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

F. Affinito[*1,2,3], *M.-J. Fortin*[4], *A. Gonzalez*[1,2,3]

[*]Corresponding author: flavio.affinito@mail.mcgill.ca

1. Department of Biology, McGill University, 1205 Dr Penfield Ave., Montreal, QC H3A 1B1, Canada

2. Québec Centre for Biodiversity Science, 1205 Dr Penfield Ave., Montreal, QC H3A 1B1, Canada

3. Group on Earth Observations Biodiversity Observation Network, 1205 Dr Penfield Ave., Montreal, QC H3A 1B1, Canada

4. Department of Ecology and Evolutionary Biology, University of Toronto, 25 Willcocks Street, Toronto, ON M5S 3B2, Canada

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Abstract (350 words)

Wild salmon commercial fisheries in British Columbia (BC), Canada, have seen decreasing return and catch numbers across multiple salmon populations. Successful management of this provisioning ecosystem service (ES) has been elusive, but there is recognition that a wider social-ecological perspective is needed to support recovery. While ES monitoring is essential for evidence-based management, the social-ecological dimensions of ES pose challenges to monitoring: (i) sources of ES-relevant data are siloed and disjointed, and (ii) ES assessments 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 has not been fully implemented in any study to date. We use the EESV framework to analyze 27 years of monitoring data from diverse sources to assess change in the ES provided by wild Pacific salmon fisheries in the first 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 mixed effects, with some species benefiting and others declining. We also evaluate the government's license retirement program, finding limited success in reducing fishing effort and improving the industry's financial viability. Based on Bayesian modeling, that explicitly quantifies uncertainty, we found that ecological predictions have greater uncertainty than social or economic trends, suggesting that additional unaccounted for mechanisms influence ES supply. We were unable to include any measure of relational value, emphasizing the need to collect and incorporate cultural and relational data into ES monitoring.

Overall, our findings underscore the role of market forces in maintaining salmon ES value despite ecological unpredictability and declining catch. By demonstrating how essential variables can be used to integrate diverse data into a unified causal representation, this study advances standardized ES monitoring. This work advances the EESV framework by linking social and ecological data and it offers insight into how to monitor ES in other systems facing similar challenges.

Keywords (6 to 12)

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). The global agenda on sustainable development calls for careful management of ecosystems to ensure a good quality of life for people today, that does not threaten future generations' wellbeing (Robert, Parris, and Leiserowitz 2005). This sustainability objective calls 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).

Provisioning ecosystem services, in particular, are essential to sustainable development. Specifically, fisheries support the livelihoods of at least 600 million people worldwide and feed 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, the fishing industry has played an important role in the development of the country's culture and its food security (Castañeda et al. 2020). In British Columbia (BC), specifically, the seafood sector still plays an important role in the economy (Ministry of Agriculture and Food 2023). The strong upwelling off the coast has historically supported thriving capture fisheries and a highly productive ecosystem (Whitney and Robert 2002). Wild salmon in particular play a key role in both the marine and terrestrial ecosystems of BC (Cederholm et al. 1999), in the historical diet of indigenous communities and the culture of people living in the province (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). Hence, the management of 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 ecosystem service (DFO 2018; Kanada 2005).

Monitoring data can provide the basis for the detection and attribution of change in social-ecological systems (Schwantes et al. 2024). Yet, monitoring ecosystem services requires going beyond measures of ecological condition and the status of ecosystems providing the service to include socio-cultural variables important to causal understanding (Bennett et al.

2015). In British Columbia, commercial salmon fisheries are typically monitored and managed at the stock or management area level by a range of agencies and organisations. Each of these organisations has its own mandate (e.g. conservation or economic management) and collects monitoring data to support its needs. This results in the production of a large amount of ecosystem service data that are disjointed and disconnected, a common challenge in ecosystem service assessments (Bagstad et al. 2025). Hence, gathering, organising and analysing the array of ecological, economic and social datasets needed to monitor the status of this and other ecosystem services poses a challenge.

The essential ecosystem service variables (EESV) framework was proposed to tackle this exact challenge (Balvanera et al. 2022) by enabling detection and attribution of change (Gonzalez, Chase, and O'Connor 2023). It proposes that monitoring ecosystem services requires focusing on essential variables split into six classes (*ecological supply*, *anthropogenic contribution*, *demand*, *use*, *instrumental value*, and *relational value* – Supplementary Box 1) that are intended to capture the multidimensional nature of an ecosystem service (Balvanera et al. 2022). Under the EESV framework, monitoring data is organised into classes and used to produce essential variables that can be analysed systematically to produce indicators of change. However, the development and use of EESVs are still in their infancy and, despite their potential in standardising data needs across ecosystem services monitoring and reporting frameworks (Schwantes et al. 2024), no complete case study of EESVs is available for any ecosystem service anywhere.

The EESV framework, designed to systematise ecosystem service monitoring, can be used to understand ecosystem service dynamics of commercial Pacific salmon fisheries. Data from the different organisations involved in monitoring salmon fisheries can be organised into each class and analysed in turn. Once monitoring data are linked to EESVs, we can test causal models of a system, to estimate the status of key variables, model and detect trends in these variables and attribute the causal drivers responsible for the observed dynamics (Gonzalez, Chase, and O'Connor 2023; Schwantes et al. 2025). Hence, in this study, we acquired data from various monitoring sources to conduct a first provincial-level multi-salmon species analysis of this provisioning ecosystem service. Much is already known about Pacific salmon fisheries, and we use this knowledge with the EESV framework and monitoring data from the past 27 years to understand the change in the ecosystem service and advance our causal understanding of the system (Figure 1).

First, we identify the monitoring data available in the social-ecological system and align it with EESVs to define a causal model for the ecosystem service. Then we analyse the EESVs and drivers in the model using a set of Bayesian models to understand the dynamics in the social-ecological system and check for evidence of consistency with our causal model. Next, we assess whether a policy intervention (i.e. licence retirement) introduced in 1996 has in fact improved *instrumental value*, as intended. Using Bayesian models allowed us to deal with uncertainty explicitly and provides a measure of confidence in the relationships found. Thus, in this study, we use the case of Pacific salmon fisheries to identify EESVs and apply the framework, showing its value in detecting and attributing ecosystem service change in the context of a wild fish provisioning service and its potential for monitoring ecosystem services in support of management. Hence, with this implementation, we aim to advance the development and showcase the value of EESVs.

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 organisations 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 1a).

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 classes (Figure 2 & 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 availability, on Pacific salmon fisheries has focused on commercial fishing (Kanada 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 2 & 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).

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). There are now concerns over declining salmon returns, 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, MacDonald, and Winston 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). In fact, including drivers in studies of ecosystem service provision is often necessary to understand the dynamics of the system (Schwantes et al. 2025). 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 realised 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 salmon species. A strict licensing policy and fisheries closure system controls 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 fishers. The BC government oversees its provincial seafood industry 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 1) 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; Kanada 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, Connors, and Hertz 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 organisation: the Pacific Salmon Foundation, and the European Union's Copernicus programme (Table 1). Some datasets were publicly available while others had to be requested.

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 datasets were used without transformation, except for price per kilo data, which were obtained by dividing the income generated from the wholesale of each salmon species (wild or farmed) by the total weight sold each year.

Because data were collected by different organisations for different purposes (e.g. conservation of populations or fisheries management), some data had to be further transformed for modelling to match variables not at the same spatial resolution. Specifically, catch was summed across the province for each species and spawner abundance was summed across populations for each species. Additionally, we summed spawner abundances for North coast and South coast populations to match them with the corresponding management areas for catch fisheries (North Coast populations matched to A, C & F and South Coast populations matched to B, D, E G & H).

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

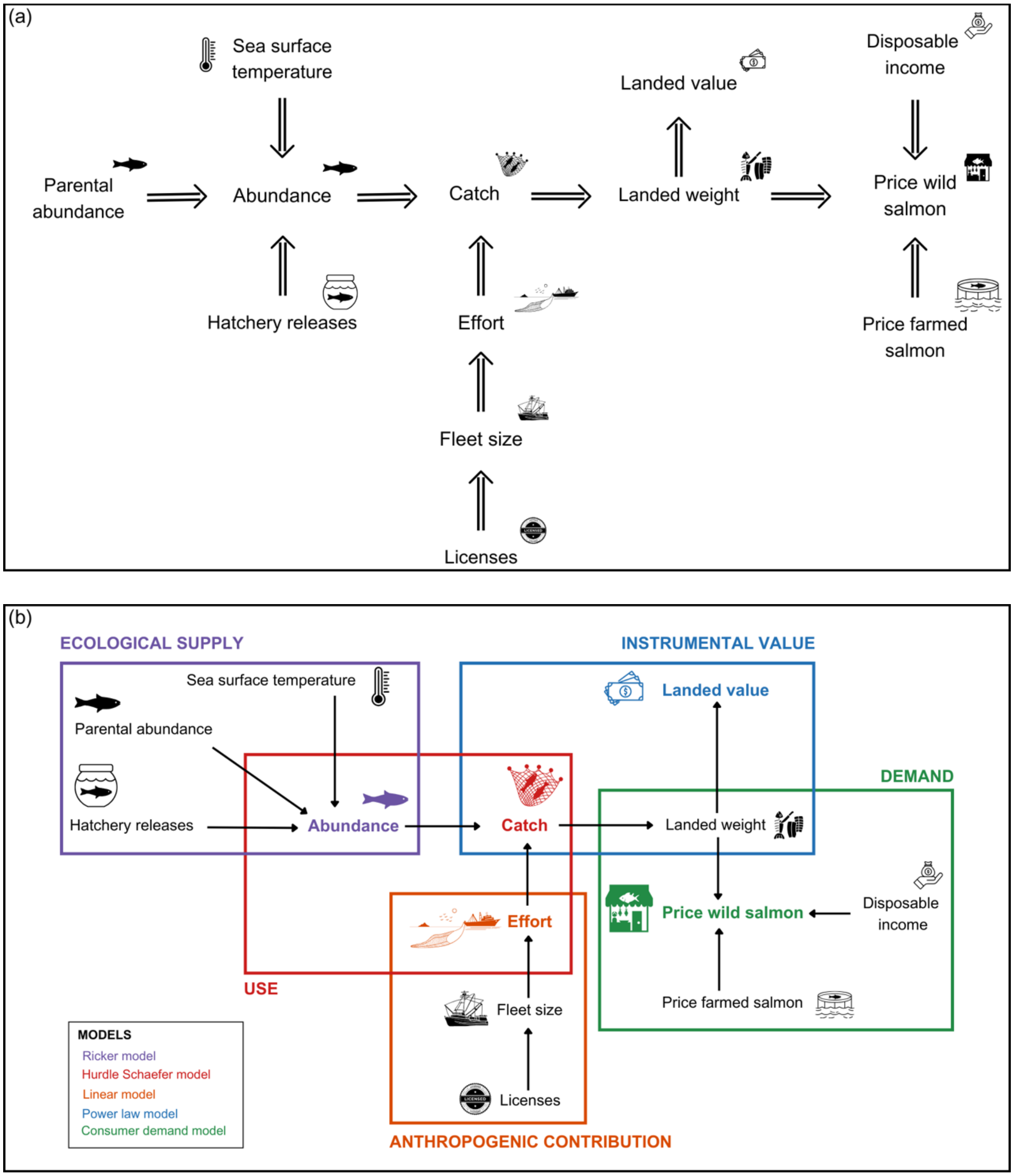

Figure 1. (a) Causal knowledge diagram representing the core causal chain, and underlying mechanistic drivers, connecting key variables in the wild salmon fisheries social-ecological system in any given year. (b) Models for each EESV identified in the causal knowledge diagram. EESVs are represented in 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 3.

EESV modelling

We modelled each EESV according to the causal knowledge graph for the Pacific salmon fishery (Figure 1). We used a Bayesian modelling framework for all EESVs. This approach allowed us to choose and customise 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 1b). 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).

For spawner abundance (*i.e., ecological supply*) we used a static Ricker stock recruitment model, the most commonly used and widely recognised mechanistic model for salmon species (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 estimate from the average generation length ago (e.g., Chum salmon spawn every four years). We extended the model to include a temperature and hatchery term on growth to account for the effect of these drivers on spawner returns. We linearized the Ricker model by applying a logarithmic transformation to the data. All parameters in the model varied by species but only the productivity and density dependence parameters were estimated hierarchically across species. We tested a set of auto-regressive models to account for the effect of time lags on *ecological supply*. However, these models did not improve fit. This is expected since the Ricker model we fit already accounted for the effect of time. Indeed, the explanatory variables parental abundance and hatchery (Figure 1) are already lagged by average generation time. The temperature variable was lagged to coincide with the migration year out to the ocean of the population, thus capturing any effect of time.

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.

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 (here, farmed salmon) and the disposable income of consumers. We fit the model estimating all parameters hierarchically per species, except for the intercept, which was estimated independently.

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 modelled as the product of abundance, effort and a catchability coefficient. 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.

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. 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 was 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

Note that the causal knowledge diagram we use here (Figure 1a) is also the first step in causal knowledge analysis, which we undertake in this article and which is fundamentally different from statistical causal analysis (Grace 2024). We use this causal model to check whether EESV observations are consistent with it and supportive of some underlying mechanistic causes that drive the system. In this article, we do not estimate causal effects but explore the plausible causal mechanisms that underpin system dynamics and discuss these within the context of the extensive knowledge base on Pacific salmon fisheries. The aim of causal knowledge analysis is thus to advance causal understanding over the long term, which in the context of monitoring has important direct implications for management, rather than estimating causal effects from observational data.

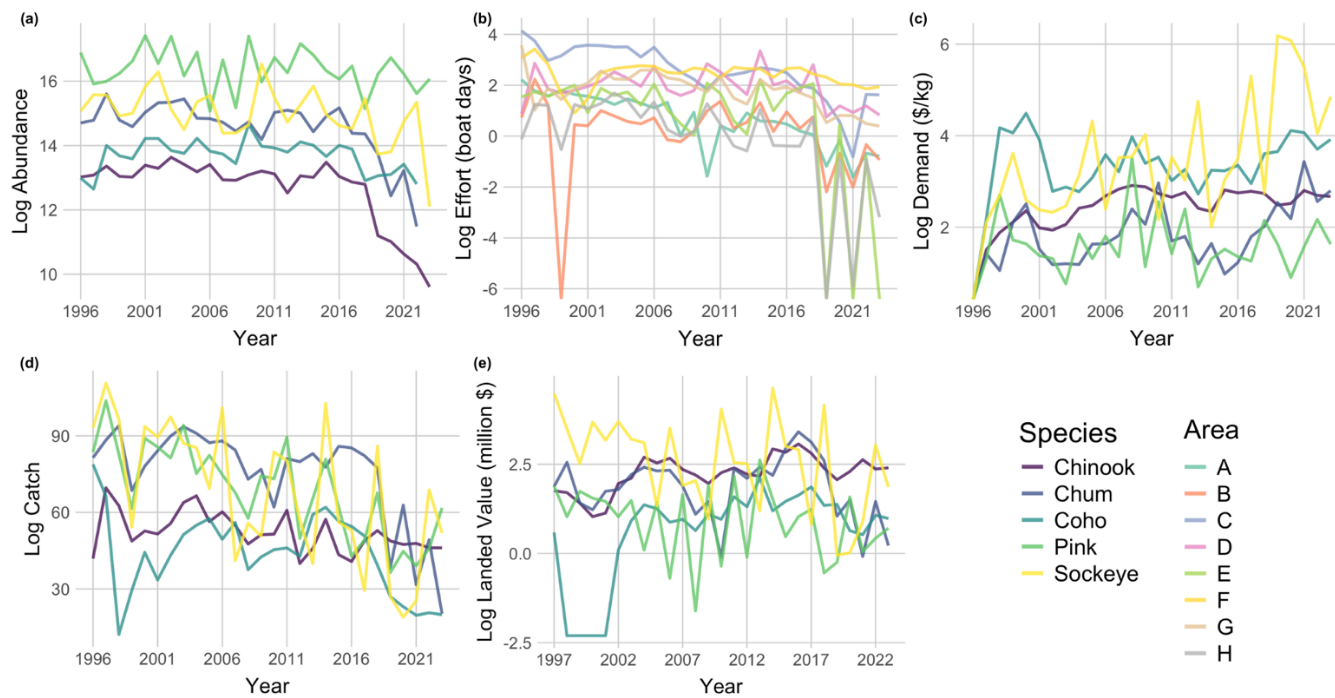

Figure 2 EESV time series for the wild fish provisioning ecosystem service of commercial BC salmon fisheries. Time series (from 1996 to 2023) are shown for each individual species for (a) *ecological supply*, (c) *demand*, (d) *use*, and (e) *instrumental value* and for each management area for (b) *anthropogenic 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.

Results

EESV dynamics

Convergence for each model was good: 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 had the highest growth rate, followed by Coho, Chum, Sockeye and Chinook (Table 2 and α parameter, Supplementary Table S3). Density dependence effects were strongest for Coho, followed by Chinook, Chum, Sockeye and Pink (Table 2 and β parameter, Supplementary Table S3). The effect of increasing sea surface temperatures was negative for all species except for Coho (credible interval overlapping 0). The negative effect of temperature was strongest for Chum, followed by Pink, Sockeye and Chinook (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 Chum abundance, which appears to benefit from the release of hatchery fish, and Pink abundance, which conversely, 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 3a). 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 3d 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 4 and Supplementary Figure S11).

The *demand* model shows a negative exponential relationship between *demand* and harvest of salmon (in tonnes) for Sockeye, Pink, Chum and Coho but not for Chinook (credible interval overlapping 0, Table 2 and parameter b_1, Supplementary Table S3), suggesting a disconnect between supply, in the economic sense, and *demand* for these two species. The price of an alternative product, farmed salmon, had no noticeable effect (all parameters' credible intervals overlapped 0) on *demand* for any species (Table 2 and parameter b_2, Supplementary

Table S3). Disposable income had a positive effect on *demand* for all species except Pink (credible interval overlapping 0), which was strongest for Sockeye then Coho (Table 2 and parameter b_3, Supplementary Table A3). 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 3c). *Demand* was highest for Sockeye, followed by Coho, Chum, Chinook, and then Pink.

In the *use* 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 the other two species with continued boom and bust dynamics following *ecological supply* (Figure 3b 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 3e). 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 1b). 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	0.376 [0.013, 1.03]	0.290 [0.006,1.13]	0.470 [0.014,1.69]	0.397 [0.011, 1.54]	3.60 [1.84, 5.31]
	Density dependence	$1.18.10^{-7}$ [$5.70.10^{-8}$, $1.78.10^{-7}$]	$1.58.10^{-6}$ [$8.24.10^{-7}$, $2.57.10^{-6}$]	$1.70.10^{-6}$ [$1.07.10^{-6}$, $2.30.10^{-6}$]	$5.41.10^{-7}$ [$3.03.10^{-7}$, $7.69.10^{-7}$]	$1.25.10^{-7}$ [$9.11.10^{-8}$, $1.60.10^{-7}$]
	Temperature effect	-0.511 [-0.713, -0.236]	-0.185 [-0.334, -0.054]	-0.078 [-0.730, 0.287]	-1.118 [-1.735, -0.664]	-0.961 [-1.883, -0.022]
	Hatchery effect	0.033 [-0.006, 0.067]	0.006 [-0.047, 0.033]	0.001 [-0.033, 0.033]	0.120 [0.068, 0.168]	-0.177 [-0.156, -0.070]
Demand	Landed weight effect	-0.552 [-0.620, -0.482]	-0.150 [-0.357, 0.085]	-0.350 [-0.435, -0.263]	-0.327 [-0.412, -0.241]	-0.230 [-0.316, -0.138]
	Price farmed salmon effect	0.202 [-0.207, 0.785]	-0.086 [-0.603, 0.299]	-0.007 [-0.460, 0.415]	0.035 [-0.391, 0.476]	-0.095 [-0.602, 0.302]
	Disposable income effect	0.961 [0.635, 1.27]	0.684 [0.370, 1.02]	0.889 [0.586, 1.24]	0.439 [0.135, 0.730]	0.205 [-0.107, 0.550]
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. Gear by management area effect size on EESV class *anthropogenic contribution* for the fleet size effect parameter (Figure 1b). 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**	1.50 [1.27, 1.76]	0.897 [0.713, 1.08]	2.12 [0.341, 4.05]	2.13 [0.235, 3.99]	2.12 [0.285, 4.02]	2.09 [0.377, 4.02]	2.15 [0.273, 4.05]	2.11 [0.303, 4.01]
	Troll	2.11 [0.217, 4.02]	2.11 [0.302, 4.05]	2.12 [0.244, 4.00]	2.11 [0.248, 3.98]	2.13 [0.305, 4.02]	3.83 [3.57, 4.08]	2.80 [2.57, 3.04]	1.82 [1.15, 2.51]
	Gillnet	2.08 [0.219, 4.00]	2.11 [0.237, 3.97]	2.32 [2.08, 2.57]	2.09 [1.71, 2.49]	1.28 [0.847, 1.71]	2.12 [0.197, 3.94]	2.10 [0.188, 3.96]	2.11 [0.233, 3.96]

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 1b). 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]

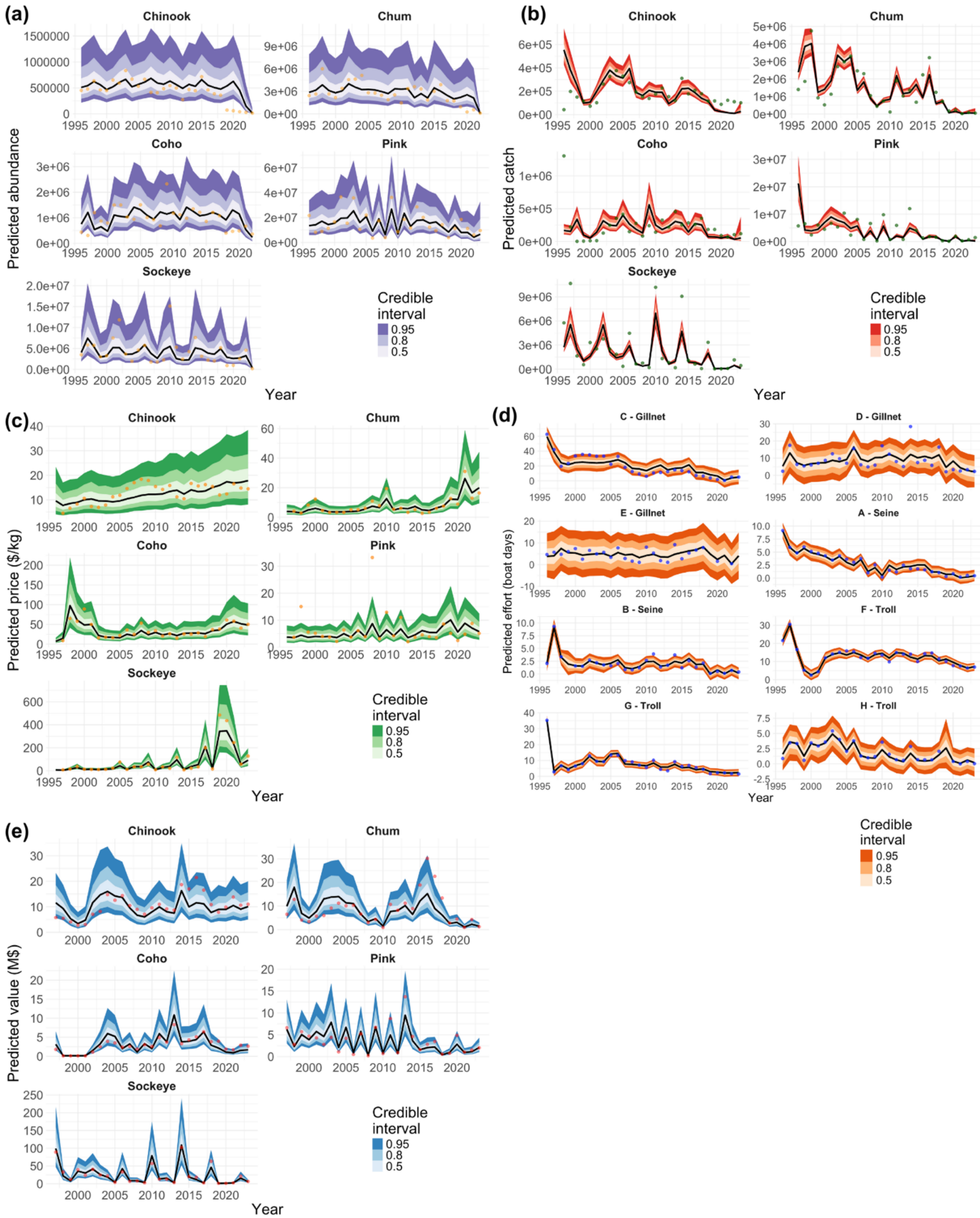

Figure 3. Model predicted time series of all EESVs assessed over the study period (1996-2023): (a) *ecological supply*, (b) *use*, (c) *demand*, (d) *anthropogenic contribution* and (e) *instrumental*

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%).

Policy effect

The slight downward trend in fleet size predicted by the model suggests that the license retirement programme introduced in 1996 (at the start of our analysis) has been somewhat effective at reducing the number of fishing boats on the water in some areas (C, F, G and H - Figure 4). However, the poor model fit, weak effect (parameter $0.619 < b_1 < 4.07$, Supplementary Table 3), and noticeable differences in pattern across management areas (some weakly declining some remaining level – Figure 4) 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 2b) and predicted in multiple areas (A, B, C, F, G, and H, Figure 3d) across the province (Supplementary Figure S10). Following the logic of the causal knowledge graph (Figure 1), we expect a consequent decline in catch (*use*), which is indeed observed (Figure 2d) and predicted (Figure 3b) for most species. However, we observed (Figure 2e) and predicted (Figure 3e) 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, per capita, the financial viability of those who remain in the fishery has indeed improved for those who remain, as intended by the policy. However, we also observed (Figure 2c) and predicted (Figure 3c) 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 licencing policy on its own led to an improvement in the financial viability for fishers.

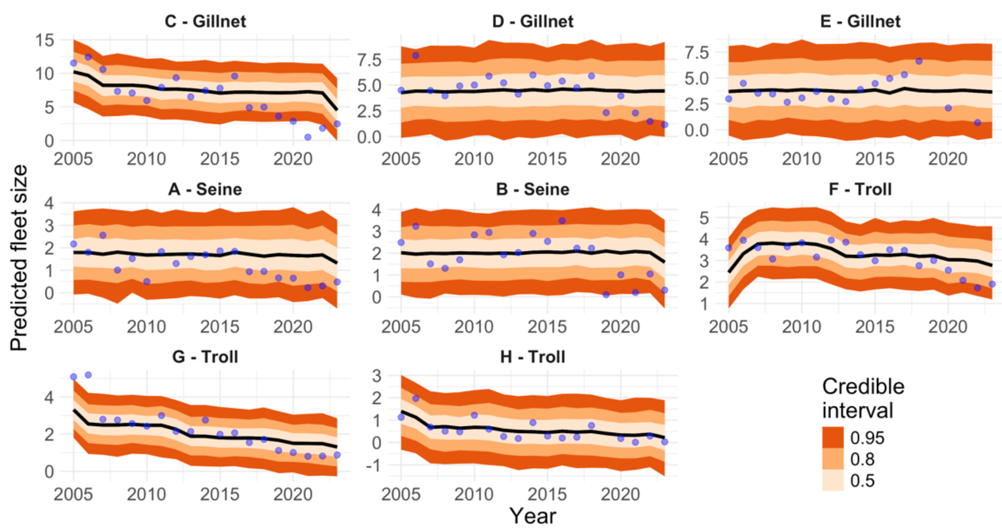

Figure 4. A weak to no predicted decline in yearly fleet size for all management areas is supported by the model containing licence numbers as explanatory variable. Observed data points (in blue) and 50%, 80%, and 95% credible intervals from light to dark.

Discussion

This paper aimed to understand the dynamics of the ecosystem services provided by commercial salmon fisheries in British Columbia by implementing the essential ecosystem service variable (EESV) framework within a causal detection and attribution analysis. Thus, we identified and modelled five essential ecosystem service variables (EESVs) to produce the first analysis of all five commercial Pacific salmon fisheries in Canada at the provincial level. We first discuss our findings in the context of these fisheries, address some limitations and avenues for improvement, comment on the advantages of using the EESV framework, and conclude on the role of EESVs in advancing monitoring of ecosystem services more generally.

EESV dynamics

A good causal understanding of the social-ecological system is required to develop the causal knowledge graph (Figure 1a), which we tested with specific EESV models (Figure 1b) 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, and O'Connor 2023). We found good support for our models, validating our choice of EESVs and the underlying mechanisms driving relationships between them and their drivers.

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 most 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, Peterman, and Pyper 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 mixed effects of hatcheries, with Chum salmon benefiting from them whilst Pink salmon declined. 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.

Socio-economic drivers were also relevant. Specifically, we found that one driver of *demand*, disposable income, increased with the price of salmon species, especially Sockeye, supporting its role as a luxury good as consumers tend to spend more freely when income is high (Silverstein and Fiske 2003). 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*.

Relationships between EESVs were important to system dynamics. Using *ecological supply* and *anthropogenic contribution* to model *use* allowed us to estimate an important parameter in fisheries management: catchability. Catchability provides an estimate of 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, Catalano, and Fleischman 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, Yang, and Li 2016). However, such a telecoupling effect assumes stable international demand, which could be influenced by factors such as shifting trade policies, competition from aquaculture (which we do not find support for), 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 3a) 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 3c,d) suggest that we can be fairly confident in the drivers used to predict them. In fact, the underlying mechanisms driving these EESVs may be simpler to understand, and monitor given their economic nature. Our approach for modelling EESVs explicitly produces estimates of uncertainty and scalable predictions. 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 the model predictions is necessary to provide a statement of confidence in our causal model (Gonzalez, Chase, and O'Connor 2023). Including uncertainty in estimates provides a measure of confidence in the detected trends and is necessary to accurately guide policy and 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 4). 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 data available in Canada (e.g. no population age structure was available across BC for any species) 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, but this precluded us from studying the ecological sustainability of the system or any feedback effects of catch on abundance. Specifically, we could not test the effect of fishing on *ecological supply* due to the metric used for abundance. Spawner abundance is measured after the fish have made it past commercial fishers, *i.e.* the effect of fishing has already happened. A more useful measure of *ecological supply* in this context would have been total run size, *i.e.* the total number of salmon returning to spawn before commercial fishers take their harvest (total run size = spawner abundance + catch). However, this data was not available for a majority of 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 had to rely on the Ricker model only and instead use 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, we believe this was appropriate due to the focus of the study on the ecosystem service using EESVs, which include many socio-economic variables. Arguably, 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).

Moreover, 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 modelling 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 modelling 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 2021), 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 are not in a usable format for analysis (*i.e.* available as scanned PDFs). 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, Copeland, and Oldemeyer 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

Some improvements can be made to our modelling approach, we did not account for all possible drivers of change in this system nor for the possibility of dynamic parameters. 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 useful for a more in-depth assessment of the system and to identify the underlying mechanisms driving its dynamics. However, the aim of the EESV approach is to focus on a subset of variables that can inform on the ecosystem service. Additionally, using analytical methods that allow key parameters (e.g. growth rate or catchability) to change over time may be useful to more accurately understand dynamics in the system but often require large amounts of data and present issues of parameter identifiability (Ye et al. 2015). Addressing both these limitations could be extensions to our work to improve the mechanistic understanding of the social-ecological system in wild Pacific salmon fisheries.

Importantly, 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 identify 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, Gould, and Pascual 2018). The EESV framework, by acknowledging the equally important role of relational values asks for them to be considered in monitoring. However, how this is to be done in practice remains an open question. One that may be answered through tighter collaboration with social scientists when designing monitoring systems. Indeed, social science methods, such as controlled interviews, surveys and workshops, are powerful techniques to understand relational values (Olander et al. 2018; Galang et al. 2025; Schulz and Martin-Ortega 2018) and should be included in ecosystem service monitoring.

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, operationalises 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 organise 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 recognisable by the scientific communities that study them.

Conclusion

Ecosystem services monitoring, whether for accounting, planning or reporting purposes, is now a priority of policy. For monitoring data to inform such policy needs, it should be used within a detection and attribution framework that enables a mechanistic causal understanding of ecosystem service dynamics. The essential ecosystem service variable (EESV) framework supports this approach by explicitly calling for the inclusion of ecological, social and economic data in ecosystem service monitoring. Where social-ecological monitoring was not explicitly done *ad hoc*, EESVs can help develop a causal understanding of the ecosystem service by bringing together data from multiple sources to understand the different dimensions of ecosystem service change. We implemented this framework in the case of wild Pacific salmon fisheries to provide novel insights into the dynamics of this ecosystem service. Our analysis points to an ecosystem service with poor resilience, largely maintained by market forces and with an unpredictable *ecological supply*. We showed this in a system where no formal social-ecological monitoring observatory is in place (Vári, Gonzalez, and Bennett 2025). Yet, considering the social-ecological dynamics of ecosystem services is essential and monitoring programmes should be developed with this in mind to avoid some of the challenges in analysis we encountered. Unfortunately, programmes that do take an integrated social-ecological monitoring approach are few (Gurney et al. 2019; Bennett, Fraser, and Winkler 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 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, Gonzalez, and Bennett 2025; Firkowski et al. 2021) that build upon existing biodiversity observation networks (Scholes et al. 2017) and provide the knowledge necessary to guide sustainable management of ecosystem services.

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