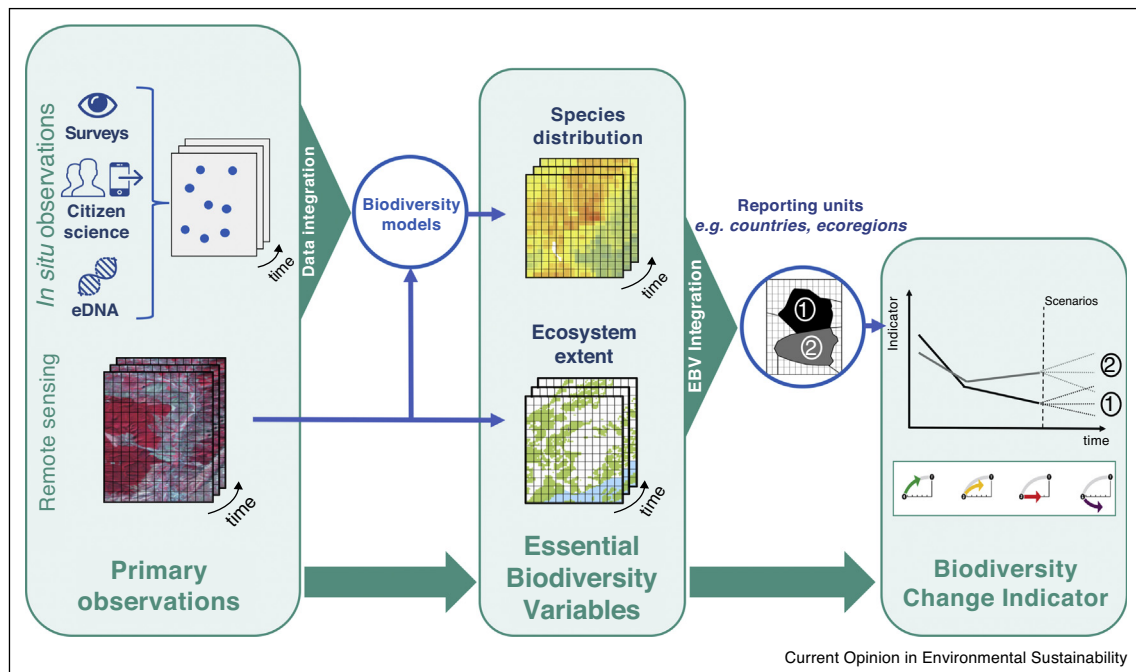
Alongside EBV development, GEO BON has been facilitating the development of Biodiversity Observations Networks (BONs) to improve the coordination and harmonization of observation systems. BONs are

organized around three categories: thematic BONs that focus on a specific biological theme, such as the freshwater and marine realms; national BONs that are endorsed by national governments; and regional BONs. Species and ecosystems, and the pressures that affect them, are not constrained by political borders. Therefore the regional and thematic BONs connect monitoring efforts for different dimensions and scales of biodiversity. National BONs are directly oriented to serve the needs of national and sub-national policy-makers and correspond to the operational scale of many monitoring initiatives. In particular, they address policy needs for reporting on multilateral environmental agreements (e.g. CBD, Ramsar Convention) and support processes such as ecosystem accounting, Environmental Impact Assessment, or land and ocean use planning. In practice, BONs produce, test and apply tools to deliver EBV-relevant data that can be upscaled and downscaled to support sustainable development and conservation decisions [22,23]. By being part of a global framework and a system of observation systems, BONs also reinforce the scientific basis of both biodiversity monitoring and indicator development.

Progress in the development of EBVs across the dimensions of biodiversity

After an initial phase during which the EBV concept has been consolidated, disseminated to, and endorsed by

Figure 2



From observations to the production of EBVs and indicators. In this example, integrated data from different primary sources of observations (e.g. *in situ*, remote sensing) are combined within biodiversity models to produce layers of spatial and temporal variation in ecosystem extent and species distribution EBVs. In some cases one EBV can be an input for a model to produce another EBV. This information is then integrated and summarised within reporting units ((1) and (2) in the figure) to calculate an indicator of biodiversity change, which can then be used, for instance, for reporting progress towards an Aichi conservation target. Note that this indicator can be processed within any spatial unit (e.g. from an ecoregion, to a country, or an entire biome). EBVs and models can also be used to project changes in the indicator using scenarios. Although both raw observations and indicators might change in the future, including with the development of new observation techniques and the expression of new user needs, the EBVs should, by definition, remain the same.

stakeholders (e.g. [16]; UNEP/CBD/COP/DEC/XI/3), the development of EBVs has faced the challenge of producing global coverage of spatially and temporally consistent observations. Major progress in the production of EBVs is expected for variables enabled by satellite remote sensing observations [24]. An example is the Global Forest Change project [25] which, building on freely available and consistently processed Landsat images, delivers decade-long time series of data which can be used to produce EBVs on ecosystem extent and fragmentation from sub-national to global scales. Further agreement and community support on a prioritized list of EBVs is important in order to encourage space agencies and the Committee on Earth Observation Satellites (CEOS) to invest into new products that fill critical gaps in monitoring biodiversity change [26,27].

For EBVs that rely on *in situ* observations, GEO BON faces challenges emerging from the lack of global monitoring schemes, the integration of datasets resulting from different collection methods, and technical issues related to data product structure, storage, workflow execution, and legal interoperability [10^{••},12]. Consequently, EBV

production workflows are now being designed to provide the necessary steps from identification and aggregation of candidate datasets to the elaboration of consistent and reproducible EBVs [28^{*}]. The development of suitable data standards is key in this process. The Darwin Core [29] has already catalysed the global sharing of species occurrence data. Its recent Event Core extension now connects related sampling events and the proposed Humboldt Core standard [30] extends this to capture inventory processes broadly — all aimed at capturing more relevant information for EBV production (e.g. absences, abundance). Further advances in the coordinated production of EBVs will require developing data standards and minimum information specifications that can be applied across all EBV classes.

Below, we outline recent progress and perspectives for coordinating the production of EBVs within the multiple dimensions of biodiversity.

Genetic level

Variables informing on genetic diversity of populations, structure and inbreeding based on the number and

frequency of alleles measured across time and species are considered key candidate EBVs. They directly inform on the genetic status at the population and species levels and are suitable for monitoring genetic erosion over time [31]. While a consultation process for agreeing on a prioritized list of genetic composition EBVs has still to be completed, the scarcity of studies collecting genetic information from populations over time, and their uneven taxonomic and geographic coverage, are major challenges for producing these variables in alignment with the requirements of global, regional, and national reporting and assessments regarding safeguarding genetic diversity as stated in the Aichi Biodiversity Targets and elsewhere (e.g. CBD's Nagoya Protocol) [32]. Progress is needed in the implementation of coordinated genetic monitoring systems with these requirements in mind, for example, combining monitoring of a necessarily reduced set of (indicator) species with models of genetic variation [33]. The popularization of Next Generation Sequencing and other techniques that provide highly detailed genetic information, and a wider use of the vast amount of biological material stored in museum collections as a complement to contemporary genetic monitoring [34], have the potential to boost the production of more comprehensive temporal series of genetic data and of EBVs.

Species level

Species-level EBVs capture dimensions of biodiversity related to populations and traits. For species populations, spatiotemporally explicit data on their distribution and abundance are growing, thanks to increased data collection, sharing, and integration activities, and to a rapid growth in citizen science that fill important data gaps [35,36]. The development of the species distribution EBV has benefitted from data infrastructures such as the Global Biodiversity Information Facility (GBIF), the Ocean Biogeographic Information System (OBIS), and Map of Life [37]. Moreover, increasingly sophisticated modelling approaches that combine species observations with remotely sensed environmental data make the global monitoring of species distributions and abundance increasingly tractable [38,39]. However, major gaps in the spatial, taxonomic, and temporal coverage continue to impose constraints on the global and regional production of Species Populations EBVs [10,40]. Future directions include the implementation of workflows for data integration [28,37] and the development of models that link *in situ* observations to environmental covariates supporting EBV production [39,41]. An on-going priority application of the Species Distribution EBV is monitoring invasive alien species from national to global scales [42,43].

The development of species trait EBVs has been slowed by the challenge of measuring traits repeatedly across time. Most available datasets (e.g. plants [44]) do not provide within species temporal variation of traits.

Exceptions are repeated measurements of fish body size and plant phenology [19], and work is under way to integrate, standardize, and harmonize such measurements.

Ecosystem level

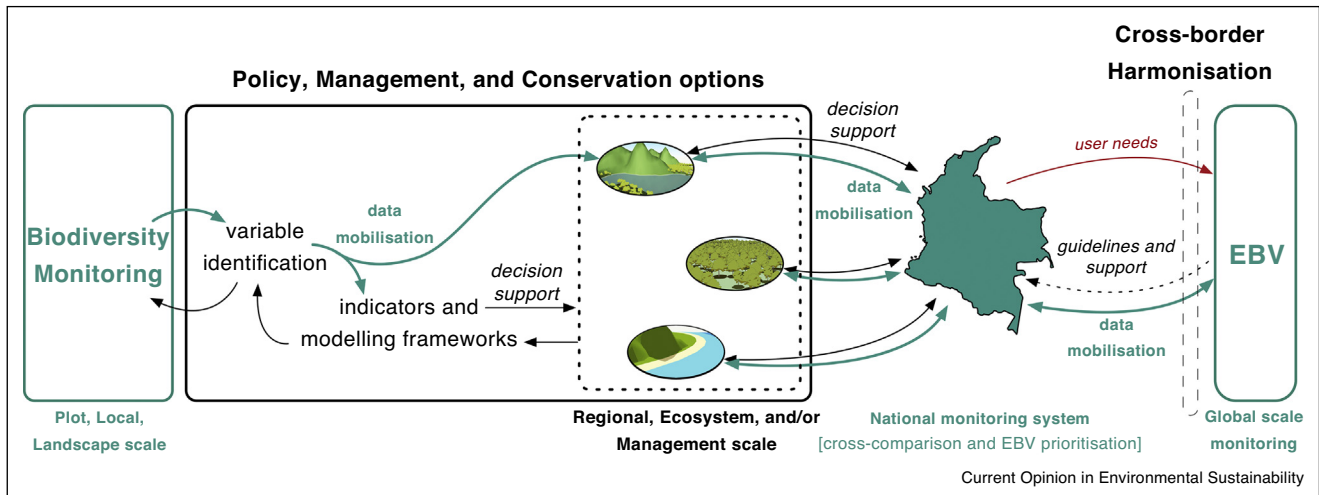
Because of the interdependence between ecosystem composition, structure and function, and all other dimensions of biodiversity, EBVs at the ecosystem level provide a synoptic perspective of critical components of biodiversity change. Satellite information that can support monitoring of structural and functional aspects of ecosystems globally has been recently detailed [24], but agreement on EBVs per structure and function still needs to be reached. Adapted workflows for translating potentially usable datasets into EBVs, as recently done for species populations [28], now need to be considered for ecosystems. One suggested priority for monitoring ecosystems is developing metrics incorporating descriptions of properties such as canopy height, leaf area, biomass [45], as well as structural biochemical components. For ecosystem function EBVs, a typology of ecosystem functions that underpins the identification of EBVs has been proposed [46]; these EBVs now need to be agreed on to better inform global initiatives and to quantify the status, degradation and collapse of ecosystems (e.g. [47]).

Development of EBVs addressing community composition within ecosystems has received far less attention to date than ecosystem structure and function. Existing approaches to deriving variables of potential relevance, such as alpha and beta diversity, typically involve estimating these collective variables from observations and models of multiple individual species [48]. Rapid advances in observation technologies such as metagenomic analysis of eDNA samples, and hyperspectral remote sensing, provide unprecedented potential for direct large-scaled monitoring of community changes [39,49,50]. Most significantly, this includes the potential to move beyond deriving variables simply as an aggregate function of species co-occurring at a given location, to consider the full diversity of traits and relationships of individual organisms into measures of overall community composition.

A cross-scale approach for identifying EBVs and users' needs

To date, the process of identifying and prioritizing EBVs has largely been based on expert knowledge about globally relevant biodiversity measurements [11]. While necessary, this approach has not yet been systematically driven or informed by users' needs at the regional, national, or local scales. There is a need to make biodiversity data more relevant for a range of users (e.g. CBD, IPBES, national and local authorities, NGOs) [51], and a need to have stronger connections to data providers to

Figure 3



A cross-scale approach for global biodiversity monitoring. National monitoring systems have to rely on a key set of policy, management and conservation options/questions to define their monitoring priorities that provide information for decision making. Once these priorities are set, indicators and modelling frameworks can be identified and described to produce effective monitoring systems that allow for data mobilization across scales. On the other side, while nations collaborate to mobilize data to inform EBVs, GEO BON contributes to the national efforts by providing guidance and support for BON development and data standards. In parallel, nations provide user needs for the development of EBVs while contributing to the global data pool on biodiversity and ecosystems. Green arrows indicate biodiversity data mobilization flows, black arrows indicate decision support flows, and finally red arrows indicate the identification of user needs.

ensure data quality and comparability across scales. This leads to the development of a complementary bottom-up approach to formulating a consistent set of EBVs globally (Figure 3) by considering context-specific user needs across a range of applications at sub-global scales (e.g. [23]). This approach mobilizes local knowledge, placing it in a broader context, by focusing on the relationships between variables to understand information needs under specific management and conservation contexts (Figure 3). By promoting a global biodiversity infrastructure based on multiple nodes, it also allows data to be quickly mobilized and standardized across scales, while empowering local and national organizations to develop their own monitoring schemes.

Developing monitoring systems and observation networks

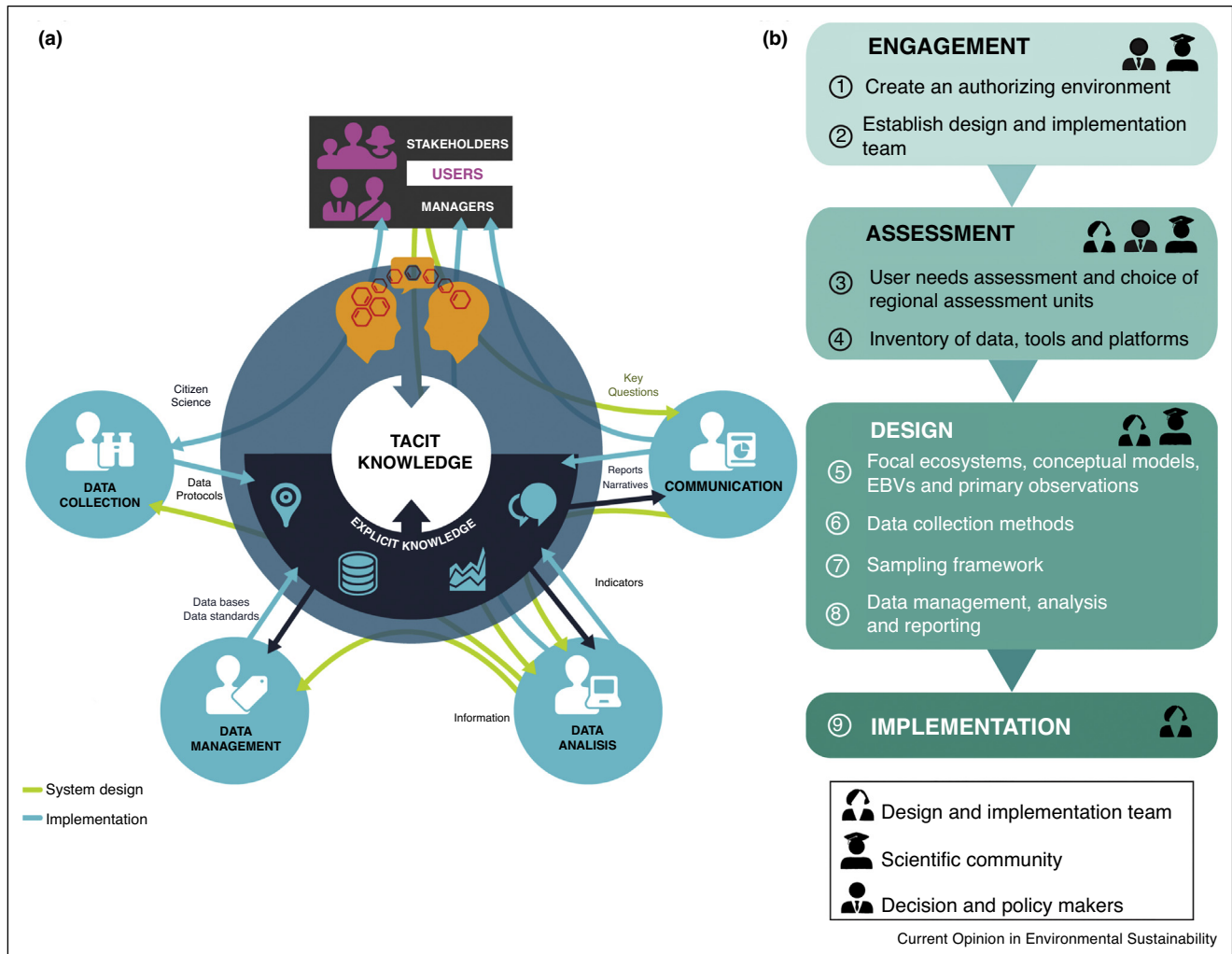
The development of Biodiversity Observation Networks aims to build a global community of practice for the collection, curation, analysis and communication of biodiversity data. Such a community will organize, enhance and link existing monitoring and observation systems and facilitate the exchange of standards in methods, tools, and frameworks to provide data and information to users, while avoiding the duplication of efforts across separate initiatives. The development of BONs should be focused on feasible implementation, building upon existing data, observation platforms, and monitoring programs such as the International Long Term Ecological Research Network [52].

Current status of the network of BONs

BONs frame their observation systems to directly address user needs, making them diverse, flexible, and autonomous in the way they operate. There are currently seven formally endorsed BONs within GEO BON [22,53–57]. National BONs, in China, France, and Colombia, have developed intensive monitoring schemes [54] or biodiversity (meta)data hubs [53]. The China BON is a notable example of a systematic, country-wide monitoring design with broad spatial and taxonomic extent: 441 sites are part of an observation system of over 9000 transects and point counts for birds, amphibians, mammals, butterflies, and vascular plants with the participation of volunteer citizen scientists at each site [54]. Illustrating a different approach, the French BON has set as its initial aim to document existing data, acquisition methods and standards to facilitate their access, sharing, and use by researchers and decision makers, and to support biodiversity management and national reporting [53].

Regional BONs are also diverse and autonomous. The Asia Pacific BON is active in promoting research collaborations, capacity building, and a culture of data sharing [56]. The Arctic BON focuses on linking and integrating existing biodiversity observation efforts and data to support conservation planning and policy-making [55]. The publication in 2017 of the ‘State of the Arctic Marine Biodiversity Report’ [58] was the culmination of the first five-year implementation phase for the Arctic Marine Biodiversity Monitoring Plan.

Figure 4



Framework and development process of Biodiversity Observation Networks (BONs). (a) Conceptual framework for national and regional biodiversity observation Systems organized around the interaction between (and integration of) basic and applied science, and end-users. (b) Nine step process for BON development defined around the engagement of the different stakeholder groups; the assessment of user needs and available data, tools, and platforms; the design of the BON *per se*; and finally, its implementation.

At the global scale, the Marine BON (MBON) is working in coordination with the Global Ocean Observing System (GOOS) and the Ocean Biogeographic Information System (OBIS) to develop Essential Ocean Variables [22,59]. The MBON facilitates the development of a common framework for the integration of marine biodiversity observations with environmental variables [13]. The goal is to facilitate the sharing of regional observations through common data standards while offering access to the advanced geospatial analysis tools of OBIS, which would in turn support future World Ocean Assessments of the UN [59], or the needs of the Barcelona Convention for instance. MBON is also working with the remote sensing community to define new satellite sensor specifications to, *inter alia*, monitor EBVs in coastal wetlands and

aquatic environments [27]. The recently endorsed Freshwater BON (FWBON) is also using the EBVs for organizing and prioritizing the steps needed to monitor the different components of freshwater biodiversity and facilitate its global assessment [13,57], while supporting the needs of the Ramsar Convention.

A process for BON development

The general approach for BON development is guided by a framework that ensures the resulting system directly serves users’ needs [60], while allowing for interoperability with other observation systems (Figure 4a). This framework emphasises the establishment of conduits between data collection, management, analysis, and communication that are driven and validated by the users.

Building the BONs around user needs further contributes to ensuring their sustainability beyond the lifespan of the funded projects that might have initiated the process of a BON development.

In practice, GEO BON suggests a stepwise, iterative approach to establishing and implementing BONs, drawing upon existing processes, standards, and tools. An example of such sequenced process is divided into nine steps applied to build each component of an observing system (Figure 4b) and involves four development phases: engagement, assessment, design, and implementation. This flexible approach has been used and adapted for the Arctic [55], Australia's New South Wales [23*] and is more recently being applied in Colombia.

The assessment phase of the development process of BONs (Figure 4b) aims to capitalize on existing infrastructures, monitoring efforts, and capacity, while identifying strength and weaknesses in terms of EBV development. For instance, the French BON identified over 130 *in situ* observation infrastructures, mostly observing EBVs within the species traits, species populations, and genetic composition classes [53]. Similarly, a Finnish assessment of the national indicators and the biodiversity monitoring programs underlying them [18] showed that aside from species populations and ecosystem structure, most EBV classes are still poorly covered by the Finnish monitoring system. The same observation was made for the Colombia BON which identified nonetheless over 100 different tools for biodiversity observation, data management and reporting [61]. These assessments thus help governments and organizations to prioritize and strategically fill key gaps in their existing or developing observation systems.

BON-in-a-Box: a catalogue for knowledge exchange

Core to the establishment of a globally harmonized system of systems is the need for the scientific community to share data, knowledge and tools to ensure the accessibility, interoperability, and reporting of biodiversity information across scales [62] (Figure 4a). There are excellent tools, protocols and software that facilitate effective biodiversity monitoring, but these are not necessarily easily discoverable or available. With this in mind, GEO BON has developed BON-in-a-Box as a technology transfer and capacity-building mechanism to improve the quantity, quality and interoperability of biodiversity observations and further support BONs development (e.g. Colombia [61]). BON-in-a-Box is an online catalogue that will connect decision makers, scientists and tool developers around the world, ensuring access to the latest technologies and methodologies (<https://boninabox.geobon.org/>). BON-in-a-Box will also allow the thematic BONs and working groups to provide regional and national BONs with state-of-the-art approaches and tools for biodiversity observations. Having such a platform for capacity

building and knowledge exchange will further support the integration of the top-down EBV development process with the bottom-up approach for BON design.

From biodiversity monitoring to addressing societal needs

Policy relevance and indicators

The policy relevance of GEO BON was acknowledged early on. Its establishment was recognised by the Conference of the Parties of the CBD (UNEP/CBD/COP/DEC/IX/15), and it has been identified as a key partner of the IPBES [2]. EBVs have also been proposed by the IPBES as an appropriate framework to determine common metrics for the biodiversity modelling, reporting, and observation communities [20]. In practice, monitoring progress towards conservation and sustainable development targets and the effectiveness of policy decisions, will be facilitated by BONs that apply the EBV framework [17*,32] (Figure 1). For instance, the linkages between the Intergovernmental Oceanographic Commission of UNESCO and GEO BON are based on the value chain between data collectors (GOOS), a community of practice that shares standards (MBON), and the data hosting and analysis services established by OBIS as a contribution to BON-in-a-Box. Furthermore, to support national reporting needs for CBD Aichi Target 9,³⁷ a modular approach was designed to set up national schemes to monitor the occurrence of invasive alien species while allowing cross-border cooperation, and accommodating for varying capacity [42,43].

Although EBVs themselves can be conceptually linked to many of the Aichi Targets [11,32] and Sustainable Development Goals [13], it is the indicators derived from them that are particularly useful to stakeholders [17*,18] (Figure 2). GEO BON and its partners are therefore developing a set of Global Biodiversity Change indicators [48] that directly report on the progress towards some of the Aichi Targets, and can inform the IPBES assessments. For instance, indicators that combine EBVs on species populations and/or community composition, and ecosystem structure, such as the 'Species Habitat Indices' and the 'Biodiversity Habitat Index' [48] can inform Aichi Targets 5 ('habitat loss halved or reduced') and 12 ('reducing risk of extinctions'). Highlighting the relevance of EBVs as the building blocks of these indicators can further increase awareness amongst policy makers of the value of globally coordinated monitoring.

Monitoring ecosystem services

Monitoring the contribution of nature to people [63] is critical to inform policy [64,65]. Data on ecosystem

³⁷ Target 9: By 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated and measures are in place to manage pathways to prevent their introduction and establishment.

services suffers from the same patchiness and incompleteness as biodiversity data. This is further complicated by the need to integrate ecological and social data. However, there have been some promising methodological developments in recent years [66,67**]. These include the integration of national statistics (e.g. census data) with *in situ* measurements, community monitoring, remote sensing and model outputs [9,66]. Therefore, an important step to advance the monitoring of ecosystem services is the definition of a conceptual and operational framework for Essential Ecosystem Service Variables (EESV) and the development of multidisciplinary interoperable data standards [13,67**]. The EESV framework includes several classes of variables, covering the different components of the ecosystem service flow from ecosystems to society, the different types of values of ecosystem services and the actual benefits obtained by society [11]. EESVs explicitly link the monitoring of ecosystem services to identifying progress towards meeting the SDGs and Aichi targets, as demonstrated in a recent assessments on current use of ecosystem service data in reporting [68].

Mainstreaming EBVs

The value of EBVs to policy will be determined by the degree to which they enable the production of indicators and their incorporation into decision making to help countries meet their internal and international obligations. Since they were proposed in the 1990s, the ECVs are now widely accepted and used to structure national reporting to the UN Framework Convention on Climate Change, for global climate annual assessments, and to support the work of the Intergovernmental Panel on Climate Change [14]. Similarly, EBVs need to be both accessible and usable by a variety of stakeholders regardless of their familiarity with their production process. To be useful, EBV datasets will need to adhere to scientific standards of peer-review, replicability and sensitivity to detect changes, as well as the inclusion of uncertainty metrics, all of which must be fully reported. A transparent process needs to be developed for the endorsement of EBV datasets by the GEO BON community to ensure appropriate data and metadata for measuring biodiversity change. EBV data products need to be made freely available according to Open Data principles, i.e. be accessible without restrictions on use, modification and sharing [28*]. Moreover, EBV data products and indicators should be resourced in a way that maximizes discoverability. One such mechanism is a GEO BON Portal that enhances the accessibility of endorsed EBV datasets. This online clearinghouse will serve as the biodiversity equivalent of the Global Observing Systems Information Centre (GOSIC) for climate variables [14], and will feed into the Global Earth Observation System of Systems (GEOSS).

Conclusion

The biodiversity crisis [3] calls for both the adoption of a common framework for biodiversity monitoring, and the

establishment of a system of harmonised biodiversity observation systems that supports it. In ten years of existence, GEO BON, largely as a volunteer effort, designed a monitoring framework around Essential Biodiversity Variables which supports the development of biodiversity change indicators. The next decade will be critical for the development of those EBVs and will require their refinement across all levels of biodiversity, the widespread use of common data and metadata standards, and the design of workflows. GEO BON has also facilitated the establishment of several national, regional, and thematic BONs, and developed a capacity building and knowledge transfer platform to further improve the design of biodiversity observation systems.

Future advances in the development of EBVs and generation of the corresponding data are expected given the current trend in technological improvement for *in situ* data acquisition, better availability of satellite remote sensing data, widespread use of emerging genetic techniques and genomic libraries, and the use of models to produce spatially and temporally comprehensive EBV data products. These developments further benefit from the establishment of national and sub-national biodiversity observation systems and the involvement of end-users in the process so as to produce policy relevant indicators (Figures 1 and 2). Ten years from now, GEO BON envisions a wide and robust network of national and regional BONs, with multiple EBV products openly available that cover the different dimensions of biodiversity and components of ecosystem services, all of which contributing to well informed local to global assessments of the status and trends of biodiversity and its contribution to society.

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- of special interest
- of outstanding interest

1. CBD: *Aichi Biodiversity Targets*. 2011.
2. Larigauderie A, Mooney HA: **The Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services: moving a step closer to an IPCC-like mechanism for biodiversity**. *Curr Opin Environ Sustain* 2010, **2**:9-14.
3. Ceballos G, Ehrlich PR, Dirzo R: **Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines**. *Proc Natl Acad Sci* 2017, **114**: E6089-E6096.
4. Scholes RJ, Mace GM, Turner W, Geller GN, Jürgens N, Larigauderie A, Muchoney D, Walther BA, Mooney HA: **Toward a global biodiversity observing system**. *Science* 2008, **321**:1044-1045.
5. Noss RF: **Indicators for monitoring biodiversity: a hierarchical approach**. *Conserv Biol* 1990, **4**:355-364.
6. Pereira HM, Navarro LM, Martins IS: **Global biodiversity change: the bad, the good, and the unknown**. *Annu Rev Environ Resour* 2012, **37**:25-50.
7. Mihoub J-B, Henle K, Titeux N, Brotons L, Brummitt NA, •• Schmelzer DS: **Setting temporal baselines for biodiversity: the limits of available monitoring data for capturing the full impact of anthropogenic pressures**. *Sci Rep* 2017, **7**:srep41591.
This paper compares the time frame of biodiversity data with the timing of anthropogenic pressures in the 20th century, and discusses the limitations of the temporal baselines that data availability imposes and their implication for biodiversity conservation.
8. Gonzalez A, Cardinale BJ, Allington GRH, Byrnes J, Arthur Endsley K, Brown DG, Hooper DU, Isbell F, O'Connor MI, Loreau M: **Estimating local biodiversity change: a critique of papers claiming no net loss of local diversity**. *Ecology* 2016, **97**:1949-1960.
9. Tallis H, Mooney H, Andelman S, Balvanera P, Cramer W, Karp D, Polasky S, Reyers B, Ricketts T, Running S *et al.*: **A global system for monitoring ecosystem service change**. *Bioscience* 2012, **62**:977-986.
10. Proença V, Martin LJ, Pereira HM, Fernandez M, McRae L, •• Belnap J, Böhm M, Brummitt N, García-Moreno J, Gregory RD *et al.*: **Global biodiversity monitoring: from data sources to Essential Biodiversity Variables**. *Biol Conserv* 2017, **213**:256-263.
This paper presents different biodiversity monitoring approaches and data sources, their spatial, temporal, and taxonomic coverages, and their relation to EBVs and indicators.
11. Pereira HM, Ferrier S, Walters M, Geller GN, Jongman RHG, Scholes RJ, Bruford MW, Brummitt N, Butchart SHM, Cardoso AC *et al.*: **Essential Biodiversity Variables**. *Science* 2013, **339**:277-278.
12. Scholes RJ, Walters M, Turak E, Saarenmaa H, Heip CH, Tuama ÉÓ, Faith DP, Mooney HA, Ferrier S, Jongman RH *et al.*: **Building a global observing system for biodiversity**. *Curr Opin Environ Sustain* 2012, **4**:139-146.
13. GEO BON: *GEO BON Implementation Plan 2017–2020. Version 1.3*. Group on Earth Observations Biodiversity Observation Network Secretariat; 2017.
14. Bojinski S, Verstraete M, Peterson TC, Richter C, Simmons A, Zemp M: **The concept of Essential Climate Variables in support of climate research, applications, and policy**. *Bull Am Meteorol Soc* 2014, **95**:1431-1443.
15. Honrado JP, Pereira HM, Guisan A: **Fostering integration between biodiversity monitoring and modelling**. *J Appl Ecol* 2016, **53**:1299-1304.
16. Walters M, Pereira HM, Ferrier S, Geller GN, Jongman R, Scholes RJ, Bruford M, Reyers B: **Essential Biodiversity Variables**. *Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) notes*. 2013.
17. Brummitt N, Regan EC, Weatherdon LV, Martin CS, • Geijzendorffer IR, Rocchini D, Gavish Y, Haase P, Marsh CJ, Schmelzer DS: **Taking stock of nature: Essential Biodiversity Variables explained**. *Biol Conserv* 2017, **213**:252-255.
This paper provides an explanation of the Essential Biodiversity Variables that is simple and accessible to a wider audience, by using an analogy with stock market.
18. Vihervaara P, Auvinen A-P, Mononen L, Törmä M, Ahlroth P, Anttila S, Böttcher K, Forsius M, Heino J, Heliölä J *et al.*: **How Essential Biodiversity Variables and remote sensing can help national biodiversity monitoring**. *Glob Ecol Conserv* 2017, **10**:43-59.
19. Schmelzer DS, Weatherdon LV, Loyau A, Bondeau A, Brotons L, Brummitt N, Geijzendorffer IR, Haase P, Kuemmerlen M, Martin CS *et al.*: **A suite of essential biodiversity variables for detecting critical biodiversity change**. *Biol Rev* 2017 <http://dx.doi.org/10.1111/brv.12332>.
20. IPBES: *The Methodological Assessment Report on scenarios and models of biodiversity and ecosystem services*. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; 2016.
21. Rosa IMD, Pereira HM, Ferrier S, Alkemade R, Acosta LA, Akcakaya HR, Belder E, den Fazel AM, Fujimori S, Harfoot M *et al.*: **Multiscale scenarios for nature futures**. *Nat Ecol Evol* 2017, **1**:1416.
22. Muller-Karger F, Kavanaugh M, Montes E, Balch W, Breitbart M, Chavez F, Doney S, Johns E, Letelier R, Lomas M *et al.*: **A Framework for a marine biodiversity observing network within changing continental shelf seascapes**. *Oceanography* 2014, **27**:18-23.
23. Turak E, Brazill-Boast J, Cooney T, Drielsma M, Delacruz J, • Dunkerley G, Fernandez M, Ferrier S, Gill M, Jones H *et al.*: **Using the essential biodiversity variables framework to measure biodiversity change at national scale**. *Biol Conserv* 2017, **213**:264-271.
This paper presents the application at the national scale, using Australia as a case study, of the EBV framework and EBV selection process to monitor biodiversity change and assess management policies.
24. Skidmore AK, Pettorelli N, Coops NC, Geller GN, Hansen M, Lucas R, Múcher CA, O'Connor B, Paganini M, Pereira HM *et al.*: **Environmental science: agree on biodiversity metrics to track from space**. *Nature* 2015, **523**:403-405.
25. Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova SA, Tyukavina A, Thau D, Stehman SV, Goetz SJ, Loveland TR *et al.*: **High-resolution global maps of 21st-century forest cover change**. *Science* 2013, **342**:850-853.
26. Paganini M, Leidner AK, Geller G, Turner W, Wegmann M: **The role of space agencies in remotely sensed essential biodiversity variables**. *Remote Sens Ecol Conserv* 2016, **2**:132-140.
27. Muller-Karger F, Hestir E, Ade C, Roberts DA, Siegel D, Miller RJ, Humm D, Izenberg N, Keller M, Morgan F, *et al.*: **Satellite sensor requirements for monitoring essential biodiversity variables of coastal ecosystems**. *Ecol Appl*, in press. <https://doi.org/10.1002/eap.1682>.
28. Kissling WD, Ahumada JA, Bowser A, Fernandez M, Fernández N, • García EA, Guralnick RP, Isaac NJB, Kelling S, Los W *et al.*: **Building essential biodiversity variables (EBVs) of species distribution and abundance at a global scale**. *Biol Rev* 2017 <http://dx.doi.org/10.1111/brv.12359>.
This paper discussed the challenges of EBV development and proposes a workflow to operationalize the building of EBVs of the Species Population class and that includes the identification and aggregation of various raw data sources, data quality control, taxonomic name matching and statistical modelling of integrated data.
29. Wiecezorek J, Bloom D, Guralnick R, Blum S, Döring M, Giovanni R, Robertson T, Vieglais D: **Darwin core: an evolving community-developed biodiversity data standard**. *PLoS One* 2012, **7**: e29715.
30. Guralnick R, Walls R, Jetz W: **Humboldt Core — toward a standardized capture of biological inventories for biodiversity**

- monitoring, modeling and assessment.** *Ecography* 2017, **40**:001-012.
31. Hoban S, Arntzen JA, Bruford MW, Godoy JA, Rus Hoelzel A, Segelbacher G, Vilà C, Bertorelle G: **Comparative evaluation of potential indicators and temporal sampling protocols for monitoring genetic erosion.** *Evol Appl* 2014, **7**:984-998.
 32. Geijzendorffer IR, Regan EC, Pereira HM, Brotons L, Brummitt N, Gavish Y, Haase P, Martin CS, Mihoub J-B, Secades C *et al.*: **Bridging the gap between biodiversity data and policy reporting needs: an Essential Biodiversity Variables perspective.** *J Appl Ecol* 2016, **53**:1341-1350.
 33. Mimura M, Yahara T, Faith DP, Vázquez-Domínguez E, Colautti RI, Araki H, Javadi F, Núñez-Farfán J, Mori AS, Zhou S *et al.*: **Understanding and monitoring the consequences of human impacts on intraspecific variation.** *Evol Appl* 2017, **10**:121-139.
 34. Habel JC, Husemann M, Finger A, Danley PD, Zachos FE: **The relevance of time series in molecular ecology and conservation biology.** *Biol Rev* 2014, **89**:484-492.
 35. Amano T, Lamming JDL, Sutherland WJ: **Spatial gaps in global biodiversity information and the role of citizen science.** *BioScience* 2016, **66**:393-400.
 36. Pimm SL, Alibhai S, Bergl R, Dehgan A, Giri C, Jewell Z, Joppa L, Kays R, Loarie S: **Emerging technologies to conserve biodiversity.** *Trends Ecol Evol* 2015, **30**:685-696.
 37. Jetz W, McPherson JM, Guralnick RP: **Integrating biodiversity distribution knowledge: toward a global map of life.** *Trends Ecol Evol* 2012, **27**:151-159.
 38. Wilson AM, Jetz W: **Remotely sensed high-resolution global cloud dynamics for predicting ecosystem and biodiversity distributions.** *PLoS Biol* 2016, **14**:e1002415.
 39. Bush A, Sollmann R, Wilting A, Bohmann K, Cole B, Balzter H, ● Martius C, Zlinszky A, Calvignac-Spencer S, Cobbold CA *et al.*: **Connecting Earth observation to high-throughput biodiversity data.** *Nat Ecol Evol* 2017, **1**:176.
- This paper discussed the potential of emerging technology, including high-throughput DNA, biodiversity modelling, and automated recording devices, combined with Earth Observations to more efficiently and timely monitor biodiversity and biodiversity change.
40. Meyer C, Kreft H, Guralnick R, Jetz W: **Global priorities for an effective information basis of biodiversity distributions.** *Nat Commun* 2015, **6**:ncmms9221.
 41. Ferrier S, Jetz W, Scharlemann J: **Biodiversity modelling as part of an observation system.** *The GEO Handbook on Biodiversity Observation Networks.* Springer; 2017:239-257.
 42. Latombe G, Pyek P, Jeschke JM, Blackburn TM, Bacher S, Capinha C, Costello MJ, Fernández M, Gregory RD, Hobern D *et al.*: **A vision for global monitoring of biological invasions.** *Biol Conserv* 2017, **213**:295-308.
 43. McGeoch MA, Genovesi P, Bellingham PJ, Costello MJ, McGrannachan C, Sheppard A: **Prioritizing species, pathways, and sites to achieve conservation targets for biological invasion.** *Biol Invasions* 2016, **18**:299-314.
 44. Kattge J, Díaz S, Lavorel S, Prentice IC, Leadley P, BöNisch G, Garnier E, Westoby M, Reich PB, Wright IJ *et al.*: **TRY — a global database of plant traits.** *Glob Change Biol* 2011, **17**:2905-2935.
 45. Saatchi SS, Harris NL, Brown S, Lefsky M, Mitchard ETA, Salas W, Zutta BR, Buermann W, Lewis SL, Hagen S *et al.*: **Benchmark map of forest carbon stocks in tropical regions across three continents.** *Proc Natl Acad Sci* 2011, **108**:9899-9904.
 46. Pettorelli N, Schulte to Bühne H, Tulloch A, Dubois G, Macinnis-Ng C, Queirós AM, Keith DA, Wegmann M, Schrodt F, Stellmes M *et al.*: **Satellite remote sensing of ecosystem functions: opportunities, challenges and way forward.** *Remote Sens Ecol Conserv* 2017 <http://dx.doi.org/10.1002/rse2.59>.
 47. Keith DA, Rodríguez JP, Brooks TM, Burgman MA, Barrow EG, Bland L, Comer PJ, Franklin J, Link J, McCarthy MA *et al.*: **The IUCN Red list of ecosystems: motivations, challenges, and applications.** *Conserv Lett* 2015, **8**:214-226.
 48. GEO BON: *Global Biodiversity Change Indicators. Version 1.2.* Group on Earth Observations Biodiversity Observation Network Secretariat; 2015.
 49. Jetz W, Cavender-Bares J, Pavlick R, Schimel D, Davis FW, Asner GP, Guralnick R, Kattge J, Latimer AM, Moorcroft P *et al.*: **Monitoring plant functional diversity from space.** *Nat Plants* 2016, **2**:nplants201624.
 50. Schneider FD, Morsdorf F, Schmid B, Petchey O, Hueni A, Schimel D, Schaepman ME: **Mapping functional diversity from remotely sensed morphological and physiological forest traits.** *Nat Commun* 2017, **8** <http://dx.doi.org/10.1038/s41467-017-01530-3>.
 51. Geijzendorffer IR, Teeffelen AJA, Allison H, Brain D, Horgan K, Itturate-Garcia M, Santos MJ: **How can global targets for biodiversity and ecosystem services guide local conservation actions.** *Curr Opin Environ Sustain* [date unknown]. <https://doi.org/10.1016/j.cosust.2017.12.011>.
 52. Haase P, Tonkin JD, Stoll S, Burkhard B, Frenzel M, Geijzendorffer IR, Häuser C, Klotz S, Kühn I, McDowell WH *et al.*: **The next generation of site-based long-term ecological monitoring: linking essential biodiversity variables and ecosystem integrity.** *Sci Total Environ* 2018, **613**:1376-1384.
 53. Fondation pour la Recherche sur la Biodiversité: *État des lieux et analyse du paysage national des observatoires de recherche sur la biodiversité, une étude de l'infrastructure ECOSCOPE.* Ed. Aurélie Delavaud et Robin Goffaux; 2016.
 54. Xu H, Cao M, Wu Y, Cai L, Cao Y, Ding H, Cui P, Wu J, Wang Z, Le Z *et al.*: **Optimized monitoring sites for detection of biodiversity trends in China.** *Biodivers Conserv* 2017, **26**:1959-1971.
 55. Gill MJ, Crane K, Hindrum R, Arneberg P, Bysveen I, Denisenko NV, Gofman V, Grant-Friedman A, Gudmundsson G, Hopcroft RR *et al.*: *Arctic Marine Biodiversity Monitoring Plan.* 2011.
 56. Yahara T, Ma K, Darnaedi D, Miyashita T, Takenaka A, Tachida H, Nakashizuka T, Kim E-S, Takamura N, Nakano S, Shirayama Y, Yamamoto H, Vergara SG: **Developing a regional network of biodiversity observation in the Asia-Pacific Region: achievements and challenges of AP BON.** In *Integrative Observations and Assessments, Ecological Research Monographs.* Edited by Nakano S, Yahara T, Nakashizuka T. Tokyo: Springer; 2014:3-28 http://dx.doi.org/10.1007/978-4-431-54783-9_1.
 57. Turak E, Harrison I, Dudgeon D, Abell R, Bush A, Darwall W, Finlayson CM, Ferrier S, Freyhof J, Hermoso V *et al.*: **Essential biodiversity variables for measuring change in global freshwater biodiversity.** *Biol Conserv* 2017, **213**:272-279.
 58. CAFF: *State of the Arctic Marine Biodiversity Report.* Conservation of Arctic Flora and Fauna International Secretariat; 2017.
 59. Costello MJ, Basher Z, McLeod L, Asaad I, Claus S, Vandepitte L, Yasuhara M, Gislason H, Edwards M, Appeltans W *et al.*: **Methods for the study of marine biodiversity.** *The GEO Handbook on Biodiversity Observation Networks.* Springer; 2017:129-163.
 60. Lindenmayer DB, Likens GE: **Adaptive monitoring: a new paradigm for long-term research and monitoring.** *Trends Ecol Evol* 2009, **24**:482-486.
 61. Sierra CA, Mahecha M, Poveda G, Álvarez-Dávila E, Gutierrez-Velez VH, Reu B, Feilhauer H, Anáya J, Armenteras D, Benavides AM *et al.*: **Monitoring ecological change during rapid socio-economic and political transitions: Colombian ecosystems in the post-conflict era.** *Environ Sci Policy* 2017, **76**:40-49.
 62. Schmeller DS, Böhm M, Arvanitidis C, Barber-Meyer S, Brummitt N, Chandler M, Chatziniolaou E, Costello MJ, Ding H, García-Moreno J *et al.*: **Building capacity in biodiversity monitoring at the global scale.** *Biodivers Conserv* 2017 <http://dx.doi.org/10.1007/s10531-017-1388-7>.
 63. Díaz S, Pascual U, Stenseke M, Martín-López B, Watson RT, Molnár Z, Hill R, Chan KMA, Baste IA, Brauman KA *et al.*: **Assessing nature's contributions to people.** *Science* 2018, **359**:270-272.

64. Maes J, Egoh B, Willemsen L, Liqueste C, Vihervaara P, Schägner JP, Grizzetti B, Drakou EG, Notte AL, Zulian G *et al.*: **Mapping ecosystem services for policy support and decision making in the European Union**. *Ecosyst Serv* 2012, **1**:31-39.
65. Pascual U, Balvanera P, Díaz S, Pataki G, Roth E, Stenseke M, Watson RT, Dessane EB, Islar M, Kelemen E: **Valuing nature's contributions to people: the IPBES approach**. *Curr Opin Environ Sustain* 2017, **26**:7-16.
66. Balvanera P, Quijas S, Karp DS, Ash N, Bennett EM, Boumans R, Brown C, Chan KMA, Chaplin-Kramer R, Halpern BS *et al.*: **Ecosystem Services**. *The GEO Handbook on Biodiversity Observation Networks*. Springer; 2017:39-78.
67. Cord AF, Brauman KA, Chaplin-Kramer R, Huth A, Ziv G, Seppelt R: **Priorities to advance monitoring of ecosystem services using Earth Observation**. *Trends Ecol Evol* 2017, **32**:416-428.
- This paper presents a framework to integrate satellite earth observation with socioeconomic data and model based analysis in order to assess the supply and demand for ecosystem services, along with the benefits for human well-being, and provides further guidance on the use of earth observations to monitor ecosystem services.
68. Geijzendorffer IR, Cohen-Shacham E, Cord AF, Cramer W, Guerra C, Martín-López B: **Ecosystem services in global sustainability policies**. *Environ Sci Policy* 2017, **74**:40-48.