Applying essential ecosystem service variables to analyse thirty years of wild salmon provisioning trends in Canada

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Abstract

Systematic monitoring of ecosystem services (ES) is crucial for achieving sustainability goals but hampered by siloed and disjointed monitoring efforts that rarely consider the full range of social, economic, and ecological variables shaping ES dynamics. The essential ecosystem service variables (EESV) framework is intended to tackle these challenges but its application remains limited. Using British Columbia's wild Pacific salmon commercial fishery as a case study, we conduct the first operationalization of the EESV framework, integrating 27 years of monitoring data from diverse sources to assess change in the ES provided by wild Pacific salmon fisheries in a multi-species analysis conducted at the provincial scale of BC. We develop and test a causal model incorporating five essential variables (salmon abundance, fishing effort, salmon catch, landed value, and market demand) and seven drivers, including sea surface temperature, hatchery releases, and fishing licenses. Our results show that rising sea surface temperatures negatively impact salmon returns, while population enhancement through hatcheries has generally weak effects, with some evidence suggesting that they may be causing declines in abundance. We also evaluate the government's license retirement program, finding limited success in reducing fishing effort and improving the industry's financial viability. Bayesian modeling highlights greater uncertainty in ecological versus socio-economic predictions, suggesting an opportunity for better monitoring. Crucially, the inability to operationalize the *relational value* EESV class underscores limitations in current monitoring programs. Overall, our findings show market forces sustaining ES value despite declining effort and uncertain ecological dynamics. By demonstrating the EESV framework's utility for integrating data into a causal representation and diagnosing monitoring system limitations, this study advances the methodology needed for standardized ES monitoring in the case of provisioning services.

Keywords

Monitoring, ecosystem services, essential variables, Pacific salmon, wild fish provisioning services

Introduction

Ecosystem degradation and the consequent decline in expected benefits from healthy ecosystems are a major policy concern (Diaz et al. 2019). Increasing national and global attention is being paid to the importance of ecosystems for the health of people and the economy (Peterson et al. 2018). This recognition has led to a push for effective management of ecosystem services (i.e., the contributions of nature to human wellbeing). Indeed, ecosystem services are already part of policy agendas worldwide, including the Kunming-Montreal Global Biodiversity Framework, which calls for nations around the world to value, maintain and enhance ecosystem services (CBD 2022). However, understanding how these ecosystem services are changing remains a significant challenge (Vaz et al. 2021; Bennett et al. 2015). While international agreements increasingly ask for their systematic monitoring, progress is hindered by conceptual ambiguity (Affinito et al. 2025), fragmented data across ecological and social domains (Vári et al. 2025), and a lack of operational frameworks designed to detect and attribute change in complex social-ecological systems (Gonzalez, Chase, et al. 2023). Addressing these gaps is crucial for providing the evidence needed to guide policy and ensure the resilience of both ecosystems and the societies that depend on them.

Ecosystem services are not simply outputs from nature, but rather emergent system properties arising from the dynamic interactions within social-ecological systems (Affinito et al.

2025). They are co-produced through interacting processes where ecological functions (e.g., fish population growth) interact with human inputs (e.g., fishing activity), demand (e.g., market price dynamics), governance (e.g., quotas), and values (e.g., economic and cultural) to improve human wellbeing (Brauman et al. 2020). Therefore, understanding and monitoring ecosystem services necessitates a holistic, social-ecological perspective that tracks these multiple, interacting dimensions to capture how changes in any part of the system affect the overall service provision.

Fisheries provide important provisioning ecosystem services (i.e., the tangible contributions of nature used and consumed by humans – food, timber, water, …), supporting the livelihoods of at least 600 million people worldwide and feeding about 3.3 billion people (FAO 2022). Additionally, local fisheries provide important cultural benefits and a sense of place to communities (Noble et al. 2016). In Canada, and specifically British Columbia (BC), the fishing industry has and continues to play an important role in the development of the country's culture, economy and food security (Ministry of Agriculture and Food 2023; Castañeda et al. 2020). The strong upwelling off the coast has historically supported thriving capture fisheries and a highly productive ecosystem (Whitney and Robert 2002). Wild Pacific salmon, in particular, are an ecological and cultural keystone species in BC. They are foundational to the ecosystems of the coast (Cederholm et al. 1999) and key to the food security, culture, economy and sovereignty of numerous First Nations, whose rights and traditional knowledge are central to modern salmon management (Atlas et al. 2021). Wild salmon also support significant recreational fisheries and are an icon for the province at large (Nesbitt and Moore 2016). However, the share of total economic value of capture fisheries has declined significantly since 1991, with wild salmon going from being the dominant capture fishery to a minor contributor (Lilian Hallin Consulting 2022) and there are significant concerns surrounding the conservation status of multiple populations (Price et al. 2017). The management of the wild BC salmon continues to be a contentious issue due to the species' ecological, financial and cultural importance. The federal and provincial governments have consequently invested significant resources in the monitoring of salmon stocks and fishing effort to help guide the sustainable management of this important fishery (DFO 2018; Canada 2005), but they have not taken an ecosystem service perspective.

Monitoring data can provide the basis for the detection and attribution of change in ecosystem services (Schwantes et al. 2024). Yet, conventional monitoring often fails to capture the full picture for ecosystem services. In British Columbia, for example, commercial salmon fisheries are monitored by various agencies focusing on specific mandates (e.g. conservation or resource management), resulting in a wealth of data that remains fragmented across ecological, economic and social domains. This disjointedness hinders integrated analysis and makes it difficult to understand the complex interactions and trade-offs inherent in ecosystem service provision, a common challenge in ecosystem service assessments globally (Bagstad et al. 2025). While many studies analyse components of the Pacific salmon social-ecological system, they often lack a standardized structure to integrate these dimensions for holistic monitoring or causal understanding of ecosystem service change.

The essential ecosystem service variables (EESV) framework was proposed specifically to address this challenge of fragmentation and enable systematic, multidimensional ecosystem service monitoring (Balvanera et al. 2022). It proposes that monitoring ecosystem services be focused on six classes of essential variables (*ecological supply*, *anthropogenic contribution*, *demand*, *use*, *instrumental value*, and *relational value* – Supplementary Box 1) representing the critical links in the co-production of ecosystem services by people and nature (Balvanera et al. 2022). By organizing observations into these classes, the framework aims to transform heterogeneous data into consistent, analytically ready variables suitable for detecting change, attributing its causes, and informing management (Gonzalez, Chase, et al. 2023). This approach advances causal understanding of ecosystem service change by structuring data along the pathway from ecological potential to realized human benefit. However, the development and operationalization of EESVs is still nascent (Schwantes et al. 2024; Theis et al. 2025), and no study has yet demonstrated a complete empirical application integrating multiple EESV classes from disparate, real-world monitoring programs over time.

Hence, the EESV framework can be used and tested to understand the ecosystem service dynamics of commercial Pacific salmon fisheries. Data from the different organizations involved in monitoring salmon fisheries can be organized into each class and analysed in turn. Once monitoring data are linked to EESVs, we can test causal representations of a system, to estimate the status of key variables, model and detect trends in these variables and attribute drivers responsible for the observed dynamics (Grace 2024; Schwantes et al. 2025).

Our primary objective in this study is, therefore, not solely to provide a novel analysis of commercial BC salmon fisheries, but also to use this data-rich system as a critical case study to operationalize and evaluate the EESV framework itself. Specifically, we aim to: (i) demonstrate how the EESV framework can be applied to integrate fragmented, long-term (27-year) monitoring data from diverse sources (ecological, economic, social) for a provisioning ecosystem service; (ii) operationalize five EESV classes (*ecological supply*, *anthropogenic contribution*, *demand*, *use* and *instrumental value*) for five salmon species at the provincial scale; (iii) use these EESVs within a causal knowledge graph (Figure 2.1) and Bayesian modeling framework to analyse the multidimensional dynamics of the ecosystem service, explore mechanistic links, and explicitly quantify uncertainty; and (iv) use this integrated analysis to assess the effects of a long-standing policy intervention (*i.e.* license retirement). While the EESV framework conceptually includes socio-cultural dimensions broadly, particularly through the *relational value* class, our operationalization focuses on the quantifiable socio-economic aspects pertinent to the commercial fishery, for which consistent time-series data are available. By undertaking this first complete application, we aim to advance the EESV framework's development, showcase its utility and limitations in a real-world context, and provide insights for designing more effective ecosystem monitoring systems.

Supplementary Box 1. ***Essential ecosystem service variable classes defined (adapted from Balvanera et al. 2022).***

Ecological supply: the ecosystem structure and functions that underlie the potential capacity of ecosystems to provide ecosystem services.

Anthropogenic contribution: the efforts that humans invest to enhance ecological supply and/or to make use of ecosystem services. These include knowledge, effort, time financial resources, materials and technology.

Demand: 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: the active or passive appropriation of an ecosystem service by people, highlighting the actual appropriation of benefits from nature (i.e. the realized benefits).

Instrumental value: the importance of an ecosystem service to societies or individuals as a means to an end (e.g. some dimension of human well-being) both in economic and/or sociocultural terms.

Relational value: the importance ascribed to how ecosystems contribute to desirable and meaningful interactions between humans and nature and between humans in relation to nature. Relational values, such as care, responsibility and stewardship, are embedded in the practices, knowledge and visions that support ecosystem management.

Methods

Understanding the system and identifying EESVs

The EESV framework takes a social-ecological perspective of ecosystem services, calling for a holistic analysis of ecological, social and economic data together. Therefore, applying the framework requires a deep understanding of the system and causal pathways influencing its dynamics. We searched public databases and discussed with fisheries scientists, government employees and non-governmental organizations to find out what data on salmon fisheries was available in British Columbia and from whom we could obtain it. We used these conversations as well as grey and primary literature to develop a causal knowledge diagram that represents the Pacific salmon fisheries system (Figure 2a).

EESVs, like other essential variables (Bojinski et al. 2014), are intended to be scientifically robust, policy relevant and cost-effective. Thus, we identified existing datasets that correspond to each of the EESV class (Figure 3 & Table 1). Identifying which variables to use as EESVs required considering whose *anthropogenic contribution, use*, *demand*, and *values* to measure. Most of the management efforts, and therefore data available, in Pacific salmon fisheries has focused on commercial fishing (Canada 2005; DFO 2018). Therefore, we focused on the ecosystem service for commercial fishers, identifying EESVs that correspond to this beneficiary group. We identified and acquired data for five of the six EESV classes: *ecological supply*, *use*, *anthropogenic contribution*, *demand*, and *instrumental value*, and seven other relevant explanatory variables (Figure 3 & Table 1). These additional explanatory variables were included due to previously published literature on Pacific salmon and the established importance of external drivers in influencing ecosystem service dynamics (Dade et al. 2019), especially when using EESVs (Schwantes et al. 2024). Despite its recognized importance within the EESV framework, and for Pacific salmon specifically, we were unable to identify consistent, quantifiable time-series data suitable for modeling the *relational value* class for commercial fishers within our study period.

Pacific salmon are keystone species due to their anadromous life-cycle, moving nutrients from rich marine ecosystems to poorer terrestrial ecosystems when they return to spawn (Cederholm et al. 1999). In BC, there are five major commercial species of Pacific salmon – *Oncorhynchus* – (Sockeye – *O. nerka*, Chinook – *O. tshawitscha*, Pink – *O. gorbuscha*, Chum – *O. kisutch,* and Coho – *O. keta*) and 463 genetically distinct conservation units (populations that spawn in specific streams or lakes and contribute to overall genetic diversity (Holtby and Ciruna 2007)). There are now concerns over declining salmon returns (Malick and Cox 2016; Atlas et al. 2022), with some conservation units listed as endangered (COSEWIC 2021; 2020). To support stable returns, reared hatchery fish are often released as smolts in rivers to boost population numbers, but the effect of this approach shows mixed results (Myers et al. 2004). Additionally, increasing water temperatures have species-specific effects on smolts, reducing survival for some populations (Marine and Cech 2004; Grant et al. 2019). These drivers are likely to affect the ecosystem service through their impact on the abundance of salmon species (*i.e.* the *ecological supply* of the provisioning service). Therefore, using a mechanistic model of salmon abundance, we check whether our causal model is supported and test the effect of these two drivers on salmon abundance.

The provisioning service provided by Pacific salmon is realized through a commercial fishery governed by the federal Department of Fisheries and Oceans (DFO). DFO therefore oversees the industry, monitoring effort and catch numbers for all commercially harvested salmon species. A strict licensing policy and harvesting control rules set out who is allowed to harvest salmon, where, when and how. Thus, fishing effort (*i.e. anthropogenic contribution* to the provisioning service) is regulated via a set of management areas along the coast that also outline what fishing gear can be used. Total catch (*i.e. use* of the provisioning service) is counted by species and management area through a mandatory reporting programme for commercial fishers. The BC government oversees its provincial seafood industry, including commercial salmon fisheries, producing reports of sales generated from the fishery (*i.e.* the provisioning service's *instrumental value*) and employment numbers. Additional relevant socio-economic data are published by Statistics Canada. Thus, we model these variables to check for consistency with our causal model (Figure 2) and understand how the socio-economic dimensions of the ecosystem service have been changing and why.

Moreover, in an effort to allow stocks to recover, a voluntary license retirement policy has been in place for 27 years and catch quotas are updated during the fishing season as salmon run returns are estimated (DFO 1999; Canada 2005). The policy was meant to lead to a "significantly improved financial viability of those who remain in the fishery" by reducing the number of fishers in the industry (DFO 1999). While it is apparent, the policy has failed in allowing stock recovery (Riddell et al. 2018), its success in improving the financial viability of remaining fishers remains to be assessed. Three decades later, we assess the effect of the policy on the ecosystem service using the EESV data we acquired, highlighting the role of monitoring data in informing management action.

Data acquisition

Datasets were acquired from the Canadian federal government (DFO and Statistics Canada), British Columbia's provincial government, a non-profit environmental organization: the Pacific Salmon Foundation (PSF), and the European Union's Copernicus programme (Table 1). Some datasets were publicly available while others had to be requested.

The primary dataset for spawner abundance was acquired from PSF, which synthesizes monitoring data primarily from DFO's New Salmon Escapement Database (NuSEDS). It is important to note that conservation unit (CU)-level abundance time series are not direct counts but are estimates derived from a standardized run reconstruction methodology designed to account for data gaps. This process involves a multi-step expansion procedure that infills data for unsurveyed indicator streams, expands these estimates to the entire CU, and adjusts for observer efficiency (Pacific Salmon Foundation 2024). The PSF also quantifies the underlying data quality for each CU as Poor, Fair, or Good based on criteria like survey method and coverage. We acknowledge that the assumptions inherent in this estimation process introduce uncertainty, which we address further in our discussion of limitations.

All datasets had the same temporal resolution (yearly) but not the same spatial resolution (national, provincial, regional or by management area). We chose to restrict our analysis to the 1996-2023 time series (27 years), where we had data for most variables (Table 1). All time-series datasets were used in their original form, except for price per kilo data, which were calculated by dividing the income generated from the wholesale of each salmon species (wild or farmed) by the total weight sold each year.

A key challenge was integrating datasets collected at different spatial scales. Specifically, for the *use* model (described below), we needed to align spawner abundance data, aggregated from individual CUs, with DFO's catch and effort data, which are reported by management area (Figure 1). To achieve this, we first summed CU-level spawner abundance estimates into two broad regions: a North Coast group and a South Coast group. We then matched these regional abundance totals to the corresponding DFO licensing areas (North Coast to areas A, C, & F; South Coast to areas B, D, E, G, & H). This spatial aggregation is a necessary simplification for a provincial-scale analysis and follows methods used by PSF for assigning catch to populations of origin (Pacific Salmon Foundation 2024).

Table 1. Time series datasets used in the study to produce EESVs and analyse trends. Not all datasets used were classed as EESVs, some were used as drivers of change or explanatory variables in the models of EESV dynamics. Resolution varied for different time series in space and in the species/population specificity of datasets (e.g. catch was available by species but not effort).

EESV class	Dataset	Available time series length	Resolution	Data source
Ecological supply	Spawner abundance	1950-2023	Population Watershed	Pacific Salmon Foundation
-	Sea surface temperature	1981-2024	Province	Copernicus climate data store
-	Hatchery releases	1954-2023	Population Watershed	Pacific Salmon Foundation
Anthropogenic contribution	Effort (boat days)	1996-2023	Management area	Department of Fisheries and Oceans
-	Fleet size	2005-2023	Management area	Department of Fisheries and Oceans
-	Commercial licenses	1998-2024	Management area	Department of Fisheries and Oceans
Demand	Price per kilo wholesale	1997-2023	Species Province	British Columbia data catalogue
-	Disposable income	1961-2023	Nation	Statistics Canada
-	Price per kilo farmed	1997-2023	Province	British Columbia data catalogue

Use	Catch	1996-2023	Species Management area	Department of Fisheries and Oceans
Instrumental value	Landed value	1997-2023	Species Province	British Columbia data catalogue
-	Landed weight	1997-2023	Species Province	British Columbia data catalogue

EESV modeling

We modeled each EESV according to the causal knowledge graph for the Pacific salmon fishery (Figure 2). We used a Bayesian modeling framework for all EESVs. This approach allowed us to choose and customize each model freely, handle missing data and produce estimates of uncertainty. Additionally, Bayesian posterior predictions allowed us to scale model predictions up as needed (e.g. from a management area to the whole province). For each EESV, we identified and used the most relevant model from the literature. When no specific mechanistic model was found, we used a power law relationship with a mechanistic interpretation or a linear model (Figure 2b). We then tested several model specifications in each case (e.g. hierarchical or not), selecting the best model based on posterior predictive fit. All models were coded in Stan (Carpenter et al. 2017) and run in R version 4.2.2 (R Core Team 2022). Below, we present each of the EESV models (Figure 2) in turn.

For spawner abundance (*i.e., ecological supply*) we used a static Ricker stock recruitment model. While other models exist, the Ricker model is a widely recognized and applied mechanistic model for Pacific salmon species due to its assumption of overcompensatory density dependence, a dynamic common to many salmon populations (Staton et al. 2020; Ricker 1954;

Myers et al. 1998). The Ricker model uses parental abundance numbers to predict the abundance of spawners in the next generation. We obtained parental abundance estimates from each time series by selecting the abundance value from one generation earlier. We extended the model to include a temperature and hatchery term to account for the effect of these drivers on spawner returns. We linearized the Ricker model by applying a logarithmic transformation as follows:

$$log(R) = \alpha + log(S) - \beta S + \theta T + \delta H$$

Where R is the spawner abundance, α is the productivity parameter, S is parental abundance, β is the density dependence parameter, δ is the effect of sea surface temperature (T), and θ is the effect of hatcheries (H). All parameters in the model varied by species but only the productivity and density dependence parameters were estimated hierarchically across species. We also tested the inclusion of a standard auto-regressive term to account for temporal auto-correlation, but found it did not improve model fit. This is expected since the Ricker model we fit already incorporates the key biologically determined time lags that drive salmon population dynamics. Specifically, it predicts abundance based on parental abundance and hatchery releases (Figure 2) from one generation ago (2-5 years depending on species) and the sea surface temperature recorded during the migration year out to the ocean. We further checked for correlation between explanatory variables and multicollinearity in the model parameter but did not find any. Additionally, we tested for a potential interaction effect between sea surface temperature and hatcheries, but the effect size was not significant (credible intervals overlapping 0) and therefore not included in our final model.

For effort, in boat days (*i.e. anthropogenic contribution*), we used a hierarchical linear model to regress effort on fleet size across management areas and gear types. We also regressed fleet size on licence count hierarchically across management areas as follows:

$$E = b_{0e} + b_{1e}F$$

$$F = b_{0f} + b_{1l}L,$$

where E is effort in boat days, b_{0e} is the effort for the average fleet size (F), b_{1e} is the effect of fleet size on effort, b_{0f} is the fleet size for the average license count (L), b_{1f} is the effect of license count on fleet size.

For price per kilo (*i.e. demand*), we used a consumer-demand econometric model developed to predict market demand for Canadian salmon products (DeVoretz 1982; Marvin Shaffer & Associates Ltd. 1989). This model assumes a linear relationship between the logarithms of *demand* and three variables: the quantity of salmon on the market, the price of the closest alternative product (farmed salmon) and the disposable income of consumers, as follows:

$$log(P) = b_0 + b_1 log(W) + b_2 log\left(P_f\right) + b_3 log(D),$$

where b_0 is the scaling parameter determining the overall of all variables on wild salmon price (P), b_1 is the elasticity parameter (establishing whether there are diminishing returns (<1) or intensification (>1)) for landed weight (W), b_2 the elasticity parameter for price of farmed salmon (P_f) and b_3 the elasticity parameter for disposable income (D). We fit the model estimating all parameters hierarchically per species, except for the intercept, which was estimated independently. We also tested for the interaction effect of harvest and price of farmed salmon and price of farmed salmon and disposable income using a linear interaction term, but these were not significant (effect size credible intervals overlapping 0). We found a high correlation between the price of farmed salmon and disposable income, resulting in unresolvable multicollinearity in our model. Therefore, we dropped the disposable income variable from the final model used in our analysis.

For catch (*i.e. use*), we applied a hurdle model to handle the excess number of zeroes in the dataset when no catch was recorded. The model includes a Bernoulli-distributed parameter to estimate the probability of no catch. For nonzero catches, we used a mechanistic Schaefer catch model (Schnute 1977). In the Schaefer equation, catch is modeled as the product of abundance, effort and a catchability coefficient as follows:

$$C = q + log(E) + log(R),$$

where C is catch, q is the catchability coefficient, E is effort and R is spawner abundance. The catchability coefficient parameter was estimated hierarchically across species and management areas. The error term and the probability of no catch parameters were estimated independently per species and per species-area combination, respectively. We tested for correlation between the explanatory variables and found none.

For landed value (*i.e. instrumental value*), we used a power law model where we regressed landed value on landed weight, itself regressed on that of catch as follows:

$$log(V) = \nu + \varpi log(W),$$

$$log(W) = \upsilon + \omega log(C),$$

where V is landed value, ν is the landed weight scaling parameter determining the overall magnitude of landed weight (W), ϖ is the weight-value elasticity, υ is the catch (C) scaling parameter, and ω catch-weight elasticity. Power laws were appropriate here as selection for larger fish or size-selective depletion can lead to a non-linear relationship between catch and landed weight. Similarly, price can vary with weight (e.g. a premium paid for larger fish or market saturation), justifying the power law. All parameters were estimated independently by species.

We evaluated each model's ability to explain variance in the data using a Bayesian alternative to R-squared (Gelman et al. 2019). This is a model-based metric that indicates the proportion of variance in future data explained by the model, based on its posterior predictions. Further, in all models where data were missing for the explanatory and/or response variable, we used an imputation method fitting the missing data as parameters to be estimated by the model alongside other parameters. Model specifications are available in Supplementary Table 1 and the code is available online at https://github.com/FlavAff/BCSalmonEESVs.

Using the causal model

Our analytical approach is grounded in causal knowledge analysis, a framework for building a mechanistic understanding of system dynamics over the long term (Grace 2024), which is also what effective monitoring systems are meant to achieve (Lindenmayer and Likens 2010). Causal knowledge analysis is distinct from statistical causal analysis. In statistical causal analysis, the aim is to estimate an unbiased causal effect from observational data, typically by controlling for potential confounding variables (Pearl 2022). In contrast, causal knowledge analysis aims to build a holistic causal understanding of a system through mechanistic modeling and hypothesis testing. Thus, our objective here is not to estimate precise causal effects of one variable on another but to use our causal knowledge diagram (Figure 2a) to investigate the plausible mechanisms (*i.e.* the underlying ecological, economic and social processes) that are driving the social-ecological system dynamics in the commercial salmon fishery. Thus, the statistical models we use were chosen specifically because they represent these mechanistic links. For instance, the Ricker model is a mechanistic representation of salmon stock-recruitment dynamics, while the Schaefer model mechanistically relates abundance and effort to catch. By fitting these models to our 27-year time series, we are testing whether the observed data are consistent with our causal understanding of how the social-ecological system functions. Our interpretation of the results, therefore, focuses on the plausibility of the overall causal model and the interplay between its components, rather than on calculating and discussing the exact magnitude of any single link. This approach allows us to advance the causal understanding that is directly relevant for the long-term monitoring and management of this complex system.

Results

EESV dynamics

Convergence for each model was good: $\hat{R}$ well below 1.1 and ESS over 400 for all parameters and inspection of trace plots confirmed good mixing of chains. Posterior predictive checks confirmed good fit for all models overall (Supplementary Figures S1-S8). However, species or area-specific fit for some EESV model predictions was not as good: *ecological supply* for Sockeye, *demand* for Chinook and Pink and *anthropogenic contribution* for areas C, D, E and H. The only model that showed a poor posterior predictive fit was the model for fleet size across areas. The proportion of variance explained by the models (Gelman et al. 2019) was high (mean > 0.8) for all EESVs (Supplementary Table S2).

In the *ecological supply* model, Pink salmon was the only species with a significantly positive growth rate, all other species had growth rates very close to 0, with credible intervals overlapping 0 (Table 2 and α parameter, Supplementary Table S3). Density dependence effects were strongest for Chinook, followed by Coho, Chum, Pink and Sockeye (Table 2 and β parameter, Supplementary Table S3). The effect of increasing sea surface temperatures was negative for all species. The negative effect of temperature was strongest for Chinook, followed by Sockeye, Pink, Chum and Coho (Table 2 and θ parameter, Supplementary Table S3). We did not find any effect of hatchery fish on *ecological supply* (all parameter credible intervals overlapped 0), except for Pink abundance, which declines with increasing hatchery releases (Table 2 and δ parameter, Supplementary Table S3). Model fit was poorer in the last 4-5 years where low recorded abundance numbers for Chinook, Chum and Coho drove down model predictions (Figure 4a). It is important to note that the fraction of sampling sites without observations has increased for these species during this time, leading to less reliable *ecological supply* measurements. The yearly dynamics of *ecological supply* for all five species revealed no general long-term trend besides the typical boom-bust dynamics of Pacific salmon (Figures 2a & 3a and Supplementary Figure S9). Credible intervals were very wide, revealing the challenge in effectively predicting yearly salmon returns for all species.

The *anthropogenic contribution* model showed a positive relationship between fleet size and effort across all management areas and gear types. This effect was largely consistent across management areas and gear types, but strongest for trolling in the North coast and weakest for purse seine fishing in the coastal waters of Vancouver Island (Table 3 and parameter b_1, Supplementary Table S3). The variance in *anthropogenic contribution* was much higher for gillnet fishing than for trolling or purse seine fishing. A clear downward trend in *anthropogenic contribution* is predicted across all management areas and gear types over time, except for gillnet fishing around Vancouver Island, which shows no clear trend (Figure 4d and Supplementary Figure S10). The fleet size model showed a consistent positive relationship between fishing licence count and fleet size (Table 3 and parameter b_1, Supplementary Table S3). A weak downward trend in fleet size over time is predicted by the model, although fit was poor for some areas (Figure 5 and Supplementary Figure S11).

The *demand* model shows a negative exponential relationship between *demand* and harvest of salmon (in tonnes) for Pink, Coho, Chum and Chinook but a positive exponential relationship for Sockeye (Table 2 and parameter b_1, Supplementary Table S3), suggesting a disconnect between supply, in the economic sense, and *demand* for this species. The price of an alternative product, farmed salmon, had a positive effect on *demand* for Chinook and Pink salmon, which was strongest for Pink, but not on others (all parameters' credible intervals overlapped 0) on *demand* for any species (Table 2 and parameter b_2, Supplementary Table S3). The model predicts an upward trend in *demand* over time for Chinook and Chum but no clear trend for the other three species. Additionally, the model also shows increasing variability in *demand* over time for Sockeye (Figure 4c). *Demand* was highest for Sockeye, followed by Coho, Chum, Chinook, and then Pink.

In the *use* model (*i.e.* the catch model), catchability coefficients (Table 4 and parameter q, Supplementary Table 3) varied between species and areas from $4.11.10^{-6}$ for Pink in the offshore waters of Vancouver Island to 0.177 for Chum in the coastal waters of Vancouver Island. A coefficient of 10^{-4} or lower indicates low catchability (*i.e.* a smaller fraction of the salmon population is caught per unit effort), while 10^{-2} or higher indicates high catchability. Overall, catchability was highest for Chum, followed by Sockeye, Pink, Chinook, and then Coho. Catchability was most variable for Coho. Catchability was highest and most variable in the management areas of purse seine fishers of the North and South coasts. Catchability was lowest in the management areas of gillnet fishers in North Vancouver Island, followed by trolling fishers around Vancouver Island. *Anthropogenic contribution* (effort) showed an exponential effect on *use*, while *ecological supply* (abundance) showed a logistic levelling-off relationship with *use*. The model predicted a decline in *use* over time for Chum, Chinook and Pink but no clear pattern for Sockeye and Coho with continued boom and bust dynamics following *ecological supply* (Figure 4b and Supplementary Figure S12). Fit of the *use* model suffered from the large range of observed yearly catch values (ranging from 1 to 9.10^6), causing outliers and issues in sampling, and the unreliability of *ecological supply* measurements over recent years. *Use* was highest for Pink, followed by Sockeye, Coho, Chum, and Chinook.

In the *instrumental value* model, the weight of fish harvested had a positive effect on *instrumental value* for all species (Table 2 and parameter b_1, Supplementary Table S3). This effect resulted in a logistic levelling off relationship between both variables for Chum, an exponential relationship for Coho and a linear relationship for Chinook, Pink and Sockeye. For the harvest model, increasing catch led to increases in harvest for all species following a logistic levelling off relationship (Table 2 and parameter b_1, Supplementary Table S3). The *instrumental value* model predicts a slow increase in value for Chinook over time but a decrease in value for all other species in recent years (2019 onwards, Figure 4e). Harvest predictions follow a similar pattern but with a less noticeable decrease in recent years for Coho (Supplementary Figure S13). Across species, Sockeye was the most valuable, followed by Chinook and Chum (in alternance across years), then Pink and Coho.

Table 2. Species-specific effect sizes on three EESV classes (*ecological supply, demand* and *instrumental value*) for each parameter in the model (Figure 2b). Effect sizes represent median parameter estimates along with 90% credible interval.

EESV class	**Parameter**	**Effect size (median [90% credible interval])**				
		Species				
		Sockeye	**Chinook**	**Coho**	**Chum**	**Pink**
Ecological supply	Growth rate	-0.084 [-0.20, 0.028]	0.075 [-0.046,0.20]	0.061 [-0.030,0.37]	0.0078 [-0.15, 0.15]	0.33 [0.15, 0.51]
	Density dependence	$8.8.10^{-8}$ [$6.1.10^{-10}$, $1.7.10^{-7}$]	$2.2.10^{-6}$ [$1.4.10^{-6}$, $3.0.10^{-6}$]	$1.7.10^{-6}$ [$1.1.10^{-6}$, $2.4.10^{-6}$]	$3.0.10^{-7}$ [$2.2.10^{-8}$, $5.1.10^{-7}$]	$1.1.10^{-7}$ [$6.8.10^{-8}$, $1.5.10^{-7}$]
	Temperature effect	-0.24 [-0.34, -0.15]	-0.25 [-0.36, -0.14]	-0.013 [-0.12, -0.093]	-0.14 [-0.25, -0.019]	-0.23 [-0.36, -0.11]
	Hatchery effect	0.058 [-0.078, 0.20]	0.25 [-0.079, 0.48]	-0.074 [-1.6, 0.0045]	0.12 [-0.0015, 0.27]	-0.66 [-0.83, -0.48]
Demand	Landed weight effect	2.4 [2.1, 2.7]	-0.28 [-0.35, -0.21]	-0.42 [-0.53, -0.32]	-0.33 [-0.43, -0.23]	-0.64 [-0.72, -0.56]
	Price farmed salmon effect	-0.10 [-0.37, 0.19]	0.64 [0.26, 1.0]	0.017 [-0.47, 0.47]	-0.40 [-0.86, 0.63]	0.76 [0.34, 1.2]
Instrumental value	Landed weight effect	0.947 [0.864, 1.03]	1.01 [0.691, 1.32]	1.51 [1.37, 1.65]	0.674 [0.573, 0.773]	0.902 [0.795, 1.01]

Table 3. Effect size of the fleet size parameter on the EESV class *anthropogenic contribution* by type of gear used and management area fished (Figure 2b). Purse seine fishing only takes place in areas C, D and E, gillnet fishing in areas A and B, and trolling in areas F, G and H. Effect sizes represent median parameter estimates along with 90% credible interval.

EESV class	**Gear**	**Effect size (median [90% credible interval])**							
		Management area							
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Anthropogenic contribution	**Seine**	1.65 [1.30, 1.84]	0.88 [0.69, 1.08]	-	-	-	-	-	-
	Troll	-	-	-	-	-	3.91 [3.32, 4.54]	2.78 [2.44, 3.11]	1.51 [0.88, 2.21]
	Gillnet	-	-	2.66 [2.24, 3.09]	2.38 [1.51, 3.26]	1.08 [0.12, 2.11]	-	-	-

Table 4. Species by management area effect size on EESV class *use* for the catchability parameter (q) in log space from the Schaefer model (Figure 2b). Effect sizes represent median parameter estimates along with 90% credible interval.

EESV class	**Species**	**Effect size (median [90% credible interval])**							
		Management area							
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Use	**Sockeye**	-2.98 [-3.44, -2.52]	-2.80 [-3.37, -2.28]	-3.70 [-4.02, -3.38]	-5.00 [-5.36, -4.65]	-3.99 [-4.47, -3.50]	-8.49 [-9.02, -7.96]	-6.85 [-7.53, -6.27]	-4.74 [-5.20, -4.30]
	Chinook	-9.89 [-10.89,-7.87]	-8.29 [-9.03, -7.15]	-5.51 [-5.84, -5.15]	-5.93 [-6.48, -5.44]	-6.74 [-7.75, -6.10]	-2.95 [-3.31, -2.59]	-3.55 [-3.91, -3.18]	-7.83 [-8.56, -7.15]

Coho	-5.58 [-6.38, -4.88]	-4.55 [-5.26, -3.84]	-8.66 [-9.51, -7.86]	-6.06 [-6.63, -5.49]	-7.74 [-8.30, -7.19]	-4.15 [-4.59, -3.71]	-6.29 [-7.13, -5.46]	-8.91 [-9.75, -8.01]
Chum	-2.77 [-3.10, -2.43]	-1.73 [-2.04, -1.42]	-4.59 [-4.90, -4.27]	-4.46 [-4.79, -4.17]	-3.56 [-3.88, -3.25]	-11.3 [-11.8, -10.6]	-9.56 [-9.99, -9.16]	-4.18 [-4.62, -3.79]
Pink	-2.23 [-2.60, -1.86]	-3.99 [-4.46, -3.52]	-6.44 [-6.79, -6.09]	-7.31 [-8.29, -6.58]	-12.3 [-13.1, -11.4]	-7.13 [[-7.54, -6.71]	-12.4 [-13.0, -11.7]	-6.96 [-7.45, -6.47]

Policy effect

The slight downward trend in fleet size predicted by the model suggests that the license retirement programmes introduced in 1996 (at the start of our analysis) have been somewhat effective at reducing the number of fishing boats on the water in some areas (C, F, G and H - Figure 5). However, the poor model fit, weak effect (parameter $0.70 < b_1 < 3.9$, Supplementary Table 3), and noticeable differences in pattern across management areas (some weakly declining, some remaining level – Figure 5) suggest that this may not have been the driving force behind a reduction in fleet size (*i.e.* another underlying causal mechanism was at play). Nevertheless, a general reduction in effort (*anthropogenic contribution*) was observed (Figure 3b) and predicted in multiple areas (A, B, C, F, G, and H, Figure 4d) across the province (Supplementary Figure S10). Following the logic of the causal knowledge graph (Figure 2), we expect a consequent decline in catch (*use*), which is indeed observed (Figure 3d) and predicted (Figure 4b) for most species. However, we observed (Figure 3e) and predicted (Figure 4e) little to no change over time in the landed value (*instrumental value*) of all species, except for Chinook, which increased slightly. Consequently, whilst effort has decreased and the size of the fishing fleet has reduced, this has not led to a loss in income, suggesting that financial viability for fishers who retained their license has indeed improved. However, we also observed (Figure 3c) and predicted (Figure 4c) an increase in price (*demand*) for all species, which likely contributed to maintaining the financial viability of the industry as catch and participation decreased, irrespective of the licence retirement programme. Therefore, it is unlikely that the licensing policy on its own led to an improvement in the financial viability for fishers.

Discussion

This paper aimed to advance the systematic monitoring of ecosystem services by operationalizing and evaluating the essential ecosystem service variables (EESV) framework through a detailed case study. We used the data-rich, complex social-ecological system of British Columbia's commercial salmon fisheries to implement the framework, integrating 27 years of monitoring data. Specifically, we operationalized five EESV classes using Bayesian models, producing the first integrated, multi-species analysis of this kind for Pacific salmon provisioning ecosystem services at the provincial scale. Here, we first examine the insights gained into the dynamics of the salmon provisioning service through this EESV application, then address the study's limitations and potential improvements, explicitly comment on the advantages and value added from applying the EESV framework, and conclude on the broader implications for advancing ecosystem services monitoring.

EESV dynamics

A good causal understanding of the social-ecological system is required to develop the causal knowledge graph (Figure 2a), which we tested with specific EESV models (Figure 2b) to check for consistency and used to explore the dynamics of the ecosystem service across EESVs. Thus, using our conceptual model, we applied a set of mechanistic models (where available) to the variables we identified to detect and attribute change in the ecosystem service (Gonzalez, Chase, et al. 2023). We found good support for our models, validating our choice of EESVs and the underlying mechanisms driving relationships between them and their drivers.

Uncertainty in our estimates, likely due to aggregating across diverse populations, limits our ability to conclude on the ecological state of BC salmon, but we found that BC-wide salmon productivity is close to zero for most species, with only Pink salmon currently at levels sufficient to replace themselves. This is a concerning result that is supported by other studies showing that some salmon population growth rates may be too low to sustain themselves (Peterman and Dorner 2012; Ruggerone et al. 2010; Losee et al. 2019). Ecological drivers affected *ecological supply*, suggesting a mechanistic relationship between population growth and temperature as well as hatcheries. Specifically, we found a negative effect of sea surface temperature on *ecological supply* for all species, despite the use of a coarse measure for temperature: the average temperature of coastal BC waters measured for the months of April-June, when the young salmon would have swum out to sea (Mueter et al. 2002). This supports the work on the effects of climate change on salmon smolts (Muñoz et al. 2015), suggesting that warmer waters are an important stressor on these fish, affecting their survival (Siegel and Crozier 2020). Additionally, we found little effect of hatcheries on most species and a decline in Pink salmon. Hatcheries are intended as a way to increase the abundance of salmon and improve returns for the fishery (Flagg 2015). Yet, additional salmon smolts also compete with natural populations increasing the negative density dependence effects common to salmon species (Ruggerone et al. 2010). These effects support the causal model and have important implications for management, suggesting that hatcheries are not having the desired outcome at the BC scale.

Socio-economic drivers were also relevant. Specifically, we found that Sockeye salmon price does not decrease as available quantities increase, the opposite response to other species. This points to Sockeye salmon being seen as a luxury good by consumers who do not respond to scarcity but may instead consider Sockeye more valuable due to its brand recognition and perceived higher quality (Fassnacht and Dahm 2018). Furthermore, we found a substitution effect of farmed salmon on Pink and Chinook salmon, suggesting that consumers may switch to these products as prices of alternatives go up. Additionally, harvest volume was a key driver of *instrumental value*, though with species-specific patterns. For Chum salmon, the value plateaued at higher harvest levels, suggesting market saturation or lower demand (Tietenberg and Lewis 2023). In contrast, for the other four species, uncertainty bounds supported either a linear or exponential increase in value, indicating that increased availability would not necessarily reduce per-unit revenue. While Sockeye remains the most valuable species, the continued value growth of Pink, Chinook, and Coho suggests, consistent with traditional economic theory, that they may be undersupplied relative to demand (Tietenberg and Lewis 2023). The underlying socio-economic mechanisms affecting these relationships have important implications for the income generated by this ecosystem service, highlighting the role of the wider economy in controlling salmon products' *demand* and *instrumental value*.

A key strength of applying the EESV framework was the ability to explicitly model the relationships between its classes, revealing how changes propagate through the system. Linking *ecological supply* and *anthropogenic contribution* to model *use* allowed us to estimate catchability; the proportion of the stock that is caught per unit effort (*i.e.* high catchability implies more catch for the same effort). Our model is not as complex as other mechanistic escapement-based or Bayesian state-space stock assessment models, which are typically fit at finer scales and incorporate stochasticity, population dynamics and observational uncertainty (Fleischman et al. 2013; Staton et al. 2017). Therefore, it should not be used to set harvest rules or quotas, but it can still inform on the overall efficiency of the fishery and the *use* of this ecosystem service, its intended purpose. We find that catchability depends on both target species and management area, which aligns with gear type. Specifically, deep water trolling fishers are more efficient at catching Chinook, whilst shallow water purse seine fishers are more efficient at catching Chum and Pink. This is expected given the schooling behaviour of these species:

Chinook swim in deeper waters whilst Pink and Chum school near the surface (Groot and Margolis 1991). Nevertheless, the wide swings in recorded catch numbers are not well captured by the model, pointing to additional underlying mechanisms driving *use* that are not accounted for here. Yet, declines in *anthropogenic contribution* for trolling and purse seine fisheries, correspond to declines in *use* (catch) for all three species. Therefore, supporting the causal knowledge graph built from EESVs.

Interestingly, this only corresponds to a decline in *instrumental value* for Chum, the only species that displayed a market saturation pattern. Thus, while *anthropogenic contribution* and *use* may be declining, *instrumental value* and *demand* are increasing or remaining level. This implies that accessing the ecosystem service (*i.e.* buying wild Pacific salmon products) is becoming more expensive for consumers. This may be sufficient to maintain the ecosystem service for fishers, who benefit from selling their catch, but should market forces push consumers to move away from what bears the hallmarks of a luxury good, it is possible we might observe a declining trend in these other dimensions of the ecosystem service. Yet, given the reliance of the wild Pacific salmon industry on foreign exports, a telecoupling effect may be sufficient to maintain the viability of the ecosystem service even with declining *use* (Liu et al. 2016). However, such a telecoupling effect assumes stable international demand, which could be influenced by factors such as shifting trade policies, competition from aquaculture, and changing consumer preferences in key export markets (Asche et al. 2015). Some of these additional variables were not included in the causal model but are likely relevant to the dynamics of *demand* and *instrumental value* through economic market mechanisms not included in the model. Therefore, while good model fit can be achieved using only the variables included in this analysis, an in-depth causal understanding of these EESVs, and thus opportunities for intervention, will require considering additional variables.

Lastly, uncertainty in our model predictions varied between EESVs. For *ecological supply* in particular, the very wide credible intervals (e.g. varying by several million for Sockeye – Figure 4a) point to unexplained variability in the data that must be due to external mechanisms not captured in the model. This result supports the fact that it is extremely challenging to accurately predict returns of Pacific salmon in the fishery and there remain misunderstood underlying mechanisms driving salmon population fluctuations (Winship et al. 2015; Rogers et al. 2013; Beamish 2022). In comparison, for *anthropogenic contribution* and *demand*, tight credible intervals (Figure 4c,d) suggest greater predictability, perhaps owing to their economic nature. This difference in uncertainty, made apparent through the multi-dimensional EESV modeling approach, provides critical information about where confidence in causal understanding is lowest and where monitoring or modeling improvements are most needed. While there are likely many ways to estimate and model EESVs, most assessments of ecosystem services fail to account for uncertainty (Boerema et al. 2017). Yet, reporting uncertainty in model predictions is necessary to provide a statement of confidence in causal models (Gonzalez, Chase, et al. 2023). Including uncertainty in estimates provides a measure of confidence in the detected trends and is necessary to make informed decisions from monitoring data.

Policy assessment

We explored the effect of the licence retirement programme implemented by DFO at the start of our analysis in 1996 (DFO 1999). The licence buyback programme is an entirely voluntary programme to reduce the number of commercial fishing vessels catching wild Pacific salmon. Despite a clear decline in effort (*anthropogenic contribution*), we find limited support for its effect in reducing overall fleet size (Figure 5). This may be due to alternative and more effective non-voluntary management practices by the government, such as targeted closures that happen on a seasonal basis, as salmon run returns are estimated (Fisheries and Oceans Canada 2021) and were not included in our analysis. These closures are intended to support salmon population recovery efforts by increasing the number of spawners that make it back to reproduce. The consequent reduction in effort and catch, however, does not appear to have led to a decrease in income (*instrumental value*), which overall remains stable. Consequently, the government's attempt to increase the per capita financial viability of the industry appears somewhat successful. However, this success seems largely driven by changes in *demand* and continued export sales, which have avoided a decline in income from reduced catch (Lilian Hallin Consulting 2022). Therefore, the complex market and environmental dynamics driving wild Pacific salmon ecological and economic returns are more likely to be responsible for the current financial viability of the industry than the government's policy. A mandatory licence buyback programme that effectively leads to a reduction in fleet size may be more effective than the current passive approach, although fisheries closures have been effective at controlling *anthropogenic contribution*. Currently, the financial viability of the industry appears to be more dependent on market forces than on the policy actions of the government.

Caveats and limitations

We were limited in our ability to model the complex ecological dynamics of salmon due to the nature of the data available in Canada (e.g. no population age structure was available for any species in our dataset) and the need to integrate datasets collected at different resolutions. We chose to focus on the species level to produce a multi-species analysis that would allow us to model the entire ecosystem service for BC using the best publicly accessible datasets.

Specifically, our analysis relies heavily on the CU-level abundance estimates provided by the Pacific Salmon Foundation (PSF), which are subject to several important assumptions (Pacific Salmon Foundation 2024). The expansion factor approach used to generate these estimates assumes that the proportional contribution of indicator streams to the CU's total abundance remains constant over time; an assumption that may be violated if habitat degradation or other pressures disproportionately affect unmonitored populations within the CU. Furthermore, the reliability of these estimates is linked to monitoring coverage, which for many CUs has declined since the late 1990s (Atkinson et al. 2024). Many CUs are classified by the PSF as 'data deficient' due to insufficient monitoring, adding uncertainty to any regional aggregations. While our Bayesian framework inherently incorporates uncertainty, it does not account for potential biases in the underlying data. These data quality issues extend to other variables like catch counts and contribute to the overall uncertainty of our model parameters. However, these issues point primarily to problems with the way social-ecological monitoring is set up today (Affinito et al. 2025; Vári et al. 2025), limiting our ability to predict ecosystem service dynamics with confidence.

Moreover, spawner abundance is measured after the fish have made it past commercial fishers, *i.e.* the effect of fishing has already happened. Another measure of *ecological supply* that reflects how fishers benefit from the ecosystem service could be total run size, *i.e.* the total number of salmon returning to spawn before commercial fishers take their harvest (*i.e.* the total capacity for the ecosystem service before it is used). However, this data was not available for many salmon populations. This is due to the monitoring methods used by DFO to count salmon being focused primarily on the streams where fish spawn. Therefore, we used spawner abundance as a proxy for total run in the model for *use*. This allowed us to effectively model the socio-economic dimensions of the ecosystem service, but limited our ability to comment on the effects of the fishery itself on salmon populations (*i.e.* the causal model only goes from the ecological to the social system). Nevertheless, this perspective is a strength of our approach, given that most ecosystem service studies tend to focus purely on the ecological dynamics of the system, failing to consider more than *ecological supply* (Seppelt et al. 2011).

Additionally, we report and discuss our results at the scale of the entire province of British Columbia. However, social and ecological dynamics are sensitive to scale, especially Pacific salmon, which is why studies tend to focus on species or stock-specific assessments both for fisheries management and conservation (Walsh et al. 2020; Walters et al. 2019). Analysing the ecosystem service at the provincial scale risks missing important local dynamics that affect the sustainability of salmon populations (*ecological supply*) and viability of the fishery for specific communities (*anthropogenic contribution*, *use,* and *instrumental value*). This was necessary due to the resolution of our datasets. Several variables were only available at the provincial scale, and none were available at a smaller temporal scale than yearly (Table 1). Matching data from disparate sources was done carefully and we chose to keep the resolution coarse to avoid introducing spurious relationships in the data. Nevertheless, where smaller-scale spatial resolution was available (e.g. *ecological supply* by spawning region and *use* by management area), we did account for this in the model and fit the data at this more precise scale to account for differences in location. We focused our analysis at the larger scale to enable comparisons between EESVs. In fact, relying on a Bayesian modeling framework to estimate EESVs allowed us to aggregate the posterior predictions to report and analyse dynamics at a larger scale than the model was fit. The ability to scale variables up or down is an important feature of the essential variable framework and we show this is feasible under our approach for modeling EESVs.

Additional specific considerations around our model and the Pacific salmon social-ecological system should be discussed. Model fit for *use* was not as good as for other EESVs (*i.e.* multiple observed data points fell outside credible intervals). The wide spread in observed catch data (observations varied by a factor of ~10^7) affected model convergence despite our use of a wide-tailed distribution (student-*t*). Additionally, spawner data in more recent years contains an increasing number of missing observations. These underestimates of abundance also affect the *ecological supply* model and lead to underestimates of *use*. A significant decline in monitoring of spawning streams since 2005 (Price et al. 2017) is likely responsible and will affect any predictions of salmon abundance that do not explicitly account for it. Finally, we conservatively matched abundance to catch by summing North and South coast spawner populations separately and assigning each of the sums to the corresponding management areas where fish were caught. It is likely that this approach overestimates the abundance of fish in more remote management areas where fewer migrating salmon populations are likely to be present (Byron and Burke 2014). We used this approach based on similar Pacific Salmon Foundation methods aimed at assigning catch to abundance (Pacific Salmon Foundation 2024), given that DFO does not monitor these variables in the same location. Adopting a formal integrated social-ecological approach to monitoring the system would avoid such mismatches and improve any predictions from monitoring data (Firkowski et al. 2021).

In addition to the recent reduction in monitoring data available for *ecological supply*, multiple data quality issues affected the length of our analysis. Specifically, the BC data catalogue informed us that, despite earlier data on *instrumental value* being available, they would not release it due to concerns around its quality and compilation methodology. This is also true for catch data, where prior to 1996 catch was recorded differently and is only available for download at the genus level (*i.e.* all species of salmon summed). Detailed reports dating back to 1951 are available from DFO, but these have not yet been digitized (*i.e.* are in scanned hand-written PDF format) and therefore cannot be easily used in the type of modeling analysis carried out here. These issues underlie the necessity of effectively funding monitoring programmes and accounting for advances in technology, sampling methods and analytical tools (Yoccoz 2012; Lindenmayer and Likens 2018). Relying solely on more recent data will affect trend detection and result in a shifting baseline effect that leads to an overall degradation of the ecosystem service as a new normal of low *ecological supply*, *use* or both settles in (Schijns and Pauly 2022; Thurow et al. 2020). The necessity to sustainably fund *in situ* data collection despite changing political priorities is not new (Lindenmayer and Likens 2010), but is crucial in this system given the ecological, social and economic importance of wild Pacific salmon.

Avenues for improvement

While our models provide a foundational understanding of the commercial salmon provisioning service, we did not account for all possible drivers of change. For example, the presence of Atlantic farmed salmon in BC has been linked to declines in wild Pacific salmon through competition with escaped fish or disease spread (Krkošek 2010; Krkošek et al. 2006). Additionally, both recreational and indigenous fisheries take place in BC, and we did not include these in our analysis, which focused on the commercial fishers beneficiary group. We also did not look for additional market forces that might have affected the price and value of Canadian salmon (e.g. the price of Japanese salmon). Including these variables in the causal model and testing their effect may be necessary for a more in-depth assessment of the system and to identify the underlying mechanisms driving its dynamics, as well as to produce more reliable parameter estimates of effect sizes as it is possible that omitted variables may in fact be as, or more, important than those used in our current models. However, our objective was to test the consistency of observed data with mechanistic models (*i.e.* causal knowledge analysis) using EESVs. Indeed, while the precise magnitude of the temperature effect we estimated might be modulated by other unmodeled stressors, the underlying physiological mechanism linking warmer waters to reduced salmon survival is well-documented (Siegel and Crozier 2020). Our results confirm that this primary mechanism is indeed a detectable and important feature of the system's dynamics. The inclusion of additional variables into the model would therefore be a logical next step in building a more comprehensive understanding of the social-ecological system. Our models are a necessary first application of the EESV framework in a complex system, demonstrating its value in causal knowledge analysis. Yet next steps will require incorporating additional beneficiary groups (e.g. recreational fishers), feedback loops and more complex market dynamics. Some of this is already doable with existing monitoring data (Affinito et al. 2025) and can take advantage of the foundations laid here.

Additionally, we did not include nor model the sixth class of EESVs: *relational value*. Identifying which relational value to use and how to quantify it was a significant challenge. Given the focus of our study on commercial fisheries and fishers, one proxy of *relational value* could be the employment numbers of salmon fishers. This metric might reflect the interest of people in engaging in the ecosystem service. In fact, employment in wild salmon fisheries has fallen dramatically since 1991 (-76%) and continues to decline year on year (-4.5% from 2021 to 2022, Lilian Hallin Consulting 2022). However, additional socio-economic factors affect people’s decision to engage in commercial fishing, which may have little to do with their values.

Relational values are too often left out of ecosystem service assessment despite their central role (Himes and Muraca 2018; Schwantes et al. 2024). In the case of Pacific salmon specifically, these fish play a central role in people's sense of place and identity in BC (Earth Economics 2021). Salmon are such a keystone species in the region, ecological and culturally, that relational values play a key role in management, policy and people's behaviour (Smith and Steel 1997). The central role that this relatively low value fishery plays in fishery policy is a reflection of its importance. By not accounting for *relational values*, policy action often leads to poorer outcomes from low buy-in and a loss of value pluralism (Himes et al. 2024). Particularly in the case of Pacific salmon, recognising and weaving the relational values of the multiple beneficiaries of the broader provisioning ecosystem service (e.g. recreational and indigenous fishers) has the potential to improve monitoring (Atlas et al. 2021) and ecosystem service provision (Chan et al. 2018). Our inability to operationalize the *relational value* EESV serves as a stark example of how current monitoring programs, even in well-resourced contexts, often fail to capture the full social-ecological picture deemed essential by frameworks like EESVs. This highlights a critical need not just for methodological advances in quantifying relational values (Olander et al. 2018; Galang et al. 2025; Schulz and Martin-Ortega 2018), but for a fundamental rethinking of monitoring priorities to include systematic collection of relevant social and cultural data.

Finally, while our analysis focused on the commercial fishing sector, due to the available province-wide datasets, a crucial avenue for expanding and enriching this work is the meaningful inclusion of Indigenous peoples as key beneficiaries and rights holders. Wild salmon are foundational not just to the historical diet of Indigenous communities but are essential to their contemporary subsistence, culture, economies, and livelihoods (Nesbitt and Moore 2016).

Furthermore, the landscape of salmon management is evolving, with many fisheries now being collaboratively managed with coastal First Nations, who often maintain their own sophisticated monitoring systems grounded in Traditional Ecological Knowledge (Atlas et al. 2021). Integrating these knowledge systems and data streams with federal and provincial monitoring efforts offers a powerful opportunity to create the holistic, social-ecological understanding that the EESV framework is designed to support. Such collaboration would directly address the gap in quantifying relational values. The deep cultural and spiritual significance of salmon to Indigenous peoples is a vital component of the ecosystem service's total value (Reid et al. 2022), yet it remains invisible in purely commercial datasets. By working with Indigenous partners, future EESV-based assessments can co-develop methods to monitor relational values, ensuring that policy and management are informed by a more pluralistic understanding of why salmon are important. This approach would not only improve monitoring but would also advance the development of more equitable and culturally resilient management strategies for this critical ecosystem service.

The value of EESVs

We were able to take advantage of a large knowledge base and existing monitoring systems to explore the detection and attribution of ecosystem service change, using the EESV framework. We recovered expected patterns, which support the validity of our approach, and revealed novel insights into the social-ecological dynamics of the ecosystem service. We were able to identify which variables to focus on and model because the EESV framework supported us in building the causal graph underlying system dynamics and helped identify which variables to use to test it. Most studies on ecosystem services continue to focus on one or two dimensions of the social-ecological system, typically *ecological supply* (Bennett et al. 2015). These assessments usually rely on large-scale models that focus primarily on ecological dynamics and assume that *demand* is linked to the location of people (Chaplin-Kramer et al. 2019; 2022). Here, we rely on field measurements of data that enable a multi-dimensional understanding of ecosystem service change that goes far beyond *ecological supply*. Thus, the EESV framework provides the foundations necessary to bridge the gap between disciplinary fields, borrowing from ecology, economics and the social sciences. This, in turn, operationalizes the potential of ecosystem services to deliver on their promise to support sustainable development (Carpenter et al. 2009). Adopting the EESV framework within multi-disciplinary teams has the potential to simplify communication between diverse fields and equally value their contribution in the monitoring of ecosystem services.

Additionally, we used the EESV framework to organize pre-existing data. Whilst there are limitations in reusing data for new purposes (Boté and Termens 2019), it is likely that the development of standards for monitoring ecosystem services will require relying on pre-collected data. In fact, essential biodiversity variables (EBVs), the precursor to EESVs, were developed by first assessing what kind of biodiversity data was available and then organising it into classes (Pereira et al. 2013; Schmeller et al. 2018). Moreover, the measure for *ecological supply* used here (abundance) is also an essential biodiversity variable, as is the genetic diversity of these populations, suggesting an avenue for the integration of EBVs with EESVs to deepen our understanding of the ecological dynamics of the salmon species in this region.

The pre-defined classes of EESVs provide a structured logic to develop the necessary variables, which should accelerate the process of identifying essential variables for each ecosystem service type. Here, we suggest a first set of five variables that could be considered for provisioning services: abundance (*ecological supply*), effort (*anthropogenic contribution*), market price (*demand*), harvest (*use*) and revenue generated (*instrumental value*). These five variables are common to many exploitative ecosystem services and recognizable by the scientific communities that study them.

Conclusion

Ecosystem services monitoring, whether for accounting, planning or reporting purposes, is now a priority of policy. This study's primary contribution lies in demonstrating the EESV framework's unique capacity to structure and integrate disparate monitoring data into a coherent, multidimensional analysis suitable for causal knowledge exploration. Unlike studies focusing on single components, the EESV approach provides the standardized architecture needed for systematic monitoring across the social-ecological system. Furthermore, the challenges encountered, particularly regarding data gaps for relational values and high uncertainty in ecological predictions, underscore the framework's diagnostic value in revealing the limitations of existing monitoring systems for holistic ecosystem service assessment. Where social-ecological monitoring was not explicitly done *ad hoc*, EESVs can therefore help develop a causal understanding of ecosystem service change by bringing together data from multiple sources to understand the different dimensions of ecosystem service co-production.
Unfortunately, programmes that do take an integrated social-ecological monitoring approach are few (Gurney et al. 2019; Bennett et al. 2021). Developing and implementing EESVs can simplify the challenge of setting up such multi-scale transdisciplinary networks and advance the ambition of Global Biodiversity Observing System that connects biodiversity observations to policy needs (Gonzalez, Vihervaara, et al. 2023), taking advantage of advances in interoperability (Affinito et

al. 2025). In the meantime, a formal detection and attribution process supported by EESVs can help establish integrated ecosystem service monitoring networks (Vári et al. 2025; Firkowski et al. 2021) that build upon existing (Scholes et al. 2017) and emerging (Gonzalez et al. 2025) biodiversity observation networks to provide the knowledge necessary to guide sustainable management of ecosystem services.

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Figure captions

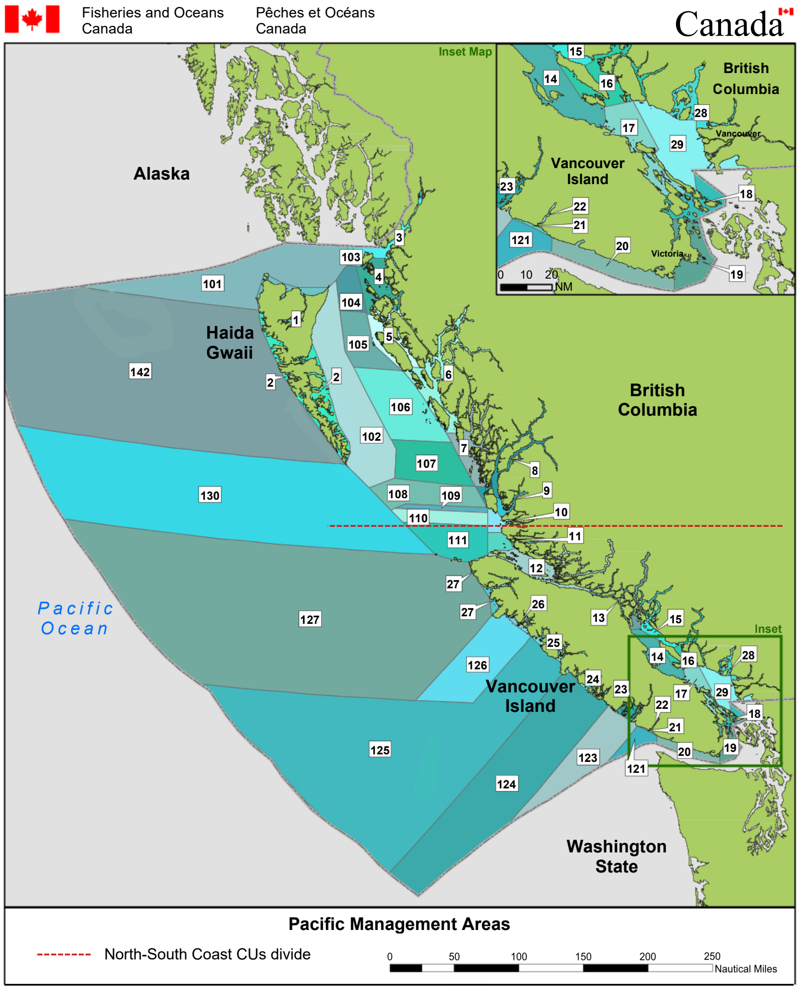

Figure 1. DFO Pacific fisheries management areas map. DFO assigns Northern areas (1-10, 101-110, 130 and 142) to Pacific salmon fisheries management areas A, C and F. Southern areas (11-29, 111 and 121-127) are assigned to Pacific salmon fisheries management areas B, D, E, G and H. The dividing line between North and South coast populations based on PSF CU data is indicative only and does not follow watershed boundaries. All populations spawning in streams above the line were considered North Coast populations and those below South Coast populations. The map is taken and adapted from DFO (Fisheries and Oceans Canada 2013).

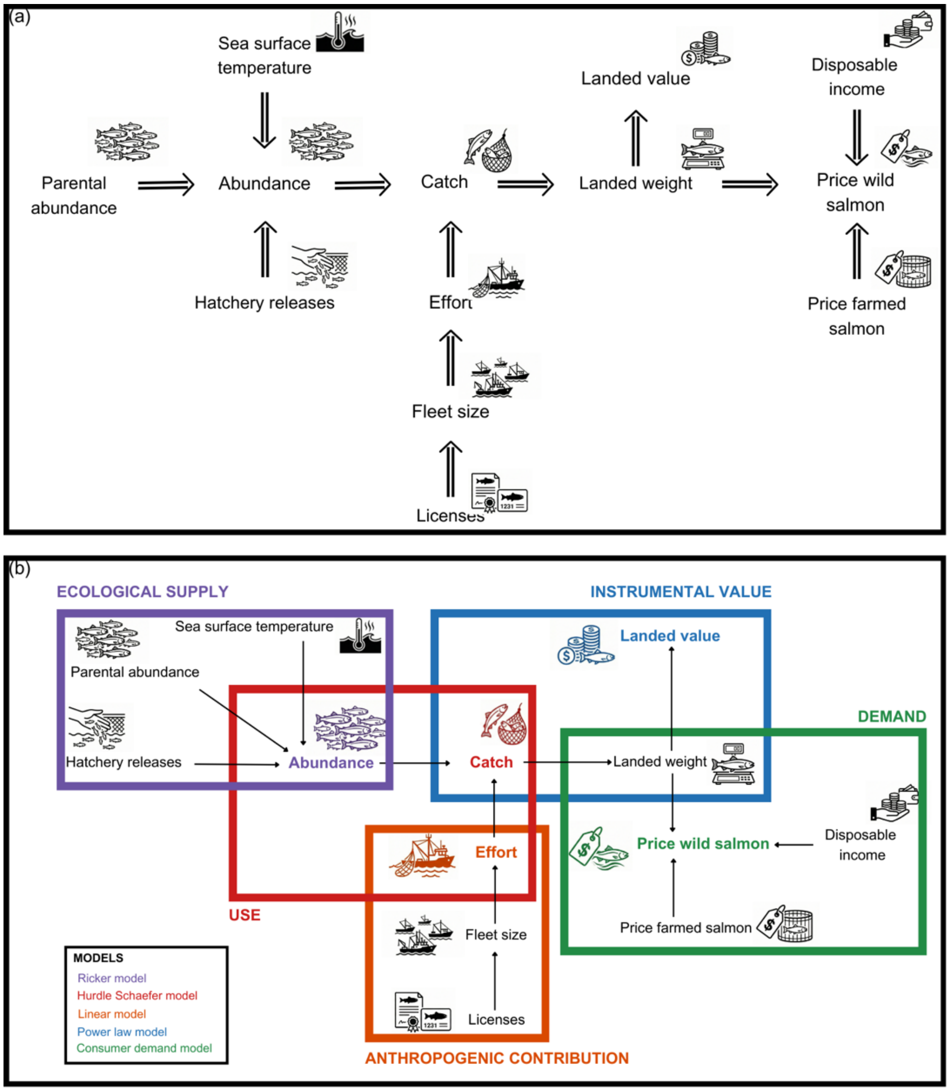

Figure 2. (a) Causal knowledge diagram representing the core causal chain, and underlying mechanistic drivers, connecting key variables in the wild salmon fisheries social-ecological system in any given year. (b) Models for each EESV are identified in the causal knowledge diagram. EESVs are represented in colour. Each box corresponds to one model including its EESV response variable and all other explanatory variables. The type of model fit to each EESV is included in the legend. Model outputs using the same colour scheme are displayed in Figure 4. All icons used in this figure were produced using Nano Banana Pro with Google Gemini.

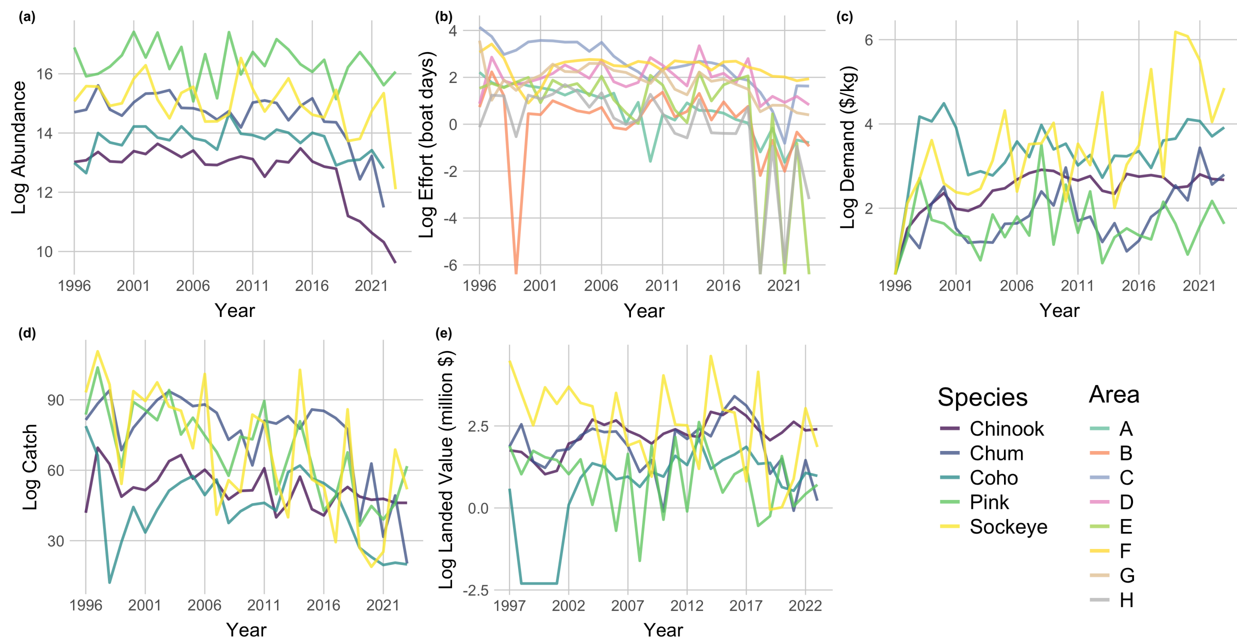

Figure 3 EESV time series for the wild fish provisioning ecosystem service of commercial BC salmon fisheries. Time series (from 1996 to 2023) are shown for each species for (a) *ecological supply*, (c) *demand*, (d) *use*, and (e) *instrumental value* and for each management area for (b) *anthropogenic contribution.* Management areas reflect a combination of location along the coast and fishing gear used. Areas A and B are for seine vessels, C to E for gillnet and F to G for trolling. Areas A, C and F cover waters in the North Coast of BC above Vancouver Island. Areas B, D, E, G and H cover waters in the South Coast of BC around Vancouver Island (Government of Canada 2017). All values are presented on the log scale.

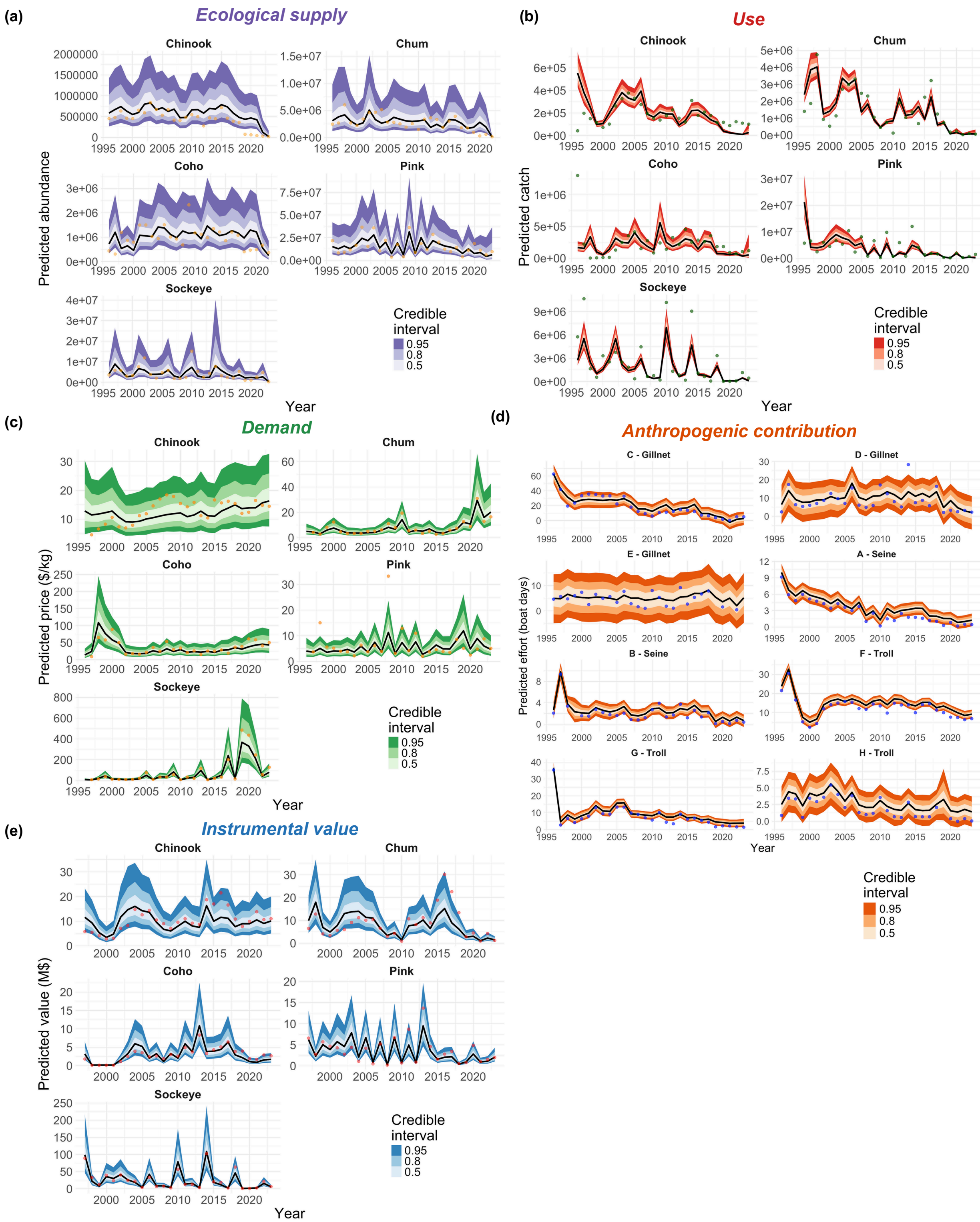

Figure 4. Model predicted time series of all EESVs assessed over the study period (1996-2023): (a) *ecological supply*, (b) *use*, (c) *demand*, (d) *anthropogenic contribution* and (e) *instrumental*

value by species (a-c, e) or management area (d). Observed data are shown as points on each graph along with credible intervals (50%, 80% and 95%).

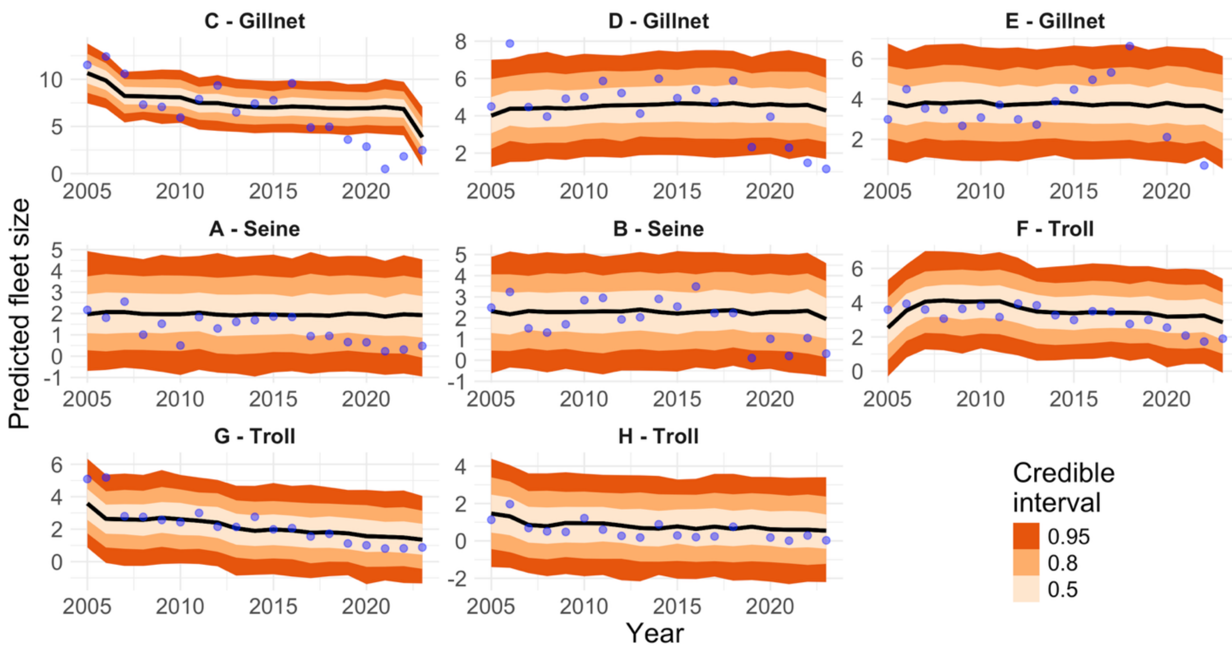

Figure 5. A weak to no predicted decline in yearly fleet size for all management areas is supported by the model containing licence numbers as explanatory variable. Observed data points (in blue) and 50%, 80%, and 95% credible intervals from light to dark.