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Opposing trends in fisheries portfolio diversity at harvester and community scales signal opportunities for adaptation

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Abstract

Understanding mechanisms that promote social-ecological resilience can inform future adaptation strategies. Among seafood dependent communities, these can be illuminated by assessing change among fisheries portfolios. Here, in collaboration with a Coast Salish Nation in British Columbia, Canada, we used expert Indigenous knowledge and network analyses to chronicle differences in fisheries portfolios pre and post a social-ecological regime shift. We then evaluated key drivers of change using semi-structured interviews. We found that while portfolios decreased in diversity of seafood types harvested and consumed among individuals overtime, portfolios increased in their diversification at the community level because more similar seafoods within less diverse individual portfolios were more commonly harvested and consumed by the Nation as a whole. Thus, diversity can operate simultaneously in opposing directions at different scales of organization. Experts identified four key mechanisms driving these changes, including commercial activities controlled by a centralized governance regime, intergenerational knowledge loss, adaptive learning to new ecological and economic opportunities, and the trading of seafood with other Indigenous communities. Unexpectedly, increased predation by marine mammals was also flagged as a key driver of change. Adaptation strategies that support access to and governance of diverse fisheries, exchange of seafoods among communities, and knowledge transfer among generations would promote social-ecological resilience, food security, and community well-being.

Key words: social-ecological systems, resilience, network analysis, Indigenous Knowledge, small-scale fisheries, ocean governance

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Introduction

Fisheries are social-ecological systems (SES) providing food and nutritional security, livelihoods and cultural well-being for 3 billion people globally (FAO 2016). However, projections of climate-induced fisheries declines (Barange et al. 2014; Cheung et al. 2013; Lotze et al. 2019) suggest that eleven percent of the earth's population could become vulnerable to undernutrition due to reduced abundance and access to marine foods (Golden et al. 2016). Repercussions of these declines are predicted to intensify in coastal areas and small island communities, where fish can comprise upwards of 50% of the total animal protein consumed (Bell et al. 2009; FAO 2016).

Yet, multiple drivers of change, acting across a diversity of spatial and temporal scales, are contributing to declining seafood catches to which human communities and ecosystems must adapt. These drivers include, but are not limited to, overfishing (Costello et al. 2016), pollution (Fleming et al. 2019), governance barriers (Plagányi et al. 2013), disruptions to intergenerational knowledge transmission (Turner et al. 2008), and cultural shifts in harvest and consumption patterns (Tam et al. 2018). Adaptation in the face of multiple disturbances is a key component of social-ecological resilience (Folke et al. 2010), an emergent system property supported by attributes such as diversity, redundancy, connectivity, knowledge integration, understanding of long-term change, and polycentric governance (Biggs et al. 2012).

Emerging theoretical and empirical evidence suggests that ecological and (or) social diversity is key to system resilience by providing options by which a system can respond to disturbances (Biggs et al. 2012). In aquatic systems, diverse portfolios of populations (Schindler et al. 2010), species (Cline et al. 2017), fisheries (Fuller et al. 2017; Sethi et al. 2014) and livelihoods (Cinner and Bodin 2010) have been shown to be more resilient to multiple disturbances, such as environmental, regulatory, and economic pressures (Beaudreau et al. 2019), than less diverse systems. At the same time, fisheries harvest portfolios, which describe the diversity (number of species), composition (identity of species) and structure (combination of species) of catches, can differ between individual and community-level due to unique adaptive responses to multiple drivers of change (Beaudreau et al. 2018). For example, changes in fisheries policies could lead to decreased diversity in the community-level fishing portfolio, while individual fishers seek to diversify their target species within that aggregate portfolio. Diversification at the community-level may arise from individual fishers specializing in a variety of fisheries (e.g., salmon specialists, halibut specialists, etc.) or generalization at the individual level (e.g., fishers targeting both salmon and halibut; Beaudreau et al. 2019). Similarly, for subsistence or food, social and ceremonial fisheries (FSC), differences may arise between the diversity of what is harvested and what is consumed as food locally.

On the Pacific coast of Canada, current fisheries governance regimes are limiting Indigenous people's access to fish (Atlas et al. 2021; Harris 2009; Jones et al. 2017; Pinkerton and Davis 2015; von der Porten et al. 2016), thereby exacerbating predicted climate-induced shortages in traditional seafood catch potential (Cheung et al. 2015; Weatherdon et al. 2016). Given these interlinked, cross-scale drivers of change, a perfect storm is brewing where communities most dependent on the marine environment for food are also the most vulnerable to climate change and inequitable governance regimes (Allison and Bassett 2017; Golden et al. 2016). For example, on BC's coast, Indigenous communities have the constitutionally protected right to harvest Pacific herring for food, but they do not have the collective choice right to manage this fishery due to unequal power and decision-making authority in the governance and management of this forage fish (Jones et al. 2017; Salomon et al. 2019; von der Porten et al. 2016). Therefore, there is a pressing need to understand barriers and opportunities to improve access to traditional seafood by co-designing management strategies that reflect community priorities and local knowledge, and co-delivering solutions that are socially-just and ecologically-sustainable (Free et al. 2020; Österblom et al. 2020; Salomon et al. 2018).

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Coastal Indigenous people in BC, Canada, self-referred to as First Nations, depend on marine resources for FSC, as well as economic purposes (Jones et al. 2004). However, First Nations people in BC are facing high rates of food insecurity, where up to 41% of households on reserve (i.e., land designated by colonial governments to First Nations) have limited access to food and (or) cannot meet their nutritional needs (Chan et al. 2011). Moreover, potential catches of both commercial and FSC marine species along the coast are projected to decrease by 4.5% to 10.7%, with an increased magnitude of change expected at lower latitudes (Weatherdon et al. 2016). Thus, future food and nutritional insecurity may be exacerbated (Marushka et al. 2019). In addition, new generations of coastal First Nations are transitioning away from traditional foods due to complex interactions between limited access to traditional marine resources (Chan et al. 2011) and generational changes in food preference (Kuhnlein and Receveur 1996). Developing strategies to adapt to climate change, contest inequitable governance regimes, and promote Indigenous food sovereignty (Coté 2016) is crucial to ensure sustainable fisheries and healthy human communities of future coastal First Nations.

Here, by weaving Indigenous and scientific knowledge, we documented the changes in food fisheries of a Coast Salish Nation in BC, Canada. Specifically, we collected qualitative and quantitative data from Indigenous food fisheries experts to document changes in individual portfolio diversity (number of different seafood types harvested by an individual), community portfolio diversity (number of seafood types harvested together by at least one community member within the community portfolio), and relative abundance of seafood harvested and consumed over the last several decades. We then documented the most important factors, identified by experts, driving these changes. Finally, to illuminate opportunities for future adaptation strategies to support SES resilience, we also identified key mechanisms driving these changes.

We hypothesized multiple non-mutually exclusive processes might be contributing to two portfolio outcomes over time. First, traditional food fisheries portfolios could diversify over time due to; (1) serial depletion of culturally preferred species (Salomon et al. 2007) resulting in an expansion to include the harvest of multiple new target species (Roughgarden 1972; Schoener 1971), (2) an increase in multiple target species preferences (Beaudreau et al. 2018), and (or) (3) advances in fishing technology increasing access to multiple new target species. Alternatively, portfolios could have become less diverse due to (1) license restrictions (Ojea et al. 2017), (2) reduced fisheries abundance due to environmental factors such as climate change (Weatherdon et al. 2016), and (or) (3) increasingly prohibitive economic costs of fishing (Pinkerton and Edwards 2009). Lastly, we hypothesized that these multiple mechanisms might be operating concurrently, influencing both the individual and community-level diversity of harvest (i.e., what is caught) and consumption (i.e., what is eaten) portfolios.

Methods

Knowledge co-production: We conducted this research in collaboration with a Coast Salish Nation (hereafter "the Nation") on the southwest coast of BC, Canada (**Fig. S1**). This project was co-produced through a process that equitably engaged the Nation's government and resource users in the research from its inception. Together, we conceptualized the project by way of in-person meetings and conference calls. First, university researchers (co-authors S Ouchi, A Salomon, T Kenney, C Wabnitz) presented published research on fisheries, climate change and human health to the Nation's government at a meeting where the Nation's research objectives were discussed, and potential future research questions were identified. The Nation identified research partners to represent the Nation over the course of the project. Additionally, interested individuals from the Nation identified themselves and participated as mentors throughout the process. Over the following months, our project's research questions were honed collaboratively, and a successful joint funding application allowed for lead author, S Ouchi, to work as an intern for the Nation. Additional funding and logistics were jointly provided through academic streams and the Nation. Finally, the results of the work were

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shared and reviewed at a community presentation and in meetings with the Nation to hone our interpretation of the results. The co-authors on this paper reflect this knowledge co-production process and the intellectual contributions of all partners.

Through the Nation's formal decision-making process, the publication of our co-produced research was endorsed with the request that the Nation remain anonymous, which we have respected throughout this piece. To respect the decision of individual experts who wanted and consented to having their knowledge recognized and shared, we have specifically attributed their knowledge throughout this piece.

Study Area. The Coast Salish Nation we partnered with has occupied their traditional territory on the northern Salish Sea for at least the last millennium (Lepofsky et al. 2015; Springer and Lepofsky 2019). Archaeological evidence suggests the Nation relied on and actively managed a diversity of marine resources throughout this time period (Caldwell et al. 2012). Since colonization in the late 1700s, profound socio-economic, ecological and cultural drivers of change have transformed the Nation's way of life (Paul et al. 2014). These include mandatory beach closures due to contamination (Fediuk and Thom 2003), marine resource shifts in the Salish Sea due to industrialized fishing (Pauly et al. 1998), and the imposition of residential schools (Barnes 2008; Paul et al. 2014). Recently, the Nation ratified a treaty with the Government of Canada and BC specifying the Nation's rights and benefits respecting land, marine and terrestrial resources, as well as self-governance. This is a unique governance context among First Nations in BC as most of the province's land is unceded, meaning that Aboriginal Title has neither been surrendered nor acquired by the Government of Canada. The Joint Fisheries Committee (comprised of the Nation, BC, and Canada government representatives) cooperatively assess, plan, and manage the Nation's fisheries. However, the Government of Canada still assumes authority for managing and conserving fish, aquatic plants and fish habitat, and allocations for different fisheries are determined each year based on stock assessments. Although this community experienced centuries of rapid changes, harvesting and eating traditional seafoods, such as sockeye salmon and Pacific herring roe (Marushka et al. 2019), continues to be a central component of cultural and day-to-day practices for most members of the community (Chan et al. 2011; Paul et al. 2014).

Semi-Structured Interviews

Participant Selection, Interview Design, and Implementation. To document changes in the Nation's food fisheries portfolios through time, we conducted in person, semi-structured interviews (Huntington 1998) and quantitative surveys with the community's traditional food fisheries experts (n=24) between June and August of 2018 (**Fig. S2**). Prior to these interviews, Ethics Board approval was acquired (Study Number: 2018s0243) and three pilot interviews with volunteers from our Nation partner were conducted to test and refine our questions, and to improve interpretation and consistency among participants. Our objective was to interview expert knowledge holders rather than a representative sample of community members. Consequently, community experts were identified by research partners and mentors from the Nation based on their expertise in traditional food fisheries (Davis and Wagner 2003; Fazey et al. 2006; Salomon et al. 2007) and deep knowledge of the social-ecological system, making them highly suited to detect changes in harvesting and consuming traditional seafood (Ban et al. 2017) and the factors driving changes (Andrachuk and Armitage 2015). Additional experts were identified from conversations with initial experts (i.e., chain-referral or snowball sampling; Bernard, 2006).

Based on this, we interviewed five self-identified women and 19 self-identified men, between the ages of 28–87 years old. Although women fill essential roles in the entire process of contemporary and traditional food fishing activities (Brown and Brown 2009; Kafarowski 2009), this disparity in gender

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may reflect the way in which we asked our Nation partners to identify food fisheries experts within the community (Parvez Butt et al. 2019) as our description of "food fishing expert" maybe have skewed the selection of experts towards one gender. More broadly, the impact colonialism has had on gender roles within resource-based activities in Indigenous communities (Mulle and Anahita 2009; Norgaard et al. 2018; Tyrrell 2009) may have equally contributed to this disparity.

During the interviews, some of which were audio recorded with consent, we took detailed notes of stories, anecdotes, observations, and knowledge to triangulate and inform our inference of the quantitative data generated by the survey and to provide a more complete understanding of potential changes in traditional food fisheries (Jick 1979). Key qualitative data are assembled in **Table 1** and drawn on for interpretation. Finally, some participants wanted and consented to being identified and their key statements were drawn on for our interpretation and subsequent communication of the results.

Traditional Food Fisheries Portfolios. Food fisheries portfolios depict generalized groups (e.g., clams) or species (e.g., sockeye salmon) of fisheries that are harvested or consumed by a group of people. Due to our interest in the nutritional health implications of climate change impacts on food fisheries and our understanding that seafood is traded among Nations, we differentiated between what was harvested and what was consumed by participants. Traditional food fisheries were defined by the Nation through previous traditional use studies, which documented traditional harvesting areas and species used, and (or) our interviews. These traditional food fisheries included many seafood types composed of finfish, shellfish, and mammals used for FSC purposes. Experts were shown a series of laminated cards, each depicting a seafood type (**Fig. S2**). We then asked experts to rank the relative abundance of traditional food fish, harvested and consumed, on an ordinal scale from 1 (low) to 7 (high), for the current decade ("current", 2010–2018) and the earliest decade for which the expert had memories of harvesting or consuming ("past"). Relative abundances were ranked for different food fisheries groups (n = 35), hereafter termed seafood types (**Table S1**). Not all seafood types were ranked by all experts, resulting in differences in the number of seafood types reported in each portfolio (**Table S2**). Furthermore, depending on factors such as 'age', 'occupation' and 'preference not to answer', not all participants were represented in each portfolio (**Table S2**).

Drivers of Change. We asked participants to describe the main drivers of change that affected their harvest and consumption portfolios. First, to get a broad perspective of all factors driving change, we documented all participants' personal, unfiltered responses to minimize researcher bias (Gelcich et al. 2014). Second, to quantitatively compare across all participants, experts then ranked ten pre-identified factors, on an ordinal scale from 1 (low) to 7 (high), on the perceived importance of the factors in driving change. These drivers of change were identified by our Nation research partners and through a literature review (**Table S3**).

Statistical analyses

Portfolio Analysis. To assess how individual-level and community-level portfolio diversity, and relative abundance of the Nation's traditional food fisheries changed before and after a social-ecological regime shift, we conducted a network analysis of the Nation's food fisheries portfolios pre- and post-1980. Two punctuated events led to profound changes in regional fisheries in the late 1970s and early 1980s: the North Pacific oceanic regime shift in 1977 (Anderson and Piatt 1999; Hare and Mantua 2000), and the collapse of Pacific herring from the Nation's primary village (pers. comm. by eleven experts; Paul et al. 2014). These events informed our 1980 social-ecological regime shift and provided rationale for aggregating portfolios into pre- and post-1980 periods. We then depicted changes in the community harvest and consumption portfolios between pre- and post-1980 using the *igraph* package in R (Csárdi and Nepusz 2019). We calculated species richness as a metric of

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Table 1. Respondents' qualitative drivers of changes in the harvest and consumption of traditional seafoods, derived from an inductive analysis of themes.

Factor driving change	Reported percent	Description	Observation (representative quote)
Modernization	50%	Modernization of community resulting in a change of traditional values	"Times are just changing. In the past people were dependent on the ocean and the food that came from it." – Elsie Paul
Environmental change	42%	Changes in the marine environment including climate change, warming waters, red tide, etc.	"Red tide is more abundant these days compared to way back when. It seems like you can't go and pick oysters or harvest clams like you used to back in the day, even in a warm spell. Red tide is always here." – Bud Louie
Change in diet	38%	Increased western food consumption	"You don't have to go fishing anymore to provide for your family… food comes from the grocery store… that just wasn't in the cards when I was a child." – Roy Francis
Over harvesting	33%	Over exploitation of marine resources (commercial, sport, FSC)	"Only harvest what you need, hurts me to see people fish too much and then waste it" – R05
Reduced Access	25%	Factors allowing or limiting access which includes private property, boats, permit cards	"My dad had a boat and was always out getting something. I don't have a boat. Boat motor and trailer is a big thing for a lot of people." – Denise Smith
Governance barriers	25%	Barriers to decision making power with other governing bodies (e.g., DFO) and within own self-governing institution	"I was on council and they opened up the herring and that decimated the whole run. We fought with DFO … We have the traditional knowledge to prove that they always spawn here. It was always about protecting their own behind." – R04
Pollution	25%	Pollution from local sources (i.e., sewage and mill)	"fecal coliform was the biggest issue in the past, we [the Nation] had tests done and it wasn't our sewage that was the sustained source." – Eugene Louie
Increasing Costs	21%	Economic cost of practicing traditional seafoods (e.g., boat expenses, cheaper grocery store food, etc.)	"Back in the day it wasn't expensive b/c people went by dugout and would walk up the river. Didn't cost anything just time and effort." – Scott Galligos
Increased Predation	21%	Competition for fish with other predators, mainly pinnipeds	"I think there is less and less stuff that you can actually go out and harvest anymore. Actual abundance out there [has decreased]. There are a lot of reasons, pollutions, predation … they put the moratorium on them [seals] years ago and their numbers are huge. The sea lions don't leave anymore, they just stay … they are taking fish right off the line." – R04
Knowledge Loss	13%	Knowledge is not being transferred to younger generations	"my brother and I would go and catch herring and drop it off door to door but some people just didn't know what to do with the herring, there is a loss of knowledge" – Roy Francis "the elders that are passing on… those values are not instilled to the youth and that art gets lost" – Lee George
Community dependence	8%	Dependence on the Nation to provide food fish allocation	"I think we have done things with the goal of being helpful, like we will go out and get communal harvest…. We will bring salmon door to door with the meaning of being a good thing…. We have unintentionally created a bad thing. There is a dependence on fish coming to the door… I don't think that is necessarily a good thing. I think a better idea would be to encourage people to go out there and do their own harvest" – Roy Francis
Advances in Technology	4%	Advancement of fishing technologies (e.g., fish finders)	"technology has changed… the technology is incredible… I have fish finders and you can tell how many fish are on the reef right below you… I am there with a dozen other boats with the same technology I have so the fish stand less of a chance." – Roy Francis

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diversity at the individual-level, degree centrality (see below for definition) as a metric of diversity at the community-level, and ranked relative abundance of all seafood types (Beaudreau et al. 2018). Portfolio nodes (spheres) in the network represent seafood types (e.g., clams, herring, sockeye, etc.). Calculations were made separately for harvest and consumption portfolios.

Individuals may have different baseline perceptions of abundance (Beaudreau and Levin 2014). Therefore, for each respondent, we calculated relative abundance for each seafood type by dividing its ordinal abundance score by the sum of abundance scores across all seafood types reported by the same respondent. Graphically, the size of each portfolio node is proportional to the mean relativized score across all participants. Portfolio links (i.e., the lines connecting nodes) represent at least one participant having reported harvesting both of the seafood types for a given time period. The thickness of the lines represents the proportion of participants that reported harvesting both seafood types in the associated time period. The position of the nodes in space represents how commonly a seafood type is reported among participants. Seafood types aggregated in the center of the portfolio are more commonly reported, whereas seafood types located at the edges are less frequently reported. Finally, portfolios were plotted in two ways. First, we present the entire network, including all seafood types reported by experts. Second, to better reveal the community portfolio diversity and relative abundance of core fisheries, we graphed only the core fisheries in the network, as determined by the commonly harvested seafood types with greater than the mean number of links.

We quantified standardized degree centrality for each portfolio, which is the number of links associated with one seafood type divided by the total number of links in the network (Freeman 1979). Seafood types with higher standardized degree centrality are more connected to other seafood types. Thus, they are more commonly harvested or consumed across the community as a whole contributing to an overall diversified portfolio. To test for an effect of the time period on standardized degree centrality across all seafood types within the entire community portfolio (i.e., an aggregate number for each seafood type among participants), we fit a beta linear regression model (*betareg* package in R; Cribari-Neto and Zeileis, 2010; Zeileis et al., 2019) with a logit link function with maximum likelihood. This model structure accounted for the proportional nature of our data. To accommodate the upper bounds of the beta distribution, we transformed standardized degree centrality as follows: $y' = [y\ (N - 1) + 0.5]/N$, where N is the sample size (Smithson and Verkuilen 2006).

To test for a difference in the individual-level diversity (i.e., species richness) of harvest (or consumption) of seafood types across all participants between pre-1980 and post-1980 periods, we ran a linear mixed-effects model using a Poisson likelihood and log link function (*lme4* package in R; Bates et al., 2022). Because species richness values were calculated for individual participants, 'participant' was included as a random effect. We used a Wald Chi^2 test statistic with the *car* package in R (Fox et al. 2019) to test for the effect of the time period on individual-level diversity. We checked the models for overdispersion and determined they were within normal range. Finally, to test for an effect of the time period on the mean relative abundance for each seafood type, we used a beta linear regression model for proportional data (as described above).

Portfolio Sensitivity Analyses. To test for the effect of the expert sample size on portfolio diversity, we calculated a species accumulation curve (Gotelli and Colwell 2001) for harvest and consumption portfolios separately. Because network analysis is sensitive to missing data (Smith et al. 2017), sensitivity analyses were also conducted on the harvest and consumption portfolios' links (lines connecting nodes) and nodes (seafood types) themselves. To test how the number of seafood types affects the standardized degree centrality scores, nodes were bootstrapped in increasing proportion (0.5, 0.6, 0.7, 0.8, 0.9, 1.0) of the total number of seafood types for 100 iterations without replacement. Similarly, links were bootstrapped with 80% of the total for 100 iterations without replacement. Finally, to inform our choice of centrality measure, we conducted Principle Component Analyses

(PCAs) across 49 measures of centrality of our networks, using the CINNA package in R (Ashtiani et al. 2019). This allowed us to determine if centrality measures correlated across the others.

Drivers of Change Analysis. We performed a qualitative analysis of experts' reasons for portfolios shifts using inductive coding of themes (Creswell and Poth 2017). Specifically, we identified dominant themes emerging from our interview recordings and notes on key drivers of change reported by participants. We then reported the percentage of participants who mentioned evidence associated with each driver of change.

Second, to test for differences between perceived importance of drivers of change in traditional seafood harvest and consumption, we constructed an ordinal logistic mixed-effects model with a cumulative link function that accounted for the ranked nature of our data (Hedeker 2008). Specifically, we treated gender, age, boat ownership, and employment as fixed effects, respondent as a random effect and ranked importance as our response variable. Models were fit using the *ordinal* package in R (Christensen 2019). Rankings between distinct numbers on the ordinal scale were rounded up to the nearest distinct level (e.g., 5.5 to 6) to minimize the number of distinct groups in our model. We identified the minimum adequate model based on Akaike's Information Criterion (AIC) using the *AICcmodavg* package in R (Mazerolle 2019) and used a likelihood ratio test to look for significant differences in ranked importance of drivers of change using the *car* package (Fox et al. 2019).

Finally, to test for differences in perceived importance of drivers of change between harvest and consumption portfolios, we constructed a second ordinal logistic mixed-effects model in the same format as above. We used likelihood ratio tests for main effects and interactions to evaluate the effect of harvesting versus consumption on the perceived importance of factors driving change using the *car* package (Fox et al. 2019). A spider diagram was used to visualize these results.

Methodological advances, limitations, and assumptions

Our methodology advances a mixed-methods approach spanning disciplinary boundaries and sovereign knowledge systems. Here we do two things. We braid knowledge from Indigenous experts and the scientific literature to document change in the harvest and consumption of food fisheries and gain better insights into drivers of change. We then used quantitative methods and Indigenous observations to assess change in both individual and community portfolio diversity, and relative abundance of fisheries harvested and consumed. This approach has both benefits and limitations. One benefit is the contribution of Indigenous knowledge to the analyses, which lends legitimacy to this research within the Nation (Pinkerton and John 2008) and bridges social and ecological sciences (Tengö et al. 2014). Moreover, the inclusion of Indigenous knowledge provided a broader cultural context and pluralistic understanding of fisheries and environmental change (Berkes et al. 2000; Reid et al. 2020). Additionally, the comparison of past and present decades allowed us to increase the time horizon of interest because experts are of different ages. Thus, we were able to explore the long-term trends and the drivers of change to capture the socio-economic, ecological, and cultural changes that the community has undergone over the time frame of the study and differentiate how much of that change is reflected in both harvesting and consumption patterns. Limitations of our study stem from reliance on retrospective observations of change from a relatively small number of participants. We report expert observations and knowledge which, like all forms of data, are subject to variation, uncertainty, and bias (Hilborn and Mangel 1997). Experts were asked to recall information from a time in their childhood that is vulnerable to shifting baseline syndrome (Papworth et al. 2009; Pauly 1995) and recall bias (O'Donnell et al. 2010). Additionally, our objective was to elicit knowledge from experts that harvest and consume traditional seafood; thus, our sample size is limited due to the limited number of experts in the resource system.

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Results

Portfolio structure

The Nation's harvest and consumption portfolios have changed over time (**Figs. 1**, **2**). While we found no significant effect of time period on the diversity of seafood types harvested across all participants at the individual-level ($\chi^2 = 0.82$, df = 1, $p = 0.37$) or consumed ($\chi^2 = 0.57$, df = 1, $p = 0.45$) (**Fig. 3A**), the number of seafood types caught and consumed tended to be lower post-1980. We did, however, find differences in the types of seafood caught versus consumed. Specifically, northern abalone (*Haliotis kamtschatkana*), Eulachon (*Thaleichthys pacificus*), Pacific Sardine (*Sardinops sagax*), and Longnose Skate (*Raja rhina*) were consumed, but not harvested by community members.

We detected a significant difference in diversification across all seafood types within the community's traditional fisheries harvest and consumption portfolios pre- and post-1980 (**Figs. 1**, **2**); the layout of the network is represented with the Fruchterman-Reingold Algorithm (Csárdi and Nepusz 2019). Specifically, standardized degree centrality, our measure of community portfolio diversity, was significantly higher post-1980 for both harvest (Z = 2.21, $p = 0.03$) and consumption (Z = 4.51, $p = 6.43e^{-6}$) portfolios (**Fig. 3B**).

Relative Abundance

Harvest Portfolios. We found a significant effect of the time period on the relative abundance of some, but not all, seafood types harvested pre- and post-1980 (**Fig. 1**, **Table S4**). Many culturally important seafoods significantly decreased in relative abundance ($p < 0.05$) post-1980 including, Pacific herring (*Clupea pallasii*, −37.6%) and Pacific herring roe (−31.1%), lingcod (*Ophiodon elongatus*) eggs (−14.4%), red sea urchin (*Mesocentrotus franciscanus*, −11.1%), green sea urchin (*Strongylocentrotus droebachiensis*, −8.9%), and harbour seal (*Phoca vitulina*, −7.9%). We detected no significant change in the relative abundance of the remaining species, such as all five salmon species (*Oncorhynchus spp.)*, clams (*Saxidomus giganteus, Leukoma staminea, Venerupis philippinarum, Clinocardium nuttallii*), Pacific halibut (*Hippoglossus stenolepis*) and spot prawns (*Pandalus platyceros*) between pre- and post-1980 harvest portfolios. Although some seafood types were reportedly caught in greater quantities post-1980, we detected no significant increases in harvested seafood types pre- versus post-1980.

Consumption Portfolios. Similar to harvest portfolios, we found a significant effect of the time period on the relative abundance of some seafood types consumed pre- and post-1980 but not others (**Fig. 2**, **Table S5**). However, unlike the harvest portfolios, we detected significant increases ($p < 0.05$) within the consumption portfolios post-1980 for Pacific halibut and spot prawns, 16.3% and 21.8%, respectively. The relative abundance of other seafood types declined significantly between the time periods, including but not limited to Pacific herring (−35.3%) and Pacific herring roe (−18.6%), lingcod eggs (−25.0%), red sea urchin (−16.1%), pink salmon (*Oncorhynchus gorbuscha,* −16.0%), green sea urchin (−15.7%), harbour seal (−15.4%), coho salmon (*Oncorhynchus kisutch,* −14.5%), and eulachon (−11.4%). We detected no significant difference between pre- and post-1980 for the remaining seafood types.

Portfolio sensitivity analyses

We found an effect of sample size on our pre-1980 portfolios (**Fig. S3**) due to a limited number of experts with knowledge from earlier decades (n = 14; **Table S2**). However, we also found that changing the proportions of seafoods considered and the subset of links between them did not alter the effect of time on standardized degree centrality for both harvest (Node: $p < 0.05$, Link: Z = 19.89,

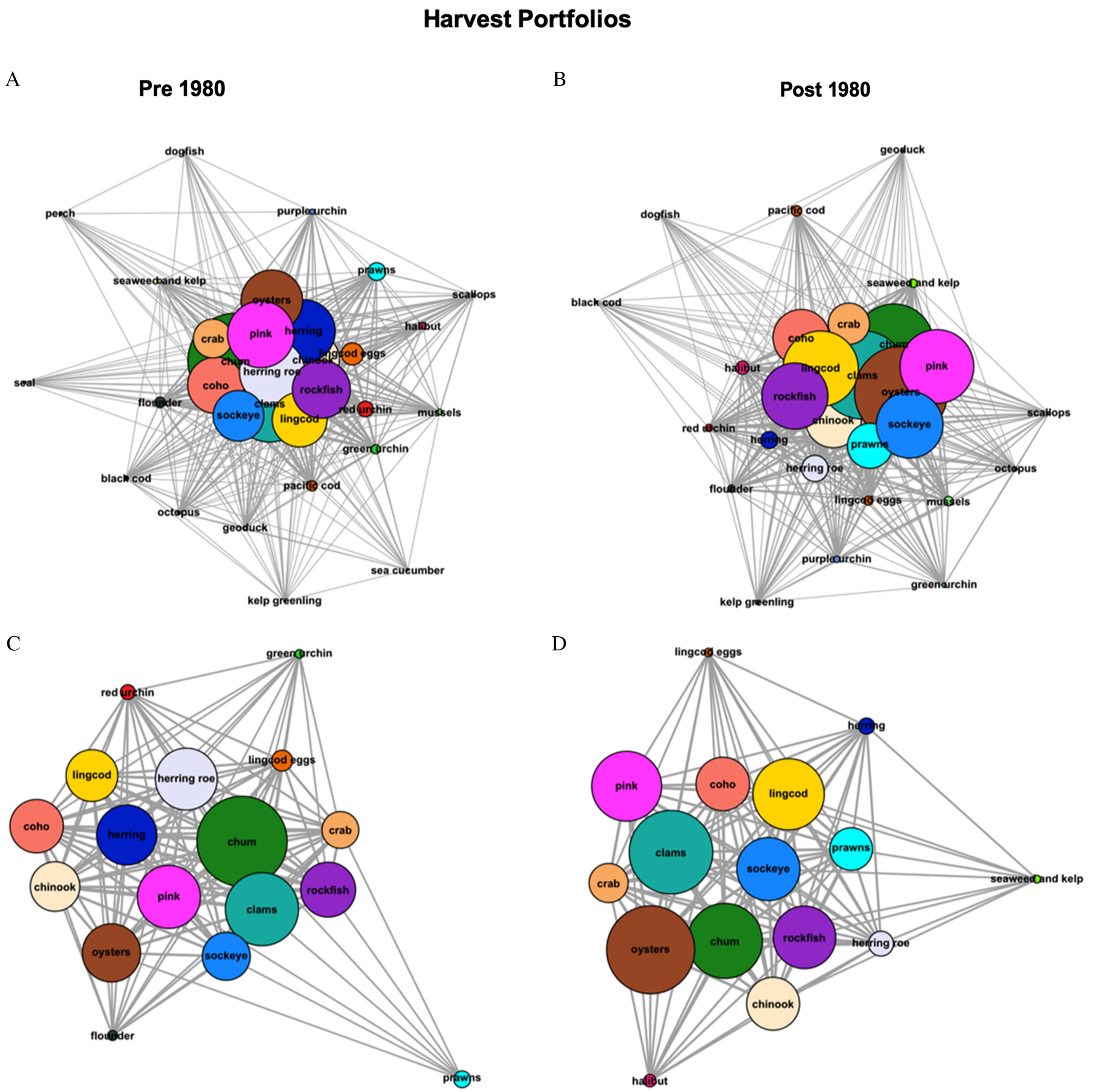

Fig. 1. Seafood harvest portfolios of the Nation pre- and post-1980 shown as entire portfolios (A, B) and portfolio cores (C, D), which represents nodes with greater than or equal to the mean number of links in the entire network. Node size reflects mean relative abundance harvested and links between nodes represent ≥ 1 report of harvesting both seafood types.

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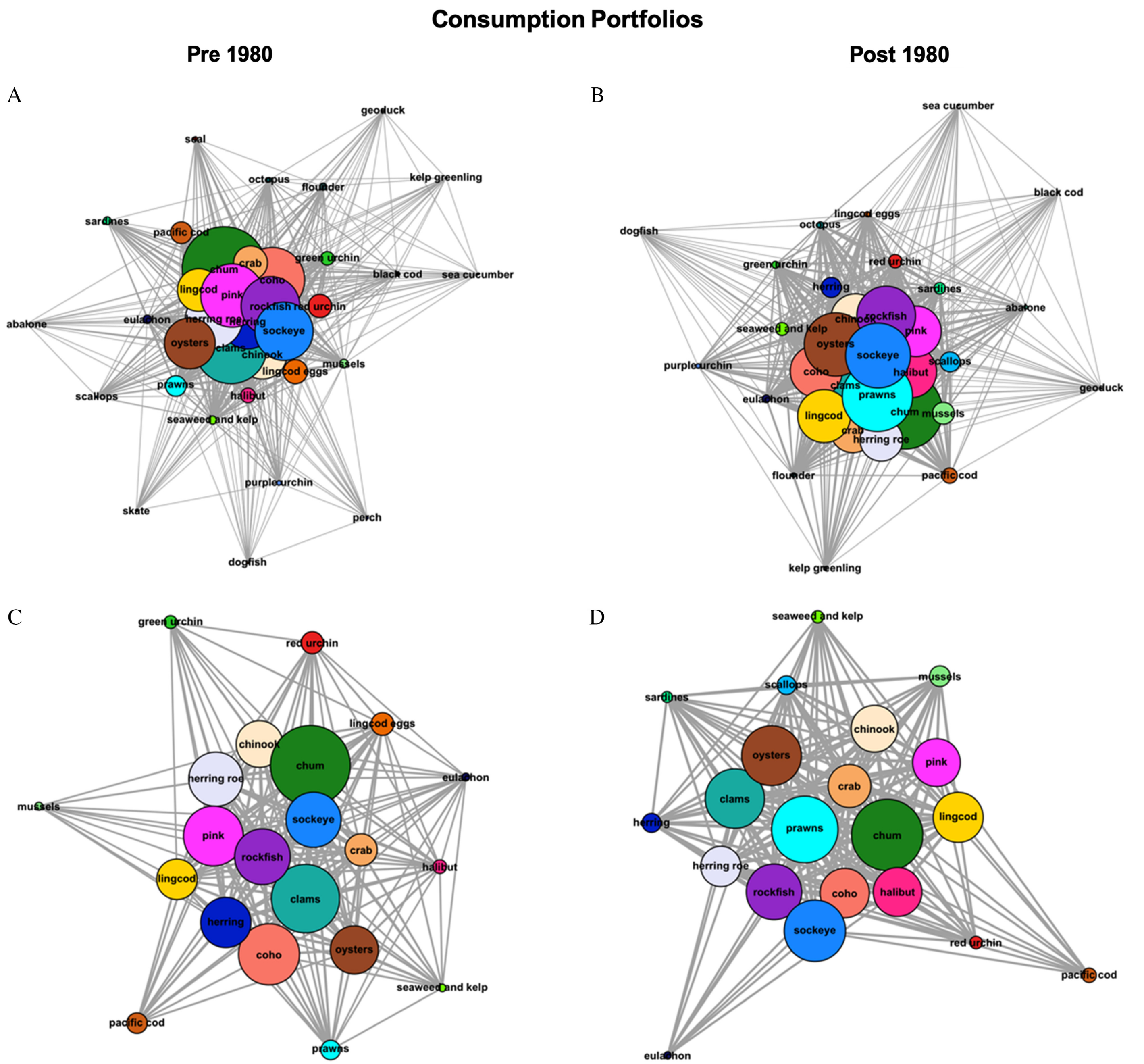

Fig. 2. Seafood consumption portfolios of the Nation pre- and post-1980 shown as entire portfolios (A, B) and portfolio cores (C, D), which represents nodes with greater than or equal to the mean number of links in the entire network. Node size reflects mean relative abundance consumed and links between nodes represent ≥ 1 report of consuming both seafood types.

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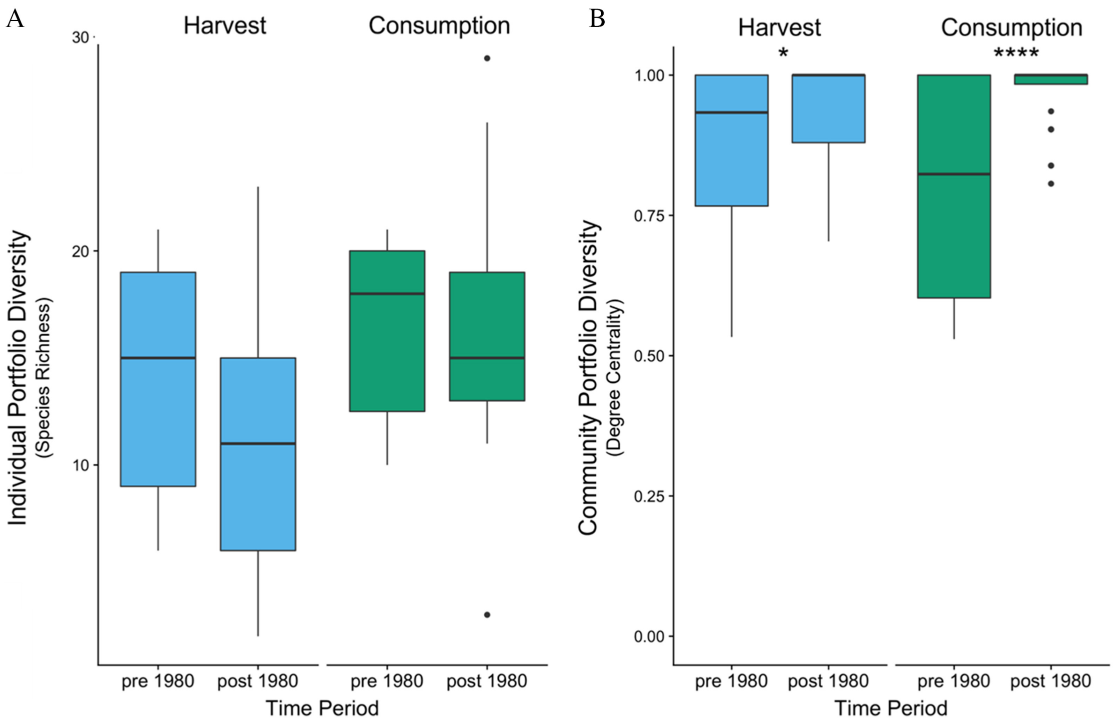

Fig. 3. Changes in A) individual portfolio diversity (i.e., species richness across all participants) and B) community portfolio diversity (i.e., standardized degree centrality) for harvest and consumption portfolios pre- and post-1980 social-ecological regime shift. ****$p < 0.0001$, *$p < 0.05$

$p < 2e^{-16}$; Figs. S4, S5) and consumption portfolios (Node: $p < 0.05$, Link: Z = 40.76, $p < 2e^{-16}$; Fig. S4, S5). Lastly, our PCAs show that degree centrality is correlated with other measures of centrality in all portfolios except for the post-1980 consumption portfolio (Fig. S6). In this case, 34 other potential metrics were worth considering based on correlation across measures.

Drivers of change

Qualitative Responses. Participants identified drivers of change for shifts in harvest and consumption portfolios prior to ranking the pre-identified factors for the quantitative analysis. These factors fell into 12 themes (Table 1), with *Modernization*, *Environmental change*, and *Change in diet* among the most frequently reported, 50%, 42% and 38%, respectively. For example, *Change in diet* was generally described as an increase in western food consumption - “You don’t have to go fishing anymore to provide for your family… food comes from the grocery store… that just wasn’t in the cards when I was a child” (pers. comm. Roy Francis). Although most factors aligned with our pre-identified factors used in the quantitative analysis (e.g., *Environmental change, Over harvesting, Reduced Access, Governance barriers, Change in diet, Pollution,* and *Knowledge loss*), there were other factors identified by our experts that were not explicitly listed on our survey. These included *Modernization, Increased Predation, Advances in Technology,* and *Community dependence.*

Quantitative Responses. From the responses of experts interviewed, we found a significant difference in their perception of the importance of pre-identified factors driving changes in harvest (Likelihood Ratio $Chi^2 = 75.33$, df = 9, $p = 1.34e^{-12}$) and consumption (Likelihood Ratio $Chi^2 = 76.86$, df = 9, $p = 6.77e^{-13}$) portfolios. *Permit barrier* was ranked as low importance, while *Ocean pollution* and *Commercial overharvesting* were ranked highest among factors driving changes in both harvest and

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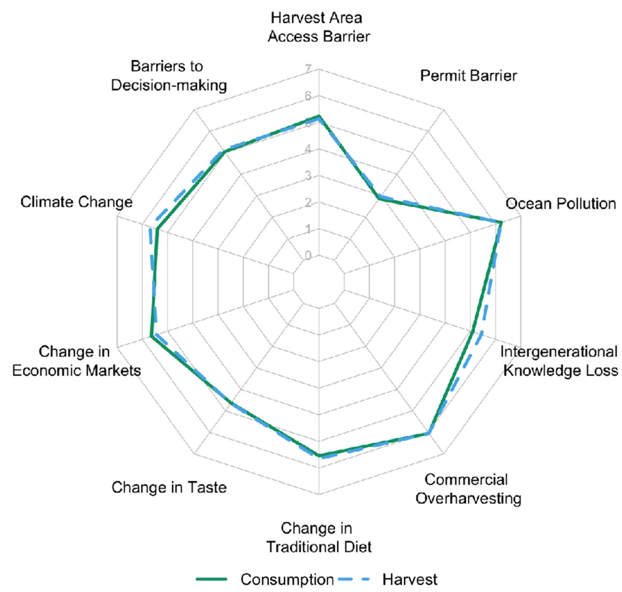

Fig. 4. Perceived importance of drivers changing seafood harvest and consumption patterns over the past seven decades ranked by experts.

consumption portfolios. We found no evidence to support the addition of respondent co-variates (e.g., age or gender) to explain the variation in the ranked importance of divers of change (**Table S6**) or differences among genders (**Fig. S7**) or age groups (**Fig. S8**). Furthermore, we found no significant difference in the interaction between drivers of change and portfolio type. In other words, there was no significant difference between harvest and consumption portfolios in terms of which factors are perceived to be important in driving changes (Likelihood Ratio $Chi^2 = 1.86$, df = 9, $p = 0.99$; **Fig. 4**).

Discussion

A growing body of evidence suggests that enhanced diversity within social-ecological systems confers resilience to a broad array of disturbances (e.g., Biggs et al. 2012; Cinner and Bodin, 2010; Folke et al. 2016; Janssen et al. 2006). Evidence of this exists among fishing-based communities worldwide (Beaudreau et al. 2019; Cinner and Bodin 2010; Fuller et al. 2017; Stoll et al. 2017). Here, we found that while the Nation's fisheries portfolios tended to decrease in diversity at the individual-level of seafoods harvested and consumed after 1980, they became significantly more diversified at the community-level (**Fig. 3**). In the past, individuals used to catch and consume a greater diversity of traditional seafood. After the early 1980s, individual harvesters tend to be more targeted in their catch and consumption patterns (i.e., fewer species). Across the community, however, fisheries portfolios became more diversified overall, as fewer but more similar types of seafoods became more commonly caught together.

Portfolio shifts

Diversity at different scales

We found that the Nation's harvest and consumption portfolios are more diversified at the community-level now, yet less diverse for individuals, compared to past decades. Specifically, we found that mean degree centrality scores of both harvest and consumption portfolios were higher post-1980

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while the number of different seafoods was smaller for individuals, though not significantly so. Decreases in portfolio diversity among individual participants were driven, in large part, by declines in harvested and consumed traditional seafoods including Pacific herring, sea urchin, sea cucumber, lingcod eggs and seal (**Fig. 3A**). This is also evident in shifting portfolio configurations, with seafood types shifting from the core of portfolios to the periphery (**Figs 1**, **2**). Concurrently, popular traditional seafood, such as salmon, rockfish, and crab, are being caught and consumed by more people, reflecting portfolio diversification at the community level. The emergence of new fisheries for deep-water benthic species, such as spot prawns and Pacific halibut, that are increasingly accessible to more harvesters, also drove increases in the community's portfolio diversity. Because more people are harvesting and consuming these species, they moved from the periphery to the core of the Nation's portfolios (**Figs 1**, **2**) without displacing other traditional seafood, which increased the number of connections within the entire portfolio. Less common seafood types such as seal, perch, and longnose skate were only mentioned by participants for the pre-1980 period, leading to a decrease in individual-level portfolio diversity but a more diversified community portfolio over time.

We also detected differences in the relative abundance of various seafood types among the harvest and consumption portfolios. For example, spot prawns and Pacific halibut consumption has increased post-1980, while harvest of key traditional seafood, such as Pacific herring, lingcod eggs, and sea urchins, has significantly decreased (**Figs 1**, **2**; **Table S4**, **S5**). These patterns in individual and community portfolio diversity and relative abundance are driven by several key social-ecological mechanisms illuminated by experts in the community.

Mechanisms driving shifts in portfolios

Four key social and ecological mechanisms were perceived by community experts as driving reduced diversity at the individual scale and increased diversification at the community scale among the Nation's food fisheries portfolios. These included industrial and commercial activities under the authority of Canada's centralized governance regime, loss in intergenerational knowledge transmission, learning and adapting to new ecological and economic opportunities, and the trade in seafood among coastal First Nations communities. In addition to these mechanisms, experts perceived commercial overharvesting and pollution as the most important factors driving shifts in fisheries portfolios, while issues surrounding fisheries access rights, now granted by the Nation's government, were perceived as less important. These results reveal social-ecological factors affecting the Nation's fisheries over the past eight decades and illuminate locally relevant adaptation strategies to bolster future resilience in this social-ecological system.

I. Industrial commercial activities and centralized colonial governance. Access to traditionally important seafood has been reduced by industrial-scale, commercial activities, such as fishing and logging, currently under the authority of a centralized governance regime. Although here we focus on FSC fisheries, many of the same species are also being exploited or indirectly impacted by commercial activities. In the Nation's territory, this is exemplified by the decline in the harvest and consumption of Pacific herring and herring eggs (**Table S4**, **S5**). While herring remain relatively central to harvest and consumption portfolios (**Figs. 1**, **2**), experts reported that herring was "fished out" of the Nation's waters in 1983 and that commercial fisheries targeting adult females for their roe for export to international markets were the main driver of this change (pers. comm. by eleven experts; Paul et al. 2014). Such reports are consistent with the literature assessing the magnitude of the Pacific herring collapse (Cleary et al. 2010; Essington et al. 2015).

Given the large ecological, economic and cultural consequences for the Nation and community, commercial overharvesting was perceived by experts as one of the most important drivers of change in harvest and consumption portfolios (**Fig. 4**). In the past, decisions to open herring fisheries were solely in the hands of Canada's federal fisheries agency, Department of Fisheries and Oceans (DFO). Today, the fisheries Minister still retains the discretion to open the fishery regardless of recommendations based on available science and other knowledge sources (Klain et al. 2014). Moreover, Indigenous livelihood objectives, self-determination, and ways of life are yet to be incorporated into herring management (von der Porten et al. 2016). For example, even though Strait of Georgia herring stocks are reported as having "spawning biomass [...] at a historic high" (DFO 2019), the Nation considers abundances to be low compared to their historical baseline and wish to conserve stocks such that they might return to the territory (pers. comm. Clint Williams). A similar tension has emerged in Sitka, Alaska, where divergent views of herring population status by the state management agency and Indigenous harvesters (Thornton and Kitka 2015) drove a lawsuit by the Sitka Tribe of Alaska seeking protection of the subsistence herring fishery. The Nation is a party to a Joint Fisheries Committee with DFO to facilitate learning and shared decision making. As a Modern Treaty Nation with rights recognized by the Government of Canada and BC, it explains why fisheries access granted by the Nation was not perceived as an important barrier by experts in the community (**Fig. 4**).

Additionally, logging related activities under the authority of a centralized governance regime have decreased the harvest and consumption of clams (pers. comm. Eugene Louie). Although clams are still centrally important traditional seafood in the Nation's harvest and consumption portfolios (**Figs. 1**,**2**), their relative abundance has decreased due to beach closures associated with pulp mill contamination and high fecal coliform levels. Pollution was also perceived as one of the most important drivers of change amongst experts. Although some beaches might be safe to harvest, ultimately, beach closure decisions reside with federal governing authorities that often operate with limited resources and available data (Flemming 2019). Consequently, clam harvest closures are often due to an absence of evidence rather than evidence of contamination.

Finally, predation by marine mammals, such as seals and sea lions, and a lack of participation in decisions surrounding these predator populations were identified as an important driver of change among portfolios (**Table 1**). Traditionally, seals were hunted and managed by the Nation (Paul et al. 2014) but are not represented in harvest or consumption portfolios post-1980 (**Fig. 1**, **2**). Seals and sea lions consume a diversity of benthic and pelagic fish, such as salmon and Pacific herring (Nelson et al. 2019). Therefore, they potentially compete with humans and other culturally important species, such as killer whales (Chasco et al., 2017), for shared prey. Currently, Canada's federal fisheries agency, DFO, has the authority to manage these marine mammals, constraining opportunities for the potential revitalization of traditional hunting and management systems (Reidy 2019).

The current centralization of decision-making authority can reduce resilience by limiting learning across multiple scales of governing institutions and eroding local trust in management (Biggs et al. 2012). In contrast, the resurgence of Indigenous governance (Corntassel 2012) can confer resilience by enabling knowledge sharing and co-production (Abson et al. 2017; Faulkner et al. 2018; Folke et al. 2005; Galafassi et al. 2018), as well as facilitating food sovereignty (Coté 2016; Walsh-Dilley et al. 2016). Transforming fisheries governance in Canada to a system that is more equitable, just and resilient will require shared decision making between colonial and Indigenous governments to equalize the distribution of power and cooperatively manage marine resources (Jones et al. 2017; Salomon et al. 2018).

II. Changes to Intergenerational knowledge transmission. Reduced diversity among the Nation's fisheries portfolios at the individual-level also was driven in part by the disruption of knowledge transmission of specific harvesting practices across generations. For example, the loss of seal from harvest and consumption portfolios is primarily due to loss of hunting knowledge associated with the legal restrictions on seal harvest in 1970. Furthermore, the substantial decreases in abundance of

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chum salmon, lingcod eggs, and red and green sea urchins, were attributed to a lack of knowledge among younger generations on how to collect and process these traditionally important seafood (**Figs. 1**, **2**). While there are "still many sea urchins out there [in the marine environment], [. . .] no one wants them. I will only go get them if an elder is wishing for them" (pers. comm. Lee George). As intergenerational knowledge loss increases, participation declines, reducing the likelihood of cultural preservation (Turner et al. 2008), in turn contributing to the erosion of SES resilience by hindering learning opportunities and impeding collective action required to respond to disturbance and changes (Biggs et al. 2012).

III. Adapting to new ecological and economic opportunities. While opportunities to transfer traditional knowledge might be declining, learning and adapting to new ecological and economic opportunities has been a key mechanism driving changes in the Nation's harvest and consumption portfolios. For instance, spot prawns have become a more central component of both the community's harvest and consumption portfolios over time, reportedly due to increased market demand (British Columbia Seafood Industry: Year in Review 2016) and modern fishing gear that facilitates access to deepwater fisheries. Spot prawns were not a traditionally important food fishery. However, community harvesters have learned to adapt to this new opportunity and harvest them for food in association with the commercial fishery. Moreover, as a result of Pacific halibut "moving into the area" (pers. comm. Lee George), the harvest and consumption of this species has increased. Halibut is now offered as part of the Nation's community food fish program in place of previously abundant seafood types like Fraser River sockeye salmon. Both learning and adapting to new opportunities are key characteristics of resilience (Biggs et al. 2012). However, human health could be negatively impacted if current trends continue since salmon species are nutritionally different from halibut, especially in terms of fatty acids, a required nutrient that salmon provide 70% of in First Nations' diets (Marushka et al. 2019). Moreover, continuously shifting to new fishing opportunities as previously abundant seafood types become less abundant could lead to the serial depletion of species, as has been shown in both commercial (Armstrong et al. 1998; Karpov et al. 2000) and subsistence fisheries (Salomon et al. 2007).

IV. Increased connectivity among communities via trade of seafood. While consumption and harvest portfolios decreased in diversity at the individual level, they also exhibited clear changes in diversification at the community-level, in part due to the seafood trade within the community itself and with other coastal communities. For example, while Pacific herring is no longer as abundant in the Nation's waters as prior to 1980 (pers. comm. by eleven experts; Paul et al. 2014), many people obtain herring eggs to consume from other coastal Indigenous communities, primarily the Heiltsuk Nation who have an active herring spawn-on-kelp food fishery (pers. comm. Paul August). Eulachon is another seafood type that is traded for with other Nations since it is consumed but not harvested by community in their traditional territory. Trade of traditional seafood with other Nations supports coast-wide connectivity, which facilitates continued familial, cultural, and economic relationships, thereby enhancing resilience to local disturbance (Biggs et al. 2012). However, the use of herring eggs and eulachon has decreased over time due to changes in traditional diet and people's taste, suggesting that decreased participation in these harvest and (or) consumption practices could reduce SES resilience. This also has implications for Indigenous health as these forage fish provide essential nutrients, such as vitamin A and essential fatty acids, in traditional diets (Marushka et al. 2019).

Adaptation opportunities in our partner Nation context

"In the summertime I would always go out on the canoe with my mother to get salmon and even then, my mother told me that it won't always be like this" (pers. comm. Doreen Point). Resilient fishing communities are better able to adapt to future disturbances, maintain their food and nutritional security and their cultural well-being. As such, our results help inform future alternative adaptation strategies that have both local and global relevance. Because we found no evidence that the perceived importance of drivers differed among individual participants, regardless of their age, gender, occupation or boat ownership, potential adaptation initiatives are likely to be perceived as relevant across the entire community. The social-ecological and political context however of coastal First Nations along Canada's Pacific coast are unique to each Nation, consequently our specific findings here may be only broadly relevant to other coastal Indigenous communities in BC.

Adaptation strategies should be tailored to specific SESs and reflect local characteristics, such as cultural norms and values (Andrachuk and Armitage 2015; Rotarangi and Stephenson 2014), social networks (Barnes et al. 2017; Bodin 2017), politics (Gelcich et al. 2010) and place-specific environmental characteristics (Olsson et al. 2006): "We always fished and there has always been fish, we traditionally managed our own [fisheries]" (pers. comm. Scott Galligos). As such, given knowledge from community experts and drawing on resilience theory, our results suggest that adaptation strategies fostering knowledge transfer to younger generations and decentralizing natural resource management authority to local scales would support resilience in this system.

While climate change was perceived as an important driver of change, it was not ranked as most important, in contrast to the majority of academic literature (Barange et al. 2014; Ford et al. 2020; Rudd 2014; Savo et al. 2017; Weatherdon et al. 2016). This is likely due to the magnitude and occurrence of other local stressors that impact the community's daily lives, including clam contamination closures. Furthermore, it is difficult to observe long term, incremental climate trends, especially if experts are not old enough to benefit from a longer time horizon. However, climate change is projected to reduce potential catches of species targeted by the community (Weatherdon et al. 2016). Therefore, changes in traditional seafood harvest and consumption portfolios could reflect, in part, species-specific changes driven by climate change, including extreme events like marine heatwaves and heat domes. When planning for the future, understanding novel drivers of change identified by Indigenous communities will be key to developing successful adaptation strategies (Cisneros-Montemayor et al. 2016; Donatuto et al. 2016; Eckert et al. 2018; Terbasket and Shields 2019). In the case of the Nation, reinvigorating traditional marine mammal hunting and stewardship may have diverse health and well-being benefits.

Implications for social-ecological resilience

Diversity within fisheries portfolios can play an essential role in fishers' adaptive capacity (Beaudreau et al. 2019; Cinner and Bodin 2010; Cinner et al. 2015; Fuller et al. 2017; Roscher et al. 2018; Stoll et al. 2017) and thus contribute to the overall resilience of SESs (Biggs et al. 2012). Diversification among different seafood types provides communities with the capacity to adapt to changes by shifting among targeted species when necessary and decreasing vulnerability to perturbations due to reduced dependence on only a few seafood types (Beaudreau et al. 2018; Fuller et al. 2017; Stoll et al. 2017).

However, the relationships between these system characteristics and resilience are not necessarily linear or unidirectional. For example, the rapid propagation of disturbances can occur in highly connected systems (Biggs et al. 2012). In fishing-dependent communities, this may mean that harvesting many species creates a relationship between seafood types where there was no ecological relationship between them before (Fuller et al. 2017). Thus, management decisions made for one seafood type could inadvertently impact many seafood types in highly connected portfolios (Armstrong et al. 1998; Karpov et al. 2000).

Here, shifts in diversity at different scales of an Indigenous community's harvest and consumption portfolios provided insight into adaptations that could support social-ecological resilience and community well-being. Future adaptation strategies should embrace local knowledge and perceptions,

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in tandem with evidence-informed decision making, if proposed management solutions are to be successfully implemented at the local level (Ban et al. 2018; Bennett 2016; Salomon et al. 2018). A strong understanding of key characteristics of SES resilience can inform the basis of ecologically sustainable and socially just adaptation strategies that support food security, food sovereignty and cultural well-being.

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Author contributions

SO, CCCW, CDG, AHB, T-AK, HMC, and AKS conceived and designed the study. SO performed the experiments/collected the data. SO, CCCW, CDG, AHB, GGS, HMC, and AKS analyzed and interpreted the data. LW contributed resources. SO, CCCW, CDG, AHB, T-AK, GGS, WWLC, HMC, and AKS drafted or revised the manuscript.

Competing interest statement

Competing interests: The authors declare there are no competing interests.

Data availability statement

Primary data generated or analyzed during this study are not publicly available due to our partner Nation's request to remain anonymous and the Indigenous knowledge shared with us was never intended to be made publicly available. However, requests can be made to the corresponding author who can make the data available on reasonable request and on the condition the Nation agrees in writing to share the data.

Supplementary material

The following Supplementary Material is available with the article through the journal website at doi:10.1139/facets-2022-0048.

Supplementary Material 1

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