Monitoring ecosystem services with essential ecosystem service variables

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In the Anthropocene, ecosystems are changing along with their capacity to support human well-being. Monitoring ecosystem services (ESs) is required to assess the changing state of human–nature interactions. To standardize the monitoring of multiple facets of ESs, the Group on Earth Observations Biodiversity Observation Network (GEO BON) recently proposed the essential ecosystem service variables (EESVs), which are organized into six classes: *Ecological Supply*, *Use*, *Demand*, *Anthropogenic Contribution*, *Instrumental Value*, and *Relational Value*. We apply the EESV framework to three case studies in British Columbia, Canada, each targeting a single ES. Using trend and intervention analysis, we show how EESVs are changing and affected by policy. We discuss key challenges and solutions while providing guidance on how to quantify EESVs. Finally, we demonstrate the potential of EESVs to harmonize metrics across conceptual frameworks, monitor ES change, and provide decision support to assess progress under various international policy conventions.

Front Ecol Environ 2024; 22(8): e2792, doi:10.1002/fee.2792

Ecosystems are central to people's quality of life. However, evidence of widespread ecosystem degradation raises concerns about the long-term supply of ecosystem services (ESs). Maintaining the sustainability of nature and human well-being over time requires systematic monitoring of ESs (IPBES 2019).

In a nutshell:

- We use essential ecosystem service variables (EESVs) to quantify changes in three ecosystem services (ESs) at different spatial scales in British Columbia, Canada: water quality filtration (regulating), commercial Chinook salmon (*Oncorhynchus tshawytscha*) fisheries (provisioning), and orca (*Orcinus orca*) whale-watching (cultural)
- We recommend that EESVs be defined to support existing conceptual frameworks and environmental conventions
- We suggest that EESVs include metadata to guide accurate data analysis, allow for multiple metrics to support many decisions and plural values, account for uncertainty in trends, and balance specificity and generality to address context-dependence
- Complementary information on causal drivers and time lag effects is needed to assess outcomes arising from policy

Yet, current studies typically rely on one-off assessments and often lack methodological standardization, hindering comparisons across space and time. To ensure that sufficient evidence exists to support trend detection in the face of global change, many local- to international-scale policy initiatives now require systematic information on changes in ESs (eg Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES], System of Environmental Economic Accounting – Ecosystem Accounting [SEEA-EA], Convention on Biological Diversity [CBD]). Such initiatives demand monitoring be standardized, policy-relevant, economically feasible, and interoperable across contexts, levels, and services. To meet this need, the Group on Earth Observations Biodiversity Observation Network (GEO BON)—an international network of experts facilitating the observation, monitoring, and delivery of biodiversity information for decision making—proposed and supported the use of the essential biodiversity variables (EBVs) framework (Pereira *et al*. 2013; Schmeller *et al*. 2018) and recently expanded it to include essential ecosystem service variables (EESVs; Balvanera *et al*. 2022).

Essential variables are standardized variables critical for detecting changes in the structure and dynamics of a facet of Earth's system (eg climate, ocean, biodiversity, ESs). In the context of ESs, EESVs track interactions between people and nature, particularly how nature contributes to human well-being through ESs (Balvanera *et al*. 2022). GEO BON proposed six EESV classes, which we summarize here (see Balvanera *et al*. [2022] for detailed descriptions). *Ecological Supply* is the ecosystem structure or function that influences an ecosystem's potential to deliver ESs. *Use* is the actualized appropriation of an ES by humans. *Demand* is the implicit or explicit desire or need for an ES. *Anthropogenic Contribution*

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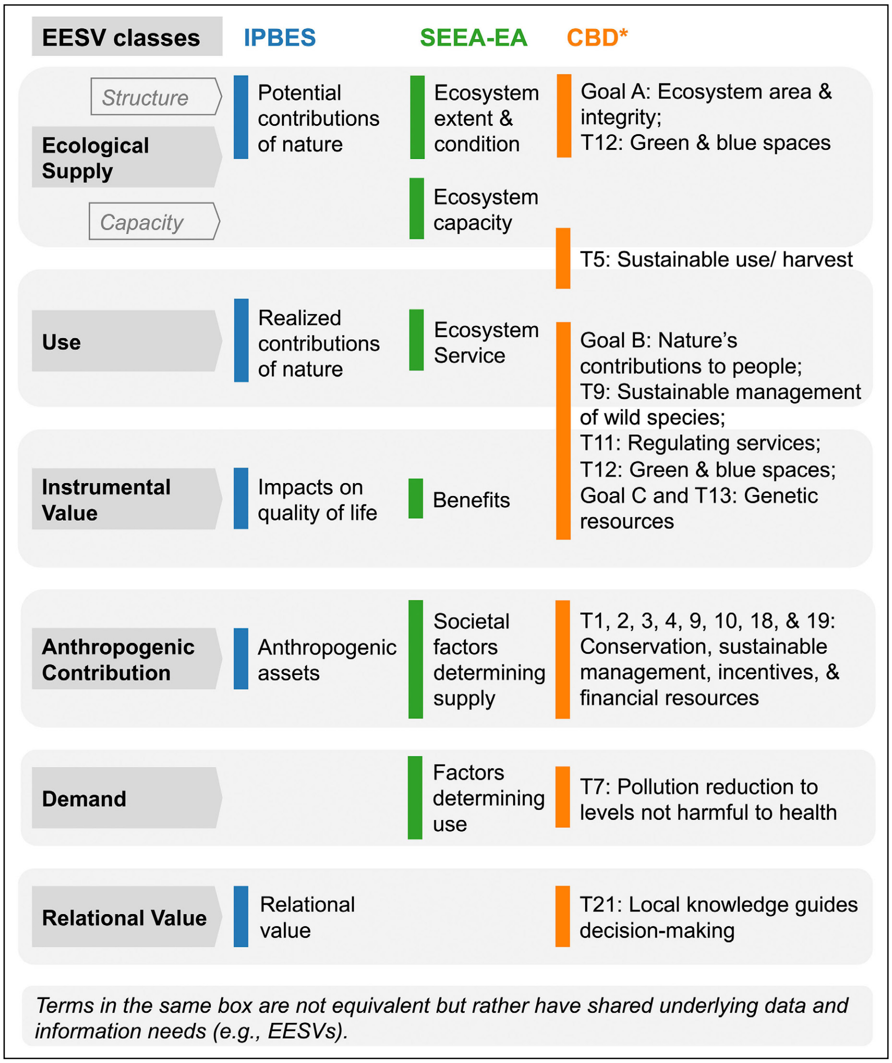

Figure 1. Potential links between essential ecosystem service variables (EESVs) and information needs among the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (IPBES 2019; Brauman *et al.* 2020), System of Environmental Economic Accounting – Ecosystem Accounting (SEEA EA) (see Annex 6.1 in United Nations *et al.* [2021]), and the Global Biodiversity Framework of the UN Convention on Biological Diversity (CBD) (*see CBD [2022] for complete descriptions of Goals and Targets [T]). Suggested links are only illustrative, not exhaustive. Terms within the same light gray rectangle are indicative of shared underlying information needs (EESVs), demonstrating the potential of EESVs to harmonize metrics across frameworks, a step toward interoperability.

is the investments humans make to increase *Ecological Supply* or *Use*, often through the process of co-production. *Instrumental Value* is the benefit(s) obtained from an ES. *Relational Value* is the importance ascribed by people to positive relationships between humans and nature and among humans via nature. *Relational Value* represents a step toward plural valuation, which seeks to include values held by diverse groups and their unique worldviews (Jacobs *et al.* 2020; IPBES 2022; Pascual *et al.* 2023).

EESVs were conceived as broad categories of variables that can be measured at the global scale (Balvanera *et al.* 2022). By focusing on multiple elements along the ES cascade, the EESV framework can support comprehensive assessments of social–ecological interactions central to sustainability (Firkowski *et al.* 2021). As such, EESVs have the potential to inform international policy conventions (eg CBD) and their monitoring requirements, while also supporting assessments by various science-policy frameworks (eg IPBES, SEEA-EA) (Figure 1). However, because monitoring efforts are usually undertaken to inform decisions at regional or local levels, scientists and decision makers need practical guidance for monitoring EESVs to understand ES change at these levels. Here, to address this knowledge gap, we present three case studies that highlight the first steps toward monitoring EESVs. We discuss challenges in applying the EESV framework and suggest pathways to overcome them.

Key steps of EESV analysis

First, we support GEO BON's initiative of knowledge hubs that engage stakeholders, rights holders, experts, interdisciplinary scholars, and decision makers to collectively determine the choice of EESVs to monitor, types of decisions to support, and whose ESs to prioritize. Following a common understanding among parties, we propose that monitoring EESVs be organized into four steps: (1) define EESVs and acquire primary data, (2) transform data into EESVs, (3) analyze and interpret trends in EESVs for decision making, and (4) use EESVs to assess the impact of policy or management interventions. We distinguish between guidelines for assimilating data into EESVs (steps 1 and 2) and aggregating EESVs from many locations into indicators for decision support at a specific level (steps 3 and 4). Results from the case studies are embedded in each step.

Study areas and case study descriptions

Our case studies are in British Columbia (BC), Canada (Figure 2a), and are part of the Pan-Canadian network for studying ESs (ResNet, www.nsercresnet.ca). Each case study focuses on a single ES, uses a different set of EESV classes, and represents an example workflow for reaching the steps defined above. Water-quality regulation (regulating ES) focuses on *Demand* and highlights challenges in developing EESVs (step 2), including the importance of delivering and reporting EESVs at fine spatiotemporal resolutions. Wild food from marine fisheries through

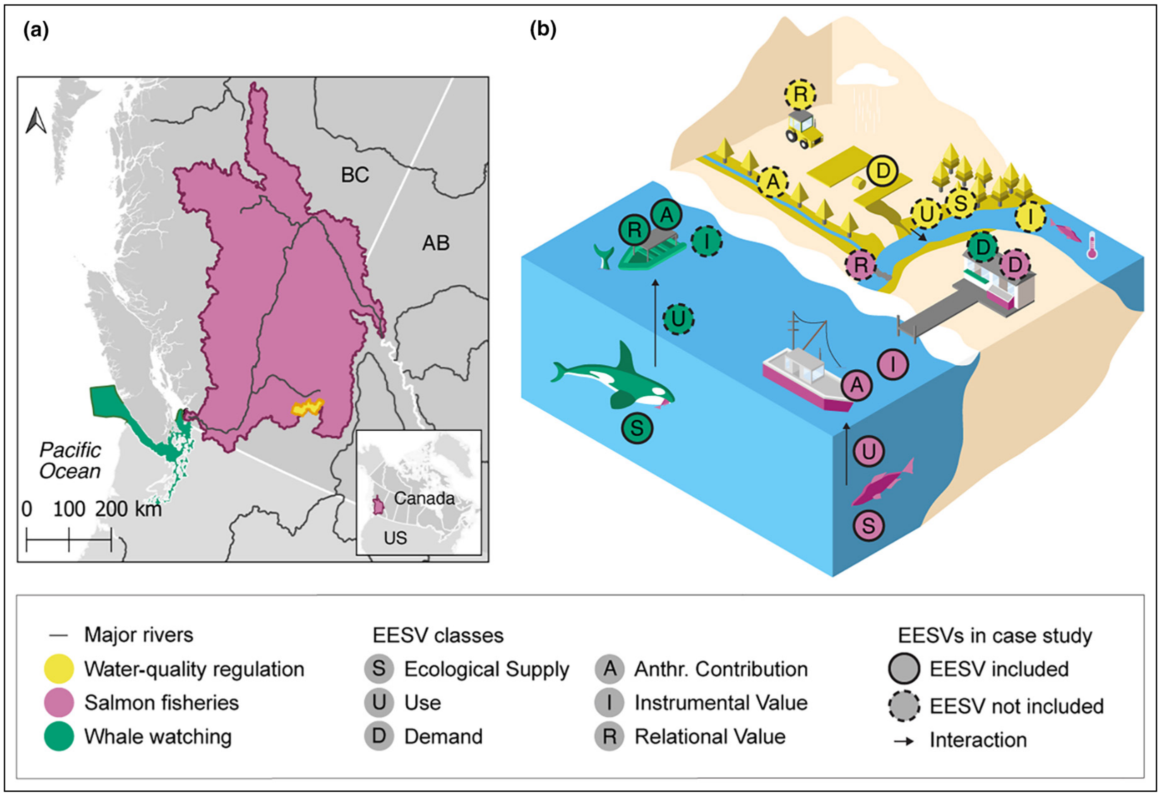

Figure 2. (a) Study areas in British Columbia, Canada, for three case studies: water-quality regulation (Salmon River watershed), wild food provisioning through Chinook salmon (*Oncorhynchus tshawytscha*) fisheries (Fraser Basin), and orca (*Orcinus orca*) whale-watching (foraging area in the Pacific Ocean; DFO 2018). Province abbreviations in map: BC (British Columbia) and AB (Alberta). (b) Conceptual figure illustrating the EESV classes and drivers of change for each case study. Interactions can occur within and among ESs through the EESV classes. For example, water-quality degradation from pollution and rising temperatures coupled with overfishing may lead to Chinook population crashes, which in turn may cascade to reduce orca whale-watching through declines in orca populations.

Chinook salmon (*Oncorhynchus tshawytscha*) fisheries (provisioning ES) focuses on *Ecological Supply*, *Use*, *Instrumental Value*, and *Anthropogenic Contribution*. This case study on wild food presents considerations on accurate trend analyses (step 3) and demonstrates how changing the spatial unit of aggregation affects the interpretation of trends. Wildlife viewing (cultural ES) through whale-watching of Southern Resident orcas (*Orcinus orca*) focuses on *Ecological Supply*, *Relational Value*, and *Anthropogenic Contribution*. This case study on wildlife viewing illustrates how EESVs can aid in policy impact assessments through intervention analyses (step 4). (See Appendix S1: Panel S1 for additional methods.)

These three ESs illustrate important conflicts over water (quality and amount), land-use intensification, fisheries, tourism, and conservation, which are likely of broad relevance. In BC, salmon fisheries are important to the way of life of Indigenous communities, the environment, and the economy. Salmon populations have declined due to climate change, overfishing, and habitat loss partly due to intensive agriculture. Water-quality regulation supports Chinook salmon in freshwater ecosystems, and as the preferred food source of orcas, adult Chinook populations in marine systems support orca whale-watching. As such, these three ESs interact across space and time (Figure 2b).

Step 1: define EESVs and acquire primary data

We begin by proposing EESVs that represent shared metrics among IPBES and SEEA-EA, ensuring EESVs inform these global initiatives (Figure 1). In practice, a few metrics are not aligned (see Appendix S1: Table S1) and therefore compromises will be required. IPBES and SEEA-EA are designed by different decision makers for specific contexts and thus use unique terms. Instead of standardizing terms, however, we propose that EESVs focus on standardizing information needs and harmonizing methods. For example, consider the case study of wild food from marine fisheries and the metric "amount of harvested food", which is conceived differently among frameworks (eg as an "ecosystem service" by SEEA-EA but a "realized nature's contribution" by IPBES). Although the terms are not standardized, there is interest in monitoring this metric, which most closely aligns with the EESV *Use*.

While the EESV framework requires variables to be comparable and interoperable across national levels to facilitate global assessments, monitoring for decision support requires data relevant to unique contexts, scales, and priorities. Thus, to balance specificity and generality, we suggest that EESVs be inclusive of many local contexts but allow for flexibility in application. For example, the EESV *Anthropogenic Contribution* for wildlife viewing can be measured broadly as infrastructure to support *Use* and measured locally as "boats accompanying wildlife" for marine systems and "road and trail density" for terrestrial systems. Furthermore, the EESV *Demand* for water-quality regulation can be defined broadly as the pollution retention needed to meet a water-quality guideline. However, pollutant type (eg nutrients, pathogens) could depend on local contexts (eg dominant polluters, needs of beneficiaries). In doing so, EESVs can be defined to support many decisions.

Throughout, we suggest that EESVs reference the target group of beneficiaries. For example, in the case study of wild food from marine fisheries, Balvanera *et al.* (2022) proposed the EESV *Use* as "fish catches used as a source of food", which does not reflect that available data typically restrict monitoring to commercial fishers. Including beneficiaries in the EESV name (eg catch of salmon by the commercial Canadian fishing fleet) or metadata could reveal data gaps and guide future funding decisions that are more inclusive of multiple beneficiary groups.

Although Balvanera *et al.* (2022) originally advocated for selecting only one EESV per EESV class to ensure feasibility, multiple EESVs may be needed when informing distinct policy or management decisions. The type of variable might also differ with multiple aspects of human well-being, each with unique units and each benefiting a unique group (eg water-quality regulation can lower disease risk for swimmers, avoid costs for wastewater treatment facilities, and increase profits for fishing industries; Keeler *et al.* 2012). (See Appendix S1: Table S1 for additional examples.)

Once EESVs were defined, we focused on EESV classes with readily available data. Nevertheless, we also identified EESVs with available data that would require additional resources and time for assimilation beyond this study (Appendix S1: Table S1). For all case studies, acquiring data depended on practical considerations (eg availability, access, ownership; Wilkinson *et al.* 2016; The First Nations principles of OCAP®, FNIGC 2022). None of the case studies had readily available data for all EESV classes and no EESV class had readily available data for all case studies. For EESV classes involving political and economic interests (eg *Demand*, *Anthropogenic Contribution*, *Instrumental Value*), data accessibility was often limited by privacy concerns, requiring data agreements, purchase, or aggregation. *Relational Values* were only available for one case study, highlighting a data gap of special importance to move valuations of ecosystems beyond market-centric ideologies and toward plural valuation, which recognizes varied notions of good quality of life across diverse groups with unique worldviews (Chan *et al.* 2016; IPBES 2022).

Step 2: transform data into EESVs

Converting data into information (eg EESVs) requires data processing and integration. ES monitoring spans many fields. Hence, data are often reported within field-specific spatial units (eg point sampling, grid, municipality, watershed) through time. Instead of aggregating to a common spatiotemporal unit, we propose that EESVs be reported at the finest spatiotemporal resolutions possible to support diverse applications, as illustrated by the water-quality regulation case study.

In this case study, we focus on *Demand*, which we define as the pollution retention needed to meet water-quality guidelines and standards (Villamagna *et al.* 2013; Baró *et al.* 2015). *Demand* represents pollutant levels that remain after ecosystems have already filtered and retained pollutants on the landscape and therefore should be considered as unsatisfied, unmet, or remaining demand (Baró *et al.* 2015; Geijzendorffer *et al.* 2015). Quantifying *Demand* requires both data on pollution levels and consensus on the desired water-quality guidelines, which may vary by use of clean water, target species, location, governing agency, and pollutant. Therefore, more than one *Demand* EESV may be needed to account for multiple pollutants and uses of clean water (eg drinking, swimming, fishing; Figure 3, a–c). Each *Demand* EESV would also require metadata justifying the associated water-quality guideline. (See Appendix S1: Panel S1 for more information on the water-quality guidelines selected in this case study.)

Here, we suggest only including *Demand* EESVs using water-quality guidelines that support known uses relevant for each water body. For instance, Shuswap Lake, in south-central BC, supports many uses, including recreation and drinking water (Figure 3a; Province of British Columbia and Pespesellkwe te Secwepemc 2022), whereas Salmon River, located in the same region, supports livestock watering, recreation, and salmon fisheries (Figure 3, b and c; Chalifour *et al.* 2022). *Demand* metrics could also be weighted by population density; however, simple spatial overlays may lead to over- or underestimates, for example when not considering non-local tourists or sociocultural preferences for different uses of clean water.

Finally, we suggest reporting EESVs at fine temporal resolutions to capture seasonal interactions among ESs. Unmet *Demand* for clean water by people who fish occurs when dissolved oxygen concentrations fall below 9.5 mg/L, a minimum threshold that protects salmon embryo development (CCME 1999). In the Salmon River, unmet *Demand* occurs primarily in the summer, but increasingly extends into September during peak spawning (Burt and Wallis 1997), when embryos are most vulnerable to low concentrations of dissolved oxygen (Figure 3, c and d; Appendix S1: Panel S1). To support diverse applications, we suggest EESVs be developed and delivered at the finest spatiotemporal resolutions possible, especially for EESVs with large variability across time (eg season) and space.

Step 3: analyze and interpret trends in EESVs for decision making

To ensure accurate EESV trend detection, we argue that associated metadata could be used to guide the selection of appropriate historical baselines and reference sites, and account for monitoring method changes and spatial bias in data quality and completeness. To illustrate this, we focus on *Ecological Supply* for the Chinook salmon fisheries case study (for additional trends on *Use*, *Instrumental Value*, and *Anthropogenic Contribution*, see Appendix S1: Panel S1). Salmon populations in BC have been declining due to many interacting drivers, including climate change, unsustainable harvest, and loss and degradation of habitat. This decline has sparked the implementation of extensive commercial fishery closures by the federal agency Fisheries and Oceans Canada. Using Generalized Least Squares (Pinheiro *et al.* 2021) for trend analysis, we demonstrate that the significant changes in Chinook spawner abundance, *Ecological Supply*, at the conservation unit level are eroded when aggregating across many populations, where the trend at a regional level (Fraser Basin) is nonsignificant (Figure 4; PSF 2022). This illustrates the need for local-level trend assessments even for regional-level decision making. Reporting EESVs at fine spatiotemporal resolutions will support trend analysis at scale(s) most relevant for different decision makers. Here, we focus on abundance trends; however, monitoring salmon populations requires many metrics (DFO 2016).

Inconsistent methods and the lack of appropriate baselines and contemporary reference sites can interfere with trend detection. We used expert-derived start years (Figure 4) to avoid artifacts from changing data quality and monitoring methods (Brown *et al.* 2020). However, some areas may still lack appropriate historical baselines. In these cases, EESVs can be compared to equivalent reference sites instead of relying solely on trend analysis (Gonzalez *et al.* 2016, 2023). Otherwise, nonsignificant trends could be interpreted as evidence for stability, when in fact they may reflect an already degraded state.

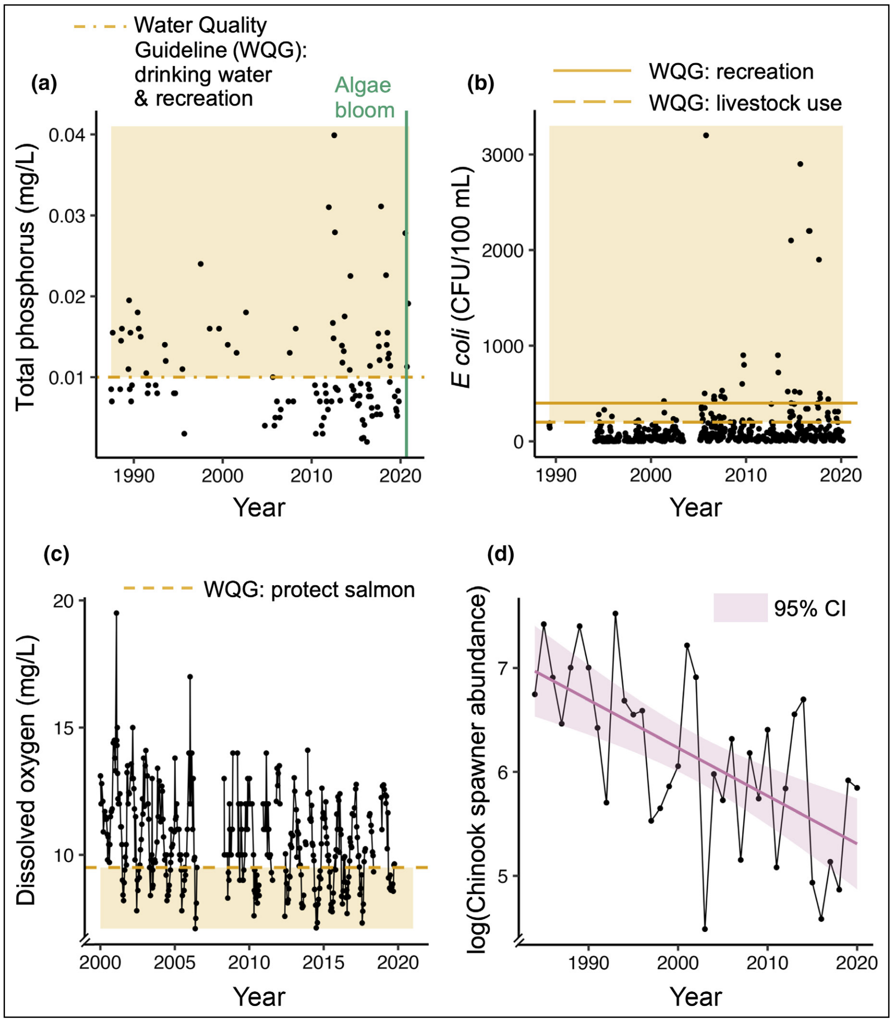

Figure 3. Unmet *Demand* over time for water-quality regulation by different beneficiaries: (a) drinking water treatment industry and recreationists, (b) recreationists and people who raise livestock (Teucher and Harker 2022), and (c) people who fish (eg industry and local communities; ECCC 2021). *Demand* is unmet (a–c, orange shading) when pollution levels exceed water-quality guidelines (WQGs), each protecting different uses of clean water for (a) Shuswap Lake and its upstream tributary (b–d) Salmon River. (c) Dissolved oxygen concentrations increasingly fall below a threshold protecting aquatic life, with potential impacts to (d) *Ecological Supply* of salmon (DFO 2021). In (a–d), black circles indicate individual data points. In (d), the dark pink line represents the Generalized Least Squares (GLS) regression, and the light pink shaded area denotes the 95% confidence interval (CI) for the GLS regression. CFU = colony forming unit.

Furthermore, when aggregating up for regional ES assessments, spatial and temporal bias in data quality and completeness can also impact trend assessments. For example, Chinook population data in southern BC are of higher quality and contain fewer missing data points (PSF 2022), which can increase this region's influence on provincial-level trends. Including metadata on appropriate baselines, changes in monitoring methods, and spatial and temporal bias in data quality could avoid misinterpretations of EESV trends.

Step 4: assess the impact of policy or management interventions

While the EESV framework accounts for multiple dimensions of ESs, the framework does not consider social and ecological drivers of change, which are complementary pieces of information needed for trend attribution and to support decision making to mitigate the effects of drivers. Here, we

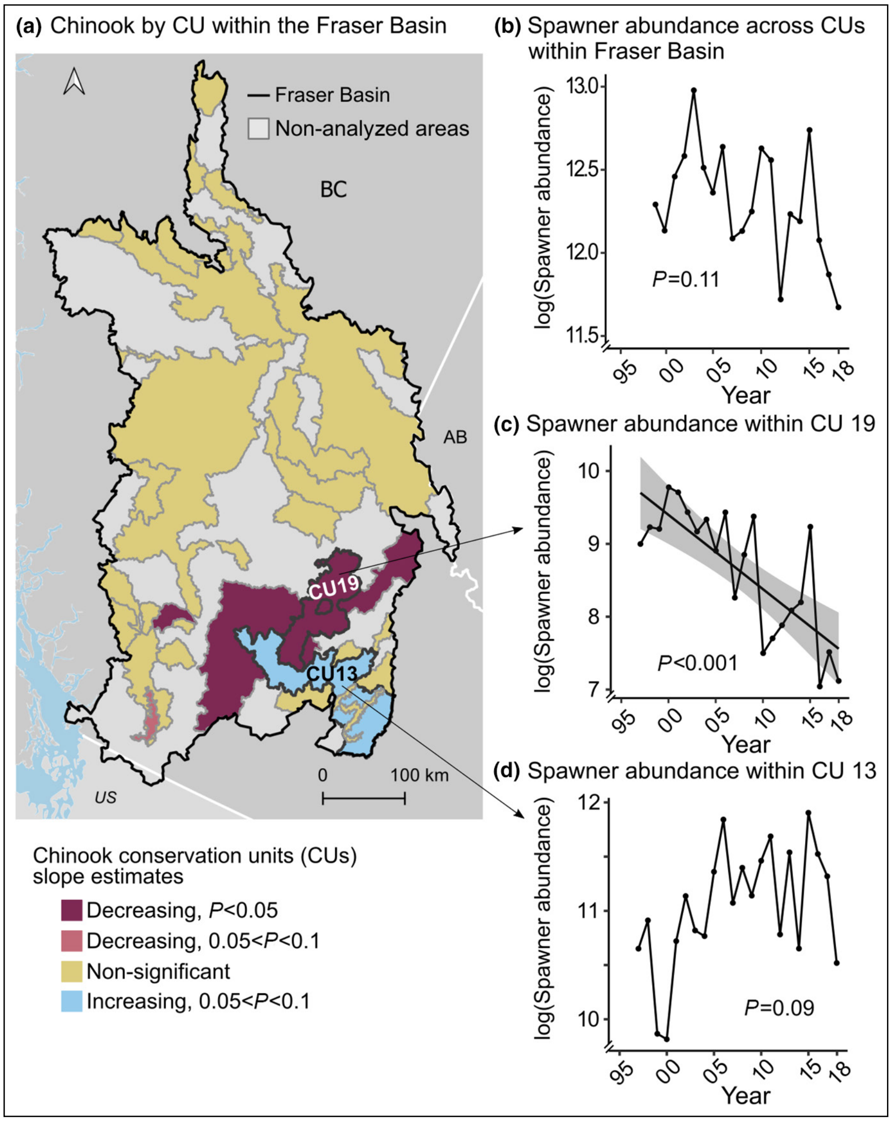

Figure 4. Assessing the impact of reporting unit size on *Ecological Supply* trends for Chinook salmon provisioning. (a) Within conservation units (CUs), trends in spawner abundance varied: five CUs were decreasing ($P < 0.05$, dark red; $0.05 < P < 0.1$, pink), one CU was increasing ($0.05 < P < 0.1$, blue), and eight CUs were nonsignificant (yellow). (b) When data were summed across CUs in the Fraser Basin, the overall trend was nonsignificant. Start years vary to avoid artifacts from inconsistent monitoring methods and data quality. Plots have different y-axes to visualize trends representing differently sized areas. In (b–d), black circles indicate individual data points. In (c), the straight black line represents the Generalized Least Squares (GLS) regression, and the gray shaded area denotes the 95% confidence interval for the GLS regression. Data source: PSF (2022).

demonstrate the value of including drivers of change and time lag effects when assessing policy impacts through a case study of the cultural ES provided by the Southern Resident orca population in BC (hereafter, Southern Residents), which focuses on *Ecological Supply*, *Anthropogenic Contribution* to improve *Use*, and *Relational Value*.

The Southern Resident population has been in decline over the past several years. In 2018, the Federal Government of Canada established its first protection policy for Southern Residents, stating that all vessels (eg commercial, recreational, kayaks) should operate 200 m away from all Southern Residents in critical habitat areas (Frayne *et al.* 2020; Kassakian and Flight 2020). Since then, the Canadian members of the whale-watching industry signed an agreement to end tours on Southern Residents or viewing them while in transit. We assessed the impact of this policy on the Southern Residents (*Ecological Supply*; CWR 2021) using an autoregressive integrated moving average (ARIMA) intervention analysis (Hyndman and Khandakar 2008; Schaffer *et al.* 2021), in which observed data are compared to a counterfactual forecast (ie a model prediction in the absence of any policies). Unlike segmented regressions, ARIMAs can account for data autocorrelation and seasonality, serving as a simple yet robust method for time-series analysis (Appendix S1: Panel S1; Schaffer *et al.* 2021).

If only information about *Ecological Supply* is considered, it could be assumed that the interventions were not helpful (Figure 5a; Akaike information criterion corrected for small samples [AICc] = 81.2). However, the best-fitting ARIMA models had as regressors the EESV *Anthropogenic Contribution* (the number of any type of vessels accompanying the Southern Residents) and an internal driver of change (the number of observed incidents between whale-watching vessels and Southern Residents; Figure 5b: AICc = 79.0; Appendix S1: Figure S3: AICc = 78.2). In addition, the best-fitting models included lagged responses to these regressors. Compared to the counterfactual forecast, the results in Figure 5b suggest that the policy had a positive effect on *Ecological Supply*.

The ARIMA intervention analysis can be applied across EESV classes and drivers. Our results further indicate that although the policy intervention by the Canadian Government had a limited effect on *Anthropogenic Contribution* (Figure 5c), the policy helped reduce the number of observed incidents between whale-watching vessels and Southern Residents (Figure 5d)—a major concern for the continuing welfare of these orcas. From an EESV perspective, understanding the policy's effect on *Use* (eg the number of people experiencing whale-watching) would also be helpful, yet data are often unavailable. However, *Anthropogenic Contribution* and *Use* are related, given that *Use* depends on the types of vessels used for whale-watching (eg a large boat carrying many passengers versus an individual kayak). Therefore, data on

Anthropogenic Contribution per vessel type may serve as a proxy for *Use* and thus be used to disentangle the policy's positive effect on *Ecological Supply* by reducing observed incidents while potentially maintaining *Use*.

This case study focused on one type of decision. Alternatively, if other competing or complementary interests were targeted (eg conservation versus economic, local visitors versus tourism), engagement with a different group of rights holders and stakeholders could determine whether additional EESVs were needed. For instance, acquired data on *Relational Value* were only representative of the general public and their awareness of the Be Whale Wise guidelines (Appendix S1: Panel S1). Including other metrics of *Relational Value* would be necessary to reflect a plurality of values, including those held by Indigenous peoples.

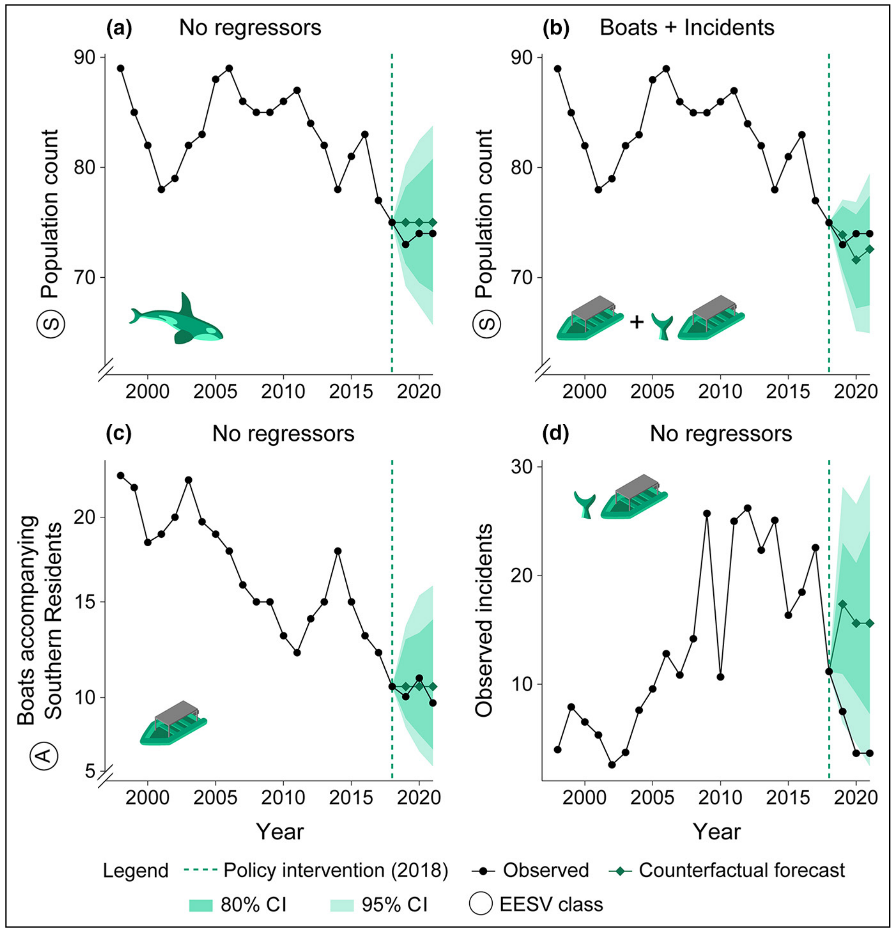

Figure 5. Autoregressive integrated moving average (ARIMA) intervention analysis reveals the positive impact of a policy on *Ecological Supply* (S) when drivers and time lag effects are considered. (a) Only considering *Ecological Supply* underestimates the policy impact on protection of Southern Resident orcas. (b) Best-fitting models included regressors and lagged responses, showing a positive effect of the intervention. (c) The policies had a limited effect on *Anthropogenic Contribution* (A), but (d) helped contain observed incidents. For *Relational Value*, see Appendix S1: Panel S1. Data from CWR (2021) for (a) and (b), and from Frayne *et al.* (2020) for (a) through (d).

Moving forward

The EESV framework was proposed to define variables that capture multiple human–nature dimensions of ESs, as represented by the six EESV classes. Although essential variables can improve efficiency, effectiveness, and ease of communication with decision makers, operationalizing the framework for monitoring is still in its infancy.

Here, we propose EESVs as common metrics, a first step toward interoperability. As GEO BON guidelines suggest, a diverse group of rights holders and stakeholders should determine which ESs to prioritize and their associated EESVs. Furthermore, periodic engagement with rights holders and stakeholders could assess EESV quality and propose improvements based on newly acquired data, knowledge, and changing values over time. Taking this adaptive and iterative monitoring approach would ensure the future usefulness of EESVs.

In addition, clarification on the definition of *Ecological Supply* could improve standardization. As defined, *Ecological Supply* encompasses multiple components: potential contributions, ecosystem structures (eg stocks, extents, conditions), capacities, and functions (Schröter *et al.* 2014; Balvanera *et al.* 2022). In the salmon fisheries example, *Ecological Supply* could be defined as potential contribution (eg ocean fish stocks; Brauman *et al.* 2020; Balvanera *et al.* 2022) or capacity (eg recruitment rates [Schröter *et al.* 2014], sustainable fish catch rates [La Notte *et al.* 2019]). These distinctions are important because different components (eg capacity, function, structure, stock, extent, condition, potential contribution) of *Ecological Supply* could support different policy decisions. For instance, in the water-quality regulation case study, capacity can be defined as the pollution that can be degraded, while meeting a water-quality guideline (La Notte *et al.* 2019). Capacity can account for spatial context (eg slope, location of streamside habitat, site of pollution), and as such could be especially valuable in informing decisions on where to focus conservation and restoration efforts.

These three case studies revealed important findings about how to define EESVs (step 1), how to develop EESVs (step 2), how to interpret trends in EESVs (step 3), and how to use EESVs in policy assessments (step 4). Metrics are often aggregated across many locations to inform a policy decision or research question at a specific level. However, trends can change sign, strength, and/or significance depending on the aggregation level. Therefore, to ensure comparability across ESs and classes and for accurate trend analysis, we suggest that EESVs be reported at both fine spatial resolutions (eg as shown in the salmon fisheries case study) and fine temporal resolutions (eg as shown in the water-quality regulation case study) so that analysis at different levels of aggregation can be conducted. Multiple EESVs are needed to account for many notions of a good quality of life and many aspects of human well-being, as shown by our multiple metrics of unmet *Demand* for clean water by different groups of beneficiaries in the water-quality regulation case study. Furthermore, our case studies highlight the importance of including detailed metadata for each EESV, including on the targeted beneficiaries (eg commercial versus local fishers), changing data quality across time as shown in the salmon fisheries case study, and justifications for selecting a health guideline in defining *Demand* as shown in the water-quality regulation case study. We also demonstrate that when using EESVs for comprehensive policy analyses, it is helpful to employ counterfactual analysis for trend attribution (Gonzalez *et al*. 2023) and consider complementary information on drivers as shown with the whale-watching case study.

In summary, we suggest EESVs (1) be developed and delivered at spatial and temporal resolutions that best support decisions at the appropriate scale(s); (2) include metadata on changing data quality; (3) use appropriate baseline years and reference sites for robust trend analysis; (4) select metrics and measures of uncertainty that are adapted to support decisions by individuals, communities, businesses, and governments; (5) endeavor to use metrics with clear units to aid in comparisons across time and study; (6) explicitly state included beneficiaries in the metadata; (7) balance specificity and generality to address local contexts (eg dominant pollutants, charismatic megafauna, dominant species caught for food); and (8) employ counterfactual analysis for trend attribution. Multiple EESVs per EESV class may be needed to account for many decisions and plural values. Even in areas with high data availability, such as BC, monitoring across all EESV classes would entail substantial time and resources. Ensuring future feasibility will require continued advances in global ES modeling (eg Chaplin-Kramer *et al*. 2019, 2022), assimilation of diverse data sources (eg remote sensing, social media, citizen science; Cord *et al*. 2017), and potential implementation of a tiered approach with method options varying with data availability (eg SEEA-EA; United Nations 2022).

Conclusion

We found that the EESV framework can (1) account for multiple dimensions of ESs, (2) provide a valuable pathway for linking data to monitoring and decision support, and (3) encourage comparisons and interconnections among ES indicators adopted by the monitoring frameworks of different policy agendas and conventions. Next steps will require tool development, method harmonization, and continued consideration of EESVs to support decision-making processes designed to implement policies for ES targets.

Acknowledgements

We thank The Whale Museum and the Soundwatch Boater Education Program for providing the data used in this manuscript. We acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC): funding reference number NSERC NETGP 523374-18. AG is supported by the Liber Ero Chair in Biodiversity Conservation. M-JF is supported by the Canada Research Chair in Spatial Ecology. Cette recherche a été financée par le Conseil de recherches en sciences naturelles et en génie du Canada (CRSNG): numéro de référence NSERC NETGP 523374-18.

Data Availability Statement

All data are already publicly available, with the exception of data from the whale-watching of the Southern Resident orcas case study, which are sensitive and only available through agreements with The Whale Museum and the Soundwatch Boater Education Program (info@whalemuseum.org).

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