Operationalising EESVs

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GEO BON Working Group on Ecosystem Services, January 2025

Background

Understanding global change is a significant challenge that requires observations recorded at multiple scales and using a diverse range of approaches. These observations produce primary data (e.g. remotely sensed images, underwater recordings, thermometer readings, …) that form the basis of our understanding of the world. To understand change however, this data must be analysed and transformed to produce indicators that can inform on trends and the impact of management actions. These indicators are required and needed in the context of international agreements and national commitments on climate and biodiversity. However, producing local, regional or global indicators from primary data is not a straightforward task. Understanding large-scale environmental change requires complex indicators that are typically composite variables including data from multiple sources (e.g. the Living Planet Index). Organising the data needed to produce indicators can be streamlined and simplified using an intermediate step between observations and indicators: essential variables.

The concept of essential variables was first developed in the 1990s to support the political agenda of the UN's Framework Convention on Climate Change (UN FCCC) and the Intergovernmental Panel on Climate Change (IPCC). The essential climate variables (ECVs) were developed to standardise observations of climate data based on three criteria: relevance, feasibility and cost effectiveness. There are now 55 essential climate variables that are compiled by the Global Climate Observing System (GCOS) to support empirical estimations of climate change, its impacts and management options (Table 1). After 2009, essential ocean variables (EOVs) were developed in parallel to ECVs to understand and predict change in the oceans (Constable *et al.*, 2016). EOVs are maintained by the Global Ocean Observing System (GOOS, Table 2). Some EOVs are also used as ECVs. Both ECVs and EOVs primarily focus on the physical and chemical aspects of terrestrial and ocean systems, with less but increasing focus having been placed on the biological dimensions of these systems (Miloslavich *et al.*, 2018). ECVs and EOVs are formally recognised by the UN FCCC as integral parts of the reporting process on climate change, featuring in COP decisions and their usefulness in corporate reporting is increasingly recognised (e.g. in the Task Force on Climate-related Financial Disclosures).

There are financial and logistical limitations to the type and quantity of data that can be acquired by monitoring systems. Essential variables help to both organise primary observations into scalable and reusable data products but also to focus data collection efforts on the most relevant data to understand and predict change. In addition, essential variables are meant to be perennial, *i.e.* always produceable and applicable, irrespective of advances in technology and data collection methods.

For example, understanding climate change requires information on snow. Many measurements go into collecting data on snow, including remote sensing, core samples and snow depth sensors that evolve over time. These measurements are collected in different locations around the world using different equipment by different people. The essential climate variable *snow* is produced from aggregation of these multiple data sources, then providing datasets on snow covered area and snow depth that can be used to produce indicators of climate change. *Snow* itself can also be analysed to understand this specific aspect of the climate system. Importantly, *snow* datasets can be produced and analysed at different scales (local to regional to global). This scalability aspect of essential variables is essential to the development and function of global observing systems and provides a crucial link between primary data from multiple locations to global trends and predictions. Without an agreed upon set of essential variables, global observing systems (e.g. GCOS and GOOS) would not function. These monitoring systems in turn provide the necessary information to guide policy and track progress.

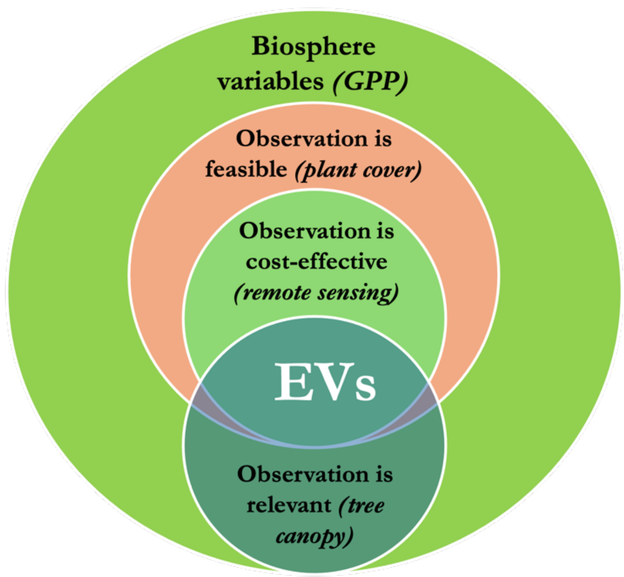

Figure 1. Essential variables (EVs) are defined as those variables that, for a given system of interest (e.g. gross primary production to understand the biosphere), are feasible to measure (e.g. plant cover), relevant (e.g. tree canopy) and cost-effective (e.g. remote sensing). Such variables remain to be identified for ecosystem services but can be grouped into defined categories (classes) that focus on important aspects of an ecosystem service (Figure 2).

EBVs & EESVs

Recognising the gap in monitoring of biological systems, essential biodiversity variables (EBVs) and, later, essential ecosystem service variables (EESVs) were proposed by the Group on Earth

Observation Biodiversity Observation Network (GEO BON). The development of EBVs was encouraged by COP decisions (CBD, 2012). Similarly to climate and ocean essential variables, EBVs and EESVs are intended to organise data, prioritise collection efforts and support the compilation of indicators of change. No global observing system currently exists for biodiversity and ecosystem services but the Global Biodiversity Framework's (GBF) monitoring framework requests that indicators be compiled by nations to track progress on biodiversity-related targets, recommending the use of EBVs (CBD, 2022). Selecting appropriate indicators for the GBF's monitoring framework was particularly challenging due to the wide selection of diverse and incomparable biodiversity indicators, highlighting the need to organise and standardise the data products needed to compile them.

EBVs and EESVs are intended to be theory driven, developed by academics to enable complete and effective monitoring of biodiversity and ecosystem services, rather than the practical data driven approach taken in the development of many existing indicators (Geijzendorffer *et al.*, 2016). However, EBVs were originally developed through a screening of all available biodiversity-relevant data based on scalability, temporal sensitivity, feasibility and relevance (Pereira *et al.*, 2013) done by a global network of academics involved in biodiversity science (GEO BON). Datasets capturing similar aspects of biodiversity (e.g. genetic diversity, species traits or species populations) were organised into classes. This approach did not provide strong conceptual foundations from the beginning (Brummitt *et al.*, 2017), limiting their applicability and widespread adoption and use (Schmeller *et al.*, 2018). Agreement on a common conceptualisation and increasing recognition of the importance of EBVs and their role in monitoring biodiversity change has accelerated their development and application (Kissling *et al.*, 2018; Jetz *et al.*, 2019), including through the use of automated indicator calculation tools (Griffith *et al.*, 2024). With the potential of these data products evident and their conceptual and technical foundations established, EBVs are now mature and ready to be used in guiding policy (Table 3).

Developing EESVs

Learning from the strengths and weaknesses of the EBV development can support GEO BON's ESWG to develop the EESVs. Contrary to EBVs, EESVs have been proposed classes first (Balvanera *et al.*, 2022). That is, the key aspects of ecosystem services to monitor and organise essential variables by have already been identified but none of the variables have been proposed. Six classes of EESVs have been proposed to date:

- **Ecological supply** refers to the ecosystem's potential capacity to provide ecosystem services
- **Anthropogenic contribution** refers to the knowledge and efforts that humans invest to enhance ecological supply and to make use of ecosystem services.
- **Demand** 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 awareness exists about such need
- **Use** refers to the active or passive appropriation of an ecosystem service by people; highlights the actual appropriation of benefits from nature.

- **Instrumental value** refers to the importance of an ecosystem services to societies or individuals as a means to achieve a specific end
- **Relational value** 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

Ecosystem services are highly context-specific, depending on the ecosystems, cultures and socio-ecological systems in which they arise, making it difficult to identify EESVs that can be aggregated from local to regional to global scales. Additionally, identifying a single variable to measure each aspect of an ecosystem service is not always straightforward (e.g. wholesale value vs retail value as a measure of the instrumental value of a fish provisioning ecosystem service) and the heterogeneity of methods used to collect data relevant to ecosystem services requires harmonisation to produce single EESVs. In many cases selecting appropriate units and scales of measurement also requires careful consideration (Brummitt *et al.*, 2017). Moreover, there are significant scientific and infrastructure costs to developing essential variables (Kissling *et al.*, 2018; Hardisty *et al.*, 2019). Finally, prioritising which EESVs for which ecosystem service to measure and report on requires participatory approaches and engagement with policymakers to focus development efforts on those EESVs that are of a higher priority. Little work has been done to develop the variables to populate these classes (Schwantes *et al.*, 2024, Table 4). The ESWG will need to take into consideration each of these challenges in developing EESVs for specific ecosystem services and within each class.

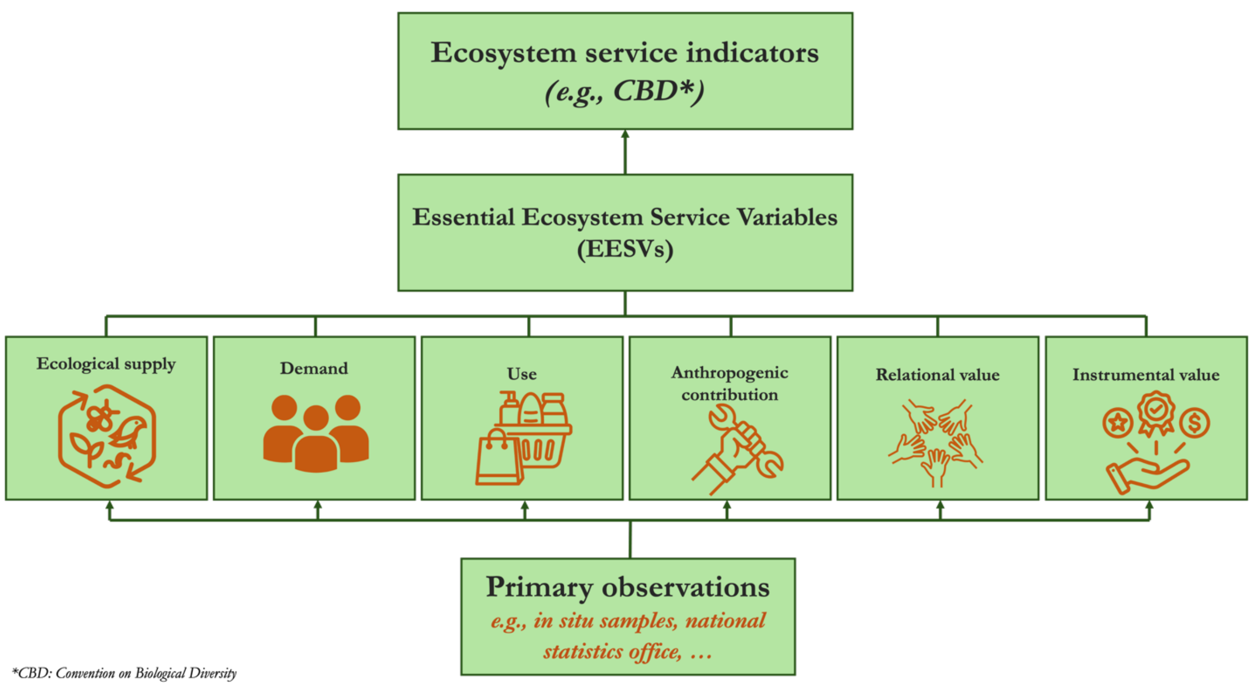

Figure 2. Essential ecosystem service variables (EESVs) organise primary observations into specific variables that correspond to an EESV class that measures a specific aspect of ecosystem services. Different types of observations will be used for each EESVs and one EESV per class should be

measured for each ecosystem service of interest to understand change in all its dimensions. These EESVs can then be used to produce more complex indicators of change such as those used in the Global Biodiversity Framework's monitoring framework.

Essential variables & indicators

Essential variables are not to be confused with indicators. Essential variables are intended to bridge the gap between primary observations and indicators, acting as a tool and conceptual bridge between the two. Essential variables standardise, harmonise and integrate observations from different sources over space and time to produce a data product that documents spatio-temporal change in a specific aspect of climate/biodiversity/ecosystem services. For example, the EBV for *population abundance* is a data product made using data from in situ observations and remote sensing that can be used to produce an overall population trend indicator for a region.

Ecosystem services cannot typically be measured directly, which has led to many indicators being developed in the field of ecosystem service science to allow for indirect measurements of one aspect or other of the ecosystem service, usually along the cascade. This has led to a proliferation of "ecosystem service indicators" that are typically incomparable across different ecosystem services. The introduction of the EESV concept requires reconceptualising or being very specific with the term "indicator" to enable operationalisation of ecosystem service monitoring.

The tendency to confound essential variables with indicators is partly due to terminology, which can, in part, be mitigated by differentiating clearly what is meant between such terms as "variable", "indicator", "data", "information" and "observation". Specifically, the meaning of the term "indicator". In some cases, indicators are simply local measures of some relevant parameter used to inform on the state of a system (e.g. phosphate concentration in a stream as a measure of stream health). In others, indicators are composite variables estimated using data from multiple sources to inform on a topic of interest (e.g. the Living Planet Index). The former can be confused with an essential variable but not the latter. Essential variables can indeed be analysed to inform on a specific aspect of the system they measure, acting in much the same way as these local indicators. However, the distinction between essential variables and indicators is important to make to enable prioritisation in data collection and effective production of data products that enable the development of multiscale integrated infrastructure for monitoring. Therefore, in the context of global observing monitoring and reporting systems, we reserve the term "indicator" for the latter case. Essential variables have a role to play in making the compilation of these composite variables possible while providing specific information that can itself be analysed. In conclusion, the definition of what is meant by the term "indicator" may be context specific but the role of essential variables in global monitoring should be seen as distinct from that of indicators.

Going forward

The concept of essential variables is well established, and their success has helped unlock funding and resources for the production of data products useful to guide policy. Currently, ecosystem service science lacks data standards but the burden of reporting is increasing in both the public and private sectors. Additionally, ecosystem service science suits itself well to the essential variable concept as many EESVs are likely to be model outputs using multiple data input sources (e.g. InVEST or ARIES). Developing practical and useable EESVs that are accessible to stakeholders will therefore be beneficial both for the academic community and for society.

The complexity of ecosystem services makes a class-by-class approach impractical. Expertise tends to be focused on specific social-ecological systems, suggesting that it may be more appropriate to develop EESVs by ecosystem service. Having pre-defined classes provides the theoretical background and framing required to organise EESVs but specifically identifying the available data and methods to produce EESVs should be done by those communities of experts most familiar with each ecosystem service.

In addition, due to the distinct conceptual and real differences between provisioning, regulating and cultural services, it may be necessary to consider dividing EESVs and their classes per type of ecosystem service to allow for aggregation and indicator compilation of fundamentally different ecosystem services (i.e. not attempting to aggregate regulating with provisioning services).

This bottom-up approach may highlight some limitations in the current conceptualisation of EESVs which would require revisiting the pre-defined classes. We suggest that the ESWG should remain open-minded to this possibility, especially if it allows streamlining of data needs and reporting efforts.

Considerable work has already been done to develop ECVs, EOVs and EBVs with some overlap becoming apparent in both data needs and outputs (O'Connor *et al.*, 2020). Taking advantage of current efforts to align EESVs with other essential variables and enable joint monitoring through sharing of resources (Muller-Karger *et al.*, 2018) should be considered a key priority to help accelerate the development of EESVs.

Given the urgent need for effective monitoring of ecosystem services, the ESWG should make all possible efforts to develop EESVs in conjunction with those stakeholders who need them (e.g. governments and corporations). This would help prioritise between EESVs and generate interest in supporting the development, deployment and testing of this tool.

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Table 1. List of essential climate variables provided by the Global Climate Observing System organised by class.

Essential Climate Variables										
Upper-air atmosphere	***Surface atmosphere***	***Atmospheric composition***	***Cryos-phere***	***Anthropo-sphere***	***Biosphere***	***Hydros-phere***	***Surface ocean physics***	***Ocean biogeoch-emistry***	***Ocean biology / ecosystems***	***Subsurface ocean physics***
Lightning	Precipitation	Aerosols	Ice sheets and ice shelves	Anthropogenic water use	Above-ground biomass	River discharge	Sea surface temperature*	Inorganic carbon*	Marine habitats	Subsurface temperature*
Clouds	Surface pressure	CO_2, methane and other GHGs	Snow	Anthropogenic greenhouse gas fluxes	Land cover	Lakes	Sea state*	Oxygen*	Plankton	Subsurface currents*
Earth radiation budget	Surface radiation budget	Ozone	Glaciers		Albedo	Ground water	Surface stress	Nutrients*		Subsurface salinity*
Upper-air wind speed and direction	Surface wind speed and direction	Precursors for aerosols and ozone	Permafrost		Fire	Soil moisture	Sea ice*	Transient tracers*		
Upper-air temperature	Surface temperature				Land surface temperature	Evaporation from land	Ocean surface heat flux*	Nitrous oxide*		
Upper-air water vapour	Surface water vapour				Leaf area index	Terrestrial water storage	Sea surface salinity*	Ocean colour		
					Fraction of absorbed photosynthetically active radiation		Surface currents*			
					Soil carbon		Sea level			

*Variable is also an essential ocean variable

Table 2. List of essential ocean variables provided by the Global Ocean Observing System organised by class.

Essential Ocean Variables			
Physics	***Biochemistry***	***Biology and ecosystems***	***Cross disciplinary (including human impact)***
Sea state	Oxygen	Phytoplankton biomass and diversity	Ocean colour
Ocean surface stress	Nutrients	Zooplankton biomass and diversity	Ocean sound
Sea ice	Inorganic carbon	Fish abundance and distribution	Marine debris*
Sea surface height	Transient tracers	Marine turtles, birds, mammals abundance and distribution	
Sea surface temperature	Particulate matter	Hard coral cover and composition	
Subsurface temperature	Nitrous oxides	Seagrass cover and composition	
Surface currents	Stable carbon isotopes	Macroalgal canopy cover and composition	
Subsurface currents	Dissolved organic carbon	Mangrove cover and composition	
Sea surface salinity		Microbe biomass and diversity*	
Subsurface salinity		Invertebrate abundance and distribution*	
Ocean surface heat flux			
Ocean bottom pressure			
Turbulent diapycnal fluxes*			

*In pilot stage

Table 3. List of essential biodiversity variables provided by the Group on Earth Biodiversity Observation Network organised by class.

Essential Biodiversity Variables					
Genetic composition	***Species populations***	***Species traits***	***Community composition***	***Ecosystem functioning***	***Ecosystem structure***
Genetic diversity (richness and heterozygosity)	Species distributions	Morphology	Community abundance	Primary productivity	Live cover fraction
Genetic differentiation (number of genetic units and genetic distance)	Species abundances	Physiology	Taxonomic/phylogenetic diversity	Ecosystem phenology	Ecosystem distribution
Effective population size		Phenology	Trait diversity	Ecosystem disturbances	Ecosystem vertical profile
Inbreeding		Movement	Interaction diversity		
		Reproduction			

Table 4. List of essential ecosystem service variables provided by the Group on Earth Biodiversity Observation Network organised by class.

Essential Ecosystem Service Variables*					
Ecological supply	***Use***	***Demand***	***Anthropogenic contribution***	***Instrumental value***	***Relational value***
TBD	TBD	TBD	TBD	TBD	TBD

*Essential ecosystem service variables are not currently developed nor available but classes to organise them have been proposed in Balvanera *et al.*, 2022