Essential Biodiversity Variables and Essential Ecosystem Services Variables for the Implementation of Biodiversity Conservation and Sustainable Development Goals

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Abstract:

As nations design a framework and a process for implementing the new goals and targets set by the Convention on Biological Diversity (CBD), the question on how to report on the successes and failures of policy implementation is becoming more salient. In this paper, we demonstrate the potential role of Essential Biodiversity Variables (EBVs), Essential Ecosystem Services Variables (EESV) and their derived indicators in monitoring, planning, and implementing multiscale policy frameworks across spatial scales. We first introduce the EBVs and EESVs and then analyze their role in the UN CBD Global Biodiversity Framework, the Systems of Environmental Economic Accounting, Sustainable Development Goals, and the Intergovernmental Platform on Biodiversity and Ecosystem Services. We illustrate how the EBVs and EESVs can be used across scales via application cases. We also discuss the use of EBVs and EESVs in scenarios and modelling for strategic policy planning. This paper presents the values of the Essential Variables in implementing biodiversity conservation and sustainable development goals, optimizing the integrative use of scientific, policy, and data frameworks and scalable and repeatable workflows from primary data to indicators.

Keywords: biodiversity, ecosystem services, conservation, sustainability, human wellbeing, policy development and implementation, Essential Variables, scalable indicators, scenarios and modelling, national operationalization

1. Introduction

The Earth Summit in 1992 brought the importance of biodiversity to the global stage through the Rio Declaration (United Nations, 1992) and established the United Nations (UN) Convention on Biological Diversity (CBD) (SCBD, 1994). This act initiated the global work on environmental economic accounts as a global framework for measuring the environment consistently. However, the environmental and socio-economic dimensions of development were not integrated into a single, coherent global framework until the adoption of the Sustainable Development Goals (SDGs) in 2015. Although the SDGs represent a monumental step in recognizing the importance of life, biodiversity and environmental health for development and human wellbeing, they include only a few indicators—metrics for change directly related to the state of biodiversity (UNEP, 2021, 2019). Even so, many of the environmental SDGs indicators do not have sufficient data for analysis (Campbell et al., 2020). The CBD Kunming-Montreal Global Biodiversity Framework (GBF) provides a new opportunity to design a coherent monitoring framework for biodiversity at the global and national level. This would fill the gap in the current monitoring framework of the SDGs by holistically capturing the state and trends of biodiversity, interactions of nature and people, and the drivers and pressures which are causing biodiversity loss and ecosystem degradation, while secondarily alleviating the (perceived) burden on nations to report on multiple frameworks, goals and targets, at multiple scales, via multiple agencies (Bhatt et al., 2020; Han et al., 2017; SCBD, 2020).

Decision-making for sustainable development and biodiversity conservation relies on science-based information designed to address specific requirements of nations, including setting goals and targets, tracking progress towards their achievement, and assessing the effectiveness of the policies implemented. One of the essential tools to achieve this are indicators that go through an endorsement process and are meant to be produced and used at various regional scales. For instance, the 17 UN SDGs are informed by a set of 248 (231 unique) global indicators, and the 20 Aichi Biodiversity Targets of the UN CBD for 2010-2020 relied on 81 primary and secondary indicators recommended by the Ad Hoc Technical Expert Group (AHTEG) and endorsed by the nations at its thirteenth Conference of Party (COP13) (SCBD, 2016). Such global frameworks are adapted at the regional and national scale, sometimes accompanied by additional sets of targets and indicators. However, wholesale adoption or making use of global indicators and datasets faces some challenges for national decision-making and biodiversity conservation (Akinyemi et al., 2021; Botts et al., 2019; Malavasi, 2020).

One challenge is that there is incomplete or missing information on biodiversity indicators for many countries. For instance, 68% of the environmental SDGs and indicators do not have sufficient data for global aggregation and analysis (Campbell et al., 2020). A second challenge is a disconnect between global and national indicators and a lack of coordination for scalable indicators. An analysis of the indicators used in the 5th National Reports to the UN CBD showed that only one-fifth of indicators used by nations matched those recommended by the CBD (Bhatt et al., 2020). This limits our ability to measure progress and impact within nations (Jones et al., 2011). The lack of basic observations contributed to the failure to achieve the 2020 Aichi Biodiversity Targets set by the parties of the CBD (CBD Secretariat, 2020; Xu et al., 2021). A third challenge is that while the frameworks and their coordination are global in scope, measures are implemented at the national and subnational levels, which is the scale at which progress needs to be tracked and buy-in ensured from national decision-makers (Bhatt et al., 2020; Bubb, 2013; GEO BON, 2021).

There is a growing understanding that an effective framework should enhance the accountability and monitoring of targets from national to global scales with the endorsement of the Kunming-Montreal GBF at the CBD COP15 (Fraixedas et al., 2022; Perino et al., 2021; Xu et al., 2021). This requires the collection of and access to primary observations. Essential Variables (EVs) have been proposed as an approach to integrate information across data types, scales and disciplines in order to provide relevant and timely data to researchers as well as decision and policy-makers (Lehmann et al., 2020; Reyers et al., 2017). Essential Variables have, for example, been developed for climate (ECVs, Bojinski et al., 2014; Miranda Espinosa et al., 2020), energy (EEVs, Ranchin et al., 2020), and the oceans (EOVs, (Miloslavich et al., 2018). Of particular relevance for policies and decision-making for biodiversity conservation, the Group on Earth Observations Biodiversity Observation Network (GEO BON) and its partners have been conceptualising and developing the Essential Biodiversity Variables (EBVs, Pereira et al., 2013) and Essential Ecosystem Services Variables (EESVs, Balvanera et al., 2022).

Here we present how the EBV and EESVs can (and sometimes already do) play a key role in informing multiple global policy frameworks concomitantly across regional scales. We also examine the relevance of Essential Variables in policy planning with the use of models and scenarios and the progress made in operationalizing accessible and repeatable data to decision workflows.

2. Complementarity of EBV & EESV

The EBVs and EESVs are a minimum set of complementary measurements selected for their ability to detect and attribute changes in biodiversity and ecosystem services, respectively. The EBVs are defined within six classes organized at the species level (i.e., genetic composition, species population, species traits) and the ecosystems level (i.e., community composition, ecosystem structure, ecosystem function) (Fernandez, In review; Pereira et al., 2013) (see Supplementary Material I for classes and definitions, SM hereafter). The EBVs are essentially time series of primary observations (similarly to EOVs, ECVs) at one location or at multiple locations, in which case they may also be rendered as time series of maps. Detailed characterizations of the variables within the classes as well as data-to-indicators workflows have been described for species populations (Jetz et al., 2019; Kissling et al., 2018a), species traits (Kissling et al., 2018b), and genetic composition (Hoban et al., 2022).

The Essential Ecosystem Services Variables assess the state and changes in ecosystem services at the interface between nature and human well-being (Balvanera et al., 2022), organised around six classes. Two classes focus on the supply side, i.e., ecological supply, which measures ecosystems' potential capacity to provide ecosystem services, and anthropogenic contributions that measures human contributions to the supply of ecosystem services (Schröter et al., 2021). Two classes cover the demand side, specifically demand that measures the human need for ecosystem services and use that measures people's realised appropriation of the ecosystem service (Brauman et al., 2020). Finally, there are two classes on values, i.e. instrumental values relating to meeting material or security needs and relational values refering to principles embedded or emerging from the interactions between people and nature (Díaz et al., 2018; IPBES, 2022; Pascual et al., 2017).

Clearly, the EBV and EESV frameworks are interlinked, as characteristics and functions of biodiversity underpin the ecological supply of ecosystem services, the use of which, in turn, affects biodiversity. For example, the distribution or abundance of each pollinator species (*species population* variables) and the diversity of pollinator species (a *community composition* variable) influence the amount and efficiency of pollination (i.e., the *ecological supply*) provided to pollination-dependent crops (Garibaldi et al., 2016; Greenleaf and Kremen, 2006). Likewise, species richness of birds and other vertebrate species supply wildlife viewing opportunities, and has been linked to higher frequencies of recreation or tourism (i.e., *relational values*) (Echeverri et al., 2022).

By design, EBVs and EESVs are scalable, sensitive to change, and their production must be feasible (see SM I for criteria). Both EBVs and EESVs are designed to be implemented across scales (i.e., grid-cell, subnational, national, regional, global), realms (i.e., freshwater, terrestrial, marine) and independent of species or ecosystem types across biological entities (e.g., mammals, phytoplankton, vegetation) (Fernandez et al., in review). In other words, species distributions and ecosystem extent should be measurable regardless of the species and ecosystem type (Christensen, T. et al., 2013; Gill, M.J. et al., 2011). Similarly, EESVs can be applied flexibly on all types of ecosystem services or nature's contributions to people (e.g. pollination-based crop production, nitrogen-retention-based water regulation) by measuring the stocks and flows of ecosystem services through space and time (Balvanera et al., 2022; Brauman et al., 2020). In practice, some of the EBV and EESV products are based on predictive models which may integrate *in-situ* and remote sensing data (Fernandez, In review; Skidmore et al., 2021). Importantly, Essential Variables provide a coherent context for the acquisition of the biodiversity data itself, thereby further guiding the collection of primary observations and the design of national and regional observatories to support it (Guerra, 2019; Navarro et al., 2017; Pereira et al., 2022; Turak et al., 2017).

3. Relevance of EBVs and EESVs in multiscale scientific and policy frameworks

Despite increasing efforts to better implement global policy frameworks, challenges remain with no international governance or agreement on methods, data formatting standards, or data sharing paradigms on biodiversity. Thus, target tracking and reporting are still done at different frequencies, scales, using different types of data by different agencies within and across the nations. Improved collaboration across institutions at the national and global level with clear roles and coordination in supporting countries with the planning and implementation of conservation and sustainability policies is needed in delivering the global goals. Identifying and operationalizing the interlinkages and dependencies between different sets of goals, targets and information that support their implementation and its monitoring would go a long way in streamlining the data-to-decision flow (Figures 1, 3). Here, standardized data layers on nature such as EBVs and EESVs can be fundamental in delivering indicators for multiple purposes (Balvanera et al., 2022; Navarro et al., 2017; Pereira et al., 2013).

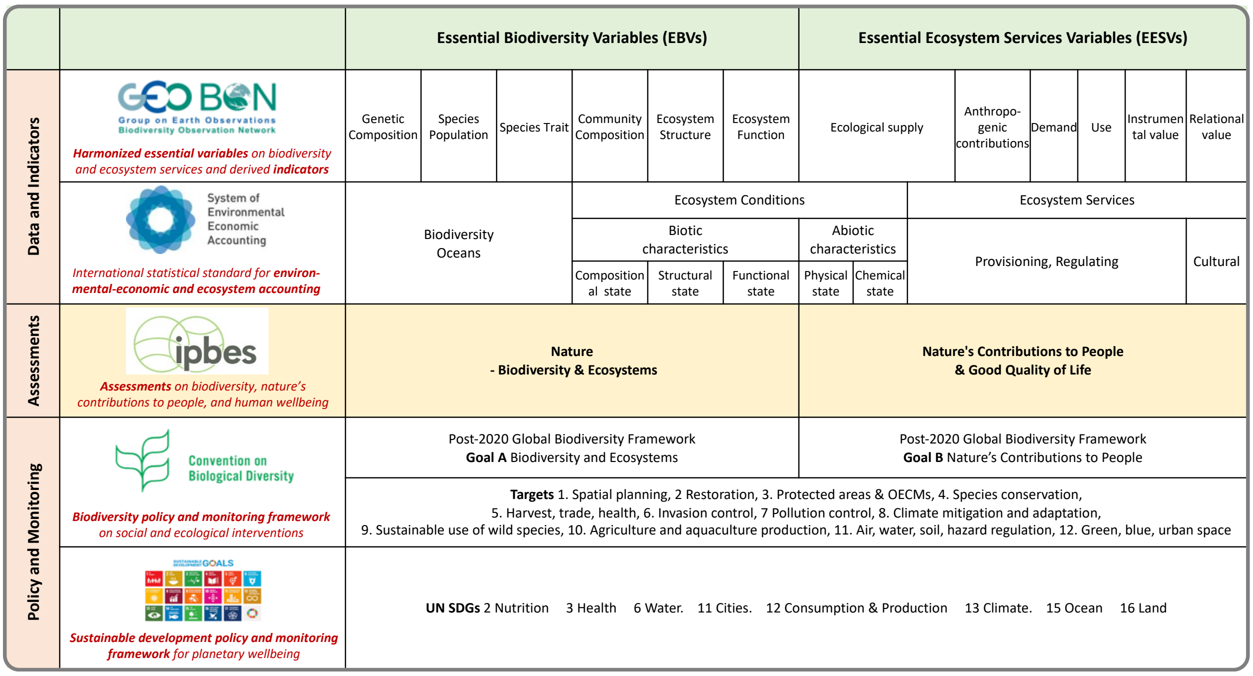


Figure 1. Institutional configuration in achieving cross-sectoral and cross-scale policy planning, implementation and reporting for biodiversity conservation and sustainable development, linking the EBVs and EESVs to data and indicators, assessments, and policy frameworks and monitoring. (*Note: There are interactions and interlinkages between EBVs and EESVs, which is not captured in this figure due to cross-mapping of EBV/EESV and SEEA frameworks. Please see Figure 3 for more.*)

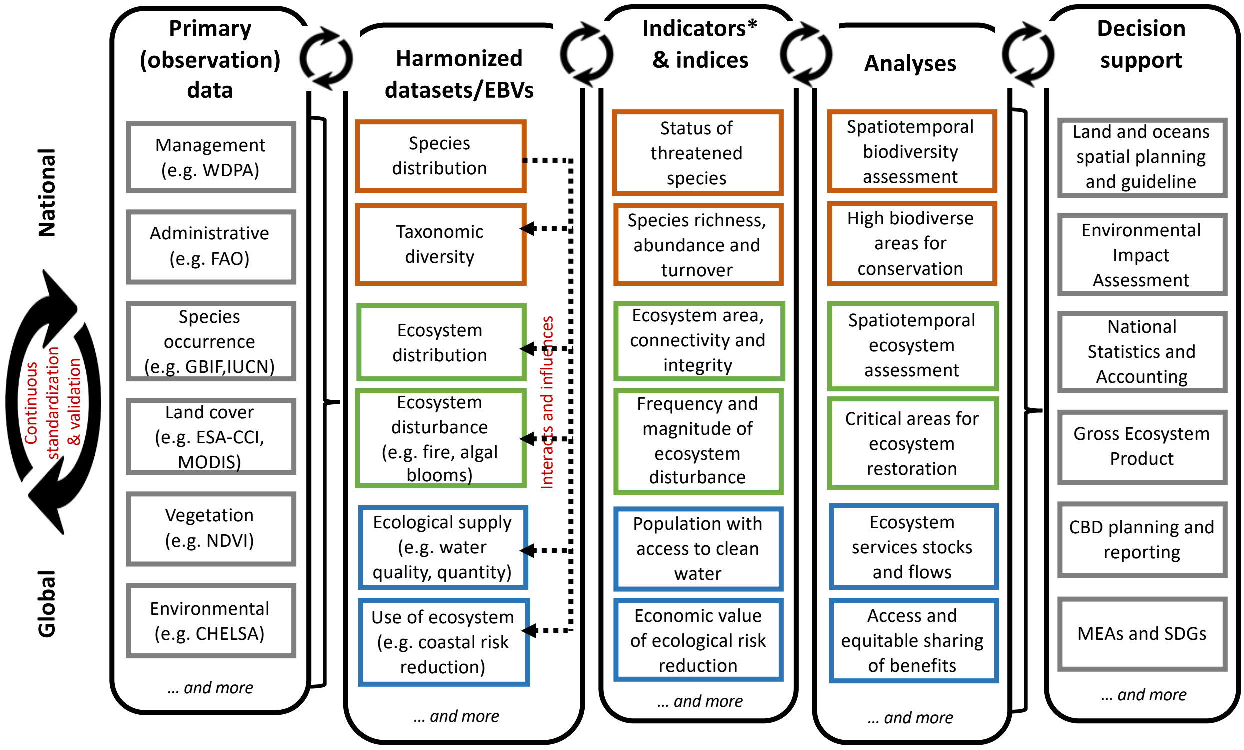
As Figure 1 shows, EBVs and EESVs inform directly on the two elements at the heart of the IPBES framework – Nature and Nature's Contributions to People (Díaz, 2015; Díaz et al., 2018). The EBV framework was used to guide the assessment on the state of nature in the Global Assessment of IPBES (IPBES, 2019). Balvanera et al. (2022) also identified indicators used in the regional, thematic, and global IPBES assessments, such as "economic importance of wildlife-based tourism" and "total [fisheries] catch globally" that relate directly to components of the EESV framework.

Further, Geijzendorffer et al (2016) showed that all six classes of EBVs were relevant, albeit to different degrees, for reporting on the Aichi biodiversity targets of the UN CBD, the Convention on Migratory Species and the Ramsar Convention for Wetlands at the global level, as well as for reporting of the various Directives of the European Union. Considering that over a third of the targets and corresponding indicators of the UN SDGs relate to the environment or interactions between people and the environment, EBVs and EESVs also have the potential to be used in tracking progress towards the achievement of several of those goals, i.e., SDGs 2 (food security), 3 (health), 6 (clean water), 11 (sustainable cities), 12 (consumption and production), 13 (climate resilience), 14 (life under water), and 15 (life on earth) (Balvanera et al., 2022; Hoban et al., 2022; Jetz et al., 2019; Kissling et al., 2018b; Skidmore et al., 2021), (UNEP, 2021, 2019) (see sections B and C of SM V for illustrations).

In 2021, the UN adopted an approach to streamline assessment and reporting on environmental data through its Systems of Environmental Economic Accounting (SEEA) framework, which integrates ecosystems and ecosystem services into national accounting systems and statistical frameworks (Hein et al., 2020). UN SEEA's Central Framework (CF) is currently being implemented by 90 countries with its Ecosystem Accounts (EA) being compiled in 37 countries. The SEEA CF and EA are reporting standards and tools for measuring the state and changes in ecosystems and ecosystem services, for which the EBV and EESV data products can be mapped for use by the countries (Figure 1, see SM II and III) (United Nations et al., 2021). Ideally, EBV and EESV data products are co-produced by government agencies that are responsible for primary observation data and the scientific community that develop the Essential Variables with them.

4. Establishing global indicator workflows with EBVs and EESVs for national implementation

EBVs and EESVs can help explain biodiversity change individually or combined with other variables. They can be integrated over space to produce indicators at a given spatial scale, and the production of the EBV and EESV datasets often uses models that establish relationships between drivers and biodiversity responses which allows to understand and attribute changes. As Figure 2 shows, often times, national government agencies conduct and hold ecological survey data (*in-situ*) and remote sensing data that can be used in developing harmonized datasets (e.g., *species distribution* variables). These EBVs can be used to derive indicators such as the status of threatened species, together with the list of threatened species from the IUCN Red List. Time series *ecosystem distribution* variable can, for example, be used to derive indicators on changes in ecosystem area by type, which can then be used in estimating connectivity and integrity of ecosystems for an assessment on critical areas for restoration. Ecosystem services variables can estimate the supply and use of, for instance, water provisioning services with human settlement and population data, to assess the availability of clean water and any risks associated with it (Chaplin-Kramer et al., 2019a, 2020). Furthermore, biodiversity, ecosystems and ecosystem services interact and influence each other, and some data layers (e.g., *ecosystem distribution* EBV as a data source for the *ecological supply* EESV) can be used in estimating multiple types of ecosystem services (e.g., pollination habitat, natural hazard reduction).



**Some EBV datasets can be used directly as indicators with simple derivation, e.g. distribution of forest, wetland.*

Figure 2. An illustrative generic workflow from primary data to decision support with examples of EBVs and EESVs. Colors are used to identify information flows from data to decision support at the level of species (orange), ecosystems (green), and ecosystem services (blue). A wide range of primary observation data can be used to derive EBVs and EESVs, which can be used independently or together to derive indicators for analysis and decision support. (*Note: The figure includes a selection of and does not include all possible datasets, variables, indicators, and analytical and decision support tools, all of which are expected to be spatially explicit despite potential discrepancies in spatial resolutions.)*

The indicators produced with EBVs, EESVs and other globally standardized geospatial data products can inform various policy tools from local to global level, e.g., in identifying highly biodiverse areas for protection using genetic, species or taxonomic diversity information (Ferrier et al., 2022; Mokany et al., 2020), degraded ecosystems for restoration via ecosystem connectivity and integrity (Hansen et al., 2021; Torres et al., 2018) or equitable benefit sharing of natural resources through the assessment on demand and supply of ecosystem services (Chaplin-Kramer et al., 2020) (Figure 2). These indicators can be used in analysis and decision support such as spatial land and sea spatial planning, environmental impact assessments, national accounting and statistics, and policy planning and reporting tools such as the CBD National Biodiversity Strategies and Action Plans (NBSAPs) and the National Reports (NRs) (Figure 2).

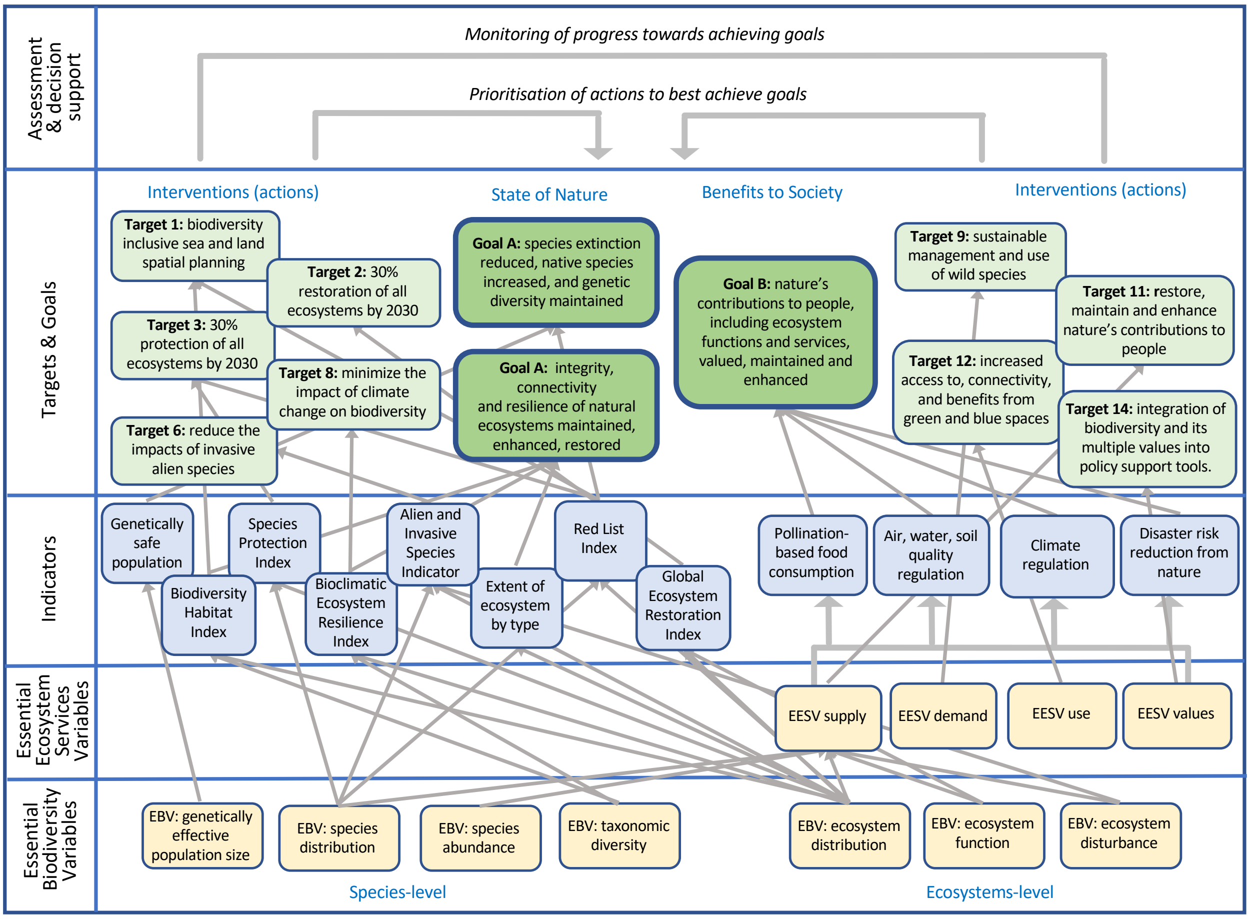


Figure 3. Linkages and interdependencies of EBVs and EESVs from speices to ecosystems and ecosystem services on multiple dimensions, and the role of EBV/EESV derived indicators in informing different components of targets and goals of the CBD GBF in prioritizing actions and monitoring progress towards achieving goals. (*Note: This figure shows a selection of essential variables, indicators, targets and goals.)*

In the CBD Kunming-Montreal GBF, EBV- and EESV-derived indicators designed for Targets will contribute to monitoring interventions (actions) and in some cases their contributions to towards achieving Goals A and B (*ex-post*) while indicators for the Goals themselves will inform the prioritisation of interventions to best achieve them (*ex-ante*) (Figure 3, Box 1). This framework aims at holistically capturing the state and trends of biodiversity, interactions of nature and people, along with the drivers and pressures that are causing biodiversity loss and ecosystem degradation (SCBD, 2022).

In the GBF, EBVs and EESVs relate directly to Goal A (on the state of nature) and Goal B (on benefits for society) respectively. As illustrative examples**,** comparatively simple indicators such as Extent of Ecosystem by Type derived from the *ecosystem distribution* EBV can inform the "area" component of Goal A on ecosystems while indices such as Red List derived with *species and ecosystem distribution* EBVs can inform the "species extinction" component of Goal A on biodiversity (Figure 3). Furthermore, indices such as Biodiversity Habitat Index can be used in informing biodiversity inclusive spatial planning (Target 1) while Biodiversity Ecosystem Restoration Index and Bioclimatic Ecosystem Resilience Index can inform the performance of action-targets such as ecosystem restoration (Target 2) and climate mitigation (Target 8). For Goal B on nature's contributions to people, supply, demand, use and value dimensions/data layers of EESVs can be used to derive indicators on benefits people receive from specific ecosystem services such as pollination-based consumption, air and water quality regulation, and disaster risk reduction from nature (Figure 3). Furthermore, each of the EESV classes (i.e., supply, demand, use, values) can inform different action-targets. For instance, the demand layer can inform how the wild species are being used sustainably (Target 9) while the supply layer of EESV can inform how the nature's contributions to people are being restored, maintained and enhanced (Target 11). The EBVs also inform the development of EESVs as biodiversity is underpinning the connectivity, integrity and resilience of ecosystems and thereby influencing the productivity and efficiency of ecosystem services (see SM IV for EBV-derived indicators and SM V for illustrative use cases).

Importantly, EBVs and EESVs produced with national data should ideally contribute to developing the global EBVs and EESVs, through which, data format and standards can be harmonized and the rigour of global models can improve with data gaps addressed through continuous cross-scale and cross-country exchange, validation and calibration. As illustrated, since several of EBVs and EESVs derived indicators inform the Goals and Targets of the CBD GBF, they can facilitate more coherent and comparable reporting and tracking of national contributions to global goals in NBSAPs and NRs, which is a legal obligation under the Convention and for which the headline indicators will be a core element (SCBD, 2022).

5. Use of EBVs and EESVs in scenarios and modelling for policy and spatial planning

Scenario analysis are useful tools for strategic policy planning and implementation, helping to screen and set achievable targets with alternative policy and management options on different drivers that affect nature and people (*Cloudy crystal balls*, 2000; IPBES, 2016). Models quantify relationships between a range of socio-economic (e.g., population, economy, energy demand, technology) and environmental (e.g., land use, climate change mitigation and adaptation, natural resource use, pollution control) drivers to inform decision options for sectoral policies (Huppmann et al., 2019; Leclere et al., 2018; Obersteiner et al., 2016; Stehfest et al., 2014). These models can quantify alternative future scenarios by setting different assumptions and goals on policy or management options (e.g., land-use planning, fishery management) based on a range of environmental trajectories (e.g. changes in temperature and precipitation) to predict their potential impact on nature and people (Cheung and Oyinlola, 2019; Harfoot et al., 2014; Sharp et al., 2016).

Given the spatial nature and scale dependencies of biodiversity conservation and sustainability issues (Malinga et al., 2015), multiscale scenarios are increasingly demanded in science-policy interfaces such as IPBES and the IPCC to support policy processes where the implementation takes place (Obermeister, 2019). Predictive models are often used in detecting and attributing changes in biodiversity, incorporating remote-sensing and *in-situ* observation data and employing advanced statistical tools and methods (Urban et al., 2022). In this respect, models that are used to develop the EBVs sand EESVs can be used to connect the past and present observations with future projections as predicting the response of EBVs to different environmental and socioeconomic drivers retrospectively can inform the potential impact of different policy options on biodiversity and ecosystems prospectively (IPBES, 2019, 2016).

Furthermore, scenario-based information generated from the models can inform national policy-making, help set future milestones in CBD NBSAPs and track progress retrospectively on the effectiveness of implemented policies in CBD NRs. Here, EBVs, EESVs and their derived indicators provide a useful means to present diverse dimensions, roles and benefits of nature with quantitative measures (Akçakaya et al., 2016). Using complementary data products that reflect diverse values of nature can, for instance, help identify the land that is essential in conserving the functional, provisional and regulating role of ecosystems as well as the land that can be used for human settlement and urban expansion (Mcdonald et al., 2008; O'Connor et al., 2021). In addition, a wide range of ecosystem services people receive from nature (e.g., climate regulation, water purification, crop production, coastal risk reduction, nature-based recreation) are being made available from ecosystem services models to support the optimization of spatial planning in conservation and sustainable development (Balvanera et al., 2022; Chaplin-Kramer et al., 2019b; Díaz et al., 2018) (see section C of SM V for illustrative use cases).

6. Discussion

Our ability to observe biodiversity, estimate its state, detect a change it its state, and attribute a cause to that change will rely on robust biodiversity data and metrics, particularly to eliminate potential causes of contention. Essential variables could play an important role in this causal framework, and for stronger inferences, they can inform actions for prioritization in conservation (Gonzalez et al., 2023). The EBV- and

EESV-derived indicators are scalable and interoperable for multiscale analyses and policy support. With advances in Earth observations, an extensive suite of models can now generate globally standardized variables on biodiversity and ecosystem service at any scale, which can be used to derive a wide range of indicators for quantifying diverse values and benefits of nature (Cord et al., 2017; Pettorelli et al., 2016; Ramirez-Reyes et al., 2019). Deployment of EBVs and EESVs as a structural component of national biodiversity and ecosystem services observation systems and for the generation of indicators greatly simplifies and promotes the harmonization of data collection and indicator production, leading to efficiencies in data collection, curation, reporting and analytics (Seebens et al., 2020; Turak et al., 2017).

Identifying and meeting the needs of end-users of information on biodiversity and ecosystem services is key to effective monitoring of local and national implementation and to improving both decision-making and accountability. Repeatable workflows by which data collection is closely coupled to policy needs at the national level can lead to improved support for biodiversity observations (Guerra, 2019; Pereira et al., 2022). A coordinated approach based on the Biodiversity Observation Network (BON) Development Process proposed by GEO BON (Navarro et al., 2017) is being deployed to establish such 'data to decision' workflows at national scales and is being implemented in regions such as Tropical Andes (Comer et al., 2022), Southeast Asia (Han et al., 2014), Europe (Pereira et al., 2022) and sub-Saharan Africa (see section B of SM V). Workflows in this context can define a series of steps and sequences of operations with specific data to be collected by specific institutions for sustainable indicators production and analysis (see SM VI). Furthermore, a unique opportunity arises in connecting the past, present and future using biodiversity and ecosystem services models (see section C of SM V), potentially informing future social, ecological and economic milestones for policy goals that are evidence-based and can be transformative (e.g., scenarios to inform IPCC and IPBES reports) (Kim et al., 2021).

The scientific community including the GEO BON will continue to evaluate the needs of society as expressed in national and international goals and conventions and focus the development of Essential Variables on biodiversity, ecosystems, and ecosystem services based on the latest advancements in ecological research and modelling and harmonizing key primary observations data (Fernandez, In review; Navarro et al., 2017). These EBV and EESV data products and indicators co-developed with stakeholders, can, *inter alia,* inform the UN SEEA framework in each nation's statistical and accounting systems to further streamline the monitoring systems nationwide and account for natural capital (Hein et al., 2020) in transforming growth-oriented economic model to more a sustainable and well-being oriented model (Otero et al., 2022). The IPBES scientific community synthesizing multiple knowledge systems can use the EBV and EESV data products to assess the state, trends and interactions across biodiversity, ecosystems, nature's contributions to people and various levels and sectors of the society to better understand the complex dynamics between nature and people (IPBES, 2019, 2016).

Over the last decades, a wide range of biodiversity and ecosystem functions and services models have been developed and used to assess the state of nature to support conservation planning and implementation (Brotons et al., 2016; Peterson et al., 2016). With an integrative use of scientific and policy frameworks through institutional collaboration in data production, knowledge synthesis and policy processes, science can contribute more effectively to identifying and realizing optimal pathways for biodiversity, climate and people. Thirty years ago, the world's nations gathered in Rio and embarked on an important journey to address the environmental and development challenges that accompanied a vision of society living in harmony with nature by 2050. Implementing a globally interoperable monitoring system for detecting changes in biodiversity via the Essential Variables will be an essential step towards assessing how close we are from making this 2050 Vision a reality and inform the course of societal decisions in this direction.

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Supplementary Materials

Essential Biodiversity Variables and Essential Ecosystem Services Variables for the Implementation of Biodiversity Conservation and Sustainable Development Goals

I. **EBV classes, definitions and criteria** (Sources: Fernandez, In review; Pereira et al., 2013)

EBV Class	Definition	EBVs (current)
Genetic Composition	The spatial and temporal variability in genetic material (e.g. DNA variants) and genetic processes (e.g. migration, genetic drift) which varies among individuals, populations, and lineages within species, and which provide for species adaptative potential	Intraspecific genetic diversity (Allelic richness, heterozygosity), Genetic Differentiation, inbreeding, Effective population size
Species Populations	The spatial and temporal variability in the distribution and abundance of species populations	Species Distributions, Species Abundances
Species Traits	Within-species variation in trait measurements along the axis of taxonomic diversity	Morphology, Physiology, Phenology, Reproduction, Movement
Community Composition	Defined as two closely coupled variables: 1) Alpha diversity – the diversity of organisms occurring in a given spatial unit; and 2) beta diversity – the dissimilarity (non-overlap) of organisms occurring within two spatial units at the same point, or at two different points, in time	Taxonomic Diversity, Phylogenetic Diversity, Functional Traits Diversity, Multi-trophic Interactions Diversity, biomass distribution
Ecosystem Structure	The horizontal and vertical physical structure of an ecosystem and its relevance to the various elements of biodiversity.	Ecosystem distribution, ecosystem vertical profile, ecosystem live cover
Ecosystem Functions	The collective life activities of plants, animals, and microbes and the effects these activities on the physical and chemical conditions of their environment. Ecosystem functions (sometimes also referred to as ecosystem processes or ecological processes) can be broadly defined as the biological, geochemical and physical processes that take place or occur within an ecosystem.	Primary Productivity, Disturbance, Secondary productivity, ecosystem phenology

Criteria	Definition
Biological	An EBV should reflect an aspect of the biological character of a level of biodiversity (genetic, species, ecosystem, or in between, as appropriate). Even though non-biological variables have their role in models and scenarios of biodiversity change they should nonetheless not be considered as EBVs.
State	While Drivers and Pressures are crucial to understand or project biodiversity change, EBVs must characterizes an aspect of the "State" of biodiversity (in the sense of the DPSIR framework). For example, the extent of forest is an EBV product (for the EBV "ecosystem extent"), while the rate of deforestation or natural regeneration are not.
Sensitive to change	Static variables, or variables that change over long timescales, while biologically relevant, will not be useful to assess change and its impact and should thus not be considered.
Ecosystem Agnostic	Ideally, an EBV should be relevant in all types of marine, freshwater, and terrestrial habitats.
Feasible	Technically feasible, scientifically proven, and economically viable to sustainably monitor the underlying biodiversity observations.
Scalable	The variable should be aggregated or disaggregated from the local to the national, regional and global scale.
Relevant	The variable should address one to multiple users' needs (e.g. scientific, policy, societal). This criteria also influences the likelihood of a community buy-in of the EBVs and EBV products.
Data available	The availability of primary observation itself, and their ability to be mobilized with common standards and integrated with other existing datasets.

II. UN SEEA Ecosystem Accounting – ecosystem classes, definitions and criteria (Source: United Nations, 2021)

The System of Environmental-Economic Accounting (SEEA) is an international statistical standard that uses a systems approach to bring together economic and environmental information to measure the contribution of the environment to the economy and the impact of the economy on the environment. The SEEA uses a structure and classifications consistent with the System of National Accounts (SNA) to facilitate the development of indicators and analysis on the economy-environment nexus.

Ecosystem Condition Account	**Abiotic Ecosystem Characteristics**	**Physical state characteristic**	The class physical state characteristics hosts the physical descriptors of the abiotic components of the ecosystem (soil, water, air…). Physical stocks that are typically being degraded (depleted) due to human pressures (e.g. soil organic carbon, water table level, impervious surfaces) are good choices, as they are sensitive to changes, and relevant for policy interpretation
		chemical state characteristic	The class chemical state characteristics contains the variables and indicators related to the chemical composition of the abiotic ecosystem components. This typically involves the accumulated stocks of various pollutants in soil, water, or air, but only if the selection criteria are met (e.g. global atmospheric CO2 concentration probably should not be seen as a condition metric). Similar to physical state characteristics, indicators should describe the state ("stocks" of pollutants) rather than the flows (emission of pollutants). This way both abiotic ECT classes accommodate major pressures in a way that is compatible with accounting (the pressures are related to the changes in the indicators).
	Biotic Ecosystem Characteristics	**Compositionnal state characteristic**	The class compositional state characteristics comprises a broad range of 'typical' biodiversity indicators, describing the composition of ecological communities from a biodiversity perspective. This includes the indicators based on the presence / abundance of a species or species group, or the diversity of specific species groups at a given location and time. From a location-based perspective (required by spatial consistency) the distribution of a species also boils down-to species composition (local presence). Compositional metrics can characterize the presence / absence or abundance individual species, taxonomic groups (birds, butterflies), or non-taxonomic guilds (e.g. soil invertebrates, macro-zoobenthos). However, indicators based on highly specialist functional groups, where even data collection was performed from a functional perspective (e.g. pollinators, N-fixers, etc.) should be considered either as functional state characteristics, or as ecosystem service indicators (if they are tightly connected to a single specific ecosystem service). Abundance metrics of very large guilds (e.g. trees, phytoplankton) comprising entire ecosystem compartments should be considered as structural state characteristics (biomass, vegetation).
		Structural state characteristic	The class structural state characteristics primarily focusses at the vegetation and biomass of the sites, comprising metrics describing the local amount of living and dead plant matter (vegetation, biomass) in an ecosystem. This class includes all metrics of vegetation density and cover, either related to the whole ecosystem, or just specific compartments (canopy layer, belowground biomass, litter...). For marine and freshwater ecosystems this class can include chlorophyll concentrations, phytoplankton abundance, or plant biomass (e.g., seagrasses). There is some overlap between compositional and structural state metrics, particularly for foundation-species-based ecosystems such as mangrove, or where species groups and vegetation compartments coincide (trees on savanna, lichens on mountain rocks). Such cases should be registered in this class.
		Functional state characteristic	The class functional state characteristics should host simple summary statistics (e.g. frequency, intensity) of relevant ecosystem processes which meet the selection criteria (see Annex 5.x) and which are not already covered by other indicators. Ecosystem functions is a hugely diverse umbrella concept, which is used in highly different ways by the various research communities. Many of the characteristics that can be seen as 'ecosystem functions' can also be seen as a compositional (e.g. species abundances), structural (e.g. plant biomass), or abiotic state descriptors (e.g. surface albedo), or even as ecosystem service indicators (ES accounts). It is a good practice to avoid placing functional characteristics into this class whenever they can find a better home in another class.

	Landscape level characteristics	**Landscape and Seascape characteristics**	The class landscape and seascape characteristics comprise the characteristics of ecosystem type mosaics, typically quantifiable at large (landscape, seascape) spatial scales. The diversity of ecosystem types in a landscape ('landscape diversity'), for example, can describe the integrity of landscapes at broader spatial scales, and also exerts influence on several ecosystem services (Verhagen et al., 2016). Metrics of landscape connectivity / fragmentation measure important landscape characteristics from the perspective of a specific ecosystem type (or group of ecosystem types). Landscape connectivity can be interpreted and measured very differently in terrestrial, freshwater, and marine biomes. Furthermore, in the case of ecosystem types, which themselves are 'mosaics' of relevant subtypes (e.g. a cropland with nested seminatural vegetation fragments), the abundance or the spatial pattern (connectivity) of these subtypes can also be hosted under this class. The proposed structure of condition accounts expects that indicators be linked to specific ecosystem types. This can be achieved by linking the landscape-level metrics (which were e.g. calculated with a moving window) to the local ecosystem type. In other words, the 'landscape diversity' of a forest should be interpreted as the diversity of the landscape in which the forest is situated.

Criteria	**Definition**
Individual criteria for characteristics, variables and indicators	
Relevance	ecosystem characteristics and their metrics should be relevant in terms of the purpose of measuring ecosystem condition
State orientation	ecosystem characteristics and their metrics should describe the state of the studied ecosystem
Framework conformity	ecosystem characteristics and their metrics should be differentiated from other components of the SEEA ecosystem accounting framework
Individual criteria for variables and indicators	
Spatial reference	ecosystem condition metrics should be linked to a specific location (mapped) or spatially referenced
Temporal reference	ecosystem condition metrics should be linked to a specific time period and be sensitive to change
Feasibility	ecosystem condition metrics should (potentially) be covered by data sources over multiple EAs of the same ET
Quantitativeness	ecosystem condition metrics should be measured at a well-defined quantitative scale that allows comparisons in space and time
Reliability	primary (measured) data should be preferred over derived data which, in turn, should be preferred over modelled data
Normality	ecosystem condition indicators should have a strong inherent 'normative' interpretation ('good' vs 'bad', this makes it possible to turn them into indicators with the use of appropriate reference levels)
Simplicity	ecosystem condition metrics should be as simple as possible
Ensemble criteria (for the whole set of variables and indicators)	
Comprehensiveness	all relevant characteristics of the ecosystem should be covered
Parsimony (or complementarity)	the final set of ecosystem condition metrics should be free of redundant (correlated) variables

III. EBV/EESV & SEEA crosswalk at the framework level (Table A) and at the indicators and metrics level (Table B)

Table A.

GEOBON EBV Framework		SEEA EEA Framework	Ecosystem Extent Account	Ecosystem Condition Account						Ecosystem Services Account			Biodiversity	Oceans
				Abiotic Ecosystem Characteristics		Biotic Ecosystem Characteristics			Landscape level					
Type	**Class**	**EBVs / EESVs**		Physical state	chemical state	Compo-sitional state	Structural state	Functional state	Landscape Seascape	Provisioning	Regulating	Cultural		
EBV	**Genetic Composition**	Intraspecific genetic diversity											x	x
		Genetic differenciation											x	x
		Inbreeding											x	x
		Effective population size											x	x
	Species Populations	Species distribution				x		x				x	x	x
		Population abundance				x		x				x	x	x
	Species Traits	Morphology											x	x
		Physiology											x	x
		Phenology											x	x
		Movement											x	x
	Community Composition	Community abundance				x							x	x
		Taxonomic/phylogenetic diversity				x							x	x
		Trait diversity				x							x	x
		Interaction diversity											x	x
	Ecosystem Structure	Ecosystem distribution	x											x
		Live cover fraction					x							x
		Vertical profile					x							x
	Ecosystem Functions	Primary productivity						x						x
		Ecosystem phenology						x						x
		Ecosystem disturbances						x						x
EESV	**Ecosystem Services**	Ecological supply		x	x					x	x			x
		Anthropological contribution								x				x
		Demand												x
		Use								x	x	x		x
		Instrumental value								x	x			x
		Relational value										x		x

Table B.

				Ecosystem Extent Account	Ecosystem Condition Account						Ecosystem Services		
					Abiotic Ecosystem Characteristics		Biotic Ecosystem Characteristics			Landscape characteristic			
Type	**Class**	**Essential Variable or derived Indicator**	**Metric**		**Physical state**	**chemical state**	**Compositionnal state**	**Structural state**	**Functional state**	**Landscape Seascape**	**Provisioning**	**Regulating**	**Cultural**
EBV	Species Populations	Species Distribution	Area of habitat				x		x				x
EBV	Species Populations	Species Distribution	Extent of Suitable Habitat, Population size				x						
EBV	Species Populations	Species Distribution	Range size, Range connectivity										
EBV	Species Populations	Species Distribution	Species distribution (current)				x		x				x
EBV	Species Populations	Population Abundance					x		x				x
EBV	Species Populations	EBV-derived indicator or cross-cutting	Species Status Information Index										
EBV	Species Populations	EBV-derived indicator or cross-cutting	Species Habitat Index				x						
EBV	Species Populations	EBV-derived indicator or cross-cutting	Species Protection Index										
EBV	Community Composition	Taxonomic diversity	Change in local bird diversity				x						
EBV	Community Composition	Taxonomic diversity	Species richness				x						
EBV	Community Composition	Taxonomic diversity	Species richness / Changes in local terrestrial diversity (PREDICTS)				x						
EBV	Community Composition	Functional Diversity	Alpha functional diversity				x						
EBV	Community Composition	Functional Diversity	Beta functional diversity				x			x			
EBV	Community Composition	Functional Diversity	Current global functional diversity of mammals and birds				x						
EBV	Community Composition	Phylogenetic Diversity	Alpha phylogenetic diversity				x						
EBV	Community Composition	Phylogenetic Diversity	Beta phylogenetic diversity				x			x			
EBV	Community Composition	Phylogenetic Diversity	Current global phylogenetic diversity of mammals and birds				x						
EBV	Community Composition	Multi-trophic interaction diversity	Interaction networks				x						

					Ecosystem Condition Account								
				Ecosystem Extent Account	Abiotic Ecosystem Characteristics		Biotic Ecosystem Characteristics			Landscape characteristic	Ecosystem Services		
Type	**Class**	**Essential Variable or derived Indicator**	**Metric**		**Physical state**	**chemical state**	**Compositionnal state**	**Structural state**	**Functional state**	**Landscape Seascape**	**Provisioning**	**Regulating**	**Cultural**
EBV	Community Composition	Biomass distribution	Biomass density by size class					x					
EBV	Community Composition	Biomass distribution	Biomass per functional type - Phytoplankton functional types and size distribution					x					
EBV	Community Composition	EBV-derived indicator or cross-cutting	Biodiversity Intactness Index				x						
EBV	Community Composition	EBV-derived indicator or cross-cutting	Biodiversity Habitat Index				x						
EBV	Community Composition	EBV-derived indicator or cross-cutting	Mean species abundance				x						
EBV	Community Composition	EBV-derived indicator or cross-cutting	Mean temperature of catch										
EBV	Community Composition	EBV-derived indicator or cross-cutting	Mean thermal tolereance										
EBV	Community Composition	EBV-derived indicator or cross-cutting	Overall organism abundance				x						
EBV	Community Composition	EBV-derived indicator or cross-cutting	Protected area connectedness index										
EBV	Community Composition	EBV-derived indicator or cross-cutting	Protected area representativeness index										
EBV	Ecosystem Structure	Ecosystem Distribution	Ecosystem distribution	x									
EBV	Ecosystem Structure	Ecosystem Distribution	Extents/areas of 69 standardized ecosystem types globally	x									
EBV	Ecosystem Structure	Ecosystem Distribution	Forest distribution	x									
EBV	Ecosystem Structure	Ecosystem Distribution	Kelp canopy extent	x									
EBV	Ecosystem Structure	Ecosystem Distribution	Seascape Ecosystem Distribution	x									
EBV	Ecosystem Structure	Ecosystem Distribution	Habitat suitability				x						
EBV	Ecosystem Structure	Ecosystem Live Cover	3D vegetation structure (various metrics related to cover, height, vertical					x					

				Ecosystem Extent Account	Ecosystem Condition Account						Ecosystem Services		
					Abiotic Ecosystem Characteristics		Biotic Ecosystem Characteristics			Landscape characteristic			
Type	**Class**	**Essential Variable or derived Indicator**	**Metric**		**Physical state**	**chemical state**	**Compositionnal state**	**Structural state**	**Functional state**	**Landscape Seascape**	**Provisioning**	**Regulating**	**Cultural**
			variability, horizontal variability)										
EBV	Ecosystem Structure	Ecosystem Live Cover	Ecosystem live cover					x					
EBV	Ecosystem Structure	Ecosystem Live Cover	Live Cover via Vegetation Continuous Fields					x					
EBV	Ecosystem Structure	Ecosystem Vertical Profile	Light attenuation coefficient (Kd 490)					x					
EBV	Ecosystem Structure	Ecosystem Vertical Profile	Vegetation Height					x					
EBV	Ecosystem Structure	Ecosystem Vertical Profile	Vegetation Vertical Profile					x					
EBV	Ecosystem Structure	EBV-derived indicator or cross-cutting	Ecosystem Fragmentation							x			
EBV	Ecosystem Structure	EBV-derived indicator or cross-cutting	Forest fragmentation							x			
EBV	Ecosystem Structure	EBV-derived indicator or cross-cutting	Forest loss year										
EBV	Ecosystem Structure	EBV-derived indicator or cross-cutting	Relative Magnitude of Fragmentation (RMF)							x			
EBV	Ecosystem Functions	Disturbance	Algal Blooms					x	x				
EBV	Ecosystem Functions	Ecosystem phenology	Land Surface Phenology						x				
EBV	Ecosystem Functions	Ecosystem phenology	Productivity Seasonality						x				
EBV	Ecosystem Functions	Net primary productivity	Net primary production						x				
EBV	Ecosystem Functions	Secondary productivity	Maximum catch potential						?				
EBV	Ecosystem Functions	EBV-derived indicator or cross-cutting	Bioclimatic Ecosystem Resilience Index						x				
EBV	Ecosystem Functions	EBV-derived indicator or cross-cutting	Distribution of Ecosystem Functional Types										
EBV	Ecosystem Functions	EBV-derived indicator or cross-cutting	Ecosystem Functional Diversity [richness, rarity, shannon]				x			x			
EESV	Ecosystem Services	Ecological Supply	Nitrogen retention									x	

				Ecosystem Extent Account	Ecosystem Condition Account						Ecosystem Services		
					Abiotic Ecosystem Characteristics		Biotic Ecosystem Characteristics			Landscape characteristic			
Type	**Class**	**Essential Variable or derived Indicator**	**Metric**		**Physical state**	**chemical state**	**Compositionnal state**	**Structural state**	**Functional state**	**Landscape Seascape**	**Provisioning**	**Regulating**	**Cultural**
EESV	Ecosystem Services	Ecological Supply	Water provision		x								
EESV	Ecosystem Services	Ecological Supply	Water quality: N, P			x							
EESV	Ecosystem Services	Ecological Supply	Carbon storage		x								
EESV	Ecosystem Services	Anthropological contribution	Food production								x		
EESV	Ecosystem Services	Demand											
EESV	Ecosystem Services	Use	Coastal risk reduction									x	
EESV	Ecosystem Services	Use	Fisheries catches								x		
EESV	Ecosystem Services	Use	Nature-based tourism										x
EESV	Ecosystem Services	Use	River flood protection									x	
EESV	Ecosystem Services	Use	Sediment retention									x	
EESV	Ecosystem Services	Instrumental value											
EESV	Ecosystem Services	Relational value											
EESV	Ecosystem Services	EBV-derived indicator or cross-cutting	Erosion control									x	
EESV	Ecosystem Services	EBV-derived indicator or cross-cutting	Pest control									x	
EESV	Ecosystem Services	EBV-derived indicator or cross-cutting	Pollination									x	

IV. EBV and EESV derived indicators for monitoring the implementation of the CBD Post-2020 Global Biodiversity Framework

(submitted in response to SBSTTA24 Peer Review on Zero Draft)

Components of the draft Goals	Goal Monitoring Elements	Indicator name	Responsible Institution	Time series, frequency	Key literature
Goal A. Increased extent of natural ecosystems (terrestrial, freshwater and marine ecosystems)	Trends in area of forest ecosystems Trends in area of other terrestrial ecosystems Trends in area of mangroves Trends in area of other marine and coastal ecosystems Trends in wetlands	Extents/areas of 59 standardized ecosystem types globally	iDiv	1992-2018, annually	Remelgado & Meyer (in review) (https://doi.org/10.6084/M9.FIGSHARE.12728006.V1)
	Trends in area of forest ecosystems Trends in area of other terrestrial ecosystems	Biodiversity Habitat Index (BHI)	CSIRO	2000, 2005, 2010, 2015, 2020, every 5 years	Hoskins et al 2020 (https://doi.org/10.1016/j.envsoft.2020.104806) (https://data.csiro.au/)
	Trends in area of other marine and coastal systems	Kelp canopy extent. Spatial coverage primarily US west coast, gradually expanding, eventually to global	SBC-LTER, KEEP, Zooniverse	1984-present	Bell, T. W. et al. 2020 (https://doi.org/10.1016/j.rse.2018.06.039) Cavanaugh et al. 2010 (https://www.kelpecosystems.org/)
	Trends in area of other marine and coastal systems	Seascape Ecosystem Distribution	Oregon State University	2002-present	Kavanaugh et al. 2014 (http://dx.doi.org/10.1016/j.pocean.2013.10.013) Kavanaugh et al. 2016 (http://doi:10.1093/icesjms/fsw086) Kavanaugh et al. 2018 (https://doi.org/10.3389/fmars.2018.00130)
		Live Cover via Vegetation Continuous Fields	NASA	2000-present annually	https://lpdaac.usgs.gov/products/mod44bv006/
	Trends in area of forest ecosystem	Forest distribution (presence and absence; fragmentation)	Temple University	2000-2018	R-package to derive EBV on forest distribution using data from Hansen et al 2013 (DOI: 10.1126/science.1244693)
		Ecosystem live cover	Temple University	2000-2015	R-package to derive EBV on tree cover using data from Sexton et al. (https://doi.org/10.1080/17538947.2013.786146)
Goal A. Ecosystem Integrity and connectivity	Trend in the area of degraded terrestrial ecosystems restored Trends in habitat connectivity	GERI - Global Ecosystem Restoration Index	iDiv	Every 5 years	Torres et al. 2018 (https://doi.org/10.1098/rstb.2017.0433) Fernández et al. 2020 (DOI: https://dx.doi.org/10.978.39817938/57)

Components of the draft Goals	Goal Monitoring Elements	Indicator name	Responsible Institution	Time series, frequency	Key literature
(terrestrial, freshwater and marine ecosystems)	Trend in the area of degraded wetlands restored Trend in the area of converted agricultural lands restored				
	Trends in fragmentation and quality of forest ecosystems Trends in fragmentation and quality of dry and sub-humid lands, grasslands and other terrestrial ecosystems Trends in integrity for all ecosystems	Biodiversity Habitat Index (BHI)	CSIRO	2000, 2005, 2010, 2015, 2020, every 5 years	Hoskins et al 2020 (https://doi.org/10.1016/j.envsoft.2020.104806)
	Trends in fragmentation and quality of forest ecosystems Trends in fragmentation and quality of dry and sub-humid lands, grasslands and other terrestrial ecosystems Trends in integrity for all ecosystems	Bioclimatic Ecosystem Resilience Index (BERI)	CSIRO	2000, 2005, 2010, 2015, 2020, every 5 years	Ferrier et al 2020 (https://doi.org/10.1016/j.ecolind.2020.106554)
	Trends in fragmentation and quality of other marine and coastal systems	Phytoplankton functional types and size distribution	Oregon State University		Kostadinov et al 2009 (https://doi.org/10.1029/2009JC005303)
	Trends in fragmentation and quality of inland waters	Algal Blooms	PBL	(1900-)1970-2015(-2070)	Beusen et al. 2015 (http://www.geosci-model-dev.net/8/4045/2015/) Janssen et al. 2019 (https://doi.org/10.1016/j.cosust.2018.09.001)
		Productivity Seasonality	Clark University	2001-2019 annually	Eastman et al. 2013 (https://doi.org/10.3390/rs5104799) Eastman et al. 2009 (https://doi.org/10.1080/01431160902755338)
		Net primary production	UBC	1981-2100	
		Distribution of Ecosystem Functional Types; Ecosystem Functional Diversity [richness, rarity, Shannon Index]	Virginia University	2001-2020 (operational)	Alcaraz-Segura et al. 2013 (https://doi.org/10.3390/rs5010127) Paruelo et al. 2001 (https://doi.org/10.1007/s10021-001-0037-9)

Components of the draft Goals	Goal Monitoring Elements	Indicator name	Responsible Institution	Time series, frequency	Key literature
	Trends in fragmentation and quality of forest ecosystems Trends in fragmentation and quality of dry and sub-humid lands, grasslands, and other terrestrial ecosystems	Relative Magnitude of Fragmentation (forest) (RMF)	University of Amsterdam	1992-2018	Naimi & Kissling 2020 (https://portal.geobon.org/ebv-detail?id=4) Naimi et al. 2019 (https://doi.org/10.1016/j.spasta.2018.10.001)
Goal A. Reduce the number of species that are threatened by X%	Trends in the area of suitable habitat for threatened species	Area of habitat by species	Sapienza University	1992-2018	Rondinini et al. 2011 PTRSB (https://doi.org/10.1098/rstb.2011.0113) Brooks et al. 2019 (https://doi.org/10.1016/j.tree.2019.06.009)
Goal A. Maintain Genetic diversity	Trends in the genetic diversity of wild species	Number of populations within species with effective population size (Ne) above 500 versus those with Ne below 500.	GEO BON, IUCN, GBIKE	annually	Hoban et al 2020 (https://doi.org/10.1016/j.biocon.2020.108654) Laikre et al 2020 (https://doi.org/10.1126/science.abb2748)
	Trends in the genetic diversity of wild species	The proportion of distinct populations maintained within species	GEO BON, IUCN, GBIKE	annually	Hoban et al 2020 (https://doi.org/10.1016/j.biocon.2020.108654) Laikre et al 2020 (https://doi.org/10.1126/science.abb2748)
	Trends in the genetic diversity of wild species	Number of species and populations in which genetic diversity is being monitored using DNA based methods	GEO BON, IUCN, GBIKE	annually	Hoban et al 2020 (https://doi.org/10.1016/j.biocon.2020.108654) Laikre et al 2020 (https://doi.org/10.1126/science.abb2748)
Goal Ax (missing elements)		Terrestrial Mean species abundance	PBL	1850 - 2050	Schipper et al. 2020 (https://doi.org/10.1111/gcb.14848)
		Species richness / Changes in local terrestrial diversity (PREDICTS)	NHM	01.1000-12.2015	Newbold et al. 2015 (https://doi.org/10.1038/nature14324) Hill et al. 2018 (https://doi.org/10.1101/311787) Kim et al. 2018 (https://doi.org/10.5194/gmd-11-4537-2018)
		Overall organism abundance	NHM	01.1000-12.2015	Newbold et al. 2015 (https://doi.org/10.1038/nature14324) Hill et al. 2018 (doi: https://doi.org/10.1101/311787) Kim et al. 2018 (https://doi.org/10.5194/gmd-11-4537-2018)

Components of the draft Goals	Goal Monitoring Elements	Indicator name	Responsible Institution	Time series, frequency	Key literature
		Current global functional diversity of mammals and birds	Sapienza University	current	Rondinini et al. 2011 PTRSB (https://doi.org/10.1098/rstb.2011.0113) Brooks et al. 2019 (https://doi.org/10.1016/j.tree.2019.06.009)
		Current global phylogenetic diversity of mammals and birds	Sapienza University	current	Rondinini et al. 2011 PTRSB (https://doi.org/10.1098/rstb.2011.0113) Brooks et al. 2019 (https://doi.org/10.1016/j.tree.2019.06.009)
		Freshwater mean species abundance	PBL	(1900-)1970-2015(-2070)	Janse et al. 2015 (https://doi.org/10.1016/j.envsci.2014.12.007)
		Marine Biomass density by size class	Memorial University of Newfoundland	1950-2005	Tittensor et al. 2018 GMD (https://doi.org/10.5194/gmd-11-1421-2018) Lotze et al. 2019 PNAS (https://doi.org/10.1073/pnas.1900194116)
		Marine Species richness	UBC	1950 - 2100	
Goal B. Nature's regulating contributions including climate regulation, disaster prevention and other	Trends in pollination and dispersal of seeds and other propagules	Pollination	PBL	1970-2050	Stehfest et al. 2014 (https://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0)
	Trends in regulation of climate	Carbon storage	PBL	1970-2050	Stehfest et al. 2014 (https://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0)
	Trends in regulation of climate	Carbon storage	Stanford University	2000-2018 (tbc)	
	Trends in pollination and dispersal of seeds and other propagules	Pollination	Stanford University	2015 land cover (but can do annually), crop types are year 2000	Chaplin-Kramer et al. 2019 (https://dx.doi.org/10.1126/science.aaw3372)
	Trends in formation, protection and decontamination of soils and sediments	Sediment retention	Stanford University	2015 land cover (but can do annually), population (every 5 years)	

Components of the draft Goals	**Goal Monitoring Elements**	**Indicator name**	**Responsible Institution**	**Time series, frequency**	**Key literature**
	Trends in regulation of hazards and extreme events	River flood protection	PBL		Ward et al. 2015 (https://doi.org/10.1038/nclimate2742)
	Trends in formation, protection and decontamination of soils and sediments	Nitrogen retention	Stanford University	2015 land cover (but can do annually), population (every 5 years)	Chaplin-Kramer et al. 2019 (https://dx.doi.org/10.1126/science.aaw3372)
	Trends in regulation of hazards and extreme events	Coastal risk reduction	Stanford University	2017 (as far back as UNEP-WCMC maps)	Chaplin-Kramer et al. 2019 (https://dx.doi.org/10.1126/science.aaw3372)
	Trends in regulation of freshwater quantity, quality, location and timing	Water quality: Nitrogen, Phosphorous	PBL	1900-2050	Beusen et al. 2015 (http://www.geosci-model-dev.net/8/4045/2015/) Janssen et al 2019 (https://doi.org/10.1016/j.scitotenv.2019.04.443)|
		Pest control	PBL	1970-2050	Stehfest et al. 2014 (https://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0)
	Trends in formation, protection and decontamination of soils and sediments	Erosion Control	PBL	1970-2050	Stehfest et al. 2014 (https://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0)
		Water provision	PBL	1900-2050	
	Trends in the provision of food and feed from biodiversity	Maximum catch potential	UBC	1950-2100	Cheung et al 2016 (https://doi.org/10.1016/j.ecolmodel.2015.12.018)
	Trends in the provision of food and feed from biodiversity	Food production (plant based)	PBL	1970-2050	Stehfest et al. 2014 (https://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0)

Note: EBVs and EESVs can be underlying datasets for deriving a range of indicators to inform the Global Biodiversity Framework. This list includes those EBVs, EESVs and their derived indicators that currently exist or are in active development. The indicators range from relatively simple derivations of EBVs and EESVs to composite indices that combine one or more EBVs and EESVs with a range of ancillary information including the Essential Oceans Variables and Essential Climate Variables.

V. Use cases of EBV and EESV compatible data products in CBD, SDG, and SEEA monitoring and reporting frameworks across regions and scale

A. Scalable indicators through model-based integration of multiple EBVs for the CBD Global Biodiversity Framework

Strong interlinkages and dependencies exist between many of the goals and targets proposed in the current draft of the post-2020 Global Biodiversity Framework (GBF), and between major components identified within each of these elements. For example, retention of species and genetic diversity will depend, at least in part, on the future area, connectivity and integrity of natural ecosystems (under draft Goal A) which will, in turn, be shaped by the interplay between multiple types of action – e.g., protected-area expansion or ecosystem restoration (under draft Targets 1 and 2). Such interlinkages pose a challenge not only for monitoring of progress, but also for assessment and prioritisation of actions which will contribute most effectively to achieving multiple targets and goals (Leadley et al., 2022).

Habitat-based biodiversity indicators (Ferrier, 2011; King et al., 2021) can make an important contribution to addressing this problem. These indicators predict the level of species (or genetic) diversity expected to persist within a given spatial reporting unit (e.g., a country, an ecoregion, or the entire planet) as a function of the state and spatial configuration of natural ecosystems across that unit. Using the EBV framework to structure and harmonise any input data required by a habitat-based indicator will allow that indicator to be generated seamlessly across multiple spatial scales, from subnational to global. This general approach is illustrated here using, as an example, CSIRO's Biodiversity Habitat Index (BHI) – a habitat-based biodiversity indicator included in the Biodiversity Indicator Partnership suite https://www.bipindicators.net/indicators/biodiversity-habitat-index), is being negotiated as a 'component indicator' in the current draft of the CBD's post-2020 monitoring framework.

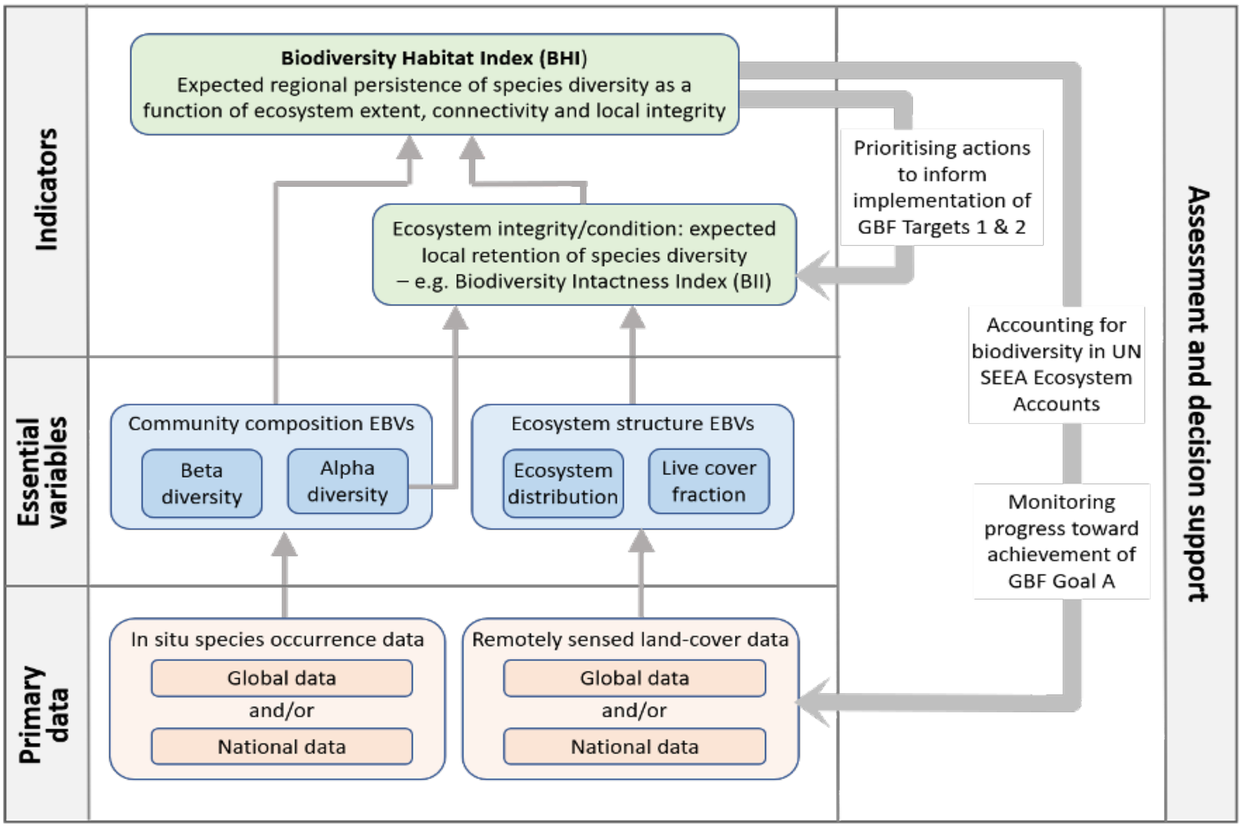

Figure S1. Biodiversity Habitat Index (BHI) data to indicators workflow for assessment decision support

The BHI assesses how changes in the condition and spatial configuration of natural habitat are expected to impact the persistence of species diversity within a region of interest. This composite indicator builds on, and adds value to, any lower-level indicator of ecosystem condition or integrity through integration with modelling of spatial variation (beta diversity) in the species composition of communities (Hoskins et al., 2020). The BHI can be reported either as the average proportion of habitat remaining for all species in the region of interest, or as the proportion of these species expected to persist over the long term, through application of the species-area relationship (Di Marco et al., 2019), while optionally accounting for the effects of habitat connectivity and climate change (Ferrier et al., 2020; Harwood et al., 2022). Recalculation of the indicator using updated remote sensing of ecosystem integrity enables monitoring of progress towards achieving goals for both ecosystems and species. Evaluation of marginal changes in the indicator expected to result from alternative spatially-explicit options for protecting or restoring habitat also provides a solid foundation for prioritising on-ground actions.

The methodological framework underpinning the BHI is purposely designed to allow the indicator to be derived from EBV datasets populated using primary observations from a wide variety of sources, across a range of spatial scales. For example, early derivation of the BHI from an ecosystem-integrity indicator (the Biodiversity Intactness Index) (Newbold et al., 2016) based on downscaling of global land-use data using remotely-sensed ecosystem structure EBVs (Hoskins et al., 2016), has now been augmented by applications employing integrity indicators derived from various other data sources – e.g. the Human Footprint Index (Mokany et al., 2020), and, in ongoing work, the Forest Landscape Integrity Index (Ferrier et al., 2022; Grantham et al., 2020).

This EBV-based approach to indicator derivation also allows the BHI to be derived at national and subnational scales using any better-quality datasets available at those scales. By using EBVs to harmonise such data into the inputs needed to generate the BHI, the indicator can be derived at these scales using the same analytical ‘machinery’ employed globally. This approach can involve replacing global data for some, or all, of the required inputs with national or subnational data. For example, as part of a collaboration between Conservation International and the Peruvian Government piloting the application of UN SEEA Ecosystem Accounts in the San Martin region of Peru, the BHI was derived by combining global community-composition modelling with best-available local mapping of ecosystem structure and integrity (H. Grantham, D. Juhn, L. Larsen, S. Ferrier, Gov. of Peru, 2016). In another typical example, highly refined modelling of spatial variation in community composition within the Pilbara region of Western Australia has enabled application of the BHI to assessing the expected cumulative impact of multiple iron-ore mining operations within that region (Mokany et al., 2022, 2019).

B. Operationalizing EBV workflows with engaging diverse stakeholders at the national scale: lessons from Africa

As part of a five-year World Bank Global Environment Facility funded project to support the mainstreaming of biodiversity information into government decision-making, NatureServe together with the South Africa National Biodiversity Institute (SANBI) and UN Environment World Conservation Monitoring Centre (UNEP-WCMC) collaborated with key stakeholders (government, NGO and academic) in Ghana and Uganda to develop and implement EBV-based workflows to repeatedly and adaptively (depending on new user needs) produce key biodiversity information products to guide biodiversity conservation. This approach was grounded through the application of SANBI's repeatable Spatial Biodiversity Assessment methodology, which follows a workflow process (Figure S2) to facilitate national-scale spatial analysis of ecosystem types to inform priority actions for conservation and restoration of threatened ecosystems (SANBI & UNEP-WCMC, 2016).

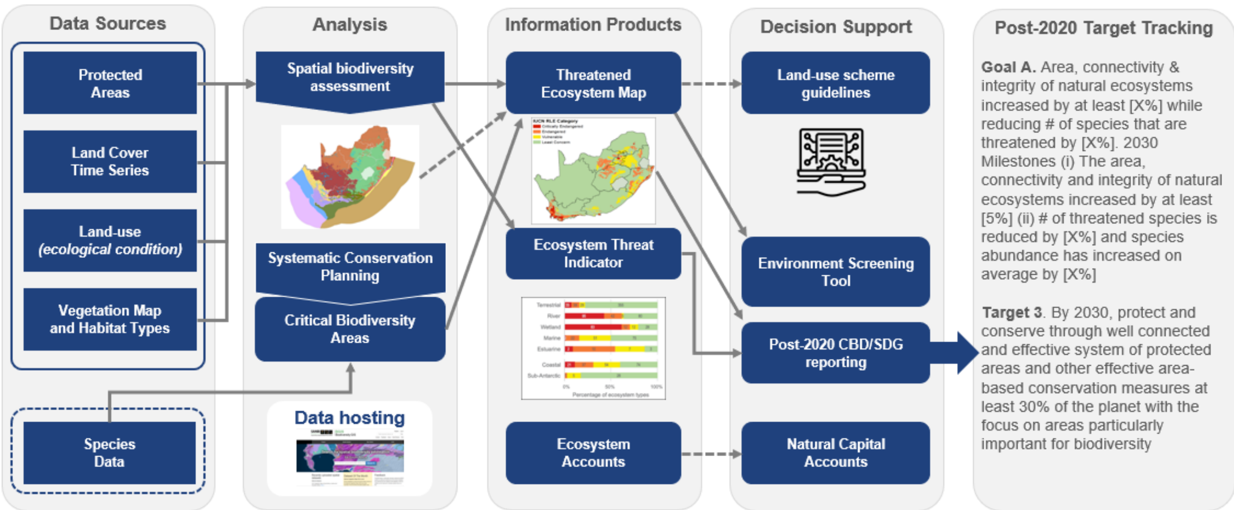

Figure S2: A repeatable workflow process for the integration of core datasets for the repeatable production of national spatial biodiversity assessments that serve multiple policy outputs. Note: solid lines depict direct outputs from the Spatial Biodiversity Assessment whereas dotted lines indicate additional outputs resulting from either additional data inputs and/or applications for policy.

In South Africa, the workflow to produce and revise national ecosystem type EBVs for spatial planning and prioritisation had led seamlessly to the production of national ecosystem accounts using the SEEA-EA approach by simply reanalysing the foundational EBVs. This has led to the production of the first national terrestrial ecosystem accounts in South Africa in partnership with Statistics SA (Statistics South Africa, 2020), with a variety of other national satellite accounts in the pipeline to further mainstream natural capital into national economic decision-making. Leveraging this foundational process and the core data inputs used, additional indicators were co-developed with stakeholders to establish a repeatable and sustained process for indicator production, led by national experts. This approach was akin to GEO BON's 9-step Biodiversity Observation Network (BON) design process (Navarro et al., 2017), taking a user-driven approach that began by identifying priority policy entry points, possible information products (e.g. maps and indicators) to inform those identified policy objectives, and then employing a co-development and consultative process to the development of workflows (Figure S3). Key to this is identifying and building a community of practice that can execute and enhance the workflows over time. In South Africa, the national Biodiversity Planning Forum hosted by SANBI brings together a network of practioners, policy-makers, technicians and academics to further applied biodiversity science for spatial planning (Botts et al., 2020, 2019).

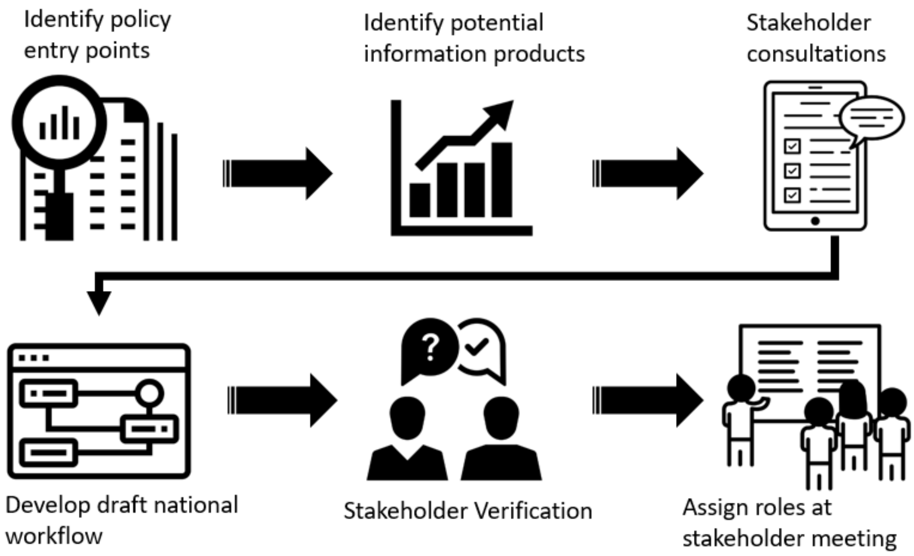

Figure S3: A process for producing user-driven workflows for priority indicators for conservation policy.

For Ghana, conceptual workflows were generated to ensure cross-integration of agency held datasets to develop indicators that can serve multiple policy objectives including those related to the Sustainable Development Goals and Ghana's National Development Plan. More specific workflows (Figure S4) were then produced for each priority indicator that profiled the input datasets and analysis approach. In essence, the workflow process serves as indicator recipes clearly defining the 'what' (data, analytics, methodologies, and tools needed), the 'who' (which institutions will play key roles) and the 'where' (where these institutions are situated within the workflows to ensure proper sequencing). A key outcome indicator of successful mainstreaming will be government investment towards community of practice forums, which would enable information and expertise to be updated annually and for specialists (individuals and institutions) of biodiversity information products to emerge over time in Ghana.

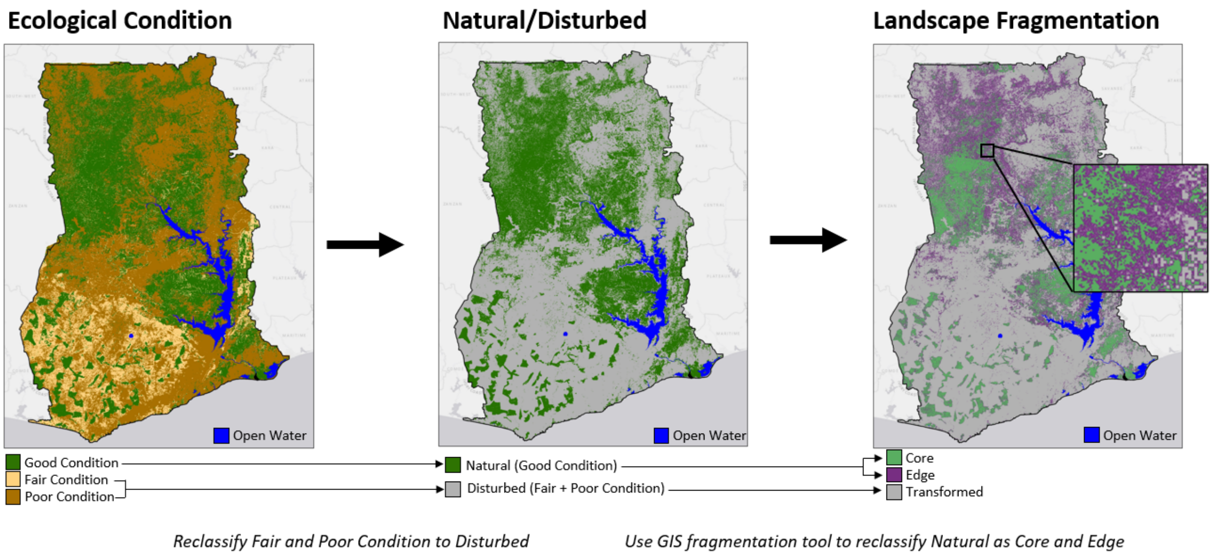

Figure S4: A workflow process leveraging some of the core data inputs for the Spatial Biodiversity Assessment to produce a spatial indicator for landscape fragmentation in Ghana. Landscape fragmentation was calculated using Morphological Spatial Pattern Analysis (Soille and Vogt, 2009).

Applying an EBV-based workflow approach at the national scale can de-mystify the indicator production process at the national scale and ensure ownership of key indicators by decision-makers through the exposure of the critical need for sustained production of key datasets. This approach also becomes selfsustaining, driving further investments in core datasets thereby yielding continually refined and more accurate results over time as well as establishing baselines and time-series for the indicators in question. Further, the workflows can be used to also define needed cross-agency collaboration and serve as structural blueprints for data curation and reporting systems that can strengthen and streamline national biodiversity reporting and monitoring. This approach is being upscaled through NatureServe led projects involving other national partners to ensure rapid adoption and implementation of the EBV workflow process at the national scale.

C. Use of EESVs in scenarios and models to support local conservation and development planning in Latin America

Throughout much of the developing world, many of the Sustainable Development Goals (SDGs) are at odds with one another. Mounting pressure for agricultural products (meeting SDGs 1 and 2) driving land conversion in rural areas competes with growing demand for a clean and stable water supply (SDG 6) to support growing urban populations (SDG 11). This conflict is mirrored in the negotiations for the post-2020 Global Biodiversity Framework for the Convention on Biological Diversity; ecosystem integrity and species diversity can be difficult to maintain while still supporting the food and water security elevated as goals for nature's contributions to people.

Water funds are one policy solution to this resource conflict, providing a financial mechanism for watershed management that promotes habitat conservation, restoration, and improved agricultural practices to protect water resources for downstream users (Arias, V. et al., 2010). City drinking water municipalities, hydropower companies, bottling corporations, and other large commercial entities like agribusiness are the beneficiaries of sustainable watershed management that invest in these funds, often administered by local watershed management associations (Goldman-Benner et al., 2012). Their multiple and diverse goals include securing ample and clean water, recharging groundwater supplies, protecting against floods, landslides, and other natural disasters, and enhancing biodiversity (Bremer et al., 2016). First introduced in Quito, Ecuador in 2000, the concept took off throughout the Latin America and has now spread throughout the world, with more than 350 such programs in operation globally and hundreds of more cities under evaluation by the Nature Conservancy and expected to show a positive return on investment (Vogl et al., 2017b).

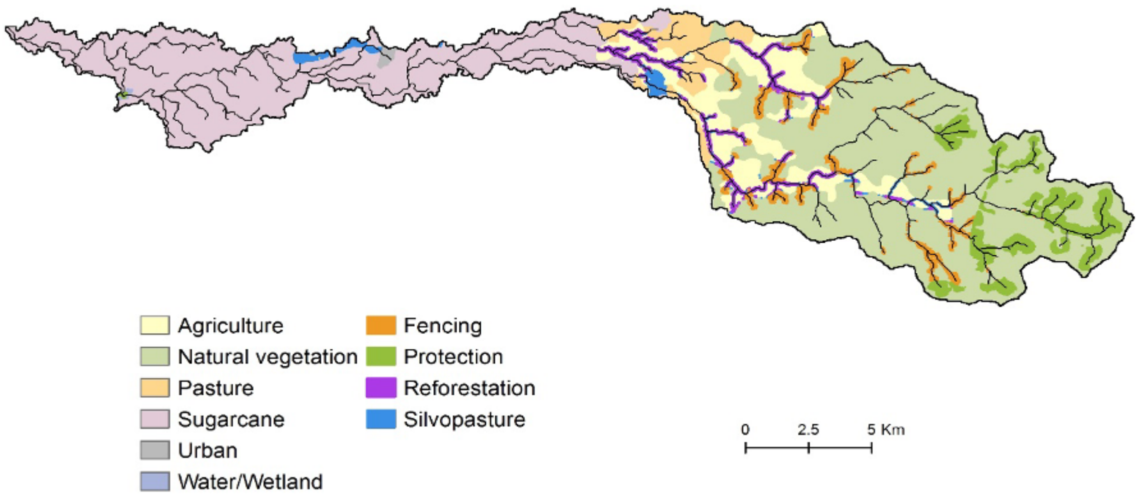

Figure S5. Example of an investment portfolio resulting from RIOS prioritization, with prioritized activities (fencing, protection, reforestation, silvopasture) in brighter colors set against the muted colors of current land use within a watershed.

A return on investment depends on how the resources are invested, and spatial targeting can identify the most cost-effective places to focus efforts. The Resource Investment Optimization System (RIOS; (Vogl et al., 2017a) uses biophysical and social data to produce a portfolio of landscape interventions to maximize delivery of desired ecosystem services (Figure S5), taking into account many of the EESVs in its optimization: the increase in the **ecological supply** of the service under a given intervention, the location and number of beneficiaries and stakeholder preferences (as a proxy for **demand**), budgets and activity feasibility (**anthropogenic contributions**). The resulting optimized portfolio can be treated as a scenario map in an ecosystem service modelling tool like InVEST (Sharp et al., 2016) to quantify the **benefit** that could be provided by the water fund, highlighting mostly **instrumental values**. Trade-offs between different services can be balanced by strategically locating application of best management practices or forest restoration in places that will make the greatest difference to explicit water fund goals (e.g. indicators of **use** like water quality or flood protection for communities) for the least opportunity cost to agricultural production. The land conserved or restored for ecosystem services can also provide co-benefits to biodiversity, which could be assessed through EBVs (e.g. ecosystem structure or function supporting species and community composition, like nesting habitat for native birds, or floral resources for pollinators) Approaches to prioritize investments, whether focused on a single or multiple objectives, can improve the production of those services up to five-fold over a random investment.

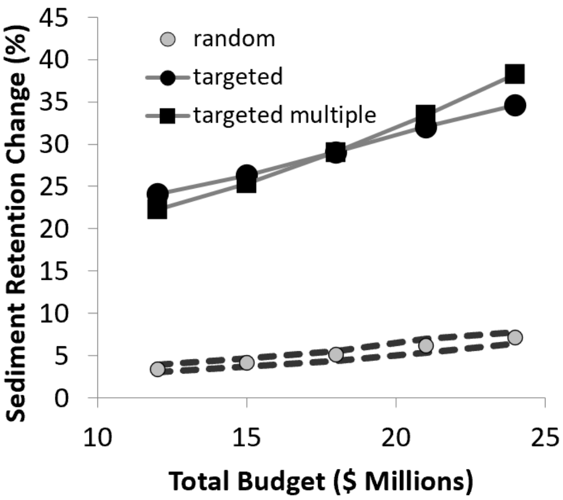

Figure S6. Return on investment for a sample watershed prioritized by RIOS ("targeted" for a single service of sediment retention; "targeted multiple" when targeted for sediment retention as well as other services) for different levels of budget, based on the cost of different prioritized activities. Random application of activities (shown in dotted lines) are only a fraction as effective.

Varying such prioritization exercises over different scenarios can help identify more resilient and robust investment strategies. Considering both current and future environmental conditions, including climate extremes in the Putomayo region of Colombia, revealed that areas with the highest levels of water yield today overlap with areas most susceptible to soil erosion in future climates (Suarez et al., 2011). In Nicaragua, modelling of agricultural productivity and hydrological ecosystem services helped guide climate adaptation planning to identify climate "hot spots," where adaptation measures are not likely to be effective because the expected change is too great, "adaptation spots," where different agricultural management can enhance agricultural production and other ecosystem services amidst climate change, and "pressure spots," where growing conditions will improve in the future and trade-offs in ecosystem services should be considered as part of development (Girvetz, E. et al., 2014). In Kenya, evaluating the impact of different scenarios on EESVs, including a variety of assumptions in regards to the different **instrumental benefits** of the Nairobi Water Fund helped build confidence that the water fund could provide a positive return on investment (Vogl et al., 2017a). In these, the use of scenarios and decision support tools to model EESVs illustrate the range of synergies and trade-offs between ecosystem services and the SDGs and CBD goals they support, and can help strike a balance to support sustainable and inclusive development.

VI. Making EBV and EESV workflows accessible and reproducible

The diversity of producers and users of EBVs and EESVs and their derived indicators calls for versatile and flexible data streams with minimum standards for the development of data products.

Providing open-access to data: The openness and accessibility of primary data and derived products is fundamental to ensure their usability and buy-in by a diverse community of users. Open access is a criterion in addition to the adoption of the FAIR principles, i.e., *Findable*, *Accessible*, *Interoperable* and *Re-usable,* by the data providers and data managers (Wilkinson et al., 2016). The interoperability itself is then supported by the adoption of common standards that allows the integration of data collected or produced by different sources (e.g., (Guralnick et al., 2018), and facilitates the traceability and scalability of those products. This would include primary data producers in government agencies, research institutes and academia, philanthropy as well as civil society.

Publishing the workflows: The workflows describing the development and production of the EBVs and EESVs should be made available to end-users and adhere to the FAIR principles (Fernandez, In review). This would include both how to document changes in one or more dimensions of biodiversity, e.g., species traits (Kissling et al., 2018) and species populations (Jetz et al., 2019), but also that describes the production of specific datasets (see (Hardisty et al., 2019) for an example on the species distribution of invasive species). Data producers must be encouraged to publish these workflows to support the reproducibility of EBVs and EESVs at the national and subnational level for, e.g., ecosystem accounting and goal/target tracking.

Making tools available: Beyond their publication, the tools and algorithms used in the development of EBVs and EESVs should be documented and made publicly available (e.g., using repositories such as GitHub). Whenever possible, capacity building (e.g., training through webinars) could be supplemented to allow the use of these tools (e.g. EBV-based indicators in Biodiversity Dashboard for the ASEAN region) by a broader range of users, in particular at the regional, national and subnational level by the implementing agencies (Han et al., 2014). Notably, this medium can foster dialogue, co-design and operationalization of novel and tailored tools as exemplified by the BioModelos platform for species distribution models in Colombia (Velásquez-Tibatá et al., 2019).

GEO BON has designed an EBV data portal (https://portal.geobon.org/) as a global repository for spatial-temporal data on biodiversity, ecosystems and ecosystem services across multiple dimensions, realms and scale. Data developers can publish their Essential Variables data products and derived indicators and document their metadata and workflow following the EBV data standard (Quoß et al., 2022). Cloud environments for biodiversity and ecosystem services data integration tools and models are still in their infancy but advancing, including the ARIES (ARtificial Intelligence for Ecosystem Services) in support of the UN SEEA Ecosystem Accounting (Martínez-López et al., 2019) and Microsoft's Planetary Computer as part of its Artificial Intelligence (AI) for Earth effort (GEO BON, 2021).

EBVs and EESVs should be developed and served by anyone, in a distributed manner, be clearly documented and follow the FAIR principles. Developing open-cloud processing capabilities would go a long way in mainstreaming the use of data and models to users without limited access to local and expensive computing infrastructures, whether it be for research or national reporting purposes. Furthermore, targeted support, training and capacity building are required to make relevant institutions and stakeholders contribute and benefit the most from the EBV workflows. This requires concerted cooperation by the funders, producers and users of the data required to analyse the state and trends of biodiversity and ecosystem services.

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