Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Environmental Sustainability

Essential ecosystem service variables for monitoring progress towards sustainability

Patricia Balvanera[1,2], Kate A Brauman[10], Anna F Cord[3,4], Evangelia G Drakou[5], Ilse R Geijzendorffer[6,7], Daniel S Karp[8], Berta Martín-López[9], Tuyeni H Mwampamba[1] and Matthias Schröter[3,9]

Global frameworks to guide consistent monitoring of changes in human–nature interactions across space and time are needed to better understand how healthy ecosystems support societies and to inform policy design. Monitoring Essential Ecosystem Service Variables (EESVs) can provide a comprehensive picture of how links between nature and people are changing. A first proposed set of EESV classes comprises: ecological supply, anthropogenic contribution, demand, use, instrumental values, and relational values. Development of specific indicators of these classes for three exemplary ecosystem services (food from fisheries, crop pollination and wildlife viewing) confirms their readiness for global operationalization. The EESV classes will advance our ability to monitor progress towards achieving the Sustainable Development Goals.

Addresses
[1] Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Universidad Nacional Autónoma de México, Mexico
[2] Unidad Académica de Estudios Territoriales, Universidad Nacional Autónoma de México, Mexico
[3] UFZ – Helmholtz Centre for Environmental Research, Department of Computational Landscape Ecology, Permoserstr. 15, 04318 Leipzig, Germany
[4] Chair of Computational Landscape Ecology, Institute of Geography, Technische Universität Dresden, Helmholtzstr. 10, 01069 Dresden, Germany
[5] Department of Geography, Harokopio University of Athens, 70, El. Venizelou Str., Kallithea, Athens, Greece
[6] Tour du Valat, Research Institute for Mediterranean Wetlands, Le Sambuc, 13200 Arles, France
[7] Louis Bolk Instituut, Kosterijland 3-5, 3981 AJ Bunnik, The Netherlands
[8] Department of Wildlife, Fish, and Conservation Biology, University of California, Davis, CA, USA
[9] Leuphana University of Lüneburg, Faculty of Sustainability, Social-ecological Systems Institute, Universitätsallee 1, 21335 Lüneburg, Germany
[10] Global Water Security Center, The University of Alabama, Tuscaloosa, USA

Corresponding author: Balvanera, Patricia (pbalvanera@iies.unam.mx)

Current Opinion in Environmental Sustainability 2022, **54**:101152

This review comes from a themed issue on **Open Issue 2022**

Edited by **Opha Pauline Dube**, **Victor Galaz** and **William Solecki**

For complete overview of the section, please refer to the article collection, "Open Issue 2022"

Available online 11th February 2022

Received: 14 June 2021; Accepted: 22 January 2022

https://doi.org/10.1016/j.cosust.2022.101152

Why monitor ecosystem services?

The benefits that societies receive from nature, referred to as ecosystem services or nature's contributions to people [1], are increasingly recognized in many local, national, and international political agendas, such as the United Nations' Agenda for Sustainable Development [2]. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) explicitly demonstrated how declines in the vital benefits that people receive from nature threaten the quality of life of current and future human generations [3].

While the richness of data that could inform our understanding of these benefits and ways to sustain them has increased remarkably in the last decades such information is not systematically accessible to guide decisions. Data on the trends of nature, society, and their interactions are generated daily at local, national and global scales by multiple sources. Yet, the recent regional, thematic and global assessments by IPBES [3–8] rely on a limited set of indicators for which data is available to report on spatial patterns, temporal trends, and potential future trajectories of ecosystem services. Indeed, much of the data needed to monitor ecosystem services are currently not organized in a way that is systematic, interoperable or comparable across scales, contexts, and types of ecosystem services. Systematizing existing monitoring efforts and developing new ones are thus urgently needed to consistently assess how interactions between nature and society change across space and time.

Essential variables at the interface between people and nature

Initiatives to develop systematic monitoring to support environmental decision making are not new. The climate community took the first step in the 1990s to guide the implementation of the Global Climate Observing System by the Parties of the UN Framework Convention on Climate Change (UNFCCC), leading to the creation of Essential Climate Variables (ECVs [9]). Ocean scientists within the Global Ocean Observing Systems adopted a similar approach leading, in 2010, to community-defined Essential Ocean Variables (EOVs) that better support weather forecasting [10] and inform the Intergovernmental Oceanographic Commission [11,12]. Efforts in the biodiversity arena followed, led by the Group on Earth Observations Biodiversity Observation Network (GEO BON), to inform the Convention on Biological Diversity (CBD) on progress towards UN Aichi Targets. Specifically, GEO BON defined broad classes of Essential Biodiversity Variables (EBVs) [13], several of which have only been fully operationalized by defining concrete essential variables (e.g. species traits [14•] and species populations [15•]). A call has been made for coordination towards Essential Sustainable Development Goal Variables [16], but, as yet, no corresponding monitoring framework is available. Finally, a list of 60 variables for monitoring social-ecological systems was suggested as a first step towards the identification of essential social-ecological variables [17]. The effective coordination among all these above initiatives is critical to support future IPBES assessments and to track progress towards achieving the Sustainable Development Goals and the post 2020 Global Biodiversity Framework of the CBD [12,18].

However, none of these efforts provide substantive insights into the role that ecosystems play in supporting thriving societies. Mapping existing monitoring strategies onto the IPBES conceptual framework (Figure 1) reveals that, while climate, ocean and biodiversity essential variables are complementary to EESVs, their focus has been on the abiotic and biotic components of nature and on human impacts on nature. Essential variables to assess how functional natural systems contribute towards achieving the UN Sustainable Development Goals are missing.

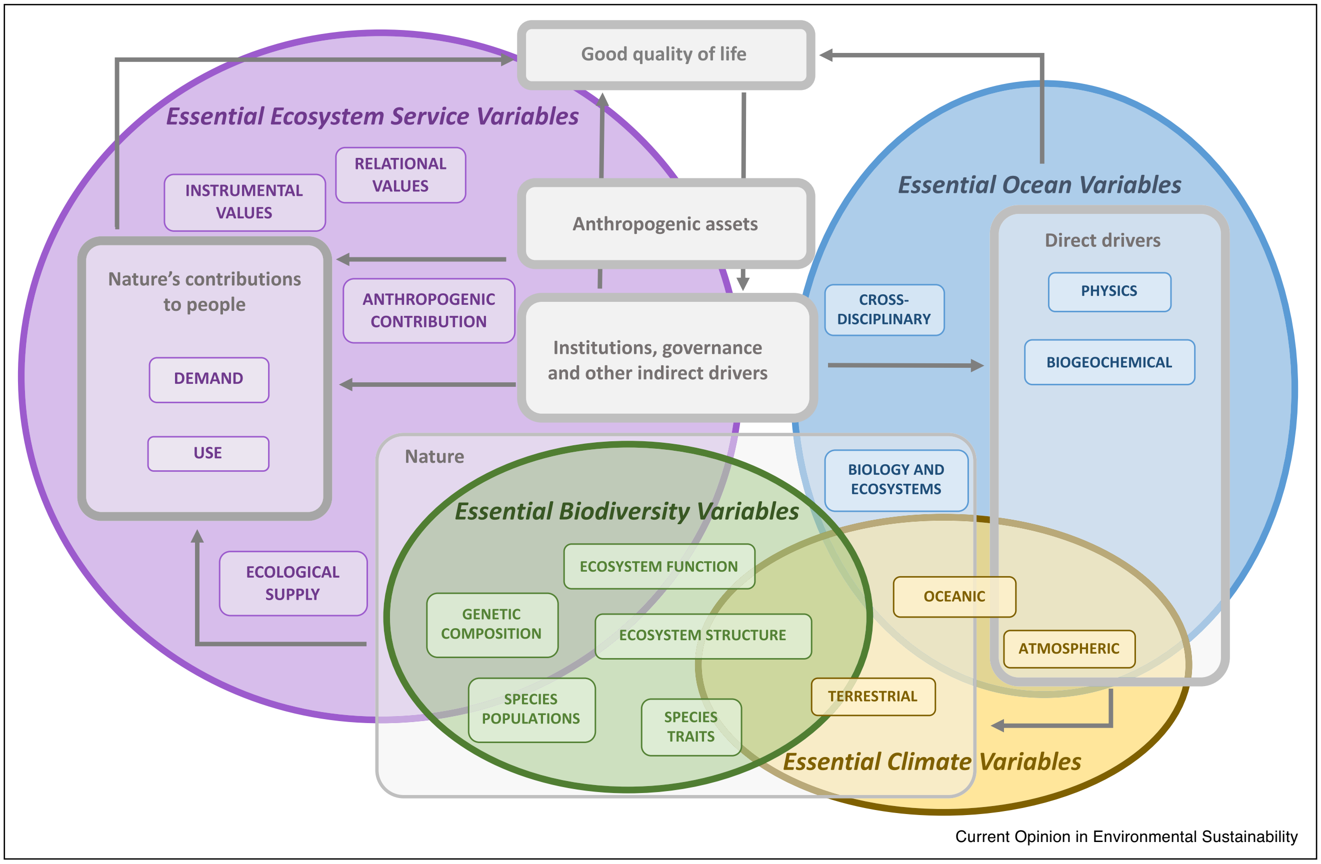
What are essential ecosystem service variables?

Identifying EESVs is an opportunity to explicitly address the above challenges. All essential variables represent a minimum collection of data or measurements that capture a specific dimension of the phenomena of interest and are critical for detecting change across space and time [13,16]. Essential variables are therefore located at the interface between data (primary observations), indicators (synthetic or derived metrics), and user-specific societal or policy goals (e.g. Sustainable Development Goals). Essential variables consolidate primary observations from multiple data sources and form the basis for grouping them. Thus, they should capture the essence of the systems being analyzed in a way that is manageable and that can swiftly inform decision makers [20]. An essential variable is relevant across spatial scales and across social-ecological contexts. Identifying essential variables illuminates key gaps in coordinated monitoring efforts by indicating what is still missing, and are thus indispensable for fulfilling monitoring and reporting purposes [16].

We define EESVs as the minimum set of core variables needed to identify key changes in the interactions between nature and society that contribute to human well-being through ecosystem services. Ecosystem services entail diverse types of interactions between nature and people, and the intensity of these interactions can vary substantially. For example, food from ocean fisheries, crop pollination by wild bees and recreational experiences with wildlife represent highly diverse types of human-nature interactions. A key challenge is therefore to identify the common denominators of nature-society interactions that are relevant to all ecosystem services and whose monitoring over space and time is most important [21].

Accordingly, **EESV classes represent shared and grouped key attributes for all ecosystem services to be monitored across space and time**. These classes can be monitored consistently across social-ecological contexts and ecosystem service classification schemes. The monitored attributes take into account multiple data types and sources, including biophysical and sociocultural field data, biophysical and socioeconomic governmental statistics, remote sensing, and model outputs. EESV classes and variables necessarily derive from and contribute to the consensus on how to operationalize ecosystem services monitoring, given the proliferation of approaches and frameworks in the past few decades. In the same way that EBV classes encompass the attributes of the different taxa, EESV classes include

Figure 1



Efforts to develop systematic monitoring of essential environmental variables (ovals with small boxes of different colors) mapped onto the IPBES conceptual framework [19] (grey rectangles) make visible the need for Essential Ecosystem Services Variables (EESVs). Efforts from the last few decades include the development of Essential Climate Variables (ECVs-yellow), Essential Ocean Variables (EOVs-blue) and Essential Biodiversity Variables (EBVs-green) and have largely addressed the direct drivers of change in nature, both its living and non-living components. While these efforts are complementary and interdependent, they have not covered the role of nature in supporting a good quality of life. Six classes of EESVs (purple oval with six boxes) span the links between nature, nature's contributions to people, anthropogenic assets, institutions, governance and other indirect drivers, and good quality of life. EESVs are needed to monitor how achieving societal goals is dependent on nature and on its interlinkages with society (see below for further detail).

cross-cutting attributes of the different types of ecosystem services (e.g. material, regulating and non-material) [1,19,22,23].

The Ecosystem Services Working Group of the intergovernmental Group on Earth Observations (GEO) Biodiversity Observation Network (GEO BON-ES [22]) is uniquely positioned to drive the identification and operationalization of these EESV classes. This global team has gone through several steps over the past 10 years, including the presentation of a conceptual framework for ecosystem service monitoring [22], reviews of the state of the art of ecosystem services monitoring using different sources of information including Earth observations [23,24], an analytical framework including five interlinked components of ecosystem services at the supply and demand interface [25], extensive literature searches, and multiple iterative online and face-to-face workshops with experts and user groups during open calls in international conferences as well as online discussions to develop ecosystem services related policy tools (GEO BON conferences in 2016, 2017 and 2019; conferences of the Program for Ecosystem Change and Society in 2015 and 2017; online meetings for the United Nations System of Environmental Economic Accounts 2019–2020). This process has allowed the group to iteratively ponder, test, adapt, identify, select, and define a first set of EESV classes and then refine these classes.

A first set of Essential Ecosystem Service Variable (EESV) classes

This initial list of EESV classes can be operationalized to document changes in different elements of ecosystem services across space, time, and societal contexts.

- Ecological supply **refers to the ecosystem structure and functions that underlie the potential capacity of ecosystems to provide ecosystem services**. It accounts for the potential [25,26••] or capacity [27] of ecosystems and their functions [28].
- Anthropogenic contribution **refers to the efforts that humans invest to enhance ecological supply and to make use of ecosystem services**. Anthropogenic contributions and ecological supply interact through the process of co-production through complex social-ecological processes, in which humans contribute knowledge, effort, time, financial resources, materials and technology to the flow of ecosystem services [1,25,29,30].
- 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**. Different stakeholder groups may differ in such demands [25,31–33].
- Use **refers to the active or passive appropriation of an ecosystem service by people**. These are the 'realized' benefits [26••,34••] that arise from passive or active management, also referred to as match [25,27] or flow [28,35].
- Instrumental value **refers to the importance of an ecosystem service to societies or individuals as a means to achieve a specific end (e.g. some dimension of human well-being)**. It denotes how the well-being of individuals or groups of people is enhanced by ecosystem services, both in economic and sociocultural terms [36,37].
- 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**. These encompass the core principles embedded into the relationships between people and nature, or among people within nature, such as care, responsibility and stewardship [38,39]. Relational values are embedded in the practices, knowledge and visions that support ecosystem management [40,41].

This first set of EESV classes covers the social and physical processes that mediate the interactions between nature and society through ecosystem services. While there are multiple ways in which the EESV classes can be organized, the six classes proposed here were chosen to encompass all components of the widely used ecosystem services cascade [42] and be compatible with the different classifications and conceptual approaches to ecosystem services and nature's contributions to people [43,44]. The EESV classes are necessarily strongly interrelated: supply must exceed demand if the flow of services is to be sustainable; instrumental value underpins demand; use sits at the intersections between supply, anthropogenic contribution and demand; instrumental and relational values arise from the human-nature interactions that lead to anthropogenic contribution and use. The set is designed to cover the complexity and reciprocity of the multiple interactions between nature and societies. The indicators and data encompassed in these classes is prevalent in the burgeoning literature on ecosystem services [42,45•,46], and are consistent with the evolutions of the EBV framework that accommodate the idea of a multidimensional data cube, where for each variable, multiple entities and multiple metrics may exist [47].

Operationalizing the EESV classes framework

EESV classes were developed to apply to a wide range of social-ecological contexts and have global coverage, but the spatial and temporal resolution and quality of the data to understand the intricacies involved has to be tested. As a proof of concept, we operationalized this set of EESV classes for three contrasting ecosystem services (Table 1): *wild food from marine fisheries*, a provisioning service or material contribution, *crop pollination by wild insects*, a regulating service/contribution, and *physical and psychological experiences from wildlife viewing*, a cultural service or non-material contribution.

The example indicators highlight that readily available data sources exist at the global level for many classes of EESVs (with different spatial and temporal resolutions). They show that the processes that underpin the linkages between nature and people for each class operate at different spatial scales. For example, demand may be driven by the dynamics of human populations, while supply by that of wild species. Proxies have been devised for other classes, while rapid technological development may grant availability of other classes within the next few years.

The EESV classes are designed to provide compelling narratives about how changes in nature across time and space are linked to food and livelihood security, nutrition, economic growth, and cultural heritage (Table 1). For instance, declining ocean health has led to the collapse of many fish populations, affecting the ecological basis for the supply of wild food from fisheries [51]. The increased density and capacity of fishing vessels reflects the increased anthropogenic contribution [52]. The demand for fish has grown with the growing human population, but especially due to the demand for cheap fish to supply large aquaculture projects [48]. The actual use of wild fish, or fish catch, varies by country and species, but shows a trend towards decline as a result of overexploitation [51]. The instrumental value of marine fisheries, especially the economic value of rare yet highly valued species, is a major driver for this overexploitation [53]. The relational

Table 1

Essential Ecosystem Service Variable (EESV) classes and EESVs with examples of associated indicators, data sources and feasibility for global monitoring of three selected ecosystem services (one material, one regulating and one non-material) across space and time. The traffic lights indicate current feasibility at the global level in terms of having access to already available data, standardized approaches or protocols (green: high data and developed standardized approaches availability, good match between data sources and EESV; yellow: either data or standardized approaches available, or data available only a proxy of the EESV, red: low data and standardized approaches availability, data needed to be compiled from various national and regional sources and many efforts needed for its consistent operationalization). The spotlights were attributed based on example data sources (see Supplementary Table S1), assessing whether the data or models are currently available and accessible, as well as how much the data or models available are a proxy or actually inform on precisely the chosen exemplary EESV (e.g. models are available to identify suitable pollinator habitat but not their actual abundance and diversity). Abbreviations refer to IPBES assessment: GA — Global Assessment, ECA — Europe and Central Asia, AF — Africa, POL — Pollination, pollinators and food production (www.ipbes.net)

EESV class	Ecosystem service (or Nature's contribution to people)	Proposed EESV	Data sources	Feasibility for operationalizing at global scale (temporal and spatial resolution)	Indicator used in IPBES (Global, regional or thematic assessments)
Ecological supply	Wild food from marine fisheries	Biomass of marine species consumed by humans	Biomass measurements at national level, per species group (e.g. tuna), per fishery type (e.g. bottom trawl fishery) — From fisheries data (www.seaaroundus.org)	 (<1 year, country or group of countries, Exclusive Economic Zone, High Seas, or Large Marine Ecosystems)	Proportion of fish stocks within biologically sustainable levels (GA)
	Crop pollination by wild insects	Abundance and diversity of wild pollinators	Modeled bee abundances — From land use/land cover maps that reflect spatial variation in nesting and floral resources; proxies available based on habitat suitability and distance to pollination-dependent crops [34••]	 (1 year, 30 m)	Suitable habitat for pollinators (GA)
	Physical and psychological experiences from wildlife viewing	Availability of megafauna-based recreational opportunities	Distribution and abundance of large mammals — From species range maps (www.iucnredlist.org/resources/spatial-data-download)	 (1–5 years, 5 km)	Richness of species used for recreational activities (ECA)
Anthropogenic contribution	Wild food from marine fisheries	Extent of physical infrastructure for fishing	Density of fishing boats per spatial unit per type of vessel (in terms of time, capital and labour) — From fishing effort data (globalfishingwatch.org/our-map/)	 (<1 year, 0.5°)	Estimated fishing effort (GA)
	Crop pollination by wild insects	Landscape interventions around agricultural fields to promote wild pollinators	Extent of planted bee habitat such as flower strips and hedgerows — From remote sensing		Not yet assessed by IPBES
	Physical and psychological experiences from wildlife viewing	Infrastructure to support wildlife viewing	Roads and trail density — From high resolution remote sensing (e.g. worldview.earthdata.nasa.gov, https://www.euspaceimaging.com/about/satellites/geoeye-1/; road density, www.globio.info/download-grip-dataset)	 (5 years, variable from 0.5 m to 500 m)	Not yet assessed by IPBES
Demand	Wild food from marine fisheries	Demand for food from fisheries	Current and projected per capita fish consumption per country — From FAO models [48]	 (10 year, country)	Not yet assessed by IPBES
	Crop pollination by wild insects	Extent of pollinator-dependent crop production	Crops dependent on animal pollination — From remotely sensed data [49]	 (1 year, 30 m)	Types and production volume of food crops reliant on animal pollination (POL)
	Physical and psychological experiences from wildlife viewing	Demand for wildlife viewing tourism	Demand for wildlife viewing — From number of wild-life tours offered in a standardized search of websites	 (5–10 years, country)	Not yet assessed by IPBES

Table 1 (*Continued*)

EESV class	Ecosystem service (or Nature's contribution to people)	Proposed EESV	Data sources	Feasibility for operationalizing at global scale (temporal and spatial resolution)	Indicator used in IPBES (Global, regional or thematic assessments)
Use	Wild food from marine fisheries	Fish catches used as a source of food	Fish catches per spatial unit, per taxa, per type of fisheries (subsistence, artisanal, industrial) — From fisheries data (www.seaaroundus.org)	 (<1 year, country or group of country Exclusive Economic Zone, High Seas, or Large Marine Ecosystems)	Total catch globally (GA)
	Crop pollination by wild insects	Crop production attributed to wild pollinators	Proportion of crop pollination needs that are met by wild pollinators — Proxies available from estimates of pollinated production/pollination-dependent production [34••]	 (1 year-30 m)	Global deficits in wild pollination (GA)
	Physical and psychological experiences from wildlife viewing	Wildlife watching experiences	Density of wildlife watching events — From geotagged pictures in social media (e.g. Flickr) of megafauna viewings	 (1–5 years)	Visitation rates to natural terrestrial, coastal, and marine areas (GA)
Instrumental value	Wild food from marine fisheries	Economic value of food from fisheries	Value ($) of fish per spatial unit (EEZs, High Seas, LMEs), per taxa, per type of fisheries (subsistence, artisanal, industrial) — From fisheries data (www.seaaroundus.org)	 (1 year, country or group of countries —Exclusive Economic Zone, High Seas, or Large Marine Ecosystems)	Not yet assessed by IPBES
	Crop pollination by wild insects	Nutrition contribution from pollinator-dependent crops	Nutrient requirements met by pollinated crop production — Proxies from estimates of maximum potential pollination-dependent nutrient production normalized by annual recommended dietary intake of a single person, and averaged across all nutrients [34••]	 (1 year, 30 m)	Nutrition contribution from pollinator-dependent crops (GA)
	Physical and psychological experiences from wildlife viewing	Revenues of the wildlife-based tourism sector	Economic gains associated with wildlife viewing — From total annual revenue of protected areas associated to entrance fees [50]	 (5–10 years, country)	Economic importance of wildlife-based tourism (AF)
Relational value	Wild food from marine fisheries	Practices that reflect responsibility ties to wild food from the ocean	Occurrence and frequency of practices that embody relational values — From UNESCO Register of good safeguarding practices (ich.unesco.org/en/lists)	 (5–10 years, country)	Number of good food safeguarding practices related with wild food (ECA)
	Crop pollination by wild insects	Cultural and spiritual practices that reflect responsibility ties to wild pollinators	Occurrence and frequency of practices that reflect relational values — From UNESCO Lists of Intangible Cultural Heritage (ich.unesco.org/en/lists) using biocultural approaches [41]	 (5–10 years, country)	Spiritual and cultural values and practices underpinned by Indigenous Peoples and Local Communities to preserve pollinators (POL)
	Physical and psychological experiences from wildlife viewing	Importance of stewardship, care and responsibility associated to wildlife viewing experiences	Occurrence and frequency of wildlife viewing events that embody relational values — From commentaries associated to geotagged pictures in social media (e.g. Flickr) associated to stewardship, care and responsibility		Level of contribution of recreational experiences in nature to local identity, sense of place and belonging (ECA)

values associated with intangible cultural practices that have tied fishers to the oceans are increasingly eroded, leading to a growing disengagement of responsibilities to fish, fishers, and the ocean [54].

Next steps for essential ecosystem service variables

Identifying the EESV classes is only the beginning of the journey. It has taken the biodiversity community five years to move from proposing a set of EBV classes [13] to concretizing and operationalizing the details for two of them, species traits [14•] and species populations [15•]. The experience gained in developing other sets of essential variables, as well as collaboration among the respective communities, will hopefully help to accelerate this journey.

The EESV classes will have to be clarified for many individual ecosystem services in the three following steps. First, instead of focusing on each class separately (as for the EBVs), we suggest that interdisciplinary expert teams be formed to focus on individual ecosystem services and assess appropriate indicators for ecological supply, anthropogenic contribution, demand, use, instrumental values and relational values. For example, while development of EESVs for pollination requires agronomists, bee specialists and nutritionists, wildlife monitoring requires psychologists, reserve and ecotourism managers and megafauna specialists. For each class, only the most informative and easily operationalizable EESV should be selected (e.g. one per service, as in Table 1) to ensure the feasibility of global monitoring. User-centered and participatory approaches would target important dimensions of ecosystem service change that provide critical information for management or policy decisions [17].

Second, collaboration between teams associated with individual ecosystem services will help reduce the number of variables to be monitored. For instance, species abundance and species trait data will likely be relevant for assessing the supply of multiple ecosystem services. Collaboration with other monitoring communities will also be necessary to identify and gather the most relevant data. For instance, the EBV and the EOV communities have monitored species abundances, which can be used to assess food supply from marine fisheries. Current models and data gathered by various ecosystem service networks, such as the Natural Capital Project [34••], can feed into pollination monitoring.

Third, a Global Ecosystem Services Monitoring System can be operationalized through the GEO BON platform, in close coordination with the Global Biodiversity Monitoring System [55]. Data of very different natures and spatio-temporal resolutions, produced by different organizations, can be coherently integrated for each EESVs class and ecosystem service, following the FAIR (findable, accessible, interoperable and reusable) principles [56]. The teleconnections between different areas of the world for within and among EESVs and ecosystem services would need to be further explored. The use of the Linked Data Principles will facilitate the interoperability among these sources [15•]. Global users such as IPBES and the CBD urgently need the EESV framework to be operationalized. The IPBES Nexus Assessment will need to go beyond the initial set of indicators used by the Global and Regional Assessments (see Table 1) to explicitly address how changes in the interlinkages between nature and society via ecosystem services lead to changes in societal outcomes. Similarly, the IPBES Business and Biodiversity Assessment can rely on the above EESV classes to measure how much and in which ways businesses depend on nature, and what are the impacts of their enterprise on nature. The United Nations System of Environmental Economic Accounts [57] for national accounting offices on how nature supports economic growth and how nature degradation leads to economic losses is aligned with the EESV classes suggested here. An integrated monitoring system encompassing climate, ocean, biodiversity, ecosystem services and essential SDG variables will be critical to monitor the progress towards the SDGs and the Post 2020 Global Biodiversity Framework. Links to other initiatives, such as the Dasgupta report on the economics of biodiversity [58], that address the integration of economic, sociocultural and environmental data on the links between nature, economy and societal wellbeing, will be instrumental in operationalizing the EESV framework.

Conclusion

The time is ripe to initiate the operationalization of Essential Ecosystem Service Variables to support policy making. A first set of EESV classes is proposed here by the GEO BON-ES team for a more robust assessment of changes at the nature-society interface to track the impact of changes in nature on the well-being of societies through ecosystem services. The EESV framework is not a straitjacket, but rather aims to foster interaction between data providers and data users. Ultimately, EESVs will enable scientists, practitioners and policy makers to fully understand the vast developments in ecosystem services in a way that is accessible and relevant to users around the world. The EESV classes framework will allow us to show how the degradation of nature directly affects societal well-being and provide critical spatial and temporal information to support decision-making towards achieving the Sustainable Development Goals.

Conflict of interest statement

Nothing declared.

CRediT authorship contribution statement

Patricia Balvanera: Conceptualization, Investigation, Writing – original draft, Writing – review and editing. **Kate A Brauman:** Investigation, Writing – original draft, Writing – review and editing. **Anna F Cord:** Conceptualization, Investigation, Writing – original draft, Writing – review and editing. **Evangelia G Drakou:** Conceptualization, Investigation, Writing – original draft, Writing – review and editing. **Ilse R Geijzendorffer:** Conceptualization, Investigation, Writing – original draft, Writing – review and editing. **Daniel S Karp:** Conceptualization, Investigation, Writing – original draft, Writing – review and editing. **Berta Martín-López:** Conceptualization, Investigation, Writing – original draft, Writing – review and editing. **Tuyeni H Mwampamba:** Conceptualization, Investigation, Writing – original draft, Writing – review and editing. **Matthias Schröter:** Investigation, Writing – original draft, Writing – review and editing.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.cosust.2022.101152.

Acknowledgements

The authors would like to thank the continued support from GEO BON to the GEO BON-ES team, through online work as well as hands-on meetings. Consultations have also been held in the context of the meetings of the Programme for Ecosystem Change and Society (PECS). The contribution of IRG was partly covered by the ECOPOTENTIAL project (Contract No. 641762) funded under the Horizon 2020 Programme by the European Commission.

References and recommended reading

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

- • of special interest
- •• of outstanding interest

1. Díaz S, Pascual U, Stenseke M, Martín-López B, Watson RT, Molnár Z, Hill R, Chan KMAA, Baste IA, Brauman KA *et al.*: **Assessing nature's contributions to people**. *Science (80-)* 2018, **359**:270-272.
2. UN: *UN: Report of the Inter-Agency and Expert Group on Sustainable Development Goal Indicators (E/CN.3/2016/2/Rev.1)*. 2016.
3. IPBES: *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. 2019.
4. IPBES: *Summary for Policymakers of the Regional Assessment Report on Biodiversity and Ecosystem Services for Africa of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. 2018.
5. IPBES: *Summary for Policymakers of the Regional Assessment Report on Biodiversity and Ecosystem Services for the Americas of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. 2018.
6. IPBES: *Summary for Policymakers of the Regional Assessment Report on Biodiversity and Ecosystem Services for Asia and the Pacific of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. IPBES; 2018.
7. IPBES: *The IPBES Regional Assessment Report on Biodiversity and Ecosystem Services for Europe and Central Asia*. 2018.
8. IPBES: *Summary for Policymakers of the Assessment Report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on Pollinators, Pollination and Food Production*. IPBES secretariat; 2016.
9. Bojinski S, Verstraete M, Peterson TC, Richter C, Simmons A, Zemp M: **The concept of essential climate variables in support of climate research, applications, and policy**. *Bull Am Meteorol Soc* 2014, **95**:1431-1443.
10. Bauer P, Thorpe A, Brunet G: **The quiet revolution of numerical weather prediction**. *Nature* 2015, **525**:47-55.
11. Bax NJ, Appeltans W, Brainard R, Duffy JE, Dunstan P, Hanich Q, Harden Davies H, Hills J, Miloslavich P, Muller-Karger FE *et al.*: **Linking capacity development to GOOS monitoring networks to achieve sustained ocean observation**. *Front Mar Sci* 2018, **5**.
12. Muller-Karger FE, Miloslavich P, Bax NJ, Simmons S, Costello MJ, Pinto IS, Canonico G, Turner W, Gill M, Montes E *et al.*: **Advancing marine biological observations and data requirements of the complementary Essential Ocean Variables (EOVs) and Essential Biodiversity Variables (EBVs) frameworks**. *Front Mar Sci* 2018, **5**:1-15.
13. Pereira HM, Ferrier S, Walters M, Geller GN, Jongman RHG, Scholes RJ, Bruford MW, Brummitt N, Butchart SHM, Cardoso AC *et al.*: **Essential biodiversity variables**. *Science (80-)* 2013, **339**:277-278.
14. • Kissling WD, Walls R, Bowser A, Jones MO, Kattge J, Agosti D, Amengual J, Basset A, Van Bodegom PM, Cornelissen JHC *et al.*: **Towards global data products of Essential Biodiversity Variables on species traits**. *Nat Ecol Evol* 2018, **2**:1531-1540.
15. • Jetz W, McGeoch MA, Guralnick R, Ferrier S, Beck J, Costello MJ, Fernandez M, Geller GN, Keil P, Merow C *et al.*: **Essential biodiversity variables for mapping and monitoring species populations**. *Nat Ecol Evol* 2019, **3**:539-551.
16. Reyers B, Stafford-smith M, Erb K, Scholes RJ, Selomane O: **Essential variables help to focus sustainable development goals monitoring**. *Curr Opin Environ Sustain* 2017, **26–27**:97-105.
17. Pacheco-Romero M, Alcaraz-Segura D, Vallejos M, Cabello J: **An expert-based reference list of variables for characterizing and monitoring social-ecological systems**. *Ecol Soc* 2020, **25**.
18. CBD: *Post 2020 Global Biodiversity Framework*. 2020 https://www.cbd.int/conferences/post2020.
19. Díaz S, Demissew S, Carabias J, Joly C, Lonsdale M, Ash N, Larigauderie A, Adhikari JR, Arico S, Báldi A *et al.*: **The IPBES Conceptual Framework - connecting nature and people**. *Curr Opin Environ Sustain* 2015, **14**:1-16.
20. Brummitt N, Regan EC, Weatherdon LV, Martin CS, Geijzendorffer IR, Rocchini D, Gavish Y, Haase P, Marsh CJ, Schmeller DS: **Taking stock of nature: essential biodiversity variables explained**. *Biol Conserv* 2017, **213**:252-255.
21. Reyers B, Selig ER: **Global targets that reveal the social–ecological interdependencies of sustainable development**. *Nat Ecol Evol* 2020, **4**:1-9.
22. Tallis H, Mooney H, Andelman S, Balvanera P, Cramer W, Karp D, Polasky S, Reyers B, Ricketts T, Running S *et al.*: **A global system for monitoring ecosystem service change**. *Bioscience* 2012, **62**:977-986.
23. Balvanera P, Quijas S, Karp DS, Ash N, Bennett EM, Boumans R, Brown C, Chan KMA, Chaplin-Kramer R, Halpern BS *et al.*: **Ecosystem services**. In *The GEO Handbook on Biodiversity Observation Networks*. Edited by Walters M, Scholes RJ. 2017:39-79.
24. Cord AF, Brauman KA, Chaplin-Kramer R, Huth A, Ziv G, Seppelt R: **Priorities to advance monitoring of ecosystem services using earth observation**. *Trends Ecol Evol* 2017, **32**:416-428.
25. Geijzendorffer IR, Martín-López B, Roche PK: **Improving the identification of mismatches in ecosystem services assessments**. *Ecol Indic* 2015, **52**:320-331.

26. •• Brauman KA, Garibaldi LA, Polasky S, Aumeeruddy-Thomas Y, Brancalion PHS, DeClerck F, Jacob U, Mastrangelo ME, Nkongolo NV, Palang H *et al.*: **Global trends in nature's contributions to people**. *Proc Natl Acad Sci U S A* 2020, **117**:32799-32805.

27. Schröter M, Barton DN, Remme RP, Hein L: **Accounting for capacity and flow of ecosystem services: a conceptual model and a case study for Telemark, Norway**. *Ecol Indic* 2014, **36**:539-551.

28. van Oudenhoven APE, Petz K, Alkemade R, Hein L, de Groot RS: **Framework for systematic indicator selection to assess effects of land management on ecosystem services**. *Ecol Indic* 2012, **21**:110-122.

29. Palomo I, Felipe-Lucia MR, Bennett EM, Martín-López B, Pascual U: **Disentangling the pathways and effects of ecosystem service co-production**. *Adv Ecol Res* 2016, **54**:245-283.

30. Bruley E, Locatelli B, Lavorel S: **Natures contributions to people: coproducing quality of life from multifunctional landscapes**. *Ecol Soc* 2021, **26**:12.

31. Schirpke U, Candiago S, Egarter Vigl L, Jäger H, Labadini A, Marsoner T, Meisch C, Tasser E, Tappeiner U: **Integrating supply, flow and demand to enhance the understanding of interactions among multiple ecosystem services**. *Sci Total Environ* 2019, **651**:928-941.

32. Washbourne C-L, Goddard MA, Le Provost G, Manning DAC, Manning P: **Trade-offs and synergies in the ecosystem service demand of urban brownfield stakeholders**. *Ecosyst Serv* 2020, **42**:101074.

33. Martín-López B, Iniesta-Arandia I, García-Llorente M, Palomo I, Casado-Arzuaga I, Del Amo DG, Gómez-Baggethun E, Oteros-Rozas E, Palacios-Agundez I, Willaarts B *et al.*: **Uncovering ecosystem service bundles through social preferences**. *PLoS One* 2012, **7**:e38970.

34. •• Chaplin-Kramer R, Sharp RP, Weil C, Bennett EM, Pascual U, Arkema KK, Brauman KA, Bryant BP, Guerry AD, Haddad NM *et al.*: **Global modeling of nature's contributions to people**. *Science* 2019, **366**:255-258.

35. Villamagna AM, Angermeier PL, Bennett EM: **Capacity, pressure, demand, and flow: a conceptual framework for analyzing ecosystem service provision and delivery**. *Ecol Complex* 2013, **15**:114-121.

36. Polasky S, Segerson K: **Integrating ecology and economics in the study of ecosystem services: some lessons learned**. *Annu Rev Resour Econ* 2009, **1**:409-434 http://dx.doi.org/10.1146/annurev.resource.050708.144110.

37. Arias-Arévalo P, Martín-López B, Gómez-Baggethun E: **Exploring intrinsic, instrumental, and relational values for sustainable management of social-ecological systems**. *Ecol Soc* 2017, **22**:43.

38. Chan KM, Gould RK, Pascual U: **Editorial overview: relational values: what are they, and what's the fuss about?** *Curr Opin Environ Sustain* 2018, **35**:A1-A7.

39. Schröter M, Başak E, Christie M, Church A, Keune H, Osipova E, Oteros-Rozas E, Sievers-Glotzbach S, van Oudenhoven APE, Balvanera P *et al.*: **Indicators for relational values of nature's contributions to good quality of life: the IPBES approach for Europe and Central Asia**. *Ecosyst People* 2020, **16**:50-69.

40. Vilá B, Arzamendia Y, Rojo V: **Vicuñas (Vicugna vicugna), Wild Andean Altiplano Camelids**. *Case Stud Environ* 2021, **4**.

41. Hill R, Nates-Parra G, Quezada-Euán JJG, Buchori D, LeBuhn G, Maués MM, Pert PL, Kwapong PK, Saeed S, Breslow SJ *et al.*: **Biocultural approaches to pollinator conservation**. *Nat Sustain* 2019, **2**:214-222.

42. Costanza R, de Groot R, Braat L, Kubiszewski I, Fioramonti L, Sutton P, Farber S, Grasso M: **Twenty years of ecosystem services: how far have we come and how far do we still need to go?** *Ecosyst Serv* 2017, **28**:1-16.

43. Pires APF, Padgurschi MCG, de Castro PD, Scarano FR, Strassburg B, Joly CA, Watson RT, de Groot R: **Ecosystem services or nature's contributions? Reasons behind different interpretations in Latin America**. *Ecosyst Serv* 2020, **42**.

44. Kadykalo AN, López-Rodriguez MD, Ainscough J, Droste N, Ryu H, Ávila-Flores G, Le Clec'h S, Muñoz MC, Nilsson L, Rana S *et al.*: **Disentangling 'ecosystem services' and 'nature's contributions to people**. *Ecosyst People* 2019, **15**:269-287.

45. • Chan KMA, Satterfield T: **The maturation of ecosystem services: social and policy research expands, but whither biophysically informed valuation?** *People Nat* 2020, **2**:1-40 http://dx.doi.org/10.1002/pan3.10137.

46. Burkhard B, Crossman N, Nedkov S, Petz K, Alkemade R: **Mapping and modelling ecosystem services for science, policy and practice**. *Ecosyst Serv* 2013, **4**:1-3.

47. Fernández N, Guralnick R, Kissling WD: **A minimum set of information standards for essential biodiversity variables**. *Biodivers Inf Sci Stand* 2019, **3**.

48. Cai J, Leung PS: *Short Term Project of Global Fish Demand and Supply Gaps*. 2017.

49. Monfreda C, Ramankutty N, Foley JA: **Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000**. *Glob Biogeochem Cycles* 2008, **22**:1-19.

50. UNWTO: *Towards Measuring the Economic Value of Wildlife Watching Tourism in Africa*. 2014.

51. Palomares MLD, Froese R, Derrick B, Meeuwig JJ, Nöel S-L, Tsui G, Woroniak J, Zeller D, Pauly D: **Fishery biomass trends of exploited fish populations in marine ecoregions, climatic zones and ocean basins**. *Estuar Coast Shelf Sci* 2020, **243**:106896.

52. Bell JD, Watson RA, Ye Y: **Global fishing capacity and fishing effort from 1950 to 2012**. *Fish Fish* 2017, **18**:489-505.

53. Tsikliras AC, Polymeros K: **Fish market prices drive overfishing of the 'big ones.'**. *PeerJ* 2014, **2**:e638.

54. Uehara T, Sakurai R, Tsuge T: **Cultivating relational values and sustaining socio-ecological production landscapes through ocean literacy: a study on Satoumi**. *Environ Dev Sustain* 2020, **22**:1599-1616.

55. Geller GN, Cavender-Bares J, Gamon JA, McDonald K, Podest E, Townsend PA, Ustin S: **Epilogue: toward a global biodiversity monitoring system**. *Remote Sensing of Plant Biodiversity*. Springer International Publishing; 2020:519-526.

56. Editors: **Essential biodiversity**. *Nat Ecol Evol* 2019, **3**:503.

57. UN: *System of Environmental Economic Accounting*. 2020.

58. Dasgupta P: *The Dasgupta Review - Independent Review on the Economics of Biodiversity Interim Report*. 2020.