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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 at local and national scales in international multilateral environmental agreements (MEAs). This greatly challenges coordinated actions to meet agreed-upon global commitments. Filling this gap requires integrated and concerted design of data-to-decision workflows. The Essential Biodiversity Variables (EBVs) and Essential Ecosystem Service Variables (EESVs) are tools that can coordinate structured and consistent monitoring, generate harmonized and scalable data products, and facilitate reporting that is useful for multiple purposes. Specifically, EBV/EESV data products are intended to synthesize information to serve the needs of the Global Biodiversity Framework (GBF), the System of Environmental-Economic Accounts Ecosystem Accounting (SEEA-EA), and assessments of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) while also informing regional, national, and sub-national conservation policy. This integrative approach works if local data collection is designed to be interoperable, and it is fundamental to improve models, forecasts, and indicators required in key policy and decision processes. Through application cases, we demonstrate the use of EBVs and EESVs in national assessments and scenario analyses for strategic policy and spatial planning with scalable and repeatable workflows from primary data to indicators for decision support.

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) organizations. 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 toward 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 four 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 UN (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), channeling key environmental and socio-economic information into existing reporting processes. 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, standardized 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*. The SEEA EA is flexible and can be used by Indigenous Peoples and local communities (IPLC) to contribute to reporting to national and MEA progress, if so desired (e.g., Larson et al. 2025; Normyle et al. 2024, Normyle et al. 2022).

Unlike the monitoring framework of the KM-GBF, which specifies concrete reporting indicators linked to 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. The SEEA EA thus provides a pathway for 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). 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 organizational 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, Vihervaara, et al. 2023). 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 standardized structure and coordination across the countries. This needs a priori planning and coordination using some reasonable international framework to implement interoperability at the level of monitoring activities to ensure data flow across scales and applications (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 focuses and needs, their common interest is in forecasting and reporting on financial risks stemming from biodiversity loss and ecosystem degradation. This requires an improved understanding and use of biological, environmental, and socio-economic data, models, and indicators for rigorous and accurate assessments of the risks, as well as appropriate 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 Earth systems 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 (ECVs) to improve the coordination of observations and modeling (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 (NCP; Balvanera et al. 2022; Díaz et al. 2018). In

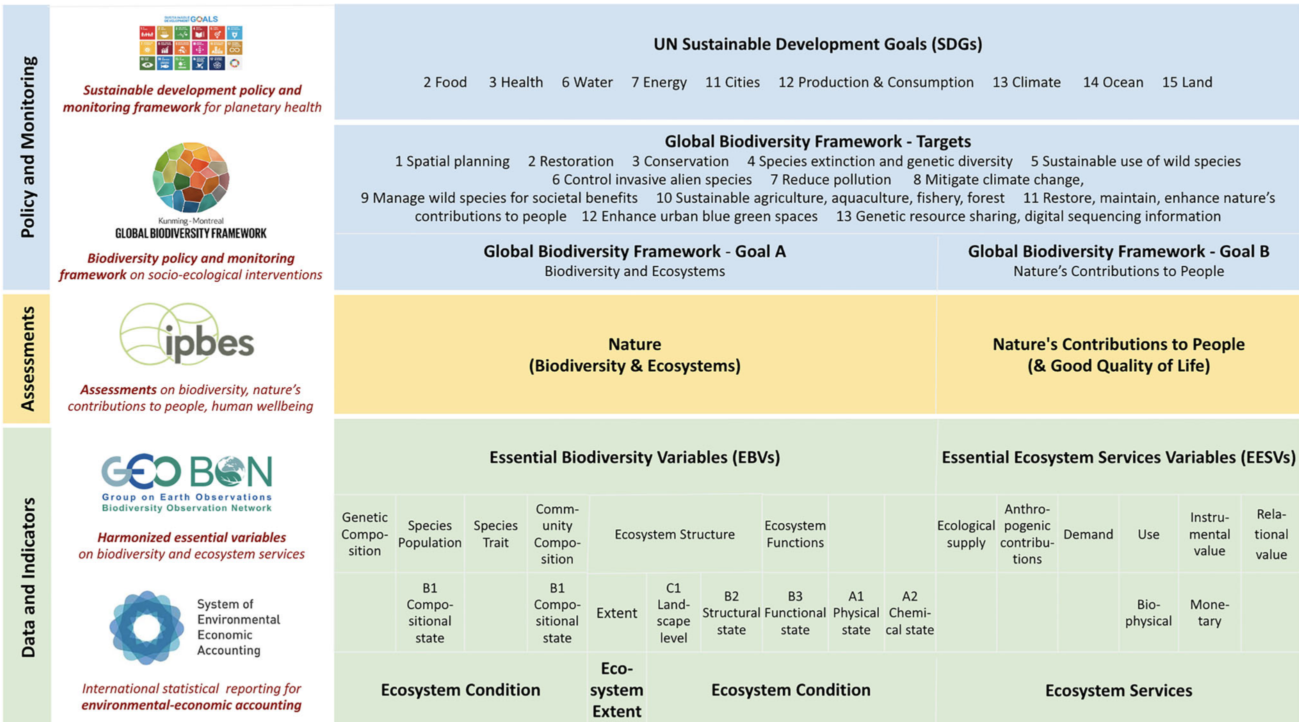

FIGURE 1 | The role of essential variables in informing MEAs with a crosswalk between EBV/EESV and SEEA EA frameworks. The basic observations (data) are collected locally to monitor local changes; when these observations are collected following standards to enable interoperability, they can be aggregated 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.

parallel, the ocean observing community defined Essential Ocean Variables (EOVs) curated by the Global Ocean Observing System (GOOS) of the Intergovernmental Oceanographic Commission (IOC-UNESCO; see Lindstrom et al. 2012; Martín Míguez et al. 2026; Miloslavich et al. 2018; Muller-Karger et al. 2018; von Schuckmann et al. 2026). The interlacing of Essential Variables (e.g., temperature ECV, nutrient and biology EOV, ecosystem distribution EBV) represents the inherent complexity of biological systems. EBVs (and EOVs as building blocks of EBVs) and EESVs are an intermediate layer of standardized and synthesized data products between primary observations and indicators of state and trends and are instrumental in coordinating ecological monitoring and data infrastructures and harmonizing indicator development (Geijzendorffer et al. 2016; Gonzalez, Vihervaara, et al. 2023).

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 harmonized data flows that are useful across monitoring frameworks. In particular, we focus on the KM-GBF and SEEA EA given their relevance to global science-policy interfaces such as the CBD and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES; Figure 1). The KM-GBF seeks the rigor and transparency in the strategic planning and reporting of evidence in biodiversity conservation initiatives across state and non-state actors. The SEEA EA aims to implement an internationally standardized framework that integrates ecosystem-based data (or natural capital) into the monitoring of economic activities in local and national accounting systems. We crosswalk EBV and EESV classes and subclasses to the SEEA EA reporting framework and EBV/EESV-based indicators to the KM-GBF monitoring framework and examine how essential variables can improve data flows across scales for synergistic implementation through interoperability. The implementation and use of EBVs/EESVs in national MEA and SEEA EA reportings and spatial planning are illustrated with use cases.

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 Supporting Information Table S1 for the 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 "organized" 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 et al. 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). For the marine environment, EOVs are organized with observation guidelines by GOOS (Muller-Karger et al. 2018; Martín Míguez et al. 2026), which in some cases represent building blocks for EBVs. 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, Ahumada, et al. 2018), *species traits* (Kissling, Walls, et al. 2018), 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. 2026).

Six EESV *classes* correspond to the main stages in the flow of ecosystem services from nature toward human society that are relevant for assessing and monitoring these flows across space and time (Balvanera et al. 2022; see Supporting Information Table S3 for the definition of classes). Two of these classes characterize 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 realized (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 do not require traditional economic "demand and supply curves" for their derivation. 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). The EESV *classes* are also closely aligned with the *levels* of the "*ecosystem service cascade*" model (Haines-Young and Potschin 2010; Heink and Jax 2019; Zhang et al. 2022).

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 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. 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 a similar pattern is described for "cascade" levels). 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). These concepts apply across terrestrial, soil, fresh water, marine, and aerial habitats and communities.

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). Further, *People's Contributions to Nature* (and "*Anthropogenic Asset" in IPBES framework*) can also be classified, measured and assessed through the *anthropogenic contribution* EESV. The EBV framework was used in the assessment on the state of nature in the Global Assessment

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 et al. 2025).

EBV/EESV classes and subclasses	Relevant data cube dimensions[a]					Other relevant dimensions	Example attributes or metrics
	Spatial	Temporal	Thematic (entity)				
			Species	Community, ecosystems	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 interactions

(Continues)

TABLE 1 | (Continued)

EBV/EESV classes and subclasses	Relevant data cube dimensions[a]					Other relevant dimensions	Example attributes or metrics
	Spatial	Temporal	Thematic (entity)				
			Species	Community, ecosystems	Ecosystem service types		
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							
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

Note: X: directly required data dimension, (x): auxiliary or indirectly required data dimensions (e.g., 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 characterize changes in morphology within space and time, i.e., Morphology = f[taxonomy, trait, location, time]). For the marine environment, the collection of basic observations is guided by the EOV framework, and these observations are used to derive or model the relevant EBV.

[a]There are two additional dimensions in the EBV/EESV data cube that are relevant across all EBV/EESV classes and subclasses (Quoß et al. 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 toward them.

of IPBES (IPBES 2019; Purvis et al. 2019). Balvanera et al. (2022) also identified indicators that are 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 modeling 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).

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 regional 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 (Martín Míguez et al. 2026; Proença et al. 2017; von Schuckmann et al. 2026; Zilioli et al. 2021).

The development of EBV data products often requires additional computations (*modeling*) to optimize the use of heterogeneous sources of data (Kissling et al. 2026; Lumbierres et al. 2024). EESVs on the other hand are often difficult to observe directly, so they also typically require some *modeling* 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 socio-economic 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). In this context, 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) *modeling* (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, for example, (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. 2019, 2022). 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 the local to the 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; von Schuckmann et al. 2026). 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 Supporting Information S8).

The development of global EBV and EESV variables requires harmonized data collection and processing (i.e., monitoring and data workflows). In particular, the biological and socio-ecological

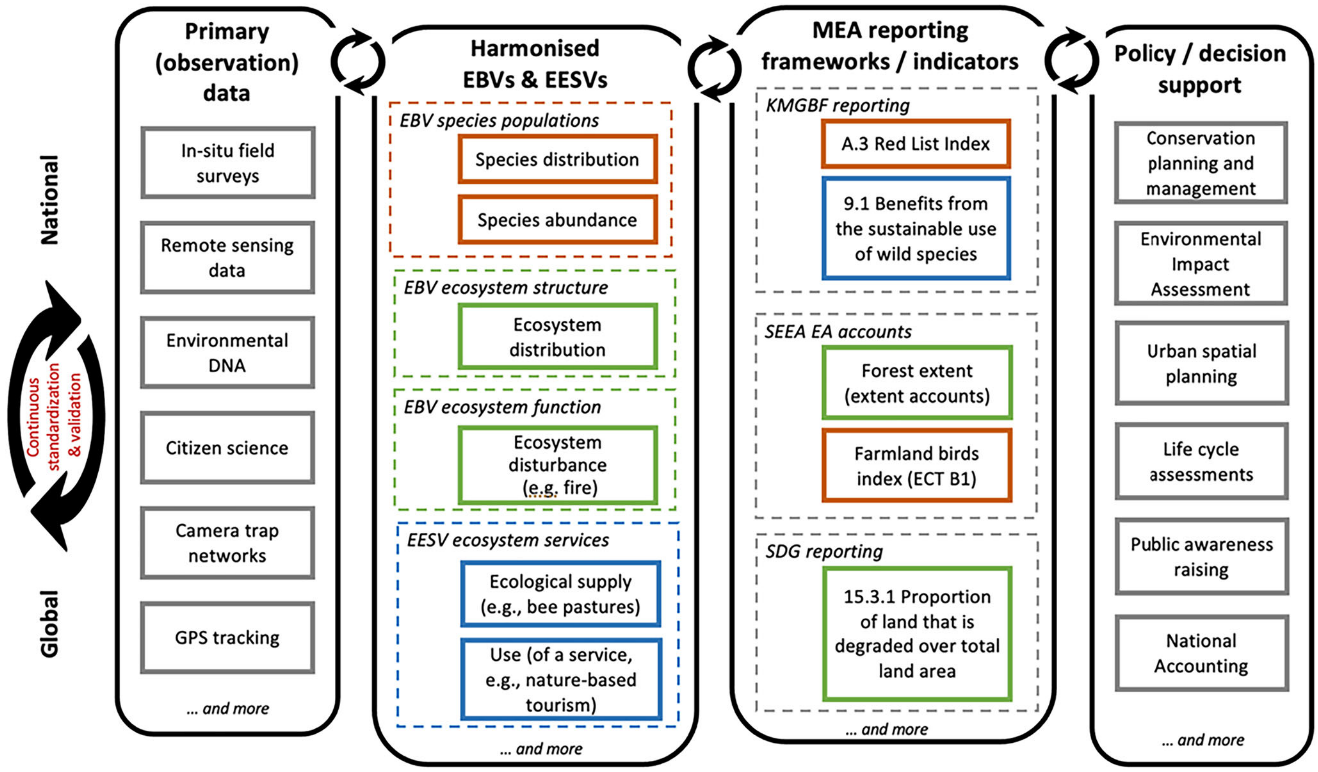

FIGURE 2 | An illustrative generic workflow from primary data to decision support with examples of EBVs and EESVs. Colors are used to identify information flows from data to decision support at the level of species (orange), ecosystems (green), and ecosystem services (blue). A wide range of primary observation data can be used to derive EBVs and EESVs, which can be used independently or together to derive reporting indicators that 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.)

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 rigor 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

Similar to EBV and EESV frameworks, SEEA EA accounts were primarily created to support and standardize 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 Supporting Information 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, Supporting Information 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 be used to calculate simple data products that meet the criteria of SEEA EA ecosystem condition accounts (Czúcz, Keith, Maes, et al. 2021), 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 deriving species and ecosystems EV data products or represented through the related ECVs and EOVs 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.

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. 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

TABLE 2 | A crosswalk of EBV and EESV classes and subclasses to the major structural elements of SEEA Ecosystem Accounts.

EBV/EESV classes and subclasses	SEEA EA Ecosystem Extent Accounts	SEEA EA Ecosystem Condition Accounts: A. Abiotic ecosystem characteristics[a]		SEEA EA Ecosystem Condition Accounts: B. Biotic ecosystem characteristics			SEEA EA Ecosystem Condition Accounts: C. Landscape level[a]	SEEA EA Ecosystem Services Accounts	
		A1 Physical state[a]	A2 Chemical state[a]	B1 Compositional state	B2 Structural state	B3 Functional state	C1 Landscape/seascape[a]	Biophysical flow	Monetary flow
Essential Biodiversity Variables									
Genetic Composition[b]									
Intraspecific genetic diversity[b]				(x)					
Genetic differentiation[b]				(x)					
Inbreeding[b]				(x)					
Effective population size[b]				(x)					
Species Populations									
Species distribution				X			(x)		
Population abundance				X					
Species Traits[b]									
Morphology[b]					(x)				
Physiology[b]						(x)			
Phenology[c]						(x)			
Movement[b]							(x)		
Community Composition									
Community abundance				X					
Taxonomic/phylogen. diversity				X					
Trait diversity				X		(x)			
Interaction diversity[b]						(x)			
Ecosystem Structure									
Ecosystem distribution	X						(x)		
Live cover fraction					X				
Vertical profile					X				

(Continues)

TABLE 2 | (Continued)

EBV/EESV classes and subclasses	SEEA EA Ecosystem Extent Accounts	SEEA EA Ecosystem Condition Accounts						SEEA EA Ecosystem Services Accounts	
		A. Abiotic ecosystem characteristics[a]		B. Biotic ecosystem characteristics			C. Landscape level[a]		
		A1 Physical state[a]	A2 Chemical state[a]	B1 Compo-sitional state	B2 Structural state	B3 Functional state	C1 Landscape/seascape[a]	Biophysical flow	Monetary flow
Ecosystem Functions									
Primary productivity						X			
Ecosystem phenology [c]						X			
Ecosystem disturbances						X			
Essential Ecosystem Service Variables									
Ecosystem Services									
Ecological supply[d]									
Anthropogenic contribution[d]									
Demand[d]									
Use								X	
Instrumental value									X
Relational value[e]									

Note: X: Clear direct correspondence, (x): possible partial or indirect correspondence (see also Supporting Information Figure S6 for a graphical presentation).

[a]*Abiotic* and *landscape-level* ECTs are not covered explicitly in EBV classes (in line with its *biotic* focus), but abiotic conditions are implicitly covered through the ECVs (e.g., temperature) and EOVs (e.g., nutrients) inform EBVs. Some EBVs (e.g., ecosystem distribution) can also be used to calculate landscape-level ECTs.

[b]EBVs that primarily describe species (genetic composition and species traits) and species interactions can only indirectly be linked to ECTs (cf., Czúcz, Keith, Maes, et al. 2021).

[c]Species *phenology* is not considered in SEEA EA condition accounts (lack of clear directionality, cf., Czúcz, Keith, Driver, et al. 2021), but as it could have an impact on the functional state of ecosystems with seasonal changes, for example, under climate change, phenology information can be of potential relevance to SEEA EA condition accounts.

[d]*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).

[e]SEEA EA monetary ecosystem service accounts exclusively cover *use* and *instrumental values* assessed as exchange values.

spectrum of potential values (including, e.g., "relational values"), as well as several additional classes underlying the delicate distinction within "supply" (e.g., *anthropogenic contributions, ecological supply*) and "demand" (e.g., *ecosystem service potential, benefit appropriated by population)*. This limitation of SEEA EA has already been addressed in the literature using "extended SEEA EA frameworks" (e.g., De Valck et al. 2023), and therefore additional classes of EESVs can also contribute to the development of extended ecosystem service accounts in SEEA EA. In addition, SEEA EA aggregates the monetary values of different ecosystem service flows in the *monetary ecosystem asset value account*. This highly aggregated account, integrating the "net present value" of the expected future flows of different ecosystem service types, does not have any counterpart in the EBV/EESV frameworks.

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 realized ecosystem services (i.e., the amount of the service actively or passively *appropriated* by people. This 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). *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). This helps with compatibility with economic accounting processes. Therefore, as SEEA EA and EESV frameworks are developed with different main purposes and users, 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 are, 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 "standard" 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). Such *species accounts* are tightly related to *species distribution*/*species abundance* EBVs, and other EBVs that can be structured as regularly updated changes in stocks, which can potentially be presented as *biodiversity accounts* in an 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, Keith, Driver, et al. 2021). SEEA EA's systematic approach toward selecting the most relevant (i.e., "essential") condition variables can 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. 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. 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. A suite of KM-GBF indicators can be constructed by aggregation directly from the Essential Variables. 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 Index," 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 (BHI)" 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 KM-GBF Goal B on NCP, Goal C on benefits from utilization of digital sequence information and more broadly of genetic resources and of traditional knowledge associated with genetic resources, and Goal D on means of implementation of the KM-GBF, the EESV classes *supply*, *demand*, *use*, and *value* can be used to derive indicators on benefits people receive from specific ecosystem services. Examples are 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 NCP are being restored, maintained, and enhanced (Target 11). The Biodiversity Beyond National Jurisdiction (BBNJ) Agreement (i.e., the High Seas Treaty) will provide important application cases for KM-GBF Target 13 relevant to GBF Goal C.

As described earlier, EBVs also inform the development of EESVs as biodiversity or ecosystem underpinning the con-

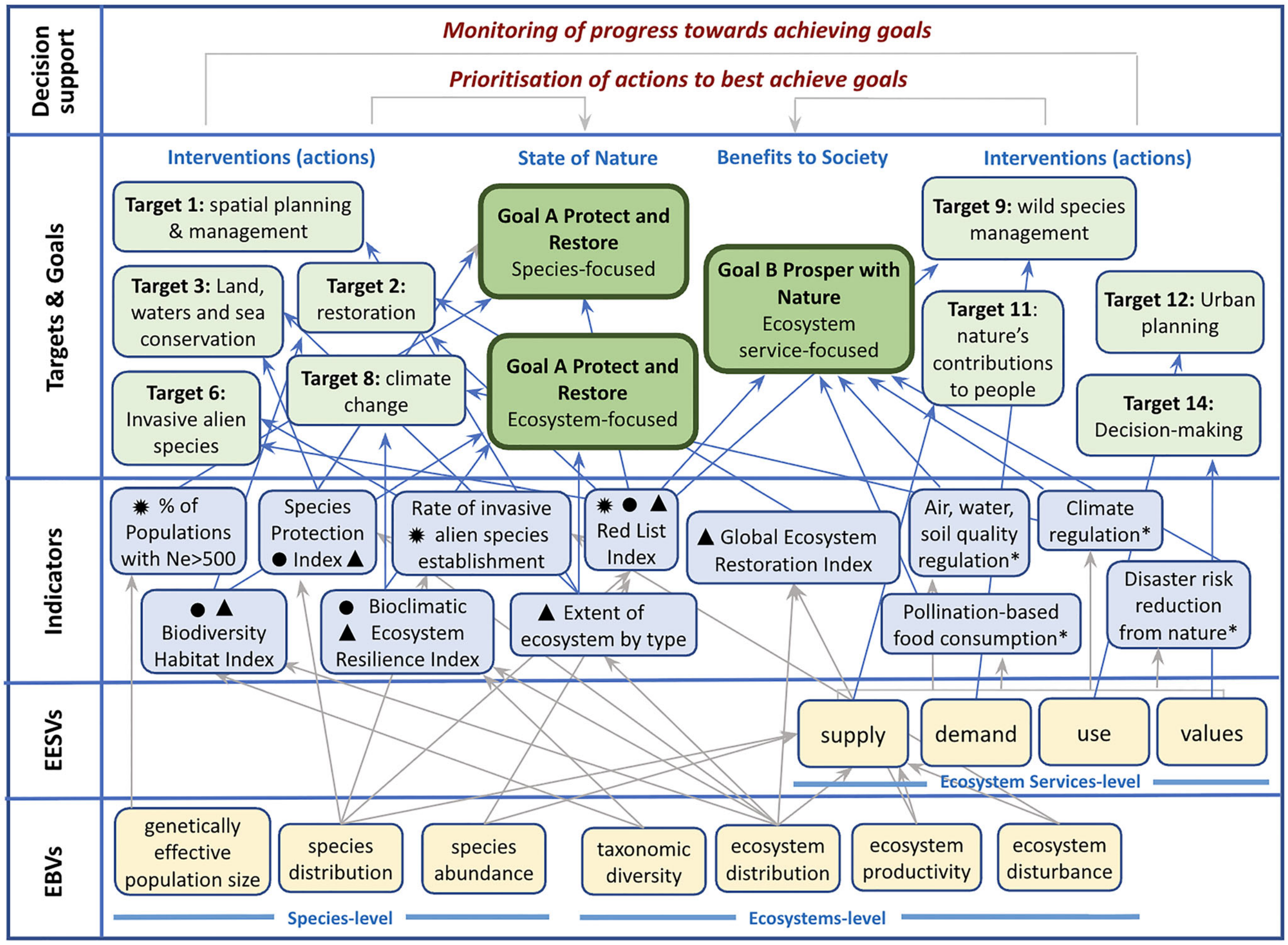

FIGURE 3 | Linkages and interdependencies from EBVs and EESVs to derived indicators that inform different components of targets and goals of the KM-GBF in prioritizing actions and monitoring progress toward achieving goals. *Note:* This figure shows a selection of essential variables, indicators, targets, and goals and is not meant to be exhaustive. Legend: ✷ headline indicator; ● component indicator; ▲complementary indicator. Note that some indicators can be of different categories depending on the goal and target. (*) The headline indicator identified for Goal B is "services provided by ecosystems," and specific indicators are being discussed. For illustrative purpose, we thus provide examples independent of the monitoring framework of the KM-GBF.

nectivity, 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.

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. This takes place 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 operationalization of EBV/EESV development by diverse stakeholders (Gonzalez et al. 2025; Guerra et al. 2019; Moersberger et al. 2024; Valdez et al. 2023). The global harmonization proposed by the EV communities of practices (e.g., GEO BON, WMO, GOOS) strongly promotes the findability, accessibility, interoperability, and reuse (FAIR principle) of EV data products and data-to-indicator workflows with metadata in a common data format (Martín Míguez et al. 2026; Bagstad et al. 2025; Lumbierres et al. 2025; Onley et al. 2025; Quoß et al. 2025; see Supporting Information 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, and hence they are diverse in context, often implemented as pilot initiatives. To enhance use in management and monitoring, and the evaluation of policy options, EBVs/EESVs should ideally be implemented through participatory processes that bridge research, government, and practitioner communities and include diverse knowledge systems, in response to local and national

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

Section	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 monitoring data and maps + SDM and habitat models	South Africa, Ghana, Uganda, Republic of Korea, France, Arctic, Tropical Andes, Europe
4.2	Prioritizing 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	Return of investment, co-benefit and trade-off analyses (water funds)	EESV-based optimization	SDGs, KM-GBF	RIOS + InVEST models	Colombia, Kenya

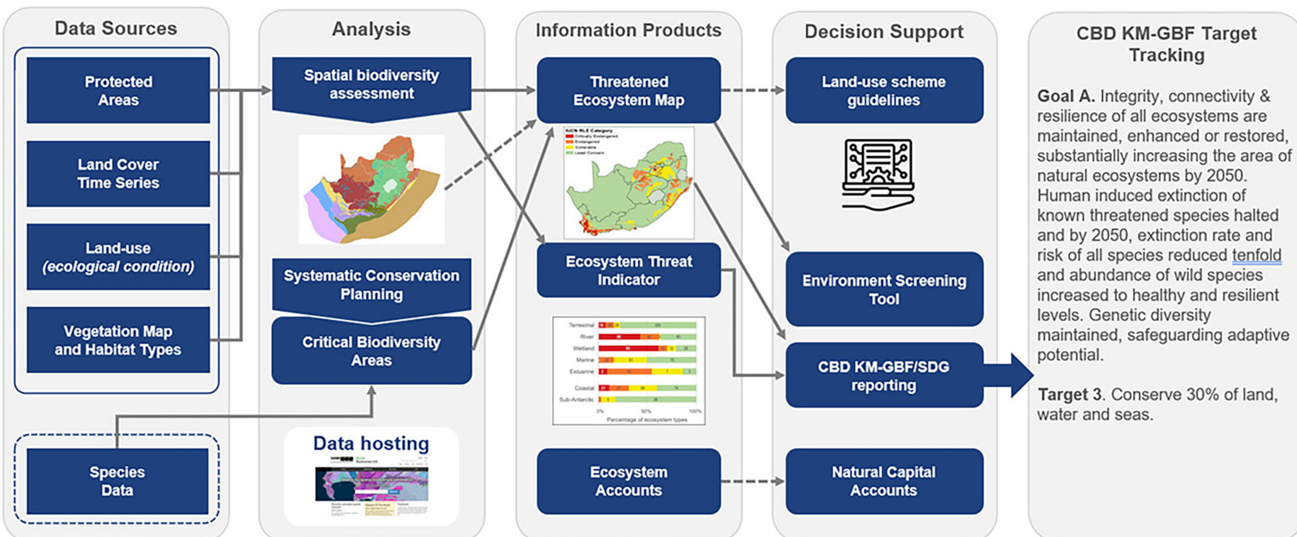

FIGURE 4 | A repeatable workflow process for the integration of core datasets for the repeatable production of national spatial biodiversity assessments that serve multiple policy outputs. *Note:* Solid lines depict direct outputs from the Spatial Biodiversity Assessment, whereas dotted lines indicate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

conservation and development needs and key social-ecological questions as they arise.

4.1 | Identifying EBVs in Data to Decision Workflows With Stakeholders

As part of a 5-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 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 and UNEP-WCMC 2016).

In South Africa, the workflow to produce and revise national *ecosystem distribution* EBVs for spatial planning and prioritization led to the production of national *ecosystem extent accounts* using the SEEA EA reporting framework by simply reanalyzing 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 nine-step 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 Supporting Information 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. 2019, 2020).

Co-designing and building a coordinated global observing system (e.g., the Global Biodiversity Observing System, GBiOS, described in Gonzalez, Vihervaara, et al. 2023) requires cooperation from the funders, producers, and users of data. It requires the coordination of monitoring across scales, which can be achieved by the development of 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. This helps to mobilize a network and coordinate the development of EBV data products and indicators among government agencies, the private sector, research communities, and citizen scientists (Gonzalez et al. 2025; Guerra et al. 2019; Moersberger et al. 2024; Navarro et al. 2017). Capacity building and support are 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. 2026). 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. 2026). In France, the French Biodiversity Data Hub (FrenchBON) developed 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 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. There are also thematic BONs, which help convergence around particular methods and applications, such as the Marine BON (MBON), the Freshwater BON (FWBON), Animal Movement BON (MOVE BON), Soil BON, the Omic BON, and the Asia-Pacific BON (AP BON).

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, for example, 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 prioritization of actions (Leadley et al. 2022).

Habitat-based biodiversity indicators (Ferrier 2011; King et al. 2021) can contribute to addressing this problem. These indicators help monitor change in status, or evaluate future scenarios, of 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 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 toward 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 prioritizing 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 harmonize 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 modeling with best available local mapping of ecosystem structure and integrity (Grantham et al. 2016). In another typical example, highly refined modeling 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 the Republic of 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 country, using EBVs derived from best available national data. Exchanging scientific knowledge and promoting global data standards between the countries will improve the capacity, interoperability, and accuracy of monitoring and modeling systems across the globe through iterative, cross-scale, and cross-regional collaboration (Figure 2; Gonzalez et al. 2025; Griffith et al. 2026; Moersberger et al. 2024).

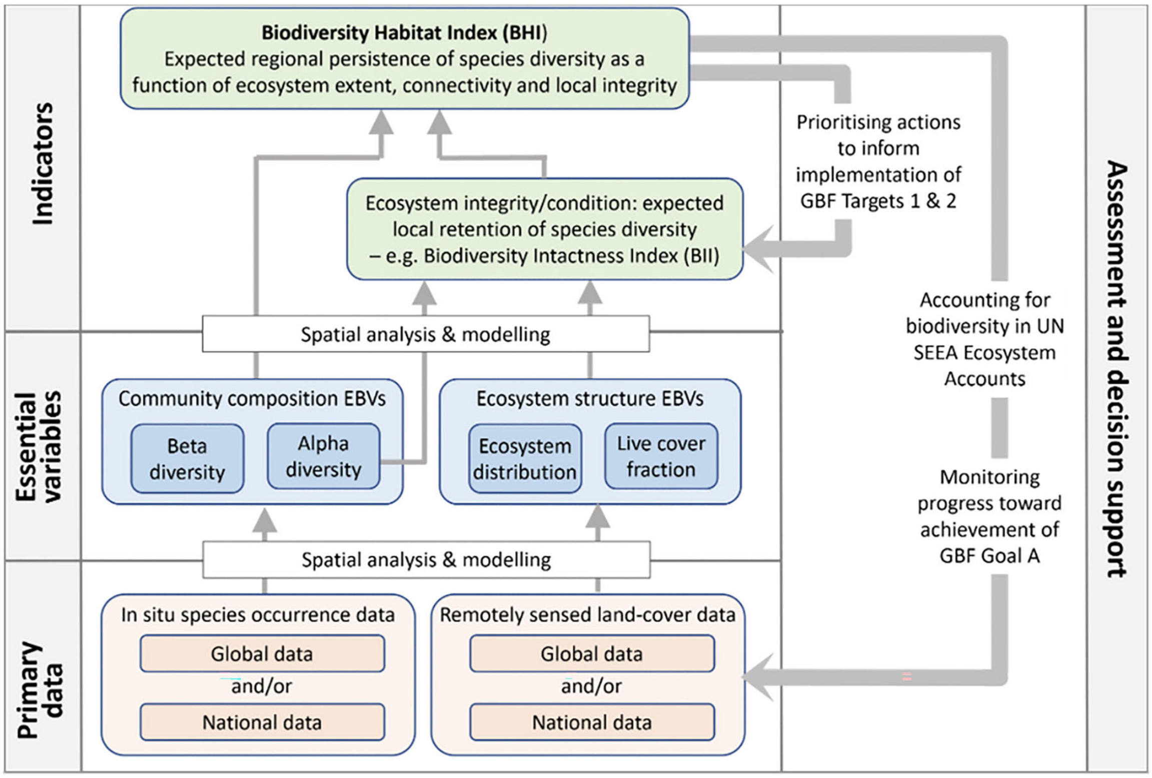

FIGURE 5 | Biodiversity Habitat Index (BHI) data to indicators workflow for assessment and decision support.

4.3 | Use of EESVs in Scenario Analyses to Support Resource Planning

Throughout the world, many components of the 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 the KM-GBF; ecosystem integrity and species diversity can be difficult to maintain while still supporting the food and water security elevated as goals for NCP. 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. 2023a, 2023b; Kim et al. 2023). These inter-relationships between goals are an area of research and practice.

Water funds are one policy solution to resource conflict. They provide a financial mechanism for watershed management that promotes habitat conservation, restoration, and improved agricultural practices to protect water resources for downstream users (Arias 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, Goldstein, et al. 2017) 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).

With 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 modeling 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).

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

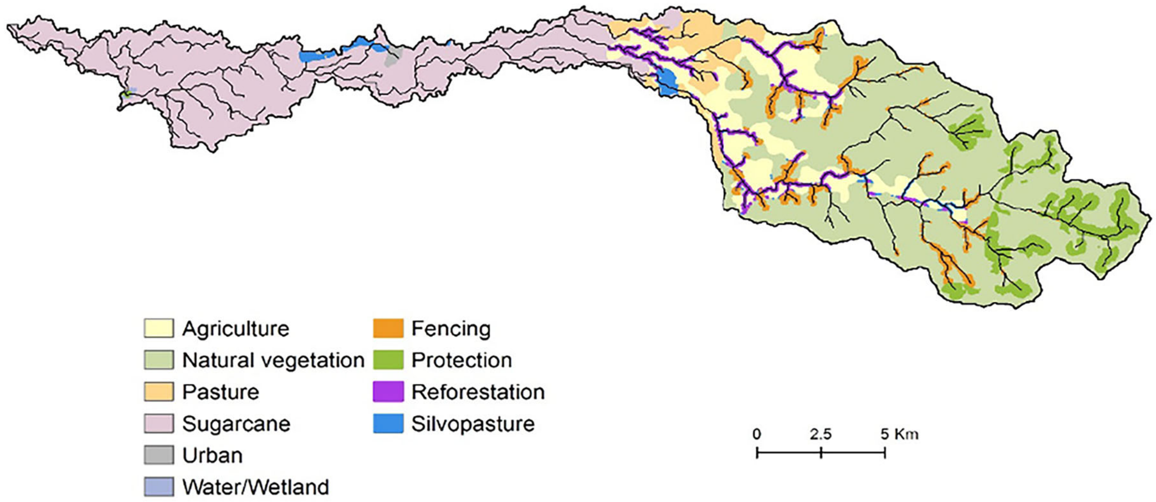

FIGURE 6 | Example of an investment portfolio resulting from RIOS prioritization in the Cauca Valley of Colombia, with prioritized activities (fencing, protection, reforestation, silvopasture) in brighter colors set against the muted colors of current land use within a watershed.

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, Bryant, et al. 2017). 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, Chase, and O'Connor 2023). The implementation of MEAs and the monitoring of progress toward their objectives are also hindered by persistent gaps in the availability and interoperability of relevant data streams. Recent advances in Earth observation and modeling 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, standardized, repeatable, and transparent at the global scale (Gonzalez, Vihervaara, et al. 2023). The reusability of EBV and EESV data products in monitoring progress of 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 | Prioritization of EBV/EESV Development

Fully understanding and characterizing the complexity of ecological systems, for example, 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. 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 derived indicators (Geijzendorffer et al. 2016) that can 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. 2020, 2022). Such variable selection should ideally involve all relevant sectors holding expertise about studied ecosystems in an inclusive process (Czúcz, Keith, Maes, et al. 2021). 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 become available from different countries and regions, it might be possible to generalize patterns and identify transferable shortlists of the “most essential” EBV variables, which can then offer a highly resource-efficient way of designing and optimizing 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 responds well to 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., preventing ecological collapse to mitigate further risks to society and the economy; Defra 2026; NGFS 2024; Pereira et al. 2024). Optimizing biodiversity and ecosystem services 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 et al. 2019; ecosystem services in Schwantes et al. 2024; supranational 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, and monitoring can be coordinated so that data and metadata can be aggregated to understand local changes in a regional and global context (Muller-Karger, Hwai et al. 2024). Unfortunately, ongoing biodiversity monitoring programs are inconsistently and unevenly aligned with EBVs and EESVs, as well as 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, modeling, 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).

Standardized 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 et al. 2025) heavily used in weather and climate modeling, as well as more recent cloud optimized 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 is substantial as demonstrated by the wide adoption of the Climate Forecast Convention for NetCDFs, as an example. As a minimum, each data record should be accompanied by date and location (including altitude or depth) and coded in a format described within the data, consistent with widely used standard units (see Supporting Information 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. Some of these challenges might be resolved in a federated data system, where national and regional agencies can retain control over their data, while leveraging harmonized definitions, metadata formats, data licensing, and user agreements (TFND 2025). Recent metadata systems, such as the I-ADOPT framework (Magagna et al. 2022; Serral et al. 2025) and the ESM ontology (Affinito et al. 2025), provide highly granular yet flexible approaches to harmonizing the semantics of observation, monitoring, and data sharing protocols, improving interoperability of the EBV/EESV frameworks. Merely by standardized structure, definitions, terminology, metadata formats, and accessible repository platforms, EBVs/EESVs can already offer a (partial) solution for the elementary harmonization 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 standardized indicator workflows is hindered by the lack of adequately standardized 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 standardized data products can help overcome these limitations, enabling the production of harmonized and scalable datasets (see Supporting Information S8 on how to make the workflows FAIR).

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 supranational (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 underpin sustained indicator production while allowing interoperability with the global standards. Several technical and logistical challenges can 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 harmonized indicators across a broad range of national and international policy contexts, including the KM-GBF and SEEA EA, as presented in this paper. There are many policies that can benefit from the transparent use of EBVs and EESVs, including the reporting frameworks of MEAs that focus on 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).

Further, Essential Variable frameworks can make national data products available for spatio-temporal analysis globally (Jetz et al. 2019; Chavez et al. 2021). Advancing models for EBVs and EESVs can also improve the causal inference, and detection and attribution capabilities, making scenario-based simulations feasible and more reliable in supporting policy processes (IPBES 2019, 2016). 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 modeling in order to represent the full value of land- and resource use decisions (Chaplin-Kramer et al. 2024). While there has been considerable progress in the development of integrated socio-ecological models during the last decades, several aspects of existing models (e.g., validity of assumptions, propagation of uncertainties) need to be transparently documented and evaluated in the data-to-decision workflow context (Kim et al. 2025). Scenario-based information generated from models will have the potential to support multi-scale policy processes with scale- and ecosystem-specific knowledge- and data-based evidence in identifying conservation actions that are relevant for the country while setting national milestones in the CBD NBSAPs and tracking progress in the CBD NRs for global aggregation.

6 | Conclusion

The EBV and EESV frameworks, by providing a consistent set of metrics to be measured and modeled across space and time, address 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 currently limit the global harmonization of monitoring efforts. Nevertheless, scientific, policy, and civil society communities will continue to evaluate the needs of monitoring and planning in biodiversity conservation as expressed in nationally, regionally, and internationally agreed goals and focus the development of knowledge products such as essential variables on critical species, ecosystems, and ecosystem services with stakeholders that are stewarding the planet Earth. EBVs and EESVs, as the backbone of a standardized ecological monitoring, have an essential role in informing global policy monitoring frameworks such as KM-GBF and SDG indicators, SEEA EA accounts, and IPBES assessments. The interoperability between essential variables and the 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 the collaboration with biodiversity science and ecological economics communities will make key contributions to mitigating nature-related risks through collective and concerted efforts. As the global community joins arms and accelerates ambitions to achieve nature- and people-positive futures, renewing our commitment to monitoring critical ecological changes across scales will be essential in enabling and guiding effective biodiversity conservation, remaining within planetary boundaries and safeguarding human security.

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Data Availability Statement

The author has provided the required Data Availability Statement, and if applicable, included functional and accurate links to said data therein.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplementary Materials