From data to decision: leveraging essential variables in standardizing biodiversity and ecosystem services monitoring and reporting

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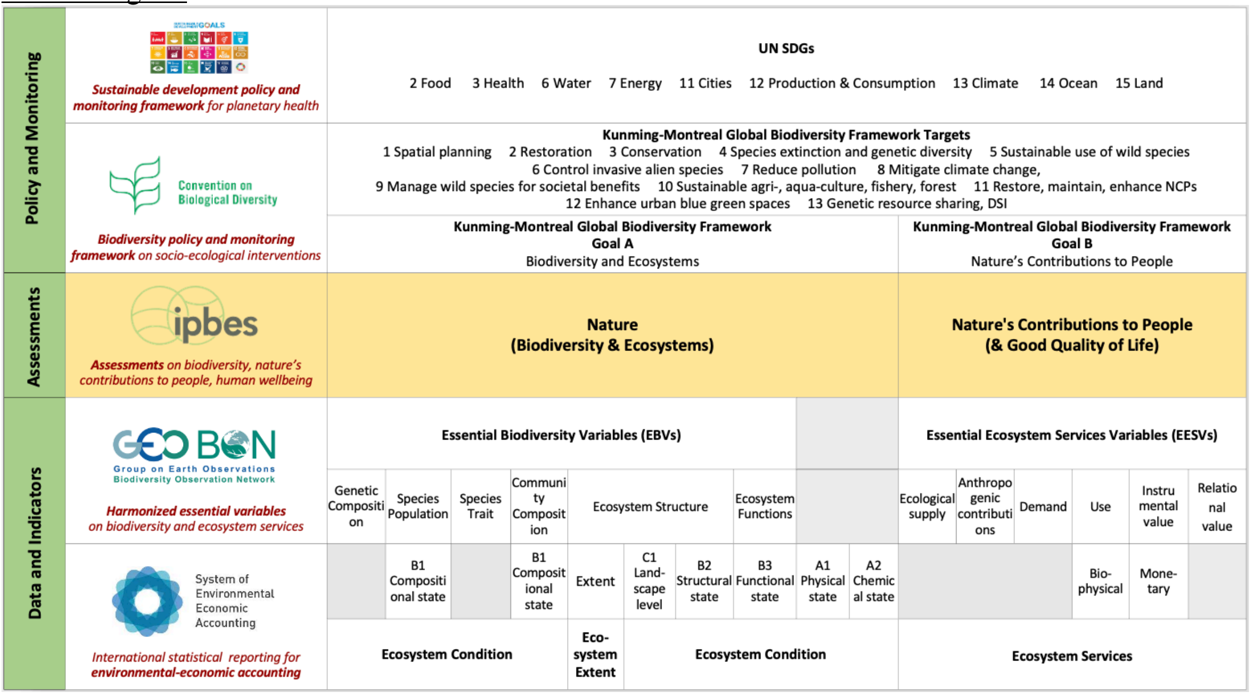
Abstract:
Fragmented systems for monitoring and assessing biodiversity and ecosystem services limit the ability to track progress as much at local scales as across international Multilateral Environmental Agreements. The situation makes it difficult to coordinate actions, and meet agreed upon global commitments. Filling this gap requires integrated design of data-to-decision workflows. The Essential Biodiversity Variables (EBVs) and Essential Ecosystem Service Variables (EESVs) are standardizing tools that can coordinate structured and consistent monitoring, generate harmonized and scalable data products, and facilitate reporting in a way that is useful for multiple purposes. Specifically, EBV/EESV data products are intended to synthesize information to serve the needs of the Kunming-Montreal Global Biodiversity Framework, the System of Environmental-Economic Accounts Ecosystem Accounting, and assessments of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. This integrative and scalable approach works if local data collection is planned with interoperability, and is fundamental to improve models and forecasts and the indicators required in key policy and decision processes. Through three application cases, we demonstrate the use of EBVs and EESVs in national assessments, modelling, and scenario analyses for strategic policy and spatial planning. These use cases illustrate scalable and repeatable workflows from primary data to indicators for decision support.

Abstract figure:



Key messages:

- Fragmented systems for monitoring and assessing biodiversity and ecosystem services limit the ability to track progress, coordinate actions, and meet global commitments.
- The integrative and scalable approach to social-ecological monitoring is fundamental to improve the rigour of indicators, models and forecasts in policy processes.
- EBVs/EESVs are foundational data products that can synthesize the state and trend of nature and derive indicators to serve the needs of the multilateral environmental agreements (MEAs).
- EBVs and EESVs are being operationalized with reproducible data-to-decision workflows to inform national assessment, policy planning and scenario analyses.
- Renewed commitments are called to monitor critical ecological changes nationally and globally with stakeholders to improve the rigour of evidence in key decision processes.

Keywords: multilateral environmental agreements, biodiversity monitoring, national accounting, essential variables, biodiversity policy, indicators, EBV, EESV, SEEA, KM-GBF

1. Introduction

The sustainable governance of socio-ecological systems requires meaningful and achievable goals and targets that reflect their interconnections, and an understanding of these systems that is based on robust scientific observation and local knowledge. Such goals and targets are typically set in major *multilateral environmental agreements* (MEA) endorsed and supervised by their Conference of the Parties (referred to as 'States' or 'countries' hereafter) and/or relevant United Nations (UN) organisations. MEAs often include a *reporting framework* consisting of *monitoring indicators* that are regularly assessed and reported across the parties, to provide an overview of the state of the governed system and to track progress towards the achievement of goals and targets. For example, the Kunming-Montreal Global Biodiversity Framework (KM-GBF) of the UN Convention on Biological Diversity (CBD) contains 4 overarching goals on the state of nature, benefit sharing and resources for implementation. These are underpinned by 23 action-oriented targets covering threats to biodiversity, meeting people's needs, and enabling conditions for mainstreaming and achieving goals (SCBD, 2022). The KM-GBF is supported by a monitoring framework, currently consisting of 42 headline, 52 component, 110 (unique) complementary, and 15 binary indicators (SCBD, 2025). The headline indicators will be a core element of the reporting process and parties are expected to report on their progress under the Convention (SCBD, 2022).

Another reporting framework that is key to MEAs is the System of Economic Environmental Accounts (SEEA), created by the Statistical Division of the United Nations (UNSD) and applied by national statistical offices worldwide (Hein et al., 2020). The SEEA Ecosystem Accounting (EA) process has been endorsed by the UN Statistical Commission as a global statistical reporting standard (United Nations, 2024), implemented through the indirect and more distant means of national accountings and the economic system. The SEEA EA reports on the state and trends of ecosystems and their services in a similar way as the System of National Accounts (also coordinated by UNSD) does for macroeconomic indicators such as the Gross Domestic Product (GDP). SEEA EA consists of five main 'accounts' designed to track the state and trajectories of socio-ecological systems based on a set of principles, standardised definitions and typologies, and supporting guidelines (Edens et al., 2022; United Nations, 2024). Each account is a structured set of reporting indicators designed to provide a representative (and ideally comprehensive) overview of a central 'topic', namely: *ecosystem extent, ecosystem condition, ecosystem services (physical flow), ecosystem services (monetary flow),* and *monetary ecosystem asset*.

Unlike the monitoring framework of the KM-GBF, which specifies concrete reporting indicators linked to the goals and targets, SEEA EA only sets the structures and principles of reporting, including the main classes of indicators and how they should be selected and/or developed, thus ensuring consistency while leaving clear zones of flexibility and responsibility to the States implementing the accounts. This makes it, to some degree, possible for each State to tailor the indicators to ecological characteristics and national priorities, while ensuring compatibility and comparability through the application of the common structures and principles. Today, SEEA EA reporting indicators are being developed in 41 States (United Nations, 2023).

A key challenge for all these international reporting frameworks is the availability of relevant data and clearly structured, regularly updated and reproducible data streams. The lack of basic observations has had consequences for the implementation of the UN Sustainable Development Goals (SDGs, in Campbell et al., 2020; UNEP, 2021, 2019), while the dearth of reporting measures contributed to the failure of achieving the Aichi Biodiversity Targets by 2020 (SCBD, 2020; Xu et al., 2021). This challenge is accentuated by the inherent complexity of biological systems: there are more species than it is possible to monitor and higher organisational units (like a 'forest' or a 'reef') can be defined and delineated in multiple ways. Accordingly, setting up data flows and monitoring systems that generate data that can be aggregated demands structure and coordination (Gonzalez et al., 2023b). Furthermore, while the MEAs and their reporting frameworks are regional or global in scope, the observations and indicators are implemented and assessed at national and subnational levels, which necessitates structure and coordination across the countries already at the level of monitoring activities and data flows (Bhatt et al., 2020; Bubb, 2013).

MEAs and other relevant international reporting frameworks such as the UN SEEA share challenges similar to efforts within the corporate sector that focus on developing nature-related reporting frameworks. Most notable are the 'core disclosure metrics' proposed by the Taskforce on Nature-related Financial Disclosures

(TNFD, 2023), and the draft 'state of nature metrics' proposed by the Nature Positive Initiative (NPI, 2025). In addition, with a focus on the use of scenarios and models, the Network on Greening Financial System (NGFS) is developing a conceptual framework and a methodological guide for national and regional central banks to utilize scenario-based approaches to assessing and mitigating nature-related risks (NGFS, 2024, 2023). While these financial institutions have slightly different focus and needs, their common interest is in being able to forecast and report on financial risks stemming from biodiversity loss and ecosystem degradation. This requires an improved understanding and use of biological and environmental data, models, and indicators for rigorous and accurate assessments of the risks and interventions for minimizing them.

One approach to overcome these challenges has been proposed through the identification, development and use of *essential variables* in national and global data-to-indicator workflows (Fernández et al., 2020; Navarro et al., 2017). The essential variables encompass a minimum set of key and complementary observations on dimensions of biodiversity collected over time that can give a comprehensive yet parsimonious description of the state and trends of the studied system (Lehman et al., 2020). The idea of essential variables was first implemented by the Global Climate Observing System (GCOS) of the World Meteorological Organization. GCOS now has a set of 55 Essential Climate Variables (ECV) to improve the coordination of observations and modelling (Bojinski et al., 2014; Ostensen et al., 2008; Roebeling et al., 2025; WMO, 2022a, 2022b). Following this success, the Group on Earth Observations Biodiversity Observation Network (GEO BON) established six classes of Essential Biodiversity Variables (EBVs) with 22 subclasses (EuropaBON, 2024; GEO BON, 2025; Pereira et al., 2013; SCBD, 2013). Six classes of Essential Ecosystem Service Variables (EESVs) were then proposed to be used combinatorially with a typology of ecosystem services or Nature's Contributions to People (Balvanera et al., 2022; Díaz et al., 2018). In parallel, the ocean observing community defined Essential Ocean Variables (EOV) curated by the Global Ocean Observing System (GOOS) of the Intergovernmental Oceanographic Commission (IOC-UNESCO; see Lindstrom et al., 2012; Miloslavich et al., 2018; Muller-Karger et al., 2018). The interlacing of Essential Variables (e.g., temperature ECV, nutrient EOV, ecosystem distribution EBV) represents the inherent complexity of biological systems. Hence, EBVs and EESVs as an intermediate layer of standardized and synthesized data products between primary observations and indicators of state and trends become useful in coordinating ecological monitoring and data infrastructures and harmonizing indicator development (Geijzendorffer et al., 2016; Gonzalez et al., 2023b).

In this paper, we explore how essential variables, more specifically, EBVs and EESVs, can support the reporting needs for the achievement of MEA goals by providing harmonised data flows that are useful across monitoring frameworks. In particular, we focus on the KM-GBF and SEEA Ecosystem Accounting (EA) given their relevance to global science-policy interfaces such as the CBD and the IPBES (Figure 1). The KM-GBF seeks the rigour of evidence for biodiversity conservation initiatives. The SEEA EA aims to implement an internationally standardized framework that integrates ecosystem-based data into the monitoring of economic systems. We crosswalk EBV and EESV classes and subclasses to the SEEA EA reporting and EBV/EESV-based indicators to KM-GBF monitoring framework and examine how essential variables can improve data flows across scales for synergistic effort. The implementation and use of EBVs/EESVs in national MEA and SEEA EA reporting and spatial planning are illustrated with use cases.

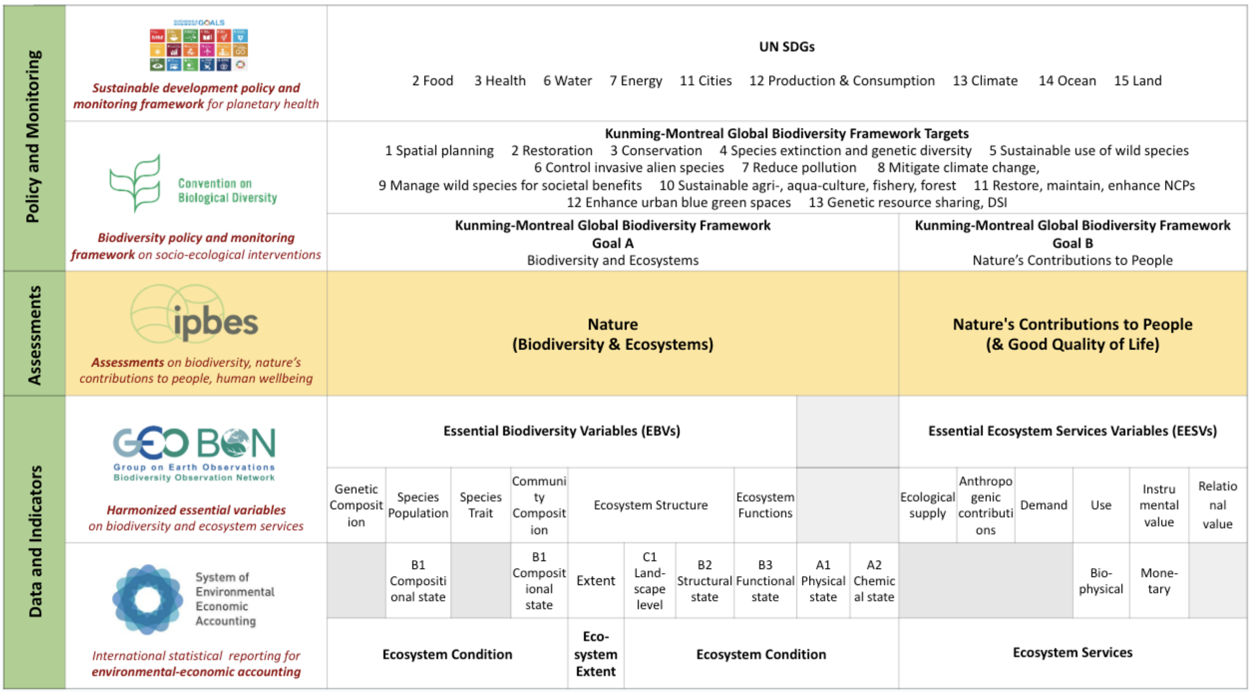


Figure 1. The role of essential variables in informing MEAs with a crosswalk between EBV/EESV and SEEA EA frameworks. The basic observations (data) are collected locally to monitor local changes; when these observations are collected following standards to enable interoperability, they can be aggregated to synthesize essential variables and to derive indicators recommended to track targets of MEAs such as CBD and SDGs. The EBV/EESV data products can be used in the IPEBS assessments in synthesizing the state and trends of nature and nature's contributions to people and inform the SEEA Ecosystem Accounting framework.

2. Essential variables for socio-ecological monitoring

The EBV framework establishes six main *classes* that describe a dimension of biodiversity, designed to provide a comprehensive yet complementary minimum set for ecological observations that can detect and attribute changes in species distributions or traits, their genetic diversity or community composition, or in the extent, distributions and functions of different ecosystems (EuropaBON, 2024; GEO BON, 2025; Pereira et al., 2013, see Supplementary Material (SM) Table S1 for the exact definition of classes and subclasses of essential variables and Table S2 for selection criteria). Some of the classes describe system characteristics that are measurable at the level of species (i.e., genetic composition, species population, species traits), while other classes are "organised" at the ecosystem level (i.e., community composition, ecosystem structure, ecosystem function). For the species distribution EBV, which is a *subclass* under the species population *class*, there will be as many spatial data layers of species as there is data for in a region or the globe. EBVs can therefore be further specified by identifying the taxonomic scope and spatio-temporal resolution of the ecological system to be described in a format of a data product (Pereira et al., 2017; Quoß, 2025). As such, a *generic* EBV variable (equivalent to *subclass)* can be further specified by defining the taxonomic scope, spatial resolution, and temporal resolution and produce *specific* EBV variables, or metrics (Table 1). The main principle for the selection of *specific* EBV variables is that they would together be representative of the studied dimension of biodiversity and ecosystems. In this paper, the hierarchy of the EBV data structure is: six main *classes* (e.g. species population, ecosystem structure), 22 *subclasses* equivalent to *generic* EBV variables (e.g. species distribution, ecosystem distribution), and *specific* EBV variables (e.g. distribution of *Panthera tigris,* distribution of tropical rainforests).

EBV variables are typically constructed based on sparse observations in space and time, and therefore, they are *interpolated* into "space-time-biology" data cubes where gaps are filled with predictions from the available data using auxiliary information (e.g. environmental conditions) and predictive models (Fernández et al., 2020). Biology here refers to different entities across EBV classes, corresponding to a species for the species-focused EBVs and to a community (of species) or ecosystems for the ecosystem-focused EBVs (Table 1, Fernández et al., 2020). The individual EBV variable can be presented as a time series if there are repeated observations at one location or as maps if observations are made at multiple locations. A standardized and transparent handling of data dimensions supports *aggregation* condensing the multidimensional complexity of socio-ecological systems into policy-relevant indicators (Allain et al., 2018). Detailed descriptions about the identification of relevant metrics, the interpolation of data cubes, as well as general data-to-indicator workflows are available for the following EBV classes: *species populations* (Jetz et al., 2019; Kissling et al., 2018a), *species traits* (Kissling et al., 2018b), and *genetic composition* (Hoban et al., 2022). The EBV framework has recently been used to co-design a continental biodiversity monitoring system in Europe covering 84 *specific essential variables* identified and prioritized across the terrestrial, freshwater and marine realms (Kissling et al., 2024).

Six EESV *classes* correspond to the main stages in the flow of ecosystem services from nature towards human society that are relevant for assessing and monitoring these flows across space and time (Balvanera et al., 2022, see SM Table S3 for exact definition of classes). Two of these classes characterise the generation of the ecosystem services: *ecological supply*, which covers the ecosystem capacity to provide ecosystem services, and *anthropogenic contributions,* encompassing the human contributions to the supply of ecosystem services (Schröter et al., 2021. The EESV class *demand* addresses the human needs for an ecosystem service, representing the number of people potentially benefiting from its use. Ideally it includes the dependence on the service based on different factors (e.g. the associated costs or the availability of potential substitutes). In contrast, the EESV class "*use*" describes the amount of the ecosystem service flow that is actually realised (appropriated) by people (Brauman et al., 2020. It should be noted that while the terms "supply" and "demand" are borrowed from economic terminology, the variables themselves are more general and does not need to involve economic demand and supply curves to derive (though this framework is certainly compatible with economic analysis). Finally, there are two classes corresponding to benefits (values) that the ecosystem services generate in a society: *instrumental values* which relate to the value of nature as an instrument of human benefits, and *relational values,* which refer to principles embedded or emerging from reciprocal and relational interactions between people and nature (Díaz et al., 2018; IPBES, 2022; Pascual et al., 2017).

An additional "socio-ecological dimension" to EESVs in a data cube corresponds to the specific type of service itself (Table 1). In an applied socio-ecological system, there are actual types of ecosystem services such as pollination, water regulation, and recreational benefits that are identified in typologies of ecosystem service defined in frameworks such as the Common International Classification of Ecosystem Services (CICES) and the Nature's Contributions to People (NCP) (Díaz et al., 2018; Haines-Young and Potschin, 2018). Accordingly, a comprehensive set of EESVs can be conceptualized as a single four-dimensional data cube, with a *spatial*, *temporal*, *ecosystem service type* and an *EESV class* as dimensions. EESV *classes* also align with the *levels* of the ecosystem service "cascade" model (Haines-Young and Potschin, 2010; Heink and Jax, 2019; Zhang et al., 2022). For some EESV class-ecosystem service type combinations, there may be multiple valid metrics while other combinations may not be derivable (cf. Czúcz et al., 2020 where this is described similarly as "cascade" level). There is, to date, no formal list of variables within the different classes of EESVs. A case study implementing the EESV framework in British Columbia (Canada) illustrates the value of operationalizing ecosystem services monitoring and bridging data to decision-making, which highlights the local context and policy dependency in the selection and development of EESV variables (Schwantes et al., 2024).

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 (Chaplin-Kramer et al., 2025). For example, the distribution or abundance of each pollinator species (*species population* EBV) and the diversity of pollinator species (a *community composition* EBV) influence the amount and efficiency of pollination (i.e., the *ecological supply* EESV) provided to pollination-dependent crops (Garibaldi et al., 2016; Greenleaf and Kremen, 2006). Likewise, species richness of birds and other charismatic or rare vertebrate species (*species population* EBV) supply wildlife viewing opportunities and can drive recreation or tourism (i.e., *relational value* EESV) (Echeverri et al., 2022).

With complementary socio-ecological monitoring capabilities, EBVs and EESVs inform 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 in the assessment on the state of nature in the Global Assessment of IPBES (IPBES, 2019; Purvis et al., 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 map to the *instrumental value* class of the EESV framework. Efforts to further integrate the use of EBVs and EESVs emphasize the importance of accounting for the dynamic changes in biodiversity and ecosystem services. Works are under way with the Nature Futures Framework – a new scenario modelling framework developed by the IPBES – that brings *intrinsic, instrumental* and *relational* values of nature in future planning where EBVs and EESVs can be integratively used in linking monitoring to forecasting (Durán et al., 2023; Kim et al., 2023; Pereira et al., 2020). A few example studies include the spatial prioritization of land use and conservation accounting for biodiversity and ecosystem services values more comprehensively (Dou et al., 2023; Haga et al., 2023; O'Connor et al., 2021) and for assessing the potential of biodiversity and ecosystem services values in meeting the demands of society equitably (Chaplin-Kramer et al., 2024).

Table 1. The most important data dimensions of EBV and EESV classes and subclasses that a comprehensive data cube would need to cover (see also Quoß, 2025). X: directly required data dimension, (x): auxiliary or indirectly required data dimensions (Examples: Morphology = f(taxonomy, trait), i.e., minimal data cube describing EBV subclass morphology should assign a number to each relevant taxonomic unit (species) for each relevant trait. A more comprehensive data cube describing morphology could additionally characterise changes in morphology within space and time, i.e. Morphology= f(taxonomy, trait, location, time)).

EBV / EESV classes and subclasses	Relevant data cube dimensions*						
	spatial	temporal	entity			other relevant dimensions	Example attributes or metrics
			species	community, ecosystem	ecosystem service types		
Essential Biodiversity Variables							
Genetic Composition (GC)							
Intraspecific genetic diversity	(x)	X	(x)			populations	allelic richness, heterozygosity
Genetic differentiation	(x)	X	(x)			populations	genetic units, distance
Inbreeding	(x)	X	(x)			populations	ideal size population
Effective population size	(x)	X	(x)			populations	degree of relatedness
Species Populations (SP)							
Species distribution	X	X	X				area of suitable habitat
Population abundance	X	X	X				estimated counts of individual species
Species Traits (ST)							
Morphology	(x)	(x)	X			trait types	volume, mass, height
Physiology	(x)	(x)	X			trait types	adaptive capacity
Phenology	X	X	X			phenological events	timing of colonization or fructification
Movement	X	X	X			movement types	dispersal ability
Reproduction	X	X	X			trait types	age at maturity
Community Composition (CC)							
Community abundance	X	X	X	(x)			number of species
Taxonomic/phylogenetic diversity	X	X	X	(x)			diversity of species
Trait diversity	X	X	X	(x)		trait types	diversity of traits
Interaction diversity	X	X	X	(x)		interaction types	multitrophic interaction
Ecosystem Structure (ES)							
Ecosystem distribution	X	X		X			forest cover
Live cover fraction	X	X		X		vegetation/canopy layers	vegetation/canopy layers
Vertical profile	X	X		X			vegetation volume/biomass
Ecosystem Functions (EF)							
Primary productivity	X	X	(x)	X			net primary productivity
Ecosystem phenology	X	X	(x)	X		phenological events	phytoplankton bloom
Ecosystem disturbances	X	X	(x)	X		disturbance event types	fire, flood, soil erosion, algal bloom
Essential Ecosystem Service Variables							
Ecosystem Services							
Ecological supply	X	X	(x)	(x)	X		megafauna-based recreational opportunities
Anthropogenic contribution	X	X	(x)	(x)	X		infrastructure to support wildlife viewing
Demand	X	X	(x)	(x)	X		consumer demand for wildlife viewing
Use	X	X	(x)	(x)	X		wildlife watching experiences
Instrumental value	X	X	(x)	(x)	X		revenues of the wildlife-based tourism
Relational value	X	X	(x)	(x)	X	value types	stewardship fostered through wildlife viewing

*There are **two additional dimensions** in the EBV/EESV data cube that are relevant across all EBV/EESV classes and subclasses (Quoß, 2025):
1) **metric** that allows for different measurements/estimates of an EBV/EESV for the same model/data product with potentially different units to be reported,
2) **scenario** that allows for different projections of an EBV/EESV in the state of future or pathways towards them.

3. Essential workflows from data to decision support

Most of the EBV classes are linked to observable characteristics of species or ecosystems, hence indicators for these classes can be aggregated from a broad range of primary observation data from field surveys, remotely sensed data, environmental DNA, and citizen science data, among others. Networks of national and region level observatories can be critical to mainstream the monitored data and make it available for global synthesis. Given the nature of primary observations needed, long-term social-ecological sites can provide unique biophysical and societal data to build EBVs and EESVs (Proença et al., 2017; Zilioli et al., 2021).

The development of EBV data products often requires additional computations (*modelling*) to optimize the use of heterogeneous sources of data (Kissling et al., 2024; Lumbierres et al., 2024). EESVs on the other hand are often difficult to observe directly, so they also typically require some *modelling* in well-documented data workflows. For EESVs, the *ecological supply* and *anthropogenic contribution* classes can be derived from geospatial data available from observations and administrative sources of the region while *demand* and *use* classes require additional socioeconomic data (e.g. population, trade) that can inform on the actual need and appropriated values of ecosystem services from the region or elsewhere. The *instrumental value* and *relational value* classes require monetary or non-monetary valuation associated with the ecosystem services available or appropriated (Balvanera et al., 2022; Chaplin-Kramer et al., 2022). EBVs and EESVs generally best explain changes in biodiversity and ecosystem services when used in a specific context or for a particular question.

The production of the EBV and EESV data products typically involves three key operations, which have been mentioned briefly in the previous sections: (1) *interpolation*, to transform sparse data points into comprehensive data cubes of the same variable; (2) *modelling* (sensu stricto), to assess a new variable from previously assessed variables (and other "ancillary" information); and (3) *aggregation*, to reduce the dimensionality of the final data cubes, and to compile them into (composite) indicators requested by the policy users. These three operations can be implemented in many ways, and they can be seen as the basic blocks of essential data workflows. An important role for models is to represent the causal relationships between the system components (e.g. drivers and biodiversity responses) which allows the detection and attribution of changes through a workflow. For instance, national government agencies may collect primary data from e.g. (*in-situ*) ecological surveys or remote sensing that can be used in developing harmonized interpolated EBV variables (e.g., for *species distribution* EBV) (Figure 2). Then these EBV variables can be combined with other types of data (e.g. lists of priority species, *species trait* EBVs, range of species habitat) to derive indicators such as the *IUCN Red List status of threatened species.* Time series of *ecosystem distribution* EBV variables can, for example, be used to derive indicators on changes in the area/extent of ecosystems by type, which can then be aggregated into the SEEA EA *ecosystem extent* accounts or used in an assessment of ecological networks for conservation planning and management. EESV variables can estimate the supply and use of, for instance, water provisioning services with geospatial human settlement/population data, to assess the availability of clean water and any risks associated with it for the population requiring it (Chaplin-Kramer et al., 2022, 2019). Importantly as mentioned earlier, species, ecosystems, and ecosystem services are changing dynamically, hence an integrated use of spatio-temporal model-based EBVs and EESVs can, to an extent, reflect the interactive nature of an ecological system. Various EBV layers (e.g., *species distribution* and *ecosystem distribution* EBVs) are in fact essential underlying data in EESV variables through the use of ecosystem services models (e.g. InVEST - Integrated Valuation of Ecosystem Services and Trade-offs, Sharp et al., 2016). Furthermore, *specific* EBV and EESV variables (e.g., species distribution EBV of *wild-crop pollinators*, ecological supply EESV of *mangroves*) can be used in estimating a range of ecosystem services (e.g., pollination services, natural hazard reduction).

Both the essential variables, as well as the reporting (or monitoring) indicators produced with them, can inform users in diverse policy and decision spaces from local to global level. For example, genetic, species or taxonomic diversity information from standardized EBVs can be used for identifying highly biodiverse areas for protection (Ferrier et al., 2024; Mokany et al., 2020). Identifying degraded ecosystem candidates for restoration using ecosystem connectivity and integrity (Hansen et al., 2021; Torres et al., 2018) or assessing the equitable sharing of benefits from natural resources using supply and demand information of ecosystem services (Chaplin-Kramer et al., 2022) are some of the practical applications of the data-to-decision workflows (Figure 2). Furthermore, for the indicators to be useful for a broad range of uses from fine-scale spatial planning to environmental impact assessment and high-level reporting as aggregates (e.g. a single number for a whole country), a transparent and easily repeatable computation workflow can enhance the development and use of indicators across the region and scale (Figure 2, see Supplement S8).

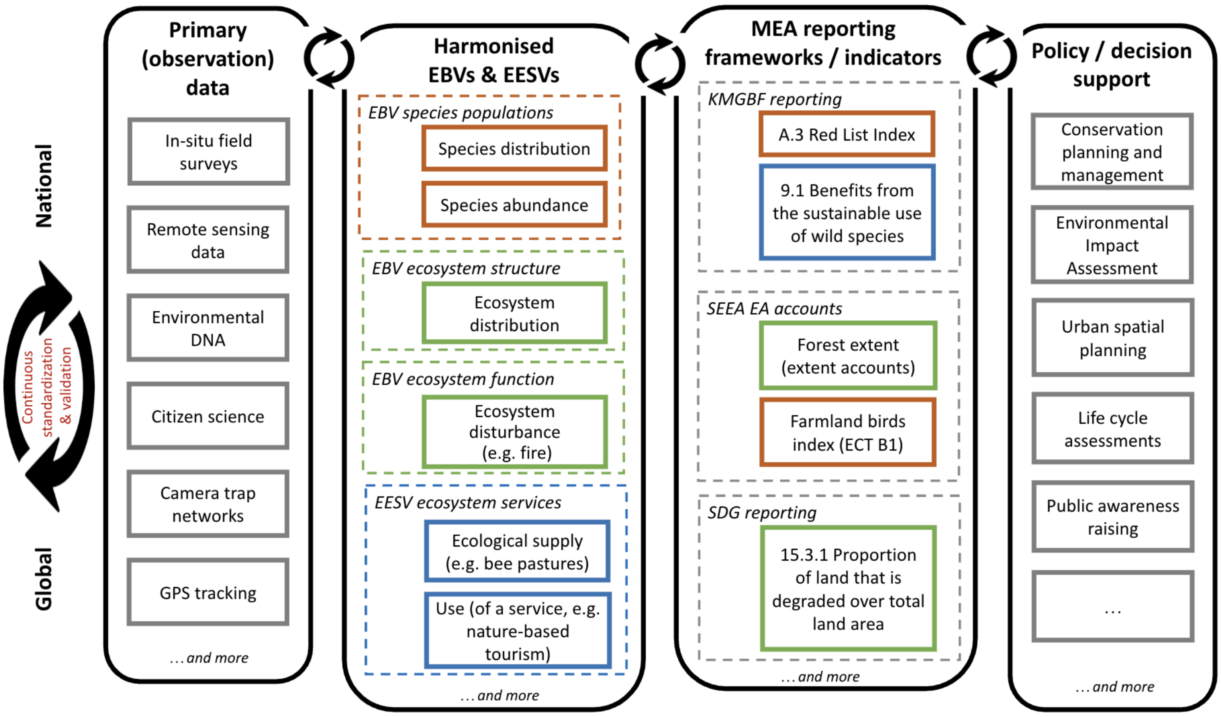


Figure 2. An illustrative generic workflow from primary data to decision support with examples of EBVs and EESVs. Colors are used to identify information flows from data to decision support at the level of species (orange), ecosystems (green), and ecosystem services (blue). A wide range of primary observation data can be used to derive EBVs and EESVs, which can be used independently or together to derive reporting indicators which can then be used for further analysis and decision support. *(Note: Some EBV and EESV data products can derive relatively simple indicators to inform policy and decision processes.)*

Importantly, the development of global EBV and EESV variables requires harmonised data collection and processing (i.e. monitoring and data workflows). In particular, the biological and socio-ecological dimension (e.g., selection of species and monitoring techniques, definition and delineation of ecosystem types) needs considerable coordination to ensure commensurability and semantic interoperability between monitoring systems and reporting frameworks (Bagstad et al., 2025). Data harmonization will improve the rigour of global models with improved accuracy through continuous cross-scale and cross-country exchange, validation and calibration (Kissling et al., 2015; Peterson and Soberón, 2018).

3.1 Essential variables for SEEA EA accounts

Similarly to EBV and EESV frameworks, SEEA EA accounts were primarily created to support and standardise reporting at a national level. The underlying definitions and principles are scale independent so they can be applied in principle at any spatial scales from local to global (see e.g. Czúcz et al., 2025; Gorman et al., 2024; Vardon et al., 2025). Two of the five accounts in SEEA EA describe the state of the ecosystems in biophysical terms: *extent* accounts report the total area covered by different ecosystem types over an accounting area; while ecosystem *condition* accounts describe the quality of these ecosystem types in terms of their main characteristics (see SM Table S4 for the definition of SEEA EA accounts and Table S5 for selection criteria). EBV variables can be used in both *extent* and *condition* accounts in a relatively straightforward way (Table 2, SM Figure S6). The *ecosystem distribution* EBV can be directly used to populate *ecosystem extent* accounts, and it can also be used as a basis for calculating further variables in the *condition* accounts (e.g. landscape-level variables in ECT C1). Most of the other EBVs can also be used to calculate simple data products that meet the criteria of SEEA EA ecosystem *condition* accounts (Czúcz et al., 2021b), and many EBVs can even be directly used as condition variables (Table 2). Nevertheless, physical and chemical condition variables (ECT classes A1 & A2) in SEEA EA are not covered by the EBV framework, even though the abiotic conditions can be underlying characteristics for the species and ecosystems and represented through the related Essential Climate and Essential Ocean Variables used to derive EBVs and EESVs. Therefore, the two abiotic ECT classes can be seen as a logical extension of the EBV framework to cover further important classes of primary data necessary for efficient environmental monitoring and governance. While the accounts in SEEA EA focus on information at the ecosystems level, EBVs at genetics and species level can underpin changes in the ecosystems and can be indirectly referred to as a complementary strength.

Table 2. A crosswalk of EBV and EESV classes and subclasses to the major structural elements of SEEA Ecosystem Accounts. X: clear direct correspondence, (x): possible partial or indirect correspondence (see also SM Figure S6 for a graphical presentation).

	SEEA EA Ecosystem Extent Accounts	**SEEA EA Ecosystem Condition Accounts**						**SEEA EA Ecosystem Service Accounts**	
		A Abiotic Ecosystem Characteristics*		B Biotic Ecosystem Characteristics			C Landscape level*		
EBV / EESV classes and subclasses		A1 Physical state*	A2 Chemical state*	B1 Compo-sitional state	B2 Structural state	B3 Functional state	C1 Landscape / seascape*	Biophysical flow	Monetary flow
Essential Biodiversity Variables									
Genetic Composition**									
Intraspecific genetic diversity**				(x)					
Genetic differentiation**				(x)					
Inbreeding**				(x)					
Effective population size**				(x)					
Species Populations									
Species distribution				X			(x)		
Population abundance				X					
Species Traits**									
Morphology**					(x)				
Physiology**						(x)			
Phenology***						(x)			
Movement**							(x)		
Community Composition									
Community abundance				X					
Taxonomic/phylogen. diversity				X					
Trait diversity				X		(x)			
Interaction diversity**						(x)			
Ecosystem Structure									
Ecosystem distribution	X						(x)		
Live cover fraction					X				
Vertical profile					X				
Ecosystem Functions									
Primary productivity						X			
Ecosystem phenology						X			
Ecosystem disturbances						X			
Essential Ecosystem Service Variables									
Ecosystem Services									
Ecological supply****									
Anthropogenic contribution****									
Demand****									
Use								X	
Instrumental value									X
Relational value*****									

*_Abiotic_ and _landscape-level_ ECTs are not covered explicitly in EBV classes (in line with its _biotic_ focus), but abiotic conditions implicitly through the ECVs (e.g. temperature) and EOVs (e.g. nutrients) inform EBVs. EBVs (e.g. ecosystem distribution) can however be used to calculate landscape-level ECTs.
**EBVs that primarily describe species (genetic composition and species traits) and species interactions can only indirectly be linked to ECTs (cf. Czúcz et al., 2021b).
***Species _phenology_ is not considered in SEEA EA condition accounts (lack of clear directionality, cf. Czúcz et al., 2021a) but as it could have impact on functional state of ecosystems with seasonal changes e.g. under climate change, phenology information can be of potential relevance to SEEA EA condition accounts.
****_Ecological supply_ (i.e., the potential/capacity of ecosystems to deliver services), _anthropogenic contributions_, and _demand_ do not have dedicated 'accounts' in the SEEA EA framework, but they are all discussed in detail (SEEA EA, Chapter 6), and they are explicitly addressed in several recent ecosystem accounting studies (e.g. La Notte et al. 2021). Both _supply_ and _use_ in SEEA EA's "supply and use" tables refer to _use_ in EESV (the actual amount of ecosystem services consumed).
*****SEEA EA monetary ES accounts exclusively cover _use_ and _instrumental values_ assessed as exchange values.

SEEA EA addresses ecosystem services in two accounts: one on the supply and use of services in *biophysical units,* and the other one in *monetary units.* These two accounts correspond to the EESV classes *use* (biophysical unit) and *instrumental value* (monetary unit). This highlights a key difference in the scope of the two frameworks: while in line with economic accounting principles SEEA EA is restricted to exchange values (i.e. "*the values at which goods, services, labour or assets (...) could be exchanged for cash*"; United Nations, 2010), EESVs cover a broader spectrum of potential values (including e.g. relational values), as well as several further components underlying the delicate balance of supply and demand (e.g. anthropogenic contributions, or ecological supply). This shortcoming has already been addressed in the literature using "extended SEEA EA frameworks" (e.g. De Valck et al., 2023), and therefore, further classes of EESVs can also contribute to the development of such extended ecosystem service accounts.

In addition, the term *supply* has a different meaning in SEEA from the classes in the EESV framework. In the context of SEEA EA, both *supply* and *use* describe the "flow" of realised ecosystem services (i.e., the amount of the service actively or passively *appropriated* by people, which is equivalent to "*use*" in the context of EESVs), whereas *ecological supply* in the context of EESVs describes the capacity/potential of an ecosystem to deliver a service (irrespective of its actual use). In other words, *supply tables* and *use tables* in SEEA EA are two different presentations of the *same* set of numbers (the amount of the service *appropriated*) with "supply" tables being grouped by the main sources (ecosystem types) and "use" tables grouped by the main users (economic sectors and other groups of beneficiaries). This structure and terminology are inherited from economic accounting (Lequiller and Blades, 2014) and is intended to ensure compatibility with it. Therefore, as SEEA EA and EESV frameworks are developed with different main purposes, the accounts and the classes where the alignments are achievable are where the interoperability can be established to build the extension into each other's domains (i.e., economic accounting and biodiversity monitoring respectively).

In addition to the "standard" accounts on ecosystem *extent, condition*, and *services*, SEEA EA also discusses the idea of *thematic accounting* which could add further detail on specific themes of policy interest. The structure and content of these thematic accounts is, however, much more open and flexible than that of the five "regular accounts". The thematic *biodiversity accounts* can, in principle, be used to enrich the information presented in ecosystem *extent* and *condition* accounts with further biodiversity metrics that do not directly fit into the basic accounts (see also King et al., 2021). For example, *condition* accounts might not be suitable to host species-level distribution or abundance data for a high number of species. Changes in species distribution ranges or population sizes can, however, be presented in an "accounting format" following SEEA EA's standard structures and principles as thematic *species accounts* (Giljohann et al., 2025; Mokany et al., 2022). Accordingly, such species accounts are tightly related to *species distribution*/*species abundance* EBVs, and other EBVs which can be structured as regularly updated changes in stocks, which can potentially also be presented as *biodiversity accounts* in a SEEA EA context.

Finally, SEEA EA's ecosystem *condition* accounts were also designed to accommodate a deliberative process; where experts from different backgrounds can collaborate on identifying and developing condition variables that are both context-relevant and feasible to characterize the studied ecosystem type (Czúcz et al., 2021a). SEEA EA's systematic approach towards selecting the most relevant (i.e., "essential") condition variables can also be seen as a simple operative *essential variable* framework. Similarly, SEEA EA's reference list of ecosystem services can be seen as a selection of services considered "essential" from the perspective of national accounting. In addition, SEEA EA *condition* accounts also propose a framework for selecting and defining meaningful reference levels for the condition variable while EBVs are intentionally value-agnostic in this respect. Hence, uses of EBVs in decision contexts that require reference values or levels can build on the SEEA EA's consensus-based and locally relevant approach or application as a starting point.

3.2. Essential variables for KM-GBF reporting and monitoring

The implementation of the CBD KM-GBF monitoring framework relies on several indicators for which EBVs and EESVs can provide major underlying data products (Figure 3). EBVs and EESVs relate directly to Goal A (on the state of nature) and Goal B (on benefits for society), respectively, and a suite of KM-

GBF indicators can be constructed directly from the EBVs, with necessary aggregation. 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. Indicators such as Red List Indices derived with *species and ecosystem distribution* EBVs can inform the "species extinction" or "the status of threatened species" component of Goal A on biodiversity (Figure 3). Indicators such as the Biodiversity Habitat Index and the Bioclimatic Ecosystem Resilience Index - both derived from *taxonomic/phylogenetic diversity*, *ecosystem distribution*, and *live cover fraction* EBVs - can inform the assessment of action-targets such as spatial planning (Target 1), ecosystem restoration (Target 2) and climate mitigation and adaptation (Target 8).

For Goal B on nature's contributions to people, the EESV classes *supply*, *demand*, *use*, and *value* can be used to derive indicators on benefits people receive from specific ecosystem services such as pollination-based crop production and consumption, air and water quality regulation and enhancement, and disaster risk reduction from nature-based infrastructure (Figure 3). The different EESV classes (e.g., supply, demand, use, values) can inform different action-targets. For instance, the demand class/layer can inform how the wild species are being used sustainably (Target 9) while the supply class/layer of EESV can inform how nature's contributions to people are being restored, maintained and enhanced (Target 11).

As described earlier, EBVs also inform the development of EESVs as biodiversity or ecosystem underpinning the connectivity, integrity, and resilience of ecosystems; and it often contributes directly to the *ecological supply*, which underlies the productivity and efficiency capacity/potential of ecosystem services. Since several of EBV- and EESV-derived indicators inform the Goals and Targets of KM-GBF, they can facilitate more coherent and comparable reporting and monitoring of national contributions to global goals in NBSAPs (National Biodiversity Strategies and Action Plans) and NRs (National Reports) by improving standardized ecological monitoring and data production.

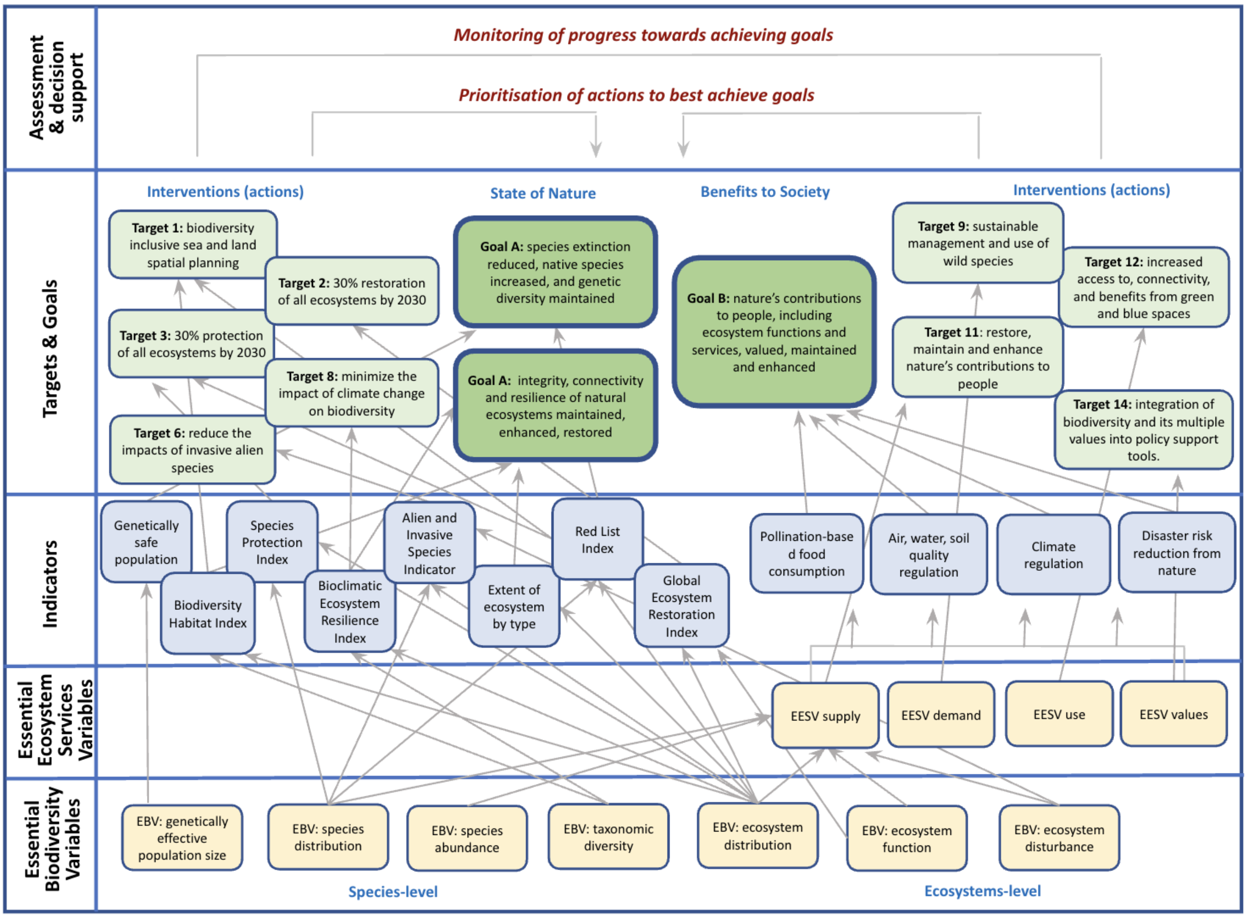


Figure 3. Linkages and interdependencies of EBVs and EESVs from species to ecosystems and ecosystem services on multiple dimensions, and the role of EBV/EESV derived indicators in informing different components of targets

and goals of the KM-GBF in prioritizing actions and monitoring progress towards achieving goals. (*Note: This figure shows a selection of essential variables, indicators, targets and goals.)*

4. Illustrative use cases of EBVs/EESVs in national planning and reporting

While EBVs and EESVs have not yet been formally adopted as international standards for ecological monitoring, they are being progressively integrated into data-to-decision workflows through collaborative projects involving EBV/EESV developers, researchers, and policymakers. Given local specificity and complexity of ecosystems and biodiversity measures, bottom-up co-production approaches are taken to improve the understanding, uptake and operatioanlization of EBV/EESV development by diverse stakeholders (Gonzalez et al., 2025; Guerra, 2019; Moersberger et al., 2024; Valdez et al., 2023). The global standardization proposed by the EV communities of practices (e.g., GEO BON, WMO, GOOS) strongly promote the findability, accessibility, interoperability, and reuse of EV data products and data-to-indicator workflows with metadata in a common data format (Bagstad et al., 2025; Lumbierres et al., 2025; Onley et al., 2025; Quoß, 2025, see SM Supplement S8). In this section, we highlight three distinct use cases that adopt the co-design process for developing EBVs/EESVs and their derived indicators for MEAs using national data, models, and data-to-decision workflows (Table 3). Today, EBV/EESV applications remain voluntary, as they are still a nascent framework, and hence it is diverse in its context, often implemented as pilot initiatives. Ideally, to enhance use in management and monitoring, and the evaluation of policy options, EBVs/EESVs should be implemented through participatory approaches that bridge research, government, and practitioner communities in response to local and national conservation and development needs and key social-ecological questions as they arise.

Table 3. Example use cases of EBVs and EESVs in MEAs by policy context

	Policy Context	EBV/EESV utility	MEA informed	Data Source	Region/country
4.1	Spatial planning, goal tracking, accounting	EBV-based data workflows	SEEA EA, KM-GBF	National ecological data and maps, monitoring program	South Africa, Ghana, Uganda, Republic of Korea, France, Arctic, Tropical Andes, Europe
4.2	Areas for protection and restoration	EBV-based indicators	KM-GBF, SEEA EA	Remote sensing and local data + BILBI model	Australia, Peru, Republic of Korea
4.3	Water Funds	EESV-based optimization	SDGs, KM-GBF	RIOS + InVEST models	Colombia, Kenya

4.1 Identifying EBVs in data to decision workflows with stakeholders

As part of a five-year World Bank Global Environment Facility (GEF) 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 Program World Conservation Monitoring Centre (UNEP-WCMC) collaborated with key stakeholders (government, NGO and academic) in South Africa, 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 implemented using SANBI's repeatable Spatial Biodiversity Assessment methodology, which follows a workflow process (Figure 4) to facilitate national-scale spatial analysis of ecosystems by type to inform priority actions for conservation and restoration of threatened ecosystems (SANBI & UNEP-WCMC, 2016).

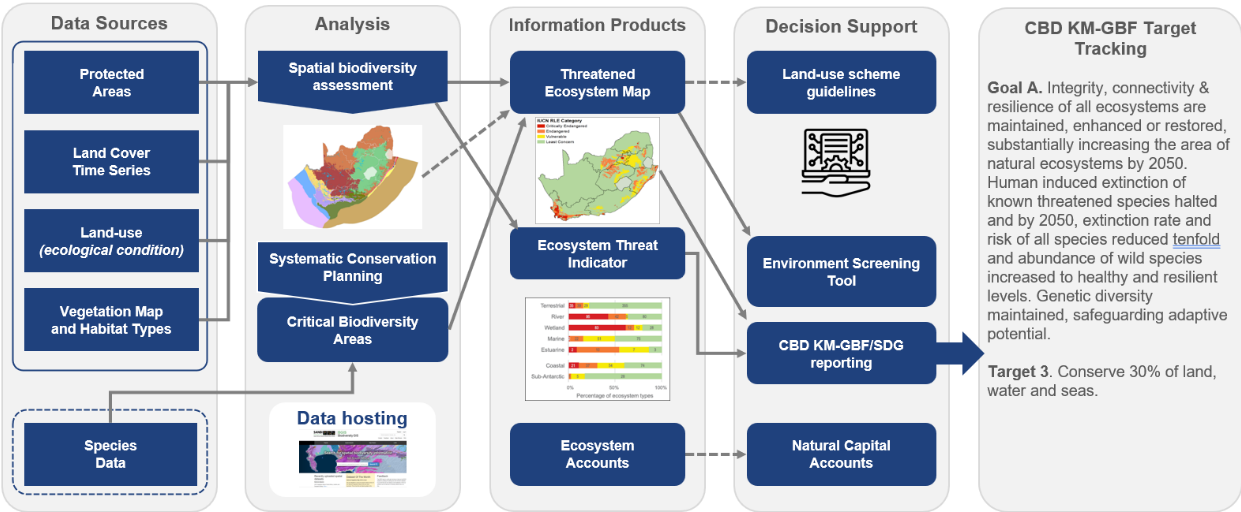


Figure 4. A repeatable workflow process for the integration of core datasets for the repeatable production of national spatial biodiversity assessments that serve multiple policy outputs. Note: solid lines depict direct outputs from the Spatial Biodiversity Assessment whereas dotted lines indicate additional outputs resulting from either additional data inputs and/or applications for policy.

In South Africa, the workflow to produce and revise national *ecosystem distribution* EBVs for spatial planning and prioritisation led to the production of national *ecosystem extent accounts* using the SEEA-EA reporting framework by simply reanalysing the foundational EBVs. This has led to the production of the first national SEEA EA accounts for terrestrial ecosystems in South Africa in partnership with Statistics South Africa (2020), with a range of other national satellite data products to further mainstream natural capital data into national economic decision-making, such as for the protected area estate and strategic water source areas. These accounts are intended to link changes in natural capital to changes in socio-economic potential. By facilitating this foundational development process with EBVs as core data, indicators were co-developed with stakeholders to establish a repeatable and sustained process for national production, led by local experts. This approach was akin to the 9-step Biodiversity Observation Network (BON) design process, 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 for the workflow development (Navarro et al., 2017, see SM Figure S7 for South Africa adapted data-to-decision development flow). In this project, identifying and building a community of practice that can execute and enhance the workflows over time was key. In South Africa, the national Biodiversity Planning Forum hosted by SANBI brings together a network of practitioners, policymakers, technicians and academics to further integrate biodiversity science for spatial planning (Botts et al., 2020, 2019).

Co-designing and building a coordinated global observing system (e.g., the Global Biodiversity Observing System, GBiOS described in (Gonzalez et al., 2023b), that aims to effectively analyse the state and trends of biodiversity and ecosystem services, requires concerted cooperation by the funders, producers and users of data. Importantly, this effort requires the coordination of monitoring across scales, which can be achieved by the development of Biodiversity Observation Networks (BONs), or similar approaches. The BON development process begins with the assessment of national and local policy context and existing ecological monitoring systems and efforts, in order to mobilize a network, and coordinate the development of EBV data products and indicators in collaboration with government agencies, observation networks, space agencies, research communities and citizen scientists (Gonzalez et al., 2025; Guerra, 2019; Moersberger et al., 2024; Navarro et al., 2017). Capacity building and support is available via platforms such as the BON in a Box, which proposes regional, national and thematic mechanisms of modular observation networks for linking ecological monitoring to EBV-based indicator development pipeline through a stakeholder-driven process (Griffith et al., 2024). The BON approach is being implemented through a successful pilot project in Europe (EuropaBON), which laid the foundation for the EU-level regional coordination of EBV production (European Commission, 2025; Kissling et al., 2024). In France, the French Biodiversity Data Hub (FrenchBON) developed as an e-infrastructure offering services and tools throughout the biodiversity data to decision workflow, including an EBV operationalization pilot (Le Bras et al., 2019; Royaux et al., 2022). There are similar active projects in the Arctic region (Gill, M.J. et al., 2011), Tropical Andes (Valdez et al., 2023), and the Republic of Korea where EBV-based indicators are being generated using national data and monitoring efforts.

4.2 Developing model-based indicators with EBVs for use across region and scale

Strong interlinkages and dependencies exist between many of the goals and targets in KM-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 Goal A). This, in turn, will be shaped by the interplay between multiple types of actions, e.g., protected-area expansion or ecosystem restoration (under Targets 1, 2, and 3). Such interlinkages pose a challenge for monitoring of progress and for assessment and prioritisation of actions (Leadley et al., 2022).

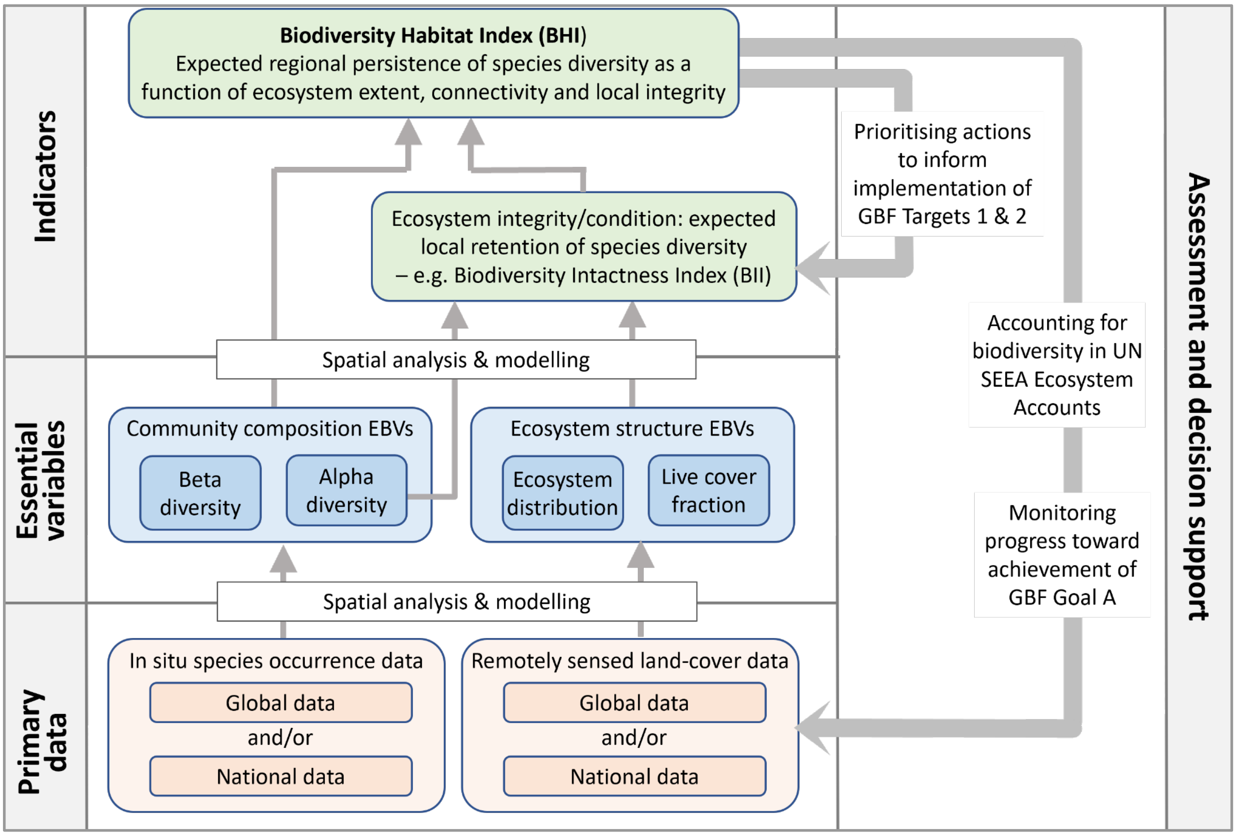


Figure 5. Biodiversity Habitat Index (BHI) data to indicators workflow for assessment decision support

Habitat-based biodiversity indicators (Ferrier, 2011; King et al., 2021) can contribute to addressing this problem. These indicators help evaluate status or scenarios on 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. In particular, the Biodiversity Habitat Index (BHI) assesses how changes in the condition and spatial configuration of natural ecosystems are expected to impact the persistence of species diversity within a region of interest (Ferrier et al., 2024; 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 (UNEP-WCMC, 2025) 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 (Figure 5). By using EBVs to harmonise such data into the inputs needed to generate the BHI, the indicator can be derived at different 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 community composition data from global biodiversity modelling with best-available local mapping of ecosystem structure and integrity (Grantham et al., 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 assess the expected cumulative impact of multiple iron-ore mining operations within that region (Mokany et al., 2019). An ongoing collaboration between CSIRO (Australia's national science agency) and South Korea's National Institute of Ecology is now also generating the BHI (along with the Bioclimatic Ecosystem Resilience Index) at high spatial resolution across the Republic of Korea, using EBVs derived from best available national data for that country. Exchanging scientific knowledge and promoting global data standards between the countries will improve the capacity, interoperability and accuracy of monitoring and modelling systems across the globe through iterative, cross-scale and cross-regional collaboration (Figure 2, Gonzalez et al., 2025; Griffith et al., 2024; Moersberger et al., 2024).

4.3 Use of EESVs in scenario analyses to support spatial planning

Throughout much of the developing world, many components of the Sustainable Development Goals (SDGs) are in competition 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 the resilience of growing urban populations (SDG 11). This conflict is mirrored in KM-GBF; 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. Additional challenges posed to climate and biodiversity science and policy are finding the mechanisms that would mitigate today's polycrisis synergistically in achieving multiple societal goals (Johnson et al. 2023, Kim et al. 2023). It is an important area of research and practice that has not yet been sufficiently explored.

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; Bremer et al., 2016). At least 53 water funds have now been established worldwide, with combined assets of $36 billion (Morningstar, 2022), and a return on investment depends on how the resources are invested, and spatial targeting can identify the most cost-effective places to focus efforts. Biophysical and social data can be used in tools like the Resource Investment Optimization System (RIOS; Vogl et al., 2017b) or the Restoration Opportunities Optimization Tool (ROOT; Beatty et al., 2018) to produce a portfolio of landscape interventions to maximize delivery of desired ecosystem services (Figure 6), taking into account many of the EESVs in its optimization. Over a dozen water funds have used such an approach (Natural Capital Project, 2018).

The increase in the *ecological supply* of the ecosystem service under a given intervention, the location and number of beneficiaries and stakeholder preferences (as a proxy for *demand*), and 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 the EBVs (e.g. ecosystem structure or function supporting species and community composition, like nesting habitat for native birds, or floral resources for pollinators).

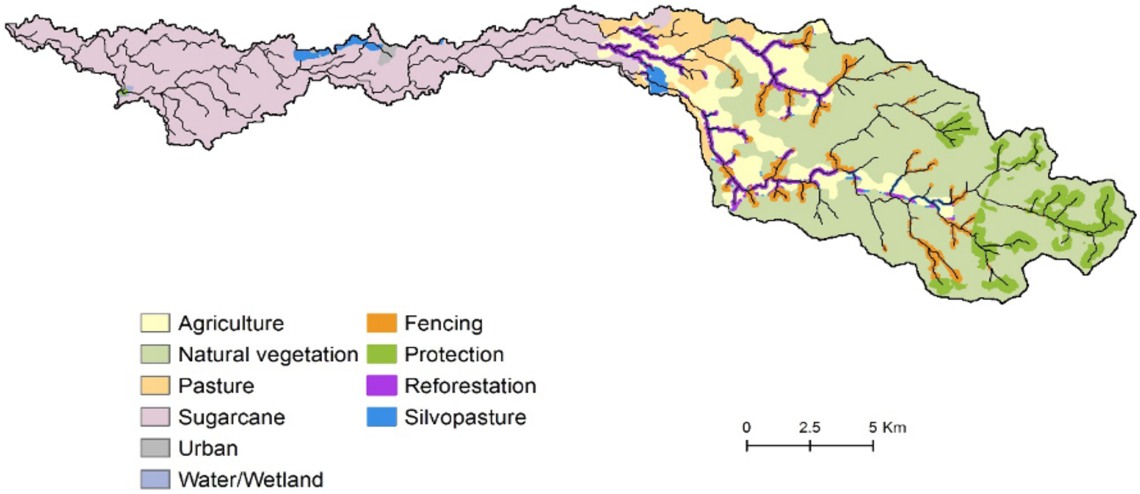


Figure 6. Example of an investment portfolio resulting from RIOS prioritization in the Cauca Valley of Colombia, with prioritized activities (fencing, protection, reforestation, silvopasture) in brighter colors set against the muted colors of current land use within a watershed.

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 Kenya, evaluating the impact of different scenarios on EESVs, including a variety of assumptions in regard 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). As water funds, and payments for ecosystem services more generally, have continued to expand, accounting for the full range of values in their design will be increasingly important to their durability. Recent review of the growing body of research on the topic has demonstrated that the long-term effectiveness and legitimacy of such investments also depend on the inclusion of local values, particularly the *relational* and *intrinsic* (Bremer et al., 2023).

Models such as BILBI and InVEST have the flexibility for trend analyses (retrospective, *ex-post*) and scenario analyses (prospective, *ex-ante*) (IPBES, 2016; Nicholson et al., 2019). This ideally enables the use of common indicators for countries to set achievable, evidence-based targets in NBSAPs and reporting on progress in NRs with national social and ecological observation data and scientific research that inform these models (Kim et al., 2023; Perino et al., 2021). The use of scenarios and models in KM-GBF implementation remains limited today with a great potential to connect ecological monitoring to decision space through an improved configuration and coordination of government funded monitoring and indicator development programs in national governance and research landscape (Kim et al., 2025).

5. Discussion

Our ability to observe biodiversity and ecosystems, estimate their state, detect changes in this state, and attribute a cause to those changes depends on the availability of robust biodiversity data and metrics (Gonzalez et al., 2023a). The implementation of MEAs, and the monitoring of progress towards their objectives is also hindered by persistent gaps in the availability and interoperability of relevant data streams. Recent advances in Earth observation and modelling technologies (Allard et al., 2023; Stephenson, 2020) make an increasing number of data products available that reflect diverse components of biodiversity and ecosystem services at multiple scales. These can then be used to derive a wide range of indicators for quantifying diverse values and benefits of nature (Cord et al., 2017; Kokkoris et al., 2024; Pettorelli et al., 2016; Ramirez-Reyes et al., 2019). Essential variables, including EBVs and EESVs, can play a key role in this process, making monitoring more structured, standardised, repeatable and transparent at the global scale (Gonzalez et al., 2023b). The reusability of EBV and EESV data products in monitoring of different global and regional MEAs (e.g. KM-GBF, SEEA EA, SDGs) as well as concrete fine-scale applications (e.g. urban spatial planning, impact assessment, life cycle assessment) make them versatile assets for conservation policy and practice. In this section, we discuss some of the key challenges and opportunities in operationalizing the EBVs/EESVs.

5.1 Priotization of EBV/EESV development

Fully understanding and characterizing the complexity of ecological systems, e.g. the high number of species and interactions, requires the collection of a tremendous amount of primary ecological data, yet, in practice, it is impossible to observe all species or assess all traits, for example. Biological systems are inherently more complex than climatic systems (Blanchet, 2024), and the current set of EBVs and EESVs classes does not offer a full standardization for these variables. Nevertheless, EBV classes provide an intermediate layer between primary data and abstract indicators (Geijzendorffer et al., 2016) that can also be used to design and structure fundamental and basic monitoring and reporting systems. This, in turn, efficiently supports the identification of the most relevant and "observable" (or already observed) components of the studied ecosystems (Lehmann et al., 2022, 2020). Such variable selection should ideally involve all relevant sectors holding expertise about the studied ecosystem type in an inclusive process (Czúcz et al., 2021b). Currently, there are very few countries/regions and ecosystem types for which such a process has taken place – with the Arctic Council's Circumpolar Biodiversity Monitoring Program (CBMP) being a prominent example (Barry et al., 2023). In the future, when a critical number of such analyses will be available from different countries and regions, it might be possible to generalise patterns and identify transferable shortlists of the "most essential" EBV variables, which can then offer a highly resource efficient way of designing and optimising monitoring systems at the international/global levels.

Identifying a priority list of concrete species, ecosystems and ecosystem services to be covered by EV data cubes fits well into existing calls for making international conservation efforts more concerted, balancing local specificity (e.g. key functional species and ecosystems for ecological stability and maintaining provisioning services) and global urgency (e.g. prevent ecological collapse to mitigate further risks to society and the economy) (NGFS, 2024; Pereira et al., 2024). Optimizing biodiversity and ecosystem service monitoring with the aim of producing scalable and versatile Essential Variable products is a cost-efficient step in that direction. While the prioritization of specific products and workflows is context-dependent, a growing number of case studies can serve as blueprints for future efforts (e.g., protected areas in Guerra, 2019; ecosystem services in Schwantes et al., 2024; regional scale in Valdez et al., 2023; Lumbierres et al., 2025; sub-national in Turak et al., 2017).

5.2 Data formatting standards

Most scientific data are ultimately collected at local scales, yet monitoring can be coordinated so that data and metadata can be aggregated to understand local change in a regional and global context (Muller-Karger et al., 2024). Unfortunately, ongoing biodiversity monitoring programmes are not always clearly aligned with EBVs and EESVs, nor with the key policy drivers (i.e., targets). Hence, target and goal tracking and reporting are still often done at different frequencies and scales by different agencies within and across the nations. There are also considerable challenges related to the international coordination of data semantics and formatting standards, limiting interoperability (Bagstad et al., 2025) on all major types of data operations (interpolation, modelling, aggregation). For interpolation and aggregation techniques, there is a lack of understanding about the "downstream" impacts of particular methodological choices in a data workflow context (Allain et al., 2018; Montero et al., 2024).

Standardised EBV and EESV variables and associated data standards can be stored as multidimensional data cubes (see Table 1) in suitable file formats, like the "classic" NetCDF format (Quoß, 2025) heavily used in weather and climate modelling, as well as several more recent cloud optimised formats (e.g. Zarr; Newman, 2024). Such data cubes can provide a solid foundation for building scalable, reproducible, and interoperable data workflows for multiscale analyses and policy support. As NetCDF offers more detailed and flexible metadata, it is still the format of choice for several collaborative model initiatives, such as The Inter Sectoral Impact Model Intercomparison Project (ISIMIP, 2025). The advantage of self-describing data files and consistent, standardized and curated metadata and standard vocabularies are substantial, as demonstrated for example by the wide adoption of the Climate Forecast Convention for NetCDFs. As a minimum, each data record should be accompanied with date and location (including altitude or depth) and coded in a format described within the data and consistent with widely-used standard units (see SM Supplement S8 on how to make EBVs and EESVs findable, accessible, interoperable, and reusable).

More systemic or structural challenges include data sovereignty concerns, institutional inertia, and semantic misalignments even across the key reporting frameworks, such as the UN SEEA EA and KM-GBF. Merely by standardised structure, definitions, terminology, metadata formats, and accessible repository platforms, EBVs/EESVs can already offer a (partial) solution for the elementary harmonisation needs of current and upcoming monitoring systems worldwide. Using standardized data formatting protocols promotes interoperability and comparability across sites, projects, and networks. The advantage of coordinated international networks is that they help members to adopt standards, including data formats that then facilitate machine reading, interpolation, and aggregation of local results to enable regional and global indicators and assessments.

5.3 Reproducible indicator workflows

Open workflows based on essential variables can de-mystify the indicator production process and ensure ownership of key indicators by decision-makers. The development of standardised indicator workflows is hindered by the lack of adequately standardised monitoring systems. In many countries, data products exist across national and regional agencies and academic institutes as a result of long-term ecological monitoring and research programs (Moussy et al., 2022). However, existing workflows are often tailored to local datasets, resulting in solutions that are fragmented and inconsistent on an international level. Further, restricted access, limited data sharing culture, and heterogeneous data structures often prevent the national and global aggregation of spatial data to assess the state and trend of biodiversity change (Mandeville et al., 2021). Adopting reproducible workflows with stadardised data products can help overcome these limitations, enabling the production of harmonized and scalable datasets.

Recent efforts have applied the production of essential variable-based workflows as a means to identify relevant indicators and other data products that can inform, track and guide policy at local, national (Gutiérrez-Vélez et al., 2024) and regional (Barry et al., 2023; Valdez et al., 2023) levels. The workflow process allows for the selected indicators to be unpacked into their constituent components (e.g., EVs and primary data) thus ensuring monitoring. Reporting systems (either existing or planned) can be structured to produce data that directly underpins sustained indicator production while allowing interoperability with the global standards. Several technical and logistical challenges can possibly be mitigated by establishing regional support centres, offering technical guidance, shared tools, and opportunities for collaboration across countries, and by promoting the integration of essential variables into national frameworks iteratively, based on capacity that expands over time. Through the exposure of the critical need for sustained production of key datasets, this approach can also become self-sustaining, driving further investments in core datasets, and thereby yielding continually refined and more accurate results over time (e.g., South Africa's Spatial Biodiversity Assessments, Reyers et al., 2017).

The workflows can support cross-agency collaboration and serve as structural blueprints for data curation and reporting systems. As illustrated through use cases around the globe, this work is actively underway in several regions (e.g., the Republic of Korea, Canada, France, the Arctic, Africa, Europe, Tropical Andes) to use the EBV/EESV frameworks and EBV/EESV-based indicators to assess and align existing biodiversity observation systems with global standards and indicators. Such an effort is starting to be institutionalized in Europe through the European Commission (2025) which after a successful pilot project EuropaBON as a regional BON, has committed to invest in the regional coordination of EBV production over the next several years. Identifying and operationalizing the interlinkages and dependencies of policy goals and indicators across regional scale and sectors would go a long way in enhancing the efficiency of streamlining the data-to-indicator workflows and the efficacy of evidence-based decision-making in policy processes.

5.4 Linking data to decision

Deployment of EBVs and EESVs as a structural component of national data workflows will greatly simplify and promote the harmonization of data collection and indicator production, leading to efficiencies in data curation, reporting and analytics (Seebens et al., 2020; Turak et al., 2017). This can help to derive harmonised indicators across a broad range of national and international policy contexts, including KM-GBF and SEEA EA, as presented in this paper. Nevertheless, there are many further policies that can benefit from the transparent use of EBVs and EESVs in their reporting workflows. This includes the reporting frameworks of MEAs that are addressing concrete groups of species or ecosystems, like the Convention on Migratory Species (migratory species), the Convention on International Trade in Endangered Species of Wild Fauna and Flora (endangered species) and the Ramsar Convention (wetlands).

Essential Variable frameworks can also make nationally developed data products available for spatio-temporal analysis globally (Jetz et al., 2019; MBARI et al., 2021). Advancing models for EBVs and EESVs can also improve the causal inference and detection and attribution science, making scenario-based simulations feasible and more reliable in supporting policy processes (IPBES, 2019, 2016). While there has been considerable progress during the last decades in socio-ecological modelling, several aspects of the new models (e.g. the validity of their assumptions, the propagation of uncertainty) need to be explored in a workflow context. Current ecosystem service models are still challenged with capturing long-term ecological feedbacks like soil degradation impacts on productivity and deforestation impacts on downwind precipitation, which limits their applicability in integrated scenario analyses-based studies (Kim et al., 2023). Similarly, the biophysical outputs of such models are not adequately linked to dynamic economic modelling in order to represent the full value of land- and resource use decisions (Chaplin-Kramer et al., 2024). Scenario-based information generated from models will have a potential to support multi-scale policy processes with scale- and ecosystem specific knowledge- and data-based evidence in identifying conservation actions relevant for the country while setting national milestones in CBD NBSAPs and tracking progress in CBD NRs for global aggregation.

6. Conclusion

The EBVs and EESVs framework, by providing a consistent set of metrics to be measured and modeled across space and time, addresses two major interoperability challenges: coordination and harmonization between monitoring activities and accessibility and reusability of datasets across MEAs. Intermittent funding, data sovereignty concerns, and institutional inertia also contribute to making the global harmonisation of monitoring efforts challenging. Nevertheless, the scientific community will continue to evaluate the needs of society as expressed in national, regional, and international goals and conventions and focus the development of knowledge products such as essential variables on critical species, ecosystems, and ecosystem services with stakeholders. EBVs and EESVs, as the backbone of a standardized ecological monitoring framework, have an essential role in informing global policy, scientific and data frameworks such as KM-GBF and SDG indicators, SEEA EA accounts and IPBES assessments. The interoperability between essential variables and SEEA EA also has an important potential for transforming the economy with nature's diverse values more thoroughly accounted for in our national accounting systems. Furthermore, an improved interoperability of data and indicators used by the corporate and financial sector through collaboration with biodiversity science and environmental economic communities will be important in progressing towards assessing and mitigating nature-related risks through collective and concerted effort. As the global community joins arms and accelerates ambitions to achieve nature- and people-positive futures, renewing our commitment to monitor critical ecological changes nationally and globally will be an essential first step towards enabling and guiding effective biodiversity conservation, remaining within planetary boundaries and safeguarding human security.

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Supplementary Materials

From data to decision: leveraging essential variables in standardizing biodiversity and ecosystem services monitoring and reporting

Table S1. EBV classes and subclasses, and their definitions

(Sources: EuropaBON, 2024; GEO BON, 2025; Pereira et al., 2013; SCBD, 2013)

EBV class and subclasses	Definition/description
Genetic composition	EBV class that captures metrics of within-species genetic variation across space and time. It Includes four generic EBVs: Infraspecific genetic diversity, Genetic differentiation, Effective population size, Inbreeding (Hoban et al., 2022).
Infraspecific genetic diversity	The level of genetic variability within species populations. It is typically captured by two complementary metrics: the number of alleles in a population (richness) and the expected and observed proportion of heterozygotes in a population at equilibrium (evenness).
Genetic differentiation	The divergence in the frequencies of alleles between populations of the same species.
Effective population size	The size of an ideal population that loses genetic variation at the same rate as the focal population.
Inbreeding	Degree of relatedness between individuals of a population.
Species populations	EBV class that accesses the spatial and temporal variability in the species populations. This includes two generic EBVs: Species distribution, Species abundance (Jetz et al., 2019).
Species distribution	The probability of occurrence of a species or group of species, measured (or modeled) along contiguous spatial and temporal units. In some cases it may be just a binary variable corresponding to the presence/absence of the species, in others it may refer to the probability that the cell is occupied by the species of interest in a given time period.
Species abundance	The estimated count of individuals or relative abundance of a species or group of species, measured (or modeled) over contiguous spatial and temporal units.
Species traits	EBV class that captures the spatial and temporal variation in trait measurements within species. This includes five generic EBVs: Morphology, Physiology, Reproduction, Phenology, Movement (Kissling et al., 2018)
Morphology	The volume, mass, height or other traits defining the form of organisms grouped by species, measured (or modeled) over contiguous over contiguous spatial and temporal units.
Physiology	Values of biochemical or physical quantities (e.g., thermal tolerance, disease resistance) describing functions of organisms grouped by species, measured (or modeled) over contiguous over contiguous spatial and temporal units.
Reproduction	Age at maturity, number of offspring and other reproduction traits of organisms grouped by species, measured (or modeled) over contiguous spatial and temporal units.
Phenology	The timing of cyclical biological phenomena, such as the presence, absence, abundance, or duration of seasonal activities of organisms, measured (or modeled) for each species over contiguous spatial and temporal units. This can include the date of emergence of leaves and flowers, the first flight of butterflies, the first appearance of migratory birds, the date of leaf coloring and fall in deciduous trees, the dates of egg-laying of birds and amphibia, or the timing of the developmental cycles of honey bee colonies.
Movement	Spatial mobility attributes of species, measured (or modeled) over contiguous spatial and temporal units (e.g. natal dispersal distance, migration routes).
Community composition	EBV class that captures inter-specific variability in trait measurements across space and time. This includes four generic EBVs: Community abundance, Taxonomic/phylogenetic diversity, Trait diversity, Interaction diversity (Mason et al., 2005; Pugh and Field, 2022).

Community abundance	The number or biomass of all individuals (belonging to one or more species) in a given community, measured (or modeled) over contiguous spatial and temporal units.
Taxonomic/phylogenetic diversity	The diversity of species and/or phylogenetic distances of organisms in ecological assemblages, measured (or modeled) over contiguous spatial and temporal units. There are several metrics that can be used, such as species richness, different Hill numbers, phylogenetic diversity, etc.
Trait diversity	The diversity of traits of organisms (including those whose species identity is unknown) within ecological assemblages, measured (or modeled) over contiguous spatial and temporal units. Typically this requires a direct measurement of the whole community for each trait of interest, providing a distribution of the trait values in a community, often in a multidimensional trait space. This trait distribution is often summarized in a single metric (e.g. functional divergence or functional richness. Alternatively, independent measurements of abundance or presence of each of the organisms in a community and a trait matrix describing the trait values for each species can be used to reconstruct the trait distribution in trait space.
Interaction diversity	The diversity and structure of multi-trophic interactions between organisms within ecological assemblages, measured (or modeled) over contiguous spatial and temporal units. Measurements of interaction diversity could include those derive from ecological networks and food web analyses.
Ecosystem structure	EBV class that captures the spatial and temporal variability of ecosystem units and the organisms defining these units. This includes three generic EBVs: Live cover fraction, Ecosystem distribution, Ecosystem vertical profile.
Ecosystem distribution	The area or probability of occurrence of one or more discrete ecosystem types, measured (or modeled) over contiguous spatial and temporal units. In some cases, this could be just a binary variable (presence/absence) or correspond to the output of a probabilistic model for one or more ecosystem types.
Live cover fraction	The ratio of the horizontal projection area covered by living organisms, such as vegetation, macroalgae or live hard coral, measured (or modeled) over contiguous spatial and temporal units.
Ecosystem vertical profile	Vertical distribution of vegetation volume and biomass in an ecosystem of interest, measured (or modeled) over contiguous spatial and temporal units.
Ecosystem function	EBV class that captures the spatio-temporal variability of the collective performance of organisms that determines the functioning of an ecosystem. This includes three generic EBVs: Primary productivity, Ecosystem phenology, Ecosystem disturbance.
Primary productivity	Estimated rate at which energy is converted to organic matter by photosynthetic producers, measured (or modeled) over contiguous spatial and temporal units.
Ecosystem phenology	The timing of cyclic processes observed at the ecosystem level, such as the start or duration of vegetation activity or phytoplankton blooms, measured (or modeled) over continuous spatial and temporal units.
Ecosystem disturbance	The amount of deviance in the functioning of each ecosystem from its regular dynamics, measured (or modeled) over contiguous spatial and temporal units. Examples include fire, flood, soil erosion.

Table S2: Suggested criteria for developing concrete metrics for an EBV class

(Sources: SCBD, 2013)

Criteria	Definition / description
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, EBV indicators must characterize 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 inclusive	Ideally, an EBV should be applicable 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 criterion 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.

Table S3: EESV classes and their definitions

(Source: Balvanera et al., 2022)

EESV Class	Definition / description
Ecological supply	It refers to the ecosystem structure and functions that underlie the potential capacity of eco- systems to provide ecosystem services. It accounts for the potential or capacity of ecosystems and their functions.
Anthropogenic contribution	It refers to the efforts that humans invest to enhance ecological supply and to make use of ecosystem services. Anthropogenic contributions and ecological supply interact through the process of co-production through complex social-eco- logical processes, in which humans contribute knowledge, effort, time, financial resources, materials and technology to the flow of ecosystem services.
Demand	It refers to the explicitly or implicitly expressed human desire or need for an ecosystem service, in terms of its quantity or quality, irrespective of whether aware- ness exists about such need. Different stakeholder groups may differ in such demands.
Use	It refers to the active or passive appropriation of an ecosystem service by people. These are the 'realized' benefits that arise from passive or active management, also referred to as match or flow.
Instrumental value	It refers to the importance of an ecosystem service to societies or individuals to achieve a specific end (e.g. some dimension of human well-being). It denotes how the well-being of individuals or groups of people is enhanced by ecosystem services, both in economic and sociocultural terms.
Relational value	It refers to the importance ascribed to how ecosystems contribute to desirable and meaningful interactions between humans and nature and between humans in relation to nature. These encompass the core principles embedded into the relationships between people and nature, or among people within nature, such as care, responsibility and stewardship. Relational values are embedded in the practices, knowledge and visions that support ecosystem management.

Table S4: SEEA EA accounts and sub-accounts (condition typology classes), and their definitions

(Sources: Czúcz et al., 2021; United Nations, 2024)

Accounts (and sub-accounts)			Definition / description
Ecosystem Extent accounts			Ecosystem extent is the size of an ecosystem asset in terms of spatial area.
Ecosystem Condition accounts	**Abiotic Ecosystem Characteristics**	**Physical state characteristics**	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 characteristics	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 CO_2 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	**Compositional state characteristics**	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 characteristics	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 characteristics	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.
Ecosystem Service accounts	**Ecosystem Service flow accounts in biophysical terms**		Ecosystem services flow accounts in physical terms that record the supply and use of ecosystem services may be compiled for a range of reasons and purposes. These include recording and monitoring the different bundles of ecosystem services supplied by different ecosystem types, identifying the users of the services and assessing how these patterns of supply and use are changing over time. This information can underpin analysis of the significance of particular ecosystems as ecosystem service suppliers, support analysis of trade-offs between different ecosystem services as part of spatial planning and land management and provide information to support delineation of areas for specific land uses, including conservation and environmental protection.
	Ecosystem Service flow accounts in monetary terms		The ecosystem services flow account in monetary terms records the monetary value of flows of ecosystem services based on their exchange values. The data from this account can be used to understand the relative economic significance of different ecosystem services (within the valuation framing of the national accounts); support aggregation of ecosystem services for the purpose of comparing the role of different ecosystem assets; understand changes in monetary value over time; underpin comparison of the inputs of different ecosystem services to different users; and support understanding of the role of ecosystem services in different locations, for example, across countries. In addition, the use of exchange values in an accounting context requires drawing clear links between the supply of ecosystem services and the users of ecosystem services. Establishing these links can highlight both the economic costs arising from the loss of ecosystem services and the role of government as a provider of public goods.
Monetary ecosystem asset accounts			Asset accounts are designed to record information on stocks and changes in stocks (additions and reductions) of assets. The ecosystem monetary asset account records this information in monetary terms for ecosystem assets based on the monetary valuation of ecosystem services and application of the net present value approach to obtain values in monetary terms for those assets at the beginning and end of each accounting period.

Table S5: Suggested criteria for identifying/developing ecosystem condition variables

(Sources: Czúcz et al., 2021b; United Nations, 2024)

Criteria	**Short description**
Conceptual criteria	
Intrinsic relevance	Characteristics and metrics should reflect existing scientific understanding of ecosystem integrity, supported by the ecological literature
Instrumental relevance	Characteristics and metrics should be related to the availability of ecosystem services (characteristics that provide most information about the highest number of services should be favoured)
Directional meaning	Characteristics and metrics need to have a potential for a consensual normative interpretation (it should be clear if a change is favourable or unfavourable)
Sensitivity to human influence	Characteristics and metrics should be responsive to known socio-ecological leverage points (key pressures, management options)
Framework conformity	Characteristics and metrics should be differentiated from other components of the SEEA ecosystem accounting framework
Practical criteria	
Validity	Metrics need to represent the characteristics they address in a credible and unbiased way
Reliability	Metrics need to be accurate, reliable, and reproducible, with potential sources of error explored and documented
Availability	Metrics covering the studied spatial and temporal extents with the required resolution need to be achievable in terms of the resources and time available
Simplicity	Metrics should be as simple as possible
Compatibility	The same characteristics should be measured with the same (compatible) metrics in the different ecosystem types and/or different ecosystem accounting areas (countries)
Ensemble criteria	
Comprehensiveness	The final set of metrics, as a whole, should cover all of the relevant characteristics of the ecosystem
Parsimony	The final set of metrics should be free of redundant (correlated) variables

Figure S6: The role of Essential Variables in Multilateral Environmental Agreements and Assessments with a crosswalk of EBV/EESV frameworks to the SEEA EA framework. The possible role of UN SDGs, CBD, SEEA, IPBES, and GEO BON (left) with the main EBV and EESV classes in populating SEEA Ecosystem Accounts (right). The solid lines indicate direct correspondence and dotted lines partial or indirect correspondence.

(Source: Authors' own)

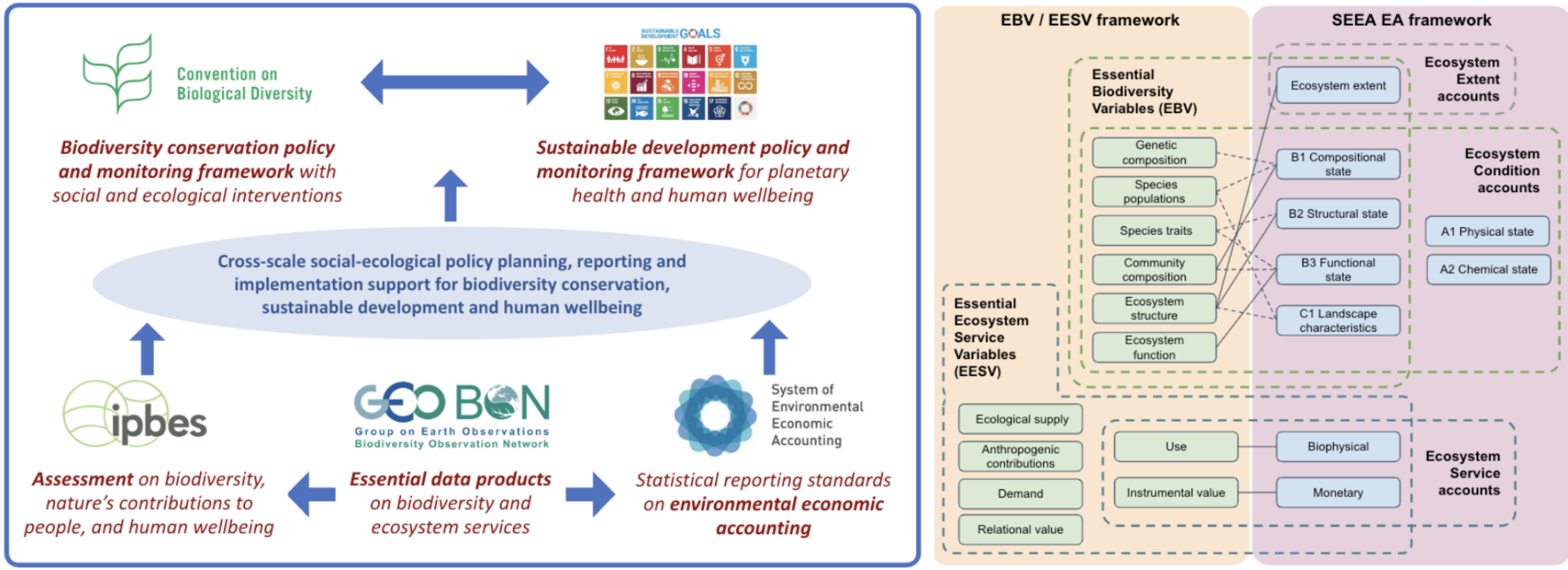
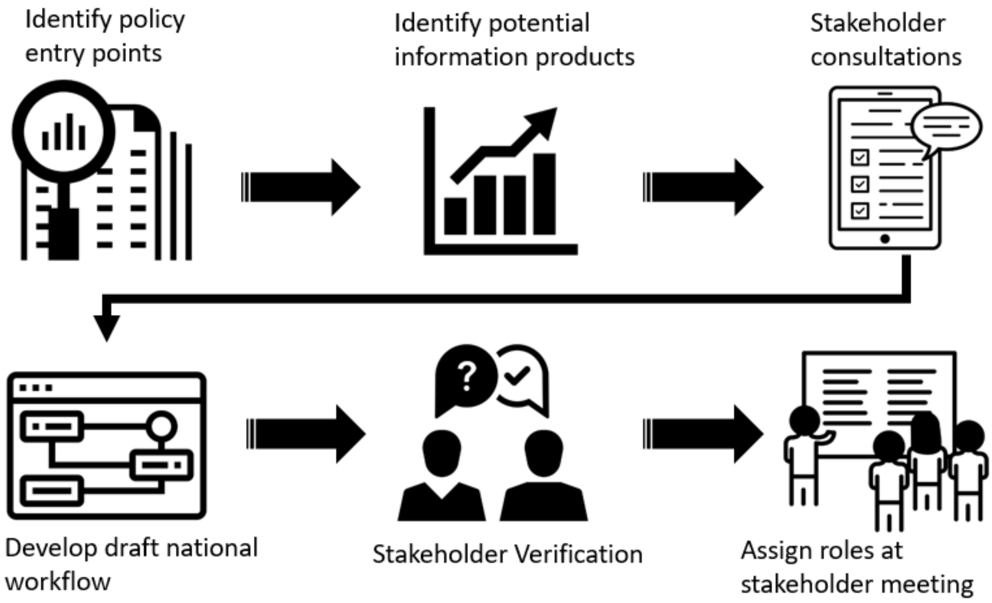


Figure S7: A process for producing user-driven workflows for priority indicators for conservation policy in South Africa.

(Source: Authors' own)



Supplement S8: Making EBVs and EESVs Findable, Accessible, Interoperable and Reusable

Essential Variables are core to biodiversity and ecosystem services monitoring, as well as to reporting on policy progress and effectiveness. The diversity of producers and users of EBVs and EESVs and their derived indicators thus calls for versatile and flexible data streams underpinned by minimum standards for the development, documentation, and reuse of data products. International data infrastructures such as GBIF and GenBank play a key role in supporting the standardization, integration and dissemination of biodiversity data —a role that should also be mirrored and amplified by national data infrastructures (Güntsch et al., 2025), including in the context of Essential Variables products. Below we detail key elements and approaches for the production of EV datasets that align with current best practices in data management and adhere to the FAIR data principles of findability, accessibility, interoperability and reusability (Wilkinson et al., 2016). While our focus here is on Essential Variables (EBVs and EESVs), these same principles should also apply to primary data and observations on biodiversity and ecosystem services, as well as to the indicators used to report on their status and trends.

Making Essential Variable products findable and accessible by facilitating the discovery and open-access to data:

The findability and accessibility of Essential Variables data products are fundamental to ensure their usability and buy-in by a diverse community of users. Data and their metadata should be findable by both humans and machines, and should be associated with permanent identifiers, such as Digital Objects Identifiers (DOIs), that link to catalogues and repositories where the data and metadata are indexed. The data products should then be accessible and directly retrievable via a standardized communication protocol (e.g. HTTP(S), FTP).

To the extent possible, data should be openly shared. Over the past decades, ecology has increasingly become a Big Data science, which has led to a growing culture of data sharing and synthesis (Farley et al., 2018). This transition has been further supported by the recognition that open access to biodiversity data is crucial in biodiversity research and for supporting effective decision-making in conservation (e.g., Onley et al., 2025). Nevertheless, the shift to full openness is still ongoing and uneven across disciplines, data types, and actors (Bagstad et al., 2025; Mandeville et al., 2021; Wetzel et al., 2018). Strengthening the findability, accessibility, and openness of EV data products requires both a continued cultural shift towards data sharing and active engagement from data producers across sectors, including government agencies, research institutes and academia, philanthropic organizations, and civil society.

Making Essential Variable products interoperable by adopting common standards and data structures:

The interoperability of Essential Variable (EV) products relies on the adoption of common standards that enable the integration of data collected or produced by different sources and methods (e.g., Guralnick et al., 2018; Hardisty et al., 2019). Interoperability also supports the traceability and scalability of those products, allowing EV products to be used in diverse workflows and contexts. For instance, the attributes and controlled vocabularies used in EBV data cubes (Table S8.1) were specifically designed to ensure consistent documentation and integration, building on the standardised metadata structure defined by the Network Common Data Form (NetCDF, Quoß et al., 2022)).

The interdisciplinary nature of ecosystem services models and data complexifies the definition of common attributes and typologies, and a community of practice needs to be developed to improve interoperability of ecosystem services data (Bagstad et al., 2025). Nevertheless, while there is to date no formal list of Essential Variables within the different classes of EESVs, most of these EBV attributes are directly applicable to EESVs datasets, that is, when documenting the class, scenario, domain and geospatial dimensions. The development and adoption of ontologies for ecosystem services, such as the ESM Ontology (Ecosystem Services Monitoring, Affinito et al., 2025) is a key challenge that is being tackled by the ES community.

To support findability, accessibility and interoperability in practice, GEO BON has developed the EBV data portal (https://portal.geobon.org/) as a global infrastructure for cataloguing and sharing EV products.

The portal enables data providers to publish spatial-temporal data cubes on species, ecosystems, and ecosystem services across multiple dimensions, realms and scale, as well as future projection scenarios (Table S8.1), in NetCDF format (Quoß, 2025), along with standardised metadata following the EBV data standards (Quoß et al., 2022).

Table S8.1 Attributes of EBV netCDF files that are specific to Essential Biodiversity Variable datasets (adapted from Balvanera et al., 2022; Quoß et al., 2022).

Level	Attribute	Comment
Root	ebv_class	EBV class of the dataset (e.g. Ecosystem Structure)
Root	ebv_name	EBV name of the dataset (e.g. ecosystem extent)
Root	ebv_scenario_	Attributes needed when scenarios are used in the production of the EBV dataset
Root	ebv_geospatial_	Geospatial attributes of the dataset (scope and description)
Root	ebv_domain	Environmental domain of the dataset, one or several of 'Terrestrial', 'Marine' or 'Freshwater'.
Root	ebv_cube_dimension	Fixed value: 'lon, lat, time, entity'
Entity	ebv_entity_	Describes the type and scope of the entity covered by the EBV dataset. Ebv_entity_type can be for instance 'Communities' with "forest birds" as the ebv_entity_scope. This can be complemented by the name and url used for the classification of the EBV entity.
Taxonomy_key	long_name	Taxonomic key corresponding to the species (or taxonomic entity) in the reference taxonomic backbone used. For instance, if the GBIF backbone is used for the taxonomy of the entities in the EBV dataset, the value would be "usageKey".

For taxonomic-level data matched with other metrics such as abundance, productivity, and other physiological and environmental data, nations and research groups should consider adoption and implementation of the Darwin Core data standard (De Pooter et al., 2017; Wieczorek et al., 2012). Such data may then be stored and distributed in NetCDF and other standard formats, and may be published for subsetting using tools like the Environmental Research Division's Data Access Program (ERDDAP). Boss et al. (2022) give recommendations on DarwinCore, NetCDF, and ERDDAP that should be implemented across ocean biodiversity and environmental monitoring networks. The recommendations are equally applicable to freshwater and terrestrial programs

Making Essential Variable products Reusable and Reproducible by documenting production workflows and enhancing access to tools:
The reusability of EV data products relies on the use of clear and machine-readable licenses (e.g., CC-BY 4.0). Another key aspect is the comprehensiveness and richness of the metadata (Wilkinson et al., 2016), including details on the models used, parameter settings, input data sources, quality control procedures, and product versioning. In addition, the availability of uncertainty layers and confidence estimates is crucial to support informed interpretation and appropriate reuse of data products (Kujala et al., 2023; Rocchini et al., 2011).

Equally important for enhancing transparency and reproducibility is the publication of the workflows themselves as standalone, FAIR-compliant products that describe the full production pipeline for the different EBVs and EESVs (Alex R. Hardisty et al., 2019). Generalised conceptual workflows have been proposed at the EBV class level to document changes in various dimensions of biodiversity, including species populations (Jetz et al., 2019; W. D. Kissling et al., 2018), species traits (W. Daniel Kissling et al., 2018), and genetic composition (Hoban et al., 2022). Moving forward, the reproducibility and reuse of EV data products will be further supported by the publication of workflows underpinning the production of specific datasets as standalone products (see Lumbierres et al., 2024 for examples covering priority EBVs identified for the European Union, and (Alex R Hardisty et al., 2019)for an example on the species distribution of invasive species).

Encouraging data producers to publish such workflows not only promotes broader adoption of standardized methods, but also enhances transparency, supports methodological improvements and knowledge exchange, facilitates alignment with regulatory reporting (e.g., for ecosystem accounting and goal/target tracking), and strengthens the integration and use of EBVs and EESVs data products across regional and national infrastructures (Kissling et al., 2024; Lumbierres et al., 2025).

Beyond EV, making the tools Findable, Accessible, Interoperable and Reusable:
Beyond the documentation of their use within workflows, the tools and algorithms used in the development of EBVs and EESVs should be documented and made publicly available. Git-based open platforms with version control such as GitHub, GitLab and BitBucket now allow any user to access, share and collaborate on the development of scripts and software (Farley et al., 2018). Computational notebook environments (e.g. Jupyter notebooks, Galaxy, RMarkdown) can further integrate these tools in documented workflows that can be executed directly by the users. The French national biodiversity data hub, for instance, is piloting the EBV operationalization via Galaxy (Le Bras et al., 2019; Royaux et al., 2022, https://geobon.org/bons/national-regional-bon/national-bon/french-bon/).

Developing open-cloud processing capabilities goes a long way in mainstreaming the use of data and models by users without limiting access to local and expensive computing infrastructures, whether it be for research or national reporting purposes. Cloud environments for biodiversity and ecosystem services data integration are advancing, including the ARIES (ARtificial Intelligence for Ecosystem Services; (Martínez-López et al., 2019) in support of the UN SEEA Ecosystem Accounting (https://seea.un.org/content/aries-for-seea), BON in Box developed by GEO BON that now allows direct computation of EBVs and derived indicators of biodiversity change (Griffith et al., 2024; https://boninabox.geobon.org/), and the Microsoft's Planetary Computer as part of its Artificial Intelligence (AI) for Earth effort. Research and Development projects funded by the AI for Earth include AI4EBV, which uses AI to derive accurate, high-resolution, time-series maps of mountain ecosystems incorporating the latest Earth observation data for a comprehensive assessment of ecosystem change and fragmentation (https://ai4ebv.eurac.edu/). The EBVs on the Cloud AI for the National Belize Marine Habitat Map (https://www.coastalzonebelize.org/portfolio/ai-for-belize-marine-habitat-map/) is another example. To fully realize the growing potential of these open-cloud processing initiatives for EV development, stronger interactions and collaboration across the communities behind them will be crucial.

Whenever possible, scaling up capacity building efforts (e.g., training through webinars) will be instrumental for the adoption and use of the available tools, open workflows, and cloud-computing infrastructures by a wider community and ranges of users, in particular by the implementing agencies at the regional, national and subnational levels (Han et al., 2014; Valdez et al., 2023). Notably, this medium can further foster dialogue, co-design and operationalization of novel and tailored tools as exemplified by the BioModelos platform for species distribution models in Colombia (https://biomodelos.humboldt.org.co/en, Velásquez-Tibatá et al., 2019).

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