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Self-governance mediates small-scale fishing strategies, vulnerability and adaptive response

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ABSTRACT

As global change accelerates, natural resource-dependent communities must respond and adapt. Small-scale fisheries, essential for coastal livelihoods and food security, are considered among the most vulnerable of these coupled social-ecological systems. While previous studies have examined vulnerability and adaptation in fisheries at the individual, household, and community level, these scales of organization are inconsistent with many of the legal and regulatory frameworks that function in practice to mediate behavior, decision-making, and adaptation. Here, we use cooperative- and privately-owned fishing enterprises in Northwest Mexico as a case study to examine how different forms of marine self-governance experience and respond to climate shocks. Leveraging social-ecological network methods to examine changes in fisheries participation and vulnerability during a recent period of pronounced regional oceanographic change, our analysis suggests that: 1) different forms of SSF self-governance (and the fishing strategies and harvest portfolios with which they are associated) help determine the impacts of and response to environmental change; and 2) that there may be important trade-offs between short-term responses which function to prevent or mitigate lost fishing revenue and long-term changes in climate vulnerability. In particular large fishing cooperatives, predicted to be highly vulnerable on the basis of network theoretic metrics, exceeded expectations (maintaining or increasing resource revenues) while demonstrating a degree of path dependency that may function to increase sensitivity and undermine resilience as climate change progresses. In providing an empirical evaluation of how self-governance arrangements characterized by different group sizes, access regimes and levels of cooperation respond to system perturbation, we aim to advance common pool resource theory while offering targeted guidance for the development of more nuanced and equitable climate adaptation policies.

1. Introduction

Accelerating environmental and socioeconomic change is profoundly impacting natural resource-dependent communities around the world, with the nature and magnitude of these impacts mediated by global patterns and processes as well as place-based vulnerability

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(Pörtner et al., 2022). Vulnerability (i.e., the degree to which a system is likely to experience harm when exposed to a hazard, see Turner et al., 2003) has been conceptualized as a combination of a system's exposure to the stressor, the degree it may be affected by the stressor (i.e., sensitivity), and its capacity to adapt (i.e., adaptive capacity) (Adger et al., 2006). Although the vulnerability framework has been applied to different human (i.e., individual, household, and community; see Adger et al., 2006, Marshall et al., 2010) and ecological (i.e., species or populations; see Hare et al., 2016, Ramos et al., 2022) units, sustainability scholars increasingly advocate for considering natural resource systems as complex and adaptive Social-Ecological Systems (SES). SES are composed of indivisible social and ecological dimensions that may interact in unplanned and unpredictable ways (Folke et al., 2006, Ostrom, 2009). Indeed, while sensitivity and adaptive capacity are often considered as latent characteristics, the long-term persistence and sustainability of SES is likely to depend upon the nature and scale of responses to specific changes and how associated impacts manifest and interact across multiple time horizons (Folke et al., 2010., Ojea et al., 2020, Green et al., 2021).

Small-scale fisheries (SSF), which employ 90 % of the world's capture fishers and provide livelihoods and food security for hundreds of millions of individuals across the globe (FAO, Duke University and WorldFish 2023), are considered among the SES most vulnerable to climate change due to their high resource dependence, direct environmental exposure, and limited capacity for geographic redistribution (Allison et al., 2009; Oestreich et al., 2019). In regions where formal regulatory capacity is weak, patterns of SSF production and commercialization are often structured by a diversity of self-governance arrangements (Chuenpagdee, 2011; Frawley et al., 2019a). Whereas cooperative fishers formally contract with others to designate roles and responsibilities — working collectively as part of jointly owned and democratically organized enterprises (i.e., fishing cooperatives) — under noncooperative strategies (i.e., patron-client relationships), individual fishers engage in informal arrangements with fisheries patrons to buy their catch in exchange for favors, loans, and/or market access (Johnson, 2010; Basurto et al., 2013). Although previous SSF assessments have focused on the vulnerability (Koehn et al., 2022) and adaptive response (Green et al., 2021) of fishing households and communities, using such organizational levels as units of analysis may obscure the roles of local institutions (i.e., self-governance arrangements) that function in practice to structure SSF operations and decision-making (Kolding et al., 2014).

Across SSF and other SES, effective and sustainable environmental governance requires a better understanding of the relationships and feedbacks connecting people and ecosystems within and across scales (Bodin et al., 2019). In recent years, social-ecological network analysis (SENA) has emerged as a promising lens to analyze the interdependencies through which humans are connected to the ecosystems in which they are embedded (Sayles et al., 2019; Kluger et al., 2020). By focusing on how patterns of relationships between system components affect processes and outcomes, SENA has helped advance scientific understanding of the impact and effectiveness of resource user coordination and cooperation (McAllister et al., 2017; Angst et al., 2018; Barnes et al., 2019), while offering researchers an empirical means of quantifying different components of SES vulnerability (Baggio et al., 2016) and adaptation (Barnes et al., 2017). Previous research has applied SENA to marine fisheries in order to investigate social organization and environmental governance (Crona & Bodin, 2010; Bodin, 2017; Barnes et al., 2019), trade networks (González-Mon et al., 2019), fishing strategies and/or harvest portfolios (Alexander et al., 2020; Frawley et al., 2021a; Quezada et al., 2023; Yletyinen et al., 2018), longitudinal changes in climate vulnerability (Kluger et al., 2019; Fisher et al., 2021; Nomura et al., 2022), and adaptive response (González-Mon et al., 2021; Salgueiro-Otero et al., 2022). Yet, efforts designed to a) integrate related insight and b) test empirical hypotheses regarding network performance are urgently needed to provide practical guidance to resource managers working to develop equitable and effective climate adaptation strategies.

Here, we employ SENA and use SSF across northwest Mexico as a case study to examine the role of local self-governance arrangements in mediating the vulnerability and adaptive response of resource users to environmental change. Northwest Mexico is an ideal setting for this study given the diversity of self-governance forms which participate in regional SSF (Basurto et al., 2013), their importance to regional livelihoods and food security (Leslie et al., 2015), and the availability of data which enables disaggregated, longitudinal analysis. Analyzing a database of 1,165,143 "trip-ticket" records describing the landings and fishing effort of 2,250 "economic units" (i.e., permit holders) over a 11-year period (2006–2016), we leverage the opportunity for a natural experiment provided by the transition between two distinct oceanographic regimes. More specifically, we (1) use fisheries participation networks and traditional bioeconomic indices to characterize and evaluate the harvest portfolios and fishing strategies associated with different forms of SSF self-governance during initial, baseline conditions (i.e., 2006–2011); (2) compare observed changes in revenue with those predicted by vulnerability theory (i.e., regional differences in environmental exposure and network topological metrics linked with sensitivity and adaptive capacity) during a period of rapid and widespread environmental change (i.e., 2012–2016); and (3) explore trade-offs associated with different types of adaptive responses and how different components of vulnerability are likely to manifest for different forms of self-governance across multiple time horizons. Our results reveal a diverse sector where the unique strengths and weaknesses of different self-governance forms give rise to uneven climate vulnerabilities. In Mexico, as around the globe, explicit consideration of such heterogeneity is needed to increase the equity and effectiveness of policies designed to sustain fisheries livelihoods and well-being in a changing climate.

2. Study system

2.1. Small-scale fisheries in Northwest Mexico and heterogeneity of self-governance forms

Multi-species and multi-gear marine SSF, conducted using 5.5—7.5 m open-hulled fiberglass boats equipped with outboard motors (referred to as *pangas*), comprise one of Northwest Mexico's principal coastal economic activities. SSF management in the region is based upon a limited entry permit system where, in theory, any commercial fisher must have a fishing permit, authorization, or concession granted by the government before harvesting from a specified area (Leslie et al., 2015). Fishing permits can be granted to collective (i.e., fishing cooperatives) or private (individual fishers or fisheries patrons, known locally as *permisionarios*) actors identified as individual economic units, with territorial use rights fisheries (i.e., TURFs, referred to locally as *concesiones*) most common across the cooperative sector (Aceves-Bueno et al., 2023). In many (if not most) cases, individual economic units are composed of multiple small-scale fishing boats (in addition to the fishers that crew them). Among fishing cooperatives, large 'community' cooperatives have traditionally relied upon democratic processes to make decisions, designate responsibilities and allocate rights (McCay et al., 2014), while in smaller 'family' cooperatives a single individual or family head will make decisions while registering employees and/or kin as members (Avila-Forcada et al., 2012, Frawley et al., 2019a). Regarding private permit holders, evidence of ownership of fishing equipment is necessary to engage in regional SSF, but active participation as a crewmember is not (Cinti et al., 2010). While some owner-operator fishers do exist (Vásquez-León, 2012, Frawley et al., 2019b), most *permisionarios* are buyers who control the fishing means of production and access rights while contracting independent fishers, or *pescadores libres*, to carry out the harvest (Cinti et al., 2010). These patrons usually supply fishing equipment (boats, motors, nets, etc.) and provide, in advance, the funds needed to cover trip costs. In exchange, fishers are required to sell their catch to the permit holder, or patron (Cinti et al., 2010, Basurto et al., 2020).

2.2. Recent oceanographic, ecological, and socioeconomic changes

Across Northwest Mexico, marine ecosystems and the SSF they support are susceptible to basin-scale variation in climate and oceanographic conditions known to influence local primary production and recruitment of fish and invertebrates (Chavez et al., 2003, Lluch-Cota et al., 2010, Aburto-Opreza et al., 2010). Over the past decade, anomalous atmospheric and oceanographic conditions observed across the North Pacific (Bond et al., 2015, Cavole et al., 2016) have substantially impacted the productivity of regional SSF. In the Gulf of California, subsurface ocean warming has been observed alongside increases in sea surface height (Frawley et al., 2019c) and persistent declines in primary productivity along the eastern coast of mainland Mexico (Robinson et al., 2016). Major fisheries targeting squid (Frawley et al., 2019c) and sardine (Giron-Nava et al., 2021) crashed, while changes in distribution and abundance have been observed for marine mammals (Elorriaga-Verplancken et al., 2016), seabirds (Velarde et al., 2015), sea turtles (Zavala-Norzagaray et al., 2017), and other taxa (Gilly et al., 2022). Along the Pacific coast of Baja California, prolonged marine heatwaves, hypoxic events, and harmful algal blooms observed during the same time period have been associated with declines in kelp forest cover (Beas-Luna et al., 2020) and declining productivity of critical benthic fisheries like abalone, sea cucumber, red urchin, and pen shells (Cavanaugh et al., 2019, Lonhart et al., 2019; Smith et al., 2022).

3. Materials and Methods

To characterize and quantify the linkages between self-governance, vulnerability, and adaptive response, we conducted an integrated analysis of spatially explicit fisheries (i.e., landings records) and environmental (i.e. remote sensing) data collected across a period of system change. In brief, we (1) reviewed, cleaned, and processed a database of geographically linked SSF landings records (2006–2016) and regional satellite oceanographic data in order to classify different forms of SSF self-governance and delineate temporal (i.e., oceanographic regimes) and spatial (i.e., ecoregions) units of analysis (*Section 3.1*); (2) used bioeconomic indices and fisheries participation networks to characterize heterogeneity in fishing strategies across ecoregions and self-governance forms (*Section 3.2*), (3) constructed generalized linear models to assess longitudinal changes in participation network structure and bioeconomic metrics (*Section 3.3*); and (4) adapted an existing vulnerability framework to integrate and interpret model outputs, comparing observed bioeconomic outcomes with those predicted with by differences in regional environmental exposure and participation network topology, and explore trade-offs in sensitivity and adaptive capacity associated with distinct adaptive responses (*Section 3.4)*. Additional details and descriptions are provided below and in the **Supplemental Methods**.

3.1. Defining a natural experiment

In defining a natural experiment capable of assessing and testing the links between self-governance, vulnerability, and adaptive response, we monitored four SSF self-governance forms in eight ecoregions (i.e., a total of 32 experimental units) across the transition between two distinct oceanographic regimes.

3.1.1. Classification of SSF self-governance forms using trip ticket records

To classify SSF self-governance forms and conduct a disaggregated analysis of regional fisheries landings and participation, we used a database containing 1,165,143 "trip-ticket" records from Baja California, Baja California Sur, Sonora, and Sinaloa between 2006 and 2016. Trip-tickets are landings reports produced by the manager and/or license holder of each registered SSF economic unit (i.e., *permisionario* or cooperative) at regular intervals (approximately one to seven days) and submitted to one of ~36 regional reporting offices. Each trip-ticket describes the number of boats used, the number of days fishing, the dates of fishing activity and the landing site alongside the weight (kg), landing price (pesos per kg), and taxonomic grouping (i.e. principal name) of each species landed (Ramírez-Rodríguez, 2011). Economic units were identified as cooperative or *permisionario* by linking a separate registration database obtained from Mexican fisheries officials describing the number of registered boats, membership size, and associated fishing permits for each economic unit. We determined size designations based on the number of boats to which fisheries volume and value of catch was principally attributed (see Table 1). Additional details concerning data structure and processing can be found in the **Supplemental Methods 1.1**.

3.1.2. Oceanographic data to delineate time periods of comparison

We obtained monthly remotely sensed oceanographic data from NOAA Coastwatch (Sea Surface Temperature (SST), 1985-Present) and Copernicus Marine Service (Primary Productivity (PP), 1997-present), using 21°to 33° latitude and −118° to −106° longitude as the spatial bounds for extraction. We converted observed values into anomalies (subtracting gridded, monthly climatological means from observed values), aggregated them into time series form representative of conditions likely to be encountered by regional SSF (i.e., the spatial, monthly mean of all grid cells within a 35 km buffer from the coast; see Frawley et al., 2021b and **Supplemental Methods 1.3.1**) and used a structural breaks analysis (Zeileis et al., 2002) to delineate time periods for comparison (Fig. 1, **Supplemental Methods 1.2**). The breakpoint we identified marks a shift in the oceanographic trajectory of the system that began in 2012. This predates a broader North Pacific Marine Heatwave described elsewhere (Bond et al., 2015; Cavole et al., 2016), but is consistent with other regional literature which detected anomalous oceanographic conditions along the Pacific coast of the Baja California peninsula (Smith et al., 2022; Medellín–Ortiz et al., 2023) and the mouth of the Gulf of California (Sanchez-Cabeza et al., 2022) as early as 2012.

3.1.3. Ecoregion clustering to delineate the spatial extent of regional subsystems

To delineate spatial units of analysis that most accurately reflected sub-regional differences in oceanography, ecological communities, and fishery operations (i.e., the bounds of distinct subsystems), we developed a clustering algorithm to group 36 fisheries reporting offices. Adapting previously established methodology (Frawley et al., 2022), this algorithm partitioned reporting offices based on (1) the georeferenced coordinates of each reporting office's physical location, (2) remotely-sense PP and (3) SST data characterizing the monthly oceanographic conditions across fishing grounds associated with each reporting office (see **Supplemental Methods 1.3.1**), and (4) the catch composition of fisheries landings associated with each reporting office. Fig. 2 displays a schematic of the clustering process and outputs, revealing that the reporting offices through which regional small-scale fishing activities are organized and administered can be optimally partitioned into eight ecoregions whose boundaries span the jurisdictions of the Mexican states (i.e., Baja California, Baja California Sur, Sonora, and Sinaloa) in which they are embedded. Although our clustering approach relied upon inputs of a different scope and scale as compared to other previous regional (Erisman et al., 2011) and sub-regional (González-Mon et al., 2021) studies, the resulting groupings were broadly consistent. A more complete description of clustering data and procedures can be found in the **Supplemental Methods 1.3.1 & 1.3.2**.

Table 1
Empirical definitions of small-scale fisheries self-governance forms across Northwest Mexico. As described in the **Supplemental Methods**, delineating parameters were determined by Mexico SSF regulatory documents (LGSC, 1994) and the field observations of the research team.

Large Cooperatives	Small Cooperatives	Small *Permisionarios*	Large *Permisionarios*
Cooperatives with > 5.5 average of number of boats (weighted by catch value) associated with each trip-ticket	Cooperatives with ≤ 5.5 average of number of boats (weighted by catch value) associated with each trip-ticket	Private permit holders with ≤ 1.5 average of number of boats(weighted by catch value) associated with each trip-ticket	Private permit holders with > 1.5 average of number of boats (weighted by catch value) associated with each trip-ticket

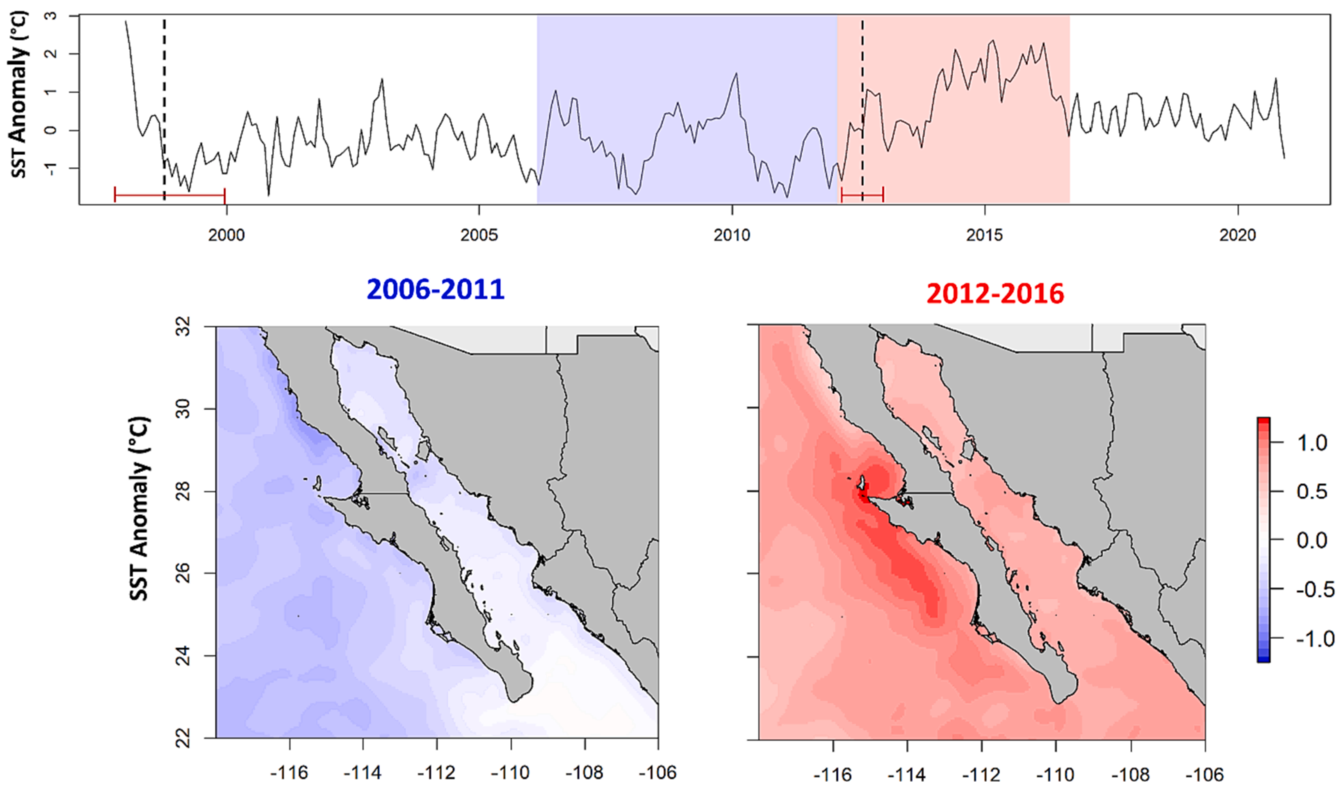


Fig. 1. Structural breaks analysis of sea surface temperatures observed off Northwest Mexico used to characterize recent, regional oceanographic change and inform the delineation of time periods for comparison. The temporal extent of the study period (i.e., the beginning and end points) was determined by data coverage and completeness across the SSF landings receipt database, while the final division (i.e., January 1, 2012 rather than June 1, 2012) was selected to avoid splitting 2012 data across time periods and minimize any confounding effects associated with seasonality. A corroborating analysis, conducted with regional primary productivity data, can be found in **Supplemental Fig. 1**.

3.2. Construction and analysis of social-ecological networks

Social-ecological network analysis, which represents systems in terms of their individual components (i.e., nodes) and the interactions between them (i.e., edges or links), is a valuable tool for studying regional and/or community-level adaptation in that it is capable of elucidating connections at multiple scales (Dee et al., 2017, Sayles et al., 2019, Nomura et al., 2022). Here we employ SENA to describe how human-environment linkages vary across different ecoregions, oceanographic regimes, and self-governance forms. Fully articulated social-ecological networks include both social and ecological nodes with social (e.g., information sharing between human actors), ecological (e.g., predator–prey relationships) and social-ecological (e.g., management and/or harvesting strategies) links, while non-articulated networks represent SES dynamics without strictly distinguishing between social and ecological nodes (Sayles et al., 2019; Kluger et al., 2020). The fisheries participation networks we chose represent non-articulated networks in which individual species, species groups, or fisheries act as nodes while the connections between them are determined by the relative extent to which actors or vessels engage in harvesting from each pair of groupings (Fuller et al., 2017, Frawley et al., 2021b, Fisher et al., 2021). In constructing our participation networks, we chose SSF taxonomic groupings as nodes (sized according to their relative contribution to total fisheries revenue) and relied upon a revenue evenness metric (proportional to the number of permit holders participating in each pair of fisheries and the evenness by which they generated revenue from each) to determine edge-weights (Fuller et al., 2017, Fisher et al., 2021, and Nomura et al., 2022). Accordingly, the size of ecological nodes, in addition to the number and strength of connections between them, are determined by human activities and interactions. While some information may be lost as compared to a fully articulated SES network, the value of this approach is in synthesizing information and reducing

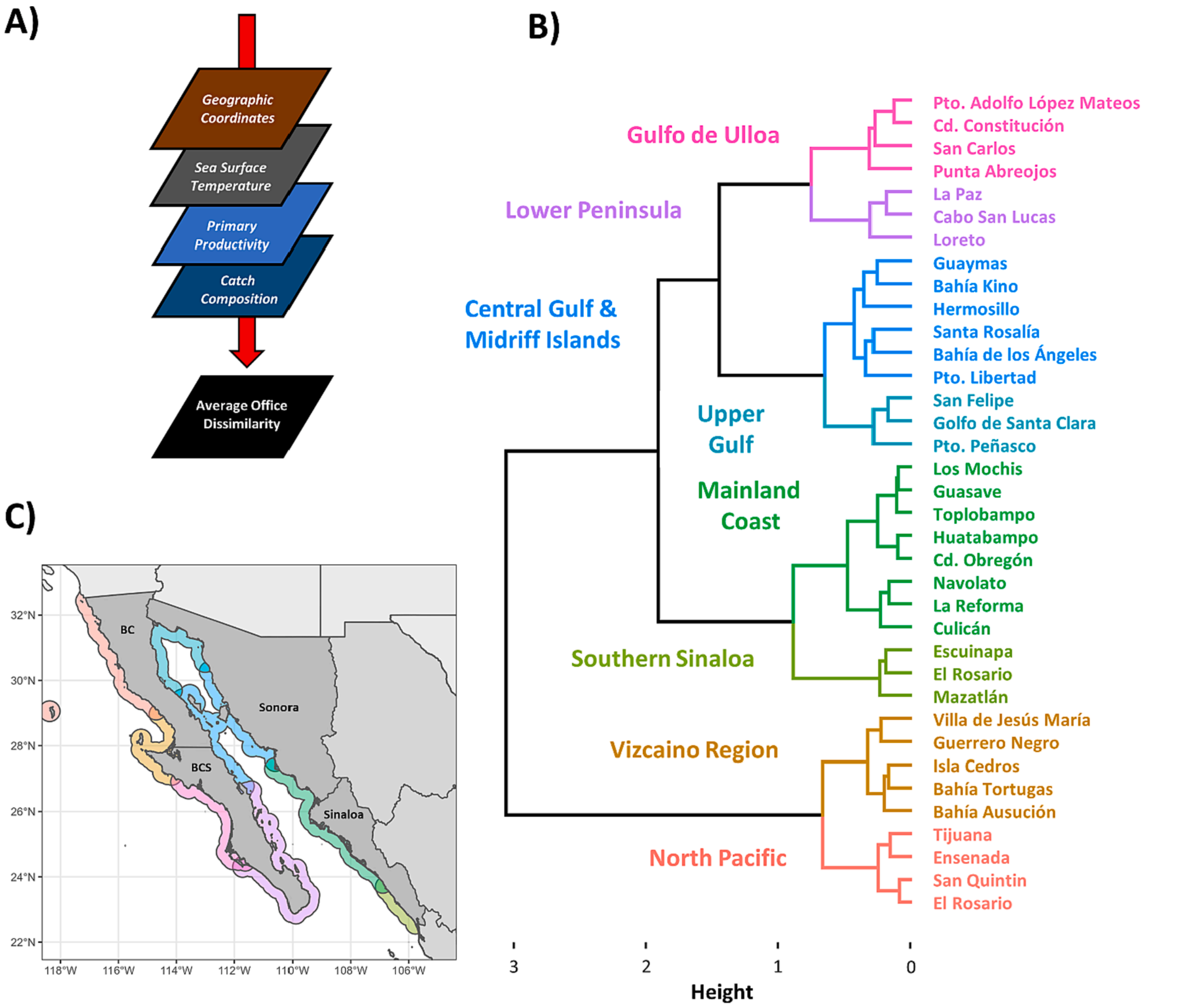


Fig. 2. Clustering procedure and outputs. **A**) Schematic of data layers used to determine average reporting office dissimilarity. **B**) Dendrogram depicting the results of hierarchical clustering and similarity between reporting offices as grouped into eight ecoregions. **C**) Map depicting the spatial distribution of each ecoregion across Baja California (BC), Baja California Sur (BCS), Sonora, & Sinaloa.

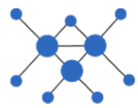
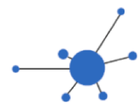
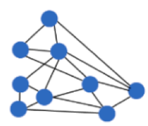
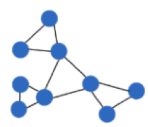
complexity so that networks can be qualitatively assessed, interpreted, and monitored by fisheries managers and practitioners (see Harvey et al., 2019). We created annual fisheries participation networks for each experimental unit, i.e., each self-governance form in each ecoregion.

Changes in network topology over time can reveal the extent to which shocks and stressors lead to indirect or lasting changes in patterns of resource use (Frawley et al., 2021a, Fisher et al., 2021, Nomura et al., 2022). In our analysis, we focused on three network-level metrics that previous literature has related to the vulnerability and the response capacity of individuals and communities subjected to perturbation: network centralization, network modularity, and mean degree (Table 2). Where appropriate, we also used dimension reduction (i.e., a Principal Component Analysis, PCA) and established bioeconomic indices (i.e., fisheries diversification and revenue variability and change; see Finkbeiner, 2015; Richerson & Holland, 2017) to characterize fishing strategies and contextualize and interpret heterogeneity in network structure and function. While bioeconomic indices reveal aggregate trends to which each permit holder contributes equally, network metrics are sensitive to dynamics driven by a small number of permit holders with a comparatively large impact on the SES (González-Mon et al., 2021). Additional detail concerning network construction and calculation of bioeconomic indices, including use of PCA, can be found in the **Supplemental Methods 2.1 & 2.2**.

3.3. Generalized linear models to assess longitudinal change

Previous research has shown that participation networks may vary significantly over time in size and composition (Fisher et al., 2021, Nomura et al., 2022). To account for significant correlations (**Supplemental Table 2**) between topological metrics and differences in number of nodes and permit holders in each network (i.e., distinguishing structural changes that might influence the vulnerability of SSF to those primarily attributed to variation in network size), we used generalized linear models (GLMs). Network metrics served as our response variables with node number, number of economic units, ecoregion, self-governance form, and time period (i.e., 2005–2011 vs. 2012–2016) as predictor variables. The final structure of each model was chosen using Akaike Information Criteria (AIC) and established best practices for comparing nested models (Fisher et al., 2021; see **Supplemental Methods 3.0 & Supplemental Table 3**). To compare changes in network theoretic metrics with observed outcomes, we created models of a parallel structure for bioeconomic indices with revenue and diversification as response variables and ecoregion, self-governance form,

Table 2
Theoretical framework linking social-ecological network metrics with vulnerability. Definitions, graphical summaries, connections with vulnerability, and examples from fisheries participation network studies of each of the three network theoretic metrics considered in the analysis. The mathematical equations we used to calculate these metrics can be found in **Supplemental Table 1**.

Network Metric	Definition	Graphical Summary		Relationship with Vulnerability	Fisheries Participation Network Example
		Less	More		
Network Centralization (weighted)	A measure of how much individual nodes differ among themselves in terms of their degree centrality (i.e., the number of connections each node has). This metric captures the extent to which a network is concentrated around a central node.			Networks with high centralization have higher **SENSITIVITY** to perturbations which impact the central node, but may be better able to withstand perturbations affecting all nodes uniformly (Janssen et al., 2006; Cinner & Bodin, 2010; Sayles & Baggio, 2017)	Over the past several decades, many West Coast (USA) fishing communities have become increasingly dependent upon the Dungeness crab fishery (Fuller et al., 2017; Frawley et al., 2021a). While this concentration of effort helped maintain resources revenues during a period of change impacting other regional stocks, recent climate shocks have led to acute impacts in regions where Dungeness Crab dependence is high and network complexity has been reduced (Fisher et al., 2021).
Network Modularity (weighted)	A measure of the extent to which a network is composed of subgroups.			Modularity is inversely related to **SENSITIVITY** as perturbations to more modular networks are limited to the subgroups in which they occur (Fuller et al., 2017; Dee et al., 2017).	Modular networks are composed of distinct sets of fisheries (i.e., functional forms) between which some to degree of substitution may be possible. In Alaska (USA), longline fishing boats targeting halibut, sablefish, and groundfish may be insulated from many of the environmental and/or regulatory drivers of change impacting seine fishing boats targeting herring and salmon even if they operate in the same region and/or are part of the same SES network (Addicott et al., 2019).
Mean Degree (unweighted)	A measure of the overall connectivity of a network, calculated as the average number of edges per node. Unlike other connectivity metrics (i.e., edge density), mean degree is size-scalable.			Networks with greater mean degree are thought to have higher **ADAPTIVE CAPACITY** as more overall connectedness suggests greater flexibility (see; Dee et al., 2017; Fisher et al., 2021).	Networks with high mean degree are composed of pairs of fisheries with shared participation, indicative of diverse harvest portfolios and/or fishing strategies. In the Baltic Sea (Sweden), SES networks have become less densely connected as new species-specific fishing licenses for cod, salmon, eel and small pelagic species have reduced the ability of large-scale fishers to switch between strategies associated with those species (Hentati-Sundberg et al., 2015; Yletyinen et al., 2018).

and time period as predictor variables, while including permit holder ID as a random effect to account for repeated sampling (**Supplemental Methods 3.0**). All GLMs were validated graphically, using diagnostic plots to assess the normality of residual distribution. To assess differences in network topology and bioeconomic indices between time periods, we used pairwise comparisons with a Tukey HSD Test to compare the two estimated marginal means (one for each time period) associated with each experimental unit. When making multiple comparisons (i.e., comparing trends across self-governance forms within a single region), we applied the Bonferroni adjustment to correct for the family-wise error rate.

3.4. Vulnerability assessment & characterization of adaptive response

To integrate and interpret model outputs and to quantify relative differences in vulnerability among self-governance forms across time periods, we adapted a previously established framework (Koehn et al., 2022; Marshall et al., 2010; Thiault et al., 2021) based on the metrics described below. Vulnerability is determined by the exposure and sensitivity a community or group faces (considered collectively as risk) as mediated by their adaptive capacity. We quantified the relative vulnerability of all experimental units as a product of their sensitivity and adaptive capacity observed during baseline conditions (i.e., 2006–2011) and their subsequent exposure to shifting oceanographic conditions between 2012 and 2016. We defined exposure (i.e., the degree to which a group is subjected to changing environmental conditions) as the Euclidean distance between the maximum SST anomaly and the average SST anomaly observed across fishing grounds associated with each experimental unit (**see Supplemental Methods 1.3.1**) between 2012 and 2016. We defined sensitivity (i.e., the degree to which a group may be impacted, see Table 2) as the Euclidean distance between the baseline network centralization and modularity values (i.e., the marginal means of observations made between 2005 and 2011, following adjustment for covariates included in each GLM). As an intermediary step to measure vulnerability, we calculated risk (i.e., the degree to which a group may be susceptible) as the Euclidean distance between sensitivity and exposure. As a final step, we calculated vulnerability as the Euclidean distance between risk and adaptive capacity (i.e., the ability to adapt, absorb or recover from environmental impacts, as inferred by the marginal mean of baseline mean degree values). As modeled after the approach described by Koehn et al. (2022), before each step of this sequential calculation, we scaled input values between 0 and 1, using inverse mean degree and modularity values to match the theoretical relationships described in Table 2. Finally, we compared the baseline values of sensitivity and adaptive capacity assessed for each experimental unit against those observed during the latter half of the study, allowing us to identify adaptive responses and characterize potential tradeoffs.

4. Results

Below we (1) use bioeconomic indices and fisheries participation networks to characterize heterogeneity in fishing strategies across SSF self-governance forms and ecoregions (*Section 4.1*) during initial conditions (2006–2011); (2) analyze network metrics assessed over this baseline period in combination with observed differences in subsequent (i.e, 2012–2016) regional environmental exposure to make predictions about the relative vulnerability of each region and self-governance form (*Section 4.2*); (3) compare these predictions with observed bioeconomic outcomes (*Section 4.3*); and (4) analyze corresponding changes in network structure associated with distinct adaptive responses that may function to mediate vulnerability to future shocks and stressors.

4.1. Baseline conditions

4.1.1. Heterogeneity in fishing strategies & ecological associations

Across Northwest Mexico, different SSF self-governance forms rely on distinct fishing strategies while targeting species of different ecological clades (Fig. 3). A Principal Component Analysis (Fig. 3**A & B**) designed to parse the ecological associations of catch data reported by different self-governance forms during the initial portion of the study period (2005–2011), indicated that the first three principal components explained 70.5 % of the variance in the data (PC1 = 29.7 %, PC2 = 21.7 %, PC3 = 19.1 %). Though substantial regional heterogeneity exists, overall individual large cooperatives had moderately specialized harvest portfolios (Fig. 3**C**) and a comparatively stronger association with fisheries targeting mobile benthic organisms (largest positive loading on the primary axis, 0.56; Fig. 2**A**), as driven by a strong reliance on lobster along the Pacific Coast of Baja California and shrimp within the Gulf of California (**Supplemental Fig. 2**). Indeed, large cooperatives often have exclusive access to such resources through area-based concessions (i.e., TURFs). In contrast, individual large *permisionarios* had more diversified harvest portfolios and, as compared to other forms of self-governance, a stronger association with sessile benthic organisms (the largest positive

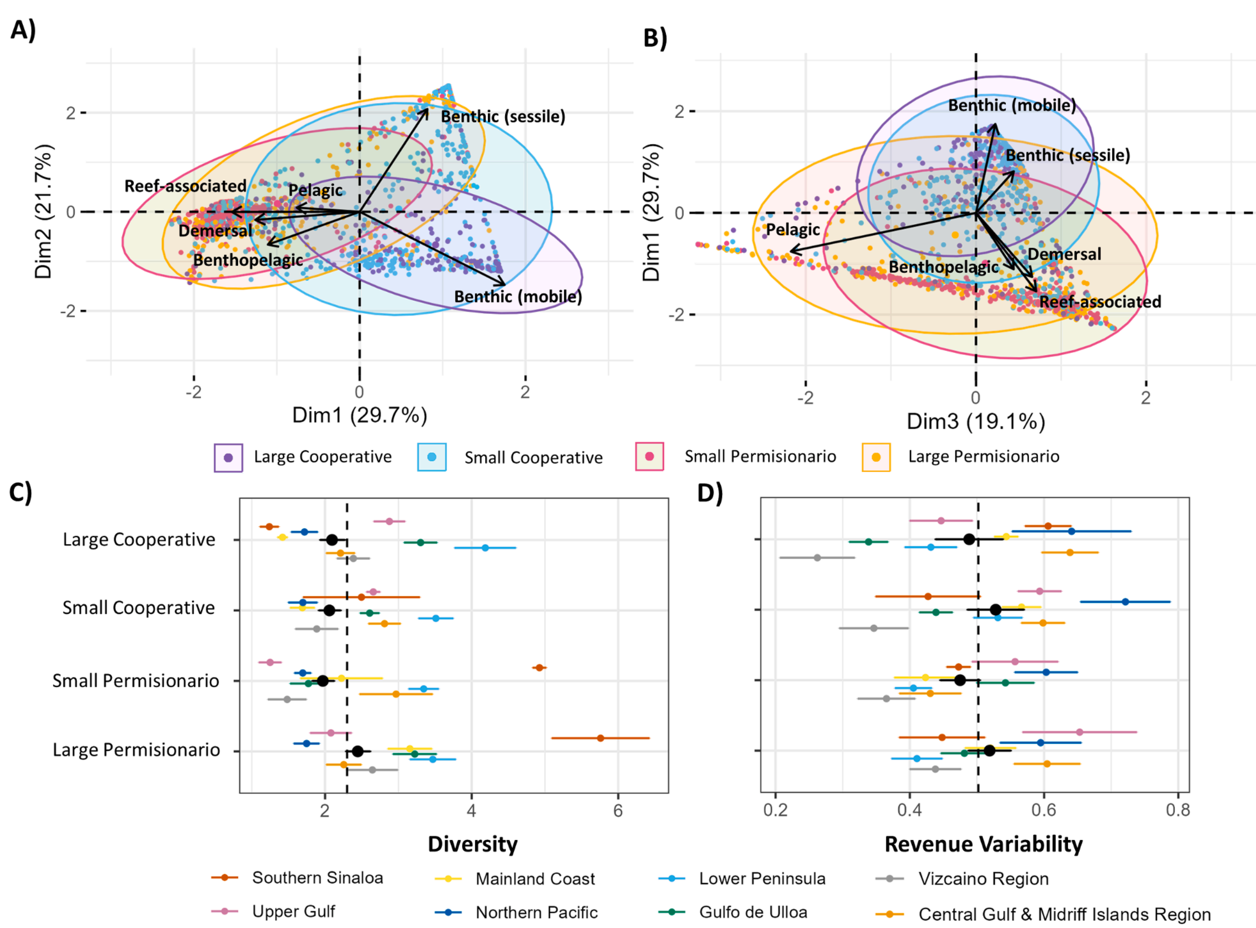


Fig. 3. Fishing strategies of SSF self-governance forms across Northwest Mexico observed during baseline conditions (2006–2011). A Principal Component Analysis reveals the ecological associations of target species for each permit holder along the first, second (**A**), and third (**B**) primary axes. Ellipses comparing associations across self-governance forms are drawn at the 85% confidence level. Bioeconomic metrics quantify corresponding differences in catch diversity (**C**) and revenue variability (**D**), with the black points representing the marginal mean (mean model predictions for the specified factor level, during the specified time period with covariates held constant) +/- SE; colored points highlighting regional means +/- SE; and the dashed line representing the population mean across all regions and organizational forms.

loading on the secondary axis, 0.78; Fig. 3A) like clams and sea urchins (**Supplemental Fig. 2**) in addition to pelagic taxa (the largest positive loading on the tertiary axis, Fig. 3B) like squid and sharks. Small cooperatives and small *permisionarios* were of low (though variable) diversity (Fig. 3C) despite broad ecological associations (**Supplemental Fig. 2**), with small *permisionarios* demonstrating a comparatively larger affinity for reef-associated taxa (the largest negative loading on the primary axis at – 0.50) as compared to other self-governance forms (Fig. 3B) and exhibiting a strong degree of specialization in regions in which they were engaged in the harvest of clams (Fig. 3C, **Supplemental Fig. 2**). Though large cooperatives were often more specialized than large *permisionarios*, they reported comparatively lower interannual income variability, while overall small cooperatives reported the highest (Fig. 3D).

4.1.2. Variation in participation network structure

Fisheries participation networks revealed differences in the structure and function of the harvest portfolios relied upon by each self-governance form associated with differences in sensitivity (i.e., weighted network centralization and modularity) and adaptive capacity (i.e., mean degree) (Fig. 4). Overall, networks composed of large cooperatives had fewer nodes of asymmetrical size (i.e., percent contribution to total revenue) linked by a limited number of strong connections. In contrast, networks composed of large *permisionarios* tended to have a larger number of more densely connected nodes across which revenue was more evenly distributed (Fig. 4A). Networks of small *permisionarios* and small cooperatives, while variable, typically exhibited an intermediate form. As follows, network metrics used to assess sensitivity and adaptive capacity (Table 2) varied substantially within and across different forms of self-governance (Fig. 4B). Networks composed of large cooperatives were typically more centralized (i.e., more dependent upon a single fishery) with lower mean degree (i.e., fewer connections between fisheries) and less modularity (i.e., consisting of fewer functional forms or sub-groups) as compared to those composed of large *permisionarios*. While the impact of any particular event likely depends upon the degree to which it impacts the central node, it follows that over extended time horizons, this form of self-governance as a whole may be comparatively more sensitive (i.e., more centralized, and less modular) to external shock and stressors and have less adaptive capacity (i.e., lower mean degree). Holistic characterization of small *permisionarios* and small cooperative networks was challenging given variable modularity estimates and their tendency to be associated with higher centralization and lower mean degree values in regions across the Pacific Coast of the Baja California peninsula as compared to those within the Gulf of California (**Supplemental Fig. 2**).

4.2. Prediction of vulnerability and assessment of expected outcomes

Considering varying levels of sensitivity and adaptive capacity associated with distinct human-environment linkages (Table 2, Fig. 4), we hypothesized that the transition between oceanographic regimes (2012–2016) would result in variegated bioeconomic outcomes across

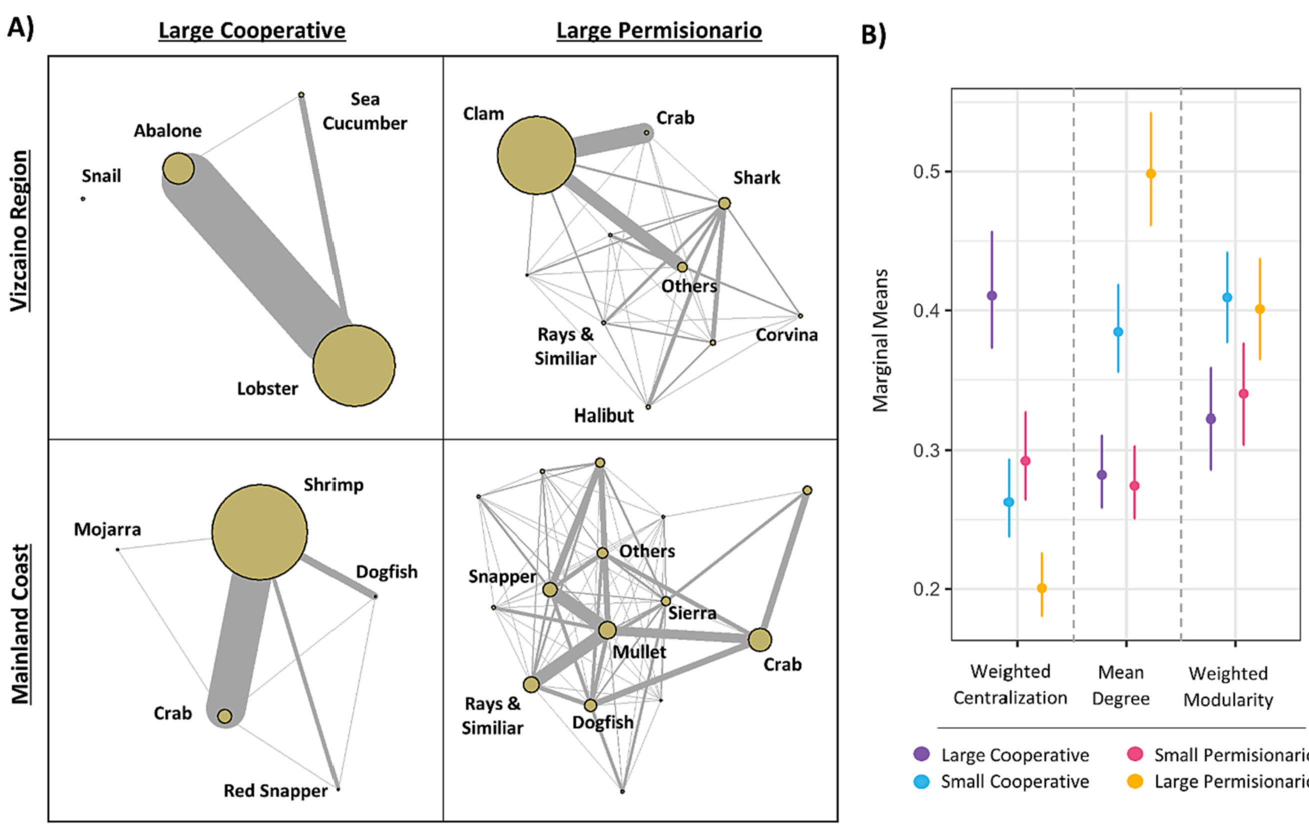


Fig. 4. **A)** Baseline (2006–2011) heterogeneity in the structure of fisheries participation networks by self-governance form across ecoregions. Principal taxonomic groupings (i.e., *Nombre Principal*) serve as the nodes (i.e., circles), and are sized by the percent contribution of that taxonomic group to the total revenue generated by the specified self-governance form in the specified ecoregion, while the edges (i.e., connections) between nodes are based on a revenue evenness metric (see **Methods**). For example, large cooperatives in the Vizcaino region generate most of their revenues from lobster and abalone fisheries. The comparatively large connection between these two fisheries (i.e., the thickness of the edge-weight) reflects the high proportion of large cooperatives participating in both fisheries while generating substantial revenues from each. **B**) Comparison of marginal means (i.e., the mean model predictions of the specified factor level, during the specified time period with covariates held constant) with associated error (95% confidence level) for weighted centralization, mean degree, and weighted modularity as obtained from the most informative generalized linear model constructed for each network metric (see **Supplemental Table 3**). The complete interaction plots (estimates for each self-governance form in each ecoregion) are shown in **Supplemental Fig. 3**.

self-governance forms that could be predicted by vulnerability theory. During the 2012–2016 period, SSF on the Pacific coast of the Baja California Peninsula were most exposed to elevated sea surface temperature anomalies, while SSF in the Central Gulf and the Upper Gulf were the least exposed (Fig. 5**A**). With large cooperatives networks assessed as the most sensitive (Fig. 5**B**), in the Vizcaino Region and the Gulf of Ulloa this self-governance form faced the largest risk due to high exposure (Fig. 5**C**). In contrast large *permisionarios*, whose networks were assessed as the least sensitive (Fig. 5**B**), and small cooperatives (whose regional networks in the Central Gulf, Southern Sinaloa, and the Mainland Coast had some of the lowest combined sensitivity scores; Fig. 5**B**) faced comparatively reduced risk (Fig. 5**C**). In predicting vulnerability, the risks faced by different self-governance forms (in aggregate or by region) were tempered or amplified by varying levels of adaptive capacity, as inferred by network mean degree (Fig. 5**D**). We predicted large *permisionario* and small cooperative networks, whose large number of connections are theorized to facilitate flexibility, to be the least vulnerable overall (with notable exceptions in the Vizcaino Region and the North Pacific). Small *permisionarios* were predicted to have high vulnerability due in part to the low number of connections and limited flexibility of their networks (most pronounced across Northern Pacific, the Vizcaino Region, and Upper Gulf networks, where specialized permit holders engaged in clam fisheries; Fig. 3**C**, **Supplemental Fig. 2**). For large cooperatives, low network connectivity led us to predict elevated vulnerability in the North Pacific, Southern Sinaloa, and the Mainland Coast (where individual cooperatives were the least diversified and most exposed) while high network connectivity was predicted to reduce vulnerability in the Lower Peninsula and Gulf of Ulloa regions (where individual cooperatives were the most diversified).

4.3. Comparison of expected and observed bioeconomic outcomes

Despite anomalous oceanographic conditions, overall SSF across Northwest Mexico generated greater annual revenue between 2012 and 2016 as compared to 2006–2011 (**Supplemental Fig. 4A**), though many of these changes were driven by an increase in the number of active permit holders (**Supplemental Fig. 4B**, **Supplemental Fig. 5A**). When comparing observed changes in revenue with predicted vulnerability as inferred by network theoretic metrics (Table 2), our analysis reveals broad, if tenuous correspondence, mediated by the type of self-governance form.

We used Pearson's correlation (**Supplemental Table 4**) to test for association between individual network metrics (i.e., modularity, centralization, and mean degree), derived vulnerability metrics (i.e., exposure, sensitivity, and vulnerability) and bioeconomic outcomes (change in total revenue per # of permit holders (Fig. 6**A**), and modeled differences in individual revenue during each time period (Fig. 6**B**)) assessed for each experimental unit.

These tests revealed only a significant negative relationship between exposure and change in total revenue/# of permit holders for each experimental unit ($r = -0.391$; $p = 0.026$), indicating that revenue was more likely to decline in regions where exposure was more pronounced.

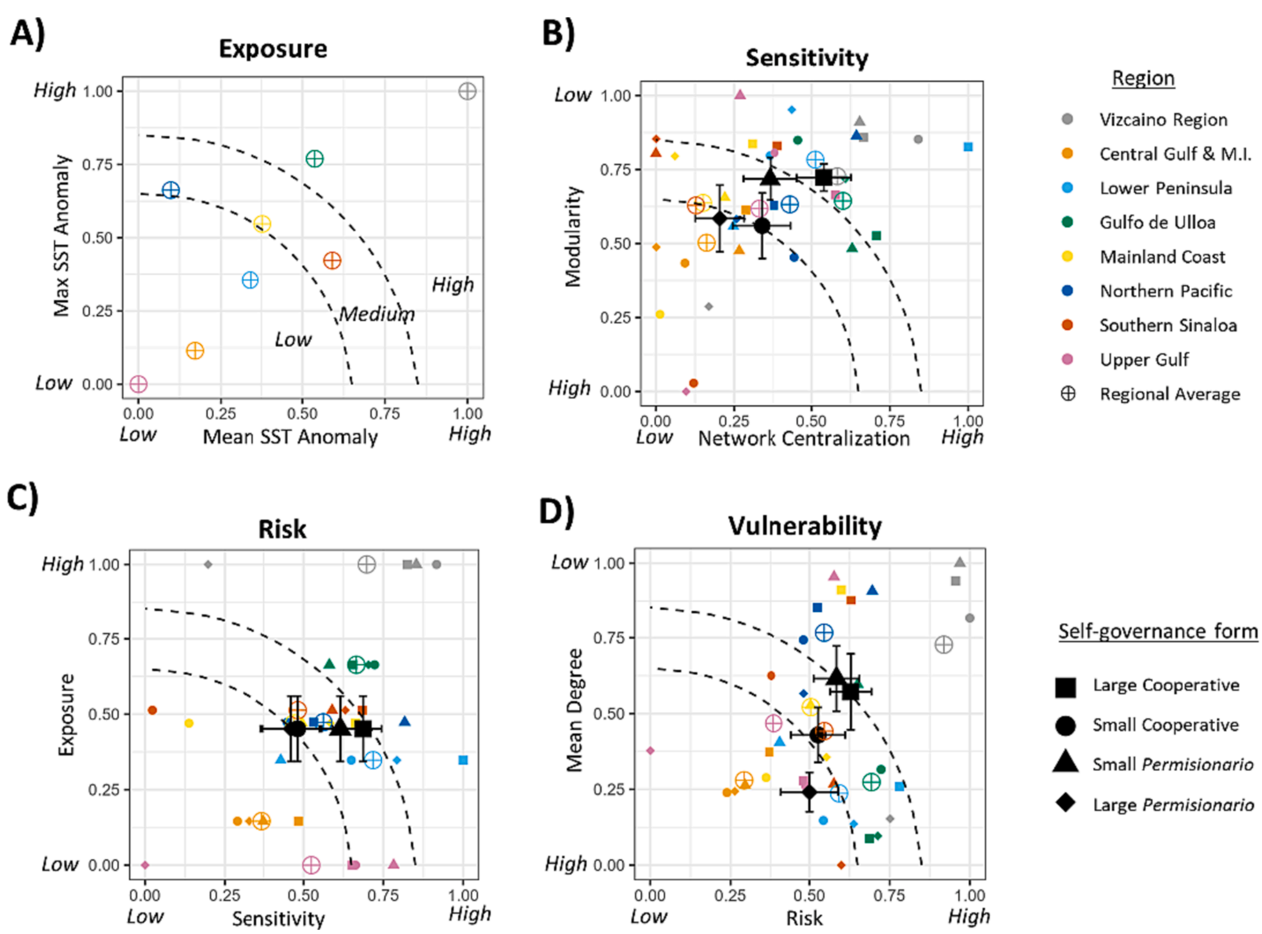


Fig. 5. Assessed **A**) Exposure; **B**) Sensitivity; and **C**) Risk (including Exposure and Sensitivity), as integrated to predict the relative (**D**) Vulnerability of each self-governance form in each region (colored shapes, with regional means displayed with the corresponding circle plus) and in aggregate (mean values +/- SE as represented by black shapes) across Northwest Mexico. Network theoretic metrics were derived from observations made during baseline conditions (2006–2011) while exposure data represents the subsequent perturbation (2012–2016) SST anomalies. Contour lines represent combinations of x and y-axis values that produce equivalent scores for each panel.

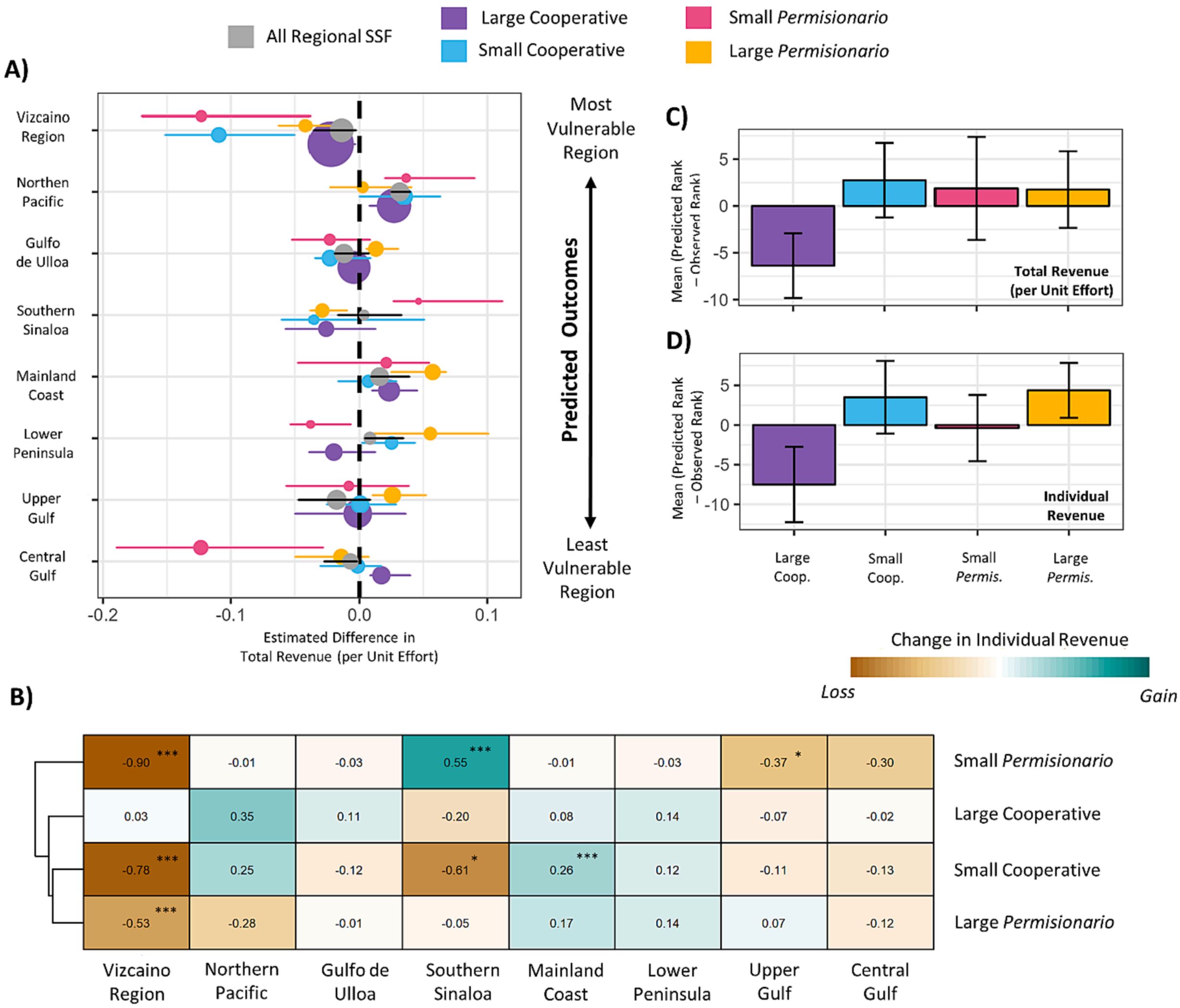


Fig. 6. Comparison of predicted vulnerability and observed bioeconomic outcomes. **A)** compares estimated differences (assessed using a Wilcox-Signed Rank Test) in the percentage of total revenue per unit effort (i.e., permit holder) reported in 2006–2011 as compared to 2012–2016 for each self-governance form (colored points) and across self-governance forms (gray points) with associated error (75 % confidence level). Point sizes are derived from mean revenue per unit effort (i.e., permit holder) across the entire study period. Regions are ordered from high to low predicted vulnerability following Fig. 5**D**. Comparisons at the species level are shown in **Supplemental Fig. 5**. **B)** depicts log transformed ratios (final/initial) of GLM estimates for changes in the revenue of individual self-governance forms, with significance determined by Tukey HSD test (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).**C** & **D** compare differences in the predicted vulnerability rank (1 = most vulnerable, 32 = least vulnerable) of each experimental unit with relative bioeconomic outcomes (1 = largest revenue decrease; 32 = largest revenue increases), considering total revenue per unit effort (**C**) and individual revenue (**D**).

However, even as significance varied, the direction of relationships across other metrics were consistent with that which would be predicted by vulnerability theory (**Supplemental Table 4**; Table 2). Of these, the strongest association was found between vulnerability and changes in individual revenue (r = -0.345; p = 0.052), wherein experimental units predicted to be more vulnerable, more commonly reported revenue losses. Mean degree (r = 0.294; p = 0.101) and Network Centralization (r = -0.172; p = 0.34) had comparatively weaker associations with the same metric, as network connectivity was (non-significantly) associated with revenue gains and network concentration was (non-significantly) associated with revenue losses. Conducting a rank comparison between predicted vulnerability and total revenue /# of permit holders (Fig. 6**C**), as well as change in individual revenue (Fig. 6**D**), for each experimental unit reveals that large cooperatives consistently exceeded expectations (i.e., more commonly increasing or maintaining revenue despite high predicted vulnerability). In contrast, small cooperatives, small *permisionarios*, and (most consistently) large *permisionarios* underperformed (i.e., more commonly reporting revenue losses despite low predicted vulnerability).

Disaggregated analysis is critical in understanding many of the regional dynamics driving trends across self-governance forms. In aggregate, revenue per permit holder decreases were most pronounced in the Vizcaino Region (the region where participation networks across self-governance form were predicted to be the most vulnerable), the Gulf of Ulloa (the third most vulnerable region), the Upper Gulf (the second least vulnerable region), and the Central Gulf (the least vulnerable region) (Fig. 6**A**). In the Vizcaino Region, Gulf of Ulloa, and the Upper Gulf declines in revenue may have been drvien in large part by the declining value of clam harvests (**Supplemental Fig. 6**), and most acutely experienced by small cooperatives, small *permisionarios*, and/or large *permisionarios* reliant upon them (Fig. 6**B**, **Supplemental Fig. 6**). Across the Baja Pacific, large cooperatives, which we assessed as highly sensitive, were able to mitigate the declines in revenue associated with another sessile benthic invertebrate (abalone) through sustained and/or elevated revenues from the lobster fishery **Supplemental Fig. 6**). Likewise, in the Central Gulf & Midriff Islands Region, revenue decreases associated with declining value of pelagic fisheries (i.e., squid and *sierra*) with broad participation, were less impactful for large cooperatives that were able to rely upon shrimp (which also supported large cooperatives in the Upper Gulf), though a decline in the total number of both large cooperatives and large *permisionarios* (Supplemental Fig. 4B, Supplemental Fig. 5A) in this region suggests that many large-scale permit holders ceased operations.

By contrast, in the North Pacific, Lower Peninsula, and Mainland Coast regions, shifting oceanographic conditions were correlated with resource booms. In the Gulf, large cooperatives benefited from the sustained productivity of shrimp harvests while increases in the revenue generated by crab, shark, and red snapper species provided benefits across multiple self-governance forms (though increases were less consistent for small *permisionarios*; Fig. 5**D, Supplemental Fig. 6**). In the North Pacific benefits accrued most exclusively to large and small cooperatives engaged in lobster and sea urchin harvests (Supplemental Fig. 6), while large *permisionarios* in the region that were focused on clam, squid and/or shark fisheries reported revenue losses that coincided with a large decline in the number of active permit holders (Supplemental Fig. 5**A**). A Tukey HSD test used to compare GLM earnings estimates for each self-governance form in each time period indicates that overall revenue declined significantly for small *permisionarios* ($p < 0.05$) and for small cooperatives ($p < 0.001$).

4.4. Changes in potential vulnerability associated with adaptive response

Analysis of changes to the structure and function of fisheries participation networks during the warm water oceanographic regime (i.e., 2012–2016) provides evidence that self-governance mediates adaptive response within SSF, leading to changes in sensitivity and adaptive capacity (Fig. 7) likely to influence vulnerability to future shocks and stressors.

In many of the regions where large cooperatives reported consistent or increased revenues, they also became more centralized and less modular (increasing sensitivity) as dependence upon central nodes (i.e., lobster, shrimp, etc.) became stronger and more uniform. Though in some regions (i.e., the Vizcaino Region and the Mainland coast) these changes to large cooperative networks may be offset by increases in mean degree (i.e., adaptive capacity), a lack of corresponding changes in harvest portfolio diversification (Supplemental Fig. 7) suggests that minimal revenues were derived from participation in expanded suites of fisheries. Indeed, during the 2012–2016 time period, large cooperatives were the least diversified of all self-governance forms (Supplemental Fig. 7). Small cooperatives, which had the largest increase in harvest portfolio diversity (Supplemental Fig. 7), in aggregate exhibited patterns similar to large cooperatives (Fig. 7**A**), though individual trajectories varied region by region (Fig. 7**B**).

Small *permisionarios*, which were comparatively most likely to report revenue decreases as compared to other self-governance forms (Fig. 5**D**), also increased the diversity of their harvest portfolios in aggregate and were associated with network changes believed to reduce sensitivity and increase adaptive capacity (Fig. 7**A & B**) as network size increased across multiple metrics (Supplemental Fig. 5). This suggests that they may be less vulnerable to future shocks and stressors. In contrast large *permisionarios*, who as a self-governance form became less prevalent in a number of regions (Supplemental Fig. 5**A**), were associated with

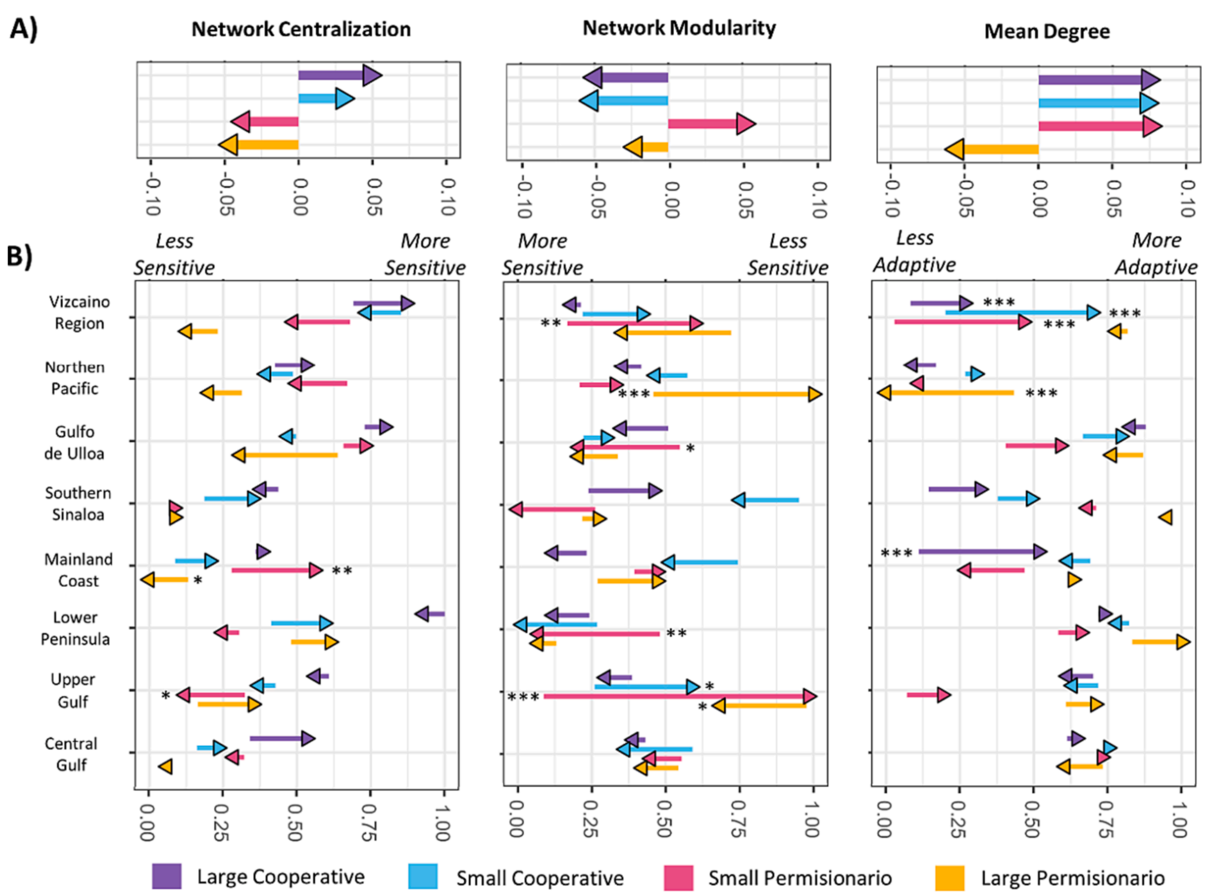


Fig. 7. Changes in participation network structure reported by self-governance form, comparing GLM marginal mean estimates from 2005 to 2011 (arrow base) to estimates from 2012 to 2016 (arrow head). Comparisons are shown for network centralization (the degree to which a network is concentrated around a single fishery), network modularity, (the degree to which a network is divided into subgroups), and mean degree (overall network connectivity). **A)** summarizes the mean change for each network theoretic metric for each self-governance form (as averaged across 8 regions) while **B)** displays trends disaggregated by region (scaling all estimates for each metric between 0 and 1). Significance values (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$) were obtained from Tukey's HSD Test.

networks that became less dependent on central fisheries (particularly in regions were clam fisheries were previously a dominant focus; Fig. 6**B; Supplemental Fig. 2**), but that were also composed of fewer and less densely connected sub-groups.

5. Discussion

Much of SSF vulnerability literature to date has focused on theoretical characteristics believed to be associated with the ability of households, communities, and fisheries systems to buffer against change while retaining their core attributes and capacity to regenerate (Oestreich et al., 2019). Yet, empirical evaluations of how such metrics translate into observed responses are scarce (Whitney et al., 2017, but see Green et al., 2021 & Galappaththi et al., 2022). Monitoring adaptive strategies and empirically evaluating how the various components and scales of vulnerability are impacted as systems react to change may allow for a more profound understanding of SES feedbacks and trade-offs (Cinner et al., 2015). Here we use vulnerability theory to examine fisheries participation networks, investigating the relationships between self-governance form, network structure, and bioeconomic outcomes during a period of system change. We find a broad correspondence, mediated by self-governance form, between observed outcomes and those predicted by vulnerability theory. Our analysis suggests that (1) different forms of SSF self-governance (and the fishing strategies and harvest portfolios with which they are associated) help determine the impacts of and response to climate shocks and stressors and (2) there may be important trade-offs between short-term responses which function to prevent or mitigate lost fishing revenue and long-term changes in climate vulnerability. We elaborate on these two main findings below.

5.1. Network centralization as a double-edged sword

Our analysis confirms that the extent to which highly centralized (i.e., dependent on a limited number of resources) social-ecological networks may be impacted by any given climate shock depends upon; (1) the exact nature of the stressor and (2) the degree to which it impacts the central node (Fuller et al., 2017; Fisher et al., 2021). During our study, highly centralized networks, dependent upon regional open access clam fisheries known to be susceptible to overharvesting (Pellowe & Leslie, 2019; Luquin-Covarrubias et al., 2022) and environmental change (Jiménez-Quiroz et al., 2021) experienced acute, negative impacts. As has been highlighted in other systems, specialization in highly vulnerable bivalve fisheries (Hare et al., 2016, Ramos et al., 2022) or mariculture operations (Kluger et al., 2019) may be a particularly risky strategy as climate change progresses. Yet existing literature (Watson et al., 2011) suggests networks with highly central nodes may be able to withstand perturbations that impact all nodes uniformly and, under certain conditions, small and/or highly centralized networks may be most efficient and favorable (Bodin et al., 2009). In our study, highly centralized networks dependent upon lobster and shrimp fisheries (typical of large cooperatives) minimally impacted by observed oceanographic changes, were consistently able to avoid and/or mitigate changes impacting other portions of the resource base.

More broadly, our findings advance previous research suggesting that network centralization may be positively correlated with collective action in resource governance (Sandström and Carlsson, 2008), indicating such patterns may be consistent whether considering social relationships or social-ecological linkages. Large cooperatives' narrow focus on benthic invertebrates like lobster, shrimp, abalone, and crab is consistent with established common pool resource theory (Ostrom, 2009), which asserts that high-value resources with limited mobility that are predictable, easy to monitor, and contained within well-defined geographic boundaries are most amenable to self-governance. Indeed, sensitivity as defined in our network analysis may be a desirable attribute when impacts of change are positive and/or beneficial (i.e., external drivers of change leading to increases in the abundance or value of fisheries resources), with highly specialized and/or centralized fishing cooperatives uniquely well-positioned to maximize resource returns (Finkbeiner, 2015). Moreover, cooperatives may have higher capacity to anticipate and respond to changes impacting their focal species if their organizational structure enables them to effectively engage in research and monitoring activities (McCay et al., 2014; Cinner et al., 2018).

Yet more centralized networks may be most vulnerable to changes affecting focal fisheries -i.e., nodes- (Janssen et al., 2006; Sayles & Baggio, 2017). The "gilded trap" theory suggests that getting "locked-in" to a single, high-value fishery may increase sensitivity to climate shocks and stressors and reduce adaptive capacity in the long-run (Steneck et al., 2011, Kittinger et al., 2013). In our analysis, self-governance forms that were most successful in negotiating oceanographic variability frequently pursued fishing strategies believed to increase their sensitivity to subsequent shocks and stressors, often becoming more dependent on the fisheries which served as focal taxa (i.e., central nodes). Conversely, many of the self-governance forms incurring the largest revenue losses (small *permisionarios* in particular) responded by diversifying harvest portfolios, increasing the number of functional forms, and reducing their dependence upon impacted fisheries. Though crustacean resources across Northwest Mexico were comparatively resilient over the course of our study period, the extensive body of literature documenting the climate-driven collapse of such fisheries is of significant concern moving forward (Arreguín-Sánchez et al., 2015; Richards et al., 2021; Szuwalski et al., 2023). Highly centralized networks may have the capacity to bounce back if disturbance is ephemeral or short-lived (Fisher et al., 2021). Yet planning for long-term SES change, where simultaneous, interacting shocks may lead to novel and unpredictable ecosystem dynamics (Cottrell et al., 2019; Ammar, 2021), may require advancing network structures that increase flexibility and decrease single-fishery dependence.

5.2. Path dependency associated with large cooperatives & TURFs

Social-ecological systems may be considered path dependent if past decisions function to constrain the direction and breadth of future choices through self-reinforcing mechanisms or positive feedbacks (Kay, 2003). Mexican fishing cooperatives are often considered a model for successful self-governance (McCay et al., 2014, Méndez-Medina et al., 2015). However, constrained functional forms (i.e., low modularity) coupled with elevated and increasing levels of dependence on a small number of resources (i.e., high centralization) reveal a degree of path dependency, particularly along the Pacific Coast of the Baja California peninsula, that may be of concern as global environmental and socioeconomic change progresses. Indeed, over extended time horizons, the harvest portfolios, access rights, and internal coordination that has historically contributed to the success of large fishing cooperatives may function to undermine system resilience.

Though large cooperatives with exclusive access to high-value resources have contributed to the sustainability and productivity of many benthic resources (Elsler et al., 2022), they may also increase the vulnerability of non-cooperative fishers that lack similar property rights. In our study, the existence of TURFs likely contributed to the asymmetrical impacts of system change across fishers and self-governance forms, in which the most significant losses were incurred by 'outsiders' (i.e., actors not belonging to the fishing cooperatives) that were excluded from high-value lobster and shrimp harvests. As has been noted in South Africa (Raemaekers et al., 2011), the delineation between the 'have' and the 'have-nots' associated with the establishment and operation of TURF fisheries may ultimately function to amplify inequality, reduce social cohesion, and incentivize illegal fishing. Parallel dynamics have been observed in Chilean TURF systems, where fishers unaffiliated with the establishment of exclusive Management and Exploitation Areas for Benthic Resources (MEABR), have seen negative impacts to their livelihoods as open access diving grounds have become scarce and overexploited (Orensanz & Parma, 2010), conflict has increased across the SSF sector (Gelcich et al., 2009), and seasonal patterns of human migration and gear rotation have been disrupted (Aburto et al., 2013). Such constraints upon fisher behavior may function to limit adaptation, now and in the future, as the displacement of resources across regional and sub-regional jurisdictional boundaries accelerates (Tokunaga et al., 2023).

For the members of large cooperatives, previous research focused on bonding and bridging social ties suggests that small, densely connected networks characterized by high-levels of reciprocity may contribute to low individual risk perception, which can impede preparedness and inhibit adaptation (Zhang et al., 2020; Salgueiro-Otero et al., 2022). While social links may enhance individual livelihood resilience following system perturbation (Kriegl et al., 2022), distinct (and as yet poorly understood) processes may manifest when considering social-ecological linkages at higher levels of organization. Indeed, long-term resource tenure and coupled with persistently elevated fisheries income may create complacency. Following the 2010 tsunami with destroyed > 50 % of SSF boats in Chile (Marín et al., 2010), non-TURF fishers accustomed to investing in equipment which provided a competitive advantage (i.e., increased loading capacity or engine power), re-assembled their fleet quicker as compared to TURF fishers (Molina, 2022). Although much attention has been given to the value of polycentric governance systems in SES (Ostrom, 2010), and the overlapping local, regional, and national structures in which large fishing cooperatives in Mexico are nested (McCay et al., 2014), questions persist regarding their capacity to respond to rapid system change. Indeed, the coordination costs required to align priorities and assign tasks across multiple actors and organizations may limit agency in the decision-making, experimentation, and adaptive learning processes thought to enhance response capacity and resilience (Olson, 1965, Fazey, 2005). Irrespective of changes in revenue, individual large and small *permisionario* networks were most dynamic during our study period (see distribution of significance values in Fig. 7**B**).

As species distributions shift and environmental variability increases, those networks that are most dynamic and flexible may be best positioned to opportunistically target transient aggregations of pelagic and/or migratory species. This dynamic is already evident across Northwest Mexico, where harvests of shark, squid, and cannonball jellyfish are dominated by large *permisionarios* capable of rapidly deploying and retracting their fishing capital while accommodating significant interannual variation in resource rents (Frawley et al., 2019b; Brotz et al., 2021). In the Northwest Pacific, often considered one of the fastest warming regions across global oceans, the resilience of Japanese coastal TURF fishers has been attributed to dynamic and flexible harvest portfolios targeting pelagic resources (Ho et al., 2020). Encouragingly, many large cooperatives in Mexico already may already possess the ability to capture a broad suite of pelagic, demersal, and reef-affiliated species (evident in regions where network connectivity (i.e., mean degree) is high and a diversity of species are landed), even if efforts to develop such fisheries have received comparatively limited investment in human and financial capital to-date.

Although we suggest that future risk associated with the narrow focus and rigid structure of current participation networks may be of concern, it is important to highlight attributes of large cooperatives not captured in our analysis that may limit sensitivity, enhance adaptive capacity, and facilitate transformation (Vilalta-Navas, 2023). Given the high-value species they target, cooperative members may have elevated baseline incomes and the short-term capacity to rely on individual or collective savings in times of crisis (Finkbeiner, 2015). In addition, for many large cooperatives, particularly those found on the Pacific Coast of Baja California and Baja California Sur, local governance structures are composed not only of fishers but also government agencies, NGOs, and academics (Zetina-Rejoń et al., 2020). In rural areas, cooperatives are not only engaged in fishing but build and/or maintain major infrastructure such as roads, and desalination and electrical plants (McCay et al., 2014). Increasingly, the social and economic capital associated with these diverse stakeholder networks has facilitated the participation of these self-governance forms in alternative industries like tourism and aquaculture (Valdez-Rojas et al., 2022), and may ultimately function to reduce their dependence on export-oriented wild fisheries. As others have argued, external support and technical assistance may be fundamental in determining vulnerability and adaptation (Ruiz-Diaz et al., 2020).

5.3. Limitations

As in other SSF studies, our power of inference is undoubtedly limited by the data to which we had access (Smith & Basurto, 2019). Although significant progress has been made in decentralizing SSF monitoring and data collection efforts across Northwest Mexico (Espinosa-Romero et al., 2014), previous studies estimated that > 50 % SSF catch is not reported (Cisneros-Montemayor et al., 2013; Morzaria-Luna et al., 2020) and accurate taxonomic identification remains a challenge (Ramírez-Rodríguez, 2011). Though we are not unable to establish a causal link between reported changes in fisheries participation and observed oceanographic anomalies, many of the recent trends in resource abundance we describe here are consistent with previous regional literature describing abalone (Smith et al., 2022), squid (Frawley et al., 2019c), clam (Jiménez-Quiroz et al., 2021), and crab (Balmori-Ramirez et al., 2021) fishery dynamics.

While we have endeavored to provide a nuanced analysis of regional SSF operations by empirically characterizing four self-governance archetypes, these discrete categories likely fail to capture the complete diversity of governance characteristics and attributes. While some private permit holders can be considered traditional generalist, owner-operator fishers with place-based ecological knowledge that are exclusively dedicated to the trade (i.e., *pescadores;* see Frawley et al., 2019a), others are better considered as rent seeking entrepreneurs who only deploy the full extent of their fisheries capital during resource booms, and/or frequently operate in locations where they have no personal or family connections (Basurto et al., 2013; Frawley et al., 2019b). Likewise, while we can generally assume capacity for collective action across northwest Mexico's older, large fishing cooperatives, there is considerable variation in the quality and performance of democratic governance across the different economic units classified as "cooperatives" in our analysis (Nenadovic et al., 2018). Critically, individual fishers may switch affiliations (moving from one self-governance form to another) within and between years. At the regional and national level, a diversity of self-governance arrangements may contribute to SES resilience as each has its own strengths and weaknesses best suited to unique challenges (Baird et al., 2019).

Beyond differences in fisheries participation and connectivity, external government support, occupational multiplicity, and community cohesion are known to play significant roles in mediating SSF vulnerability and adaptive response within and across different scales of organization. In Northwest Mexico (Frawley et al., 2019a), as elsewhere (Allison & Ellis, 2001), many fishers augment fisheries income with earnings from additional occupations as well as government cash transfers or subsidies. Access to opportunities and resources remains unequal, however, as determined by the legacy of government policies and initiatives tied to specific political promises and regional development projects (Young, 2001. Espinoza-Tenorio et al., 2011a, Wintergalen, 2022). In addition to associated differences in assets and infrastructure, other SES scholars working at the community level have highlighted the critical importance of social factors like equity, agency, cognition, and trust in determining adaptive capacity and response (Cinner et al., 2018; Galappaththi et al., 2022). Future research and fisheries management would be well-served by explicitly addressing how such factors interact with the ecological, geographic, and governance attributes that are the focus of the present analysis (see Munguia-Vega et al., 2022).

6. Conclusion

Here we evaluate the impact of climate shocks on SSF in Northwest Mexico based on results of a natural experiment where a pronounced shift in oceanographic conditions was associated with cascading changes in fisheries landings and participation. Our results make clear that self-governance plays a critical role in mediating how fishers experience and respond to system perturbation and may be responsible for many of the sub-regional dynamics likely to shape future fisheries outcomes. Beyond highlighting the value of integrated approaches in advancing ecosystem-based fisheries management and improving our understanding of the connections linking fisheries and people (Espinoza-Tenorio et al., 2011b), our work demonstrates the utility of disaggregated analyses more broadly, and the value of collecting and analyzing data representative of different forms of self-governance. In the absence of data of sufficient granularity, the critical role that different forms of self-governance play in shaping climate vulnerability and adaptation may be impossible to detect. Identifying groups of people with the greatest need is increasingly recognized as an essential component of fair and effective climate adaptation planning (Cinner et al., 2015). Indeed, as others have argued (Armitage et al., 2007), ensuring equity in interventions across regions where formal regulatory capacity is weak and natural resource use is regulated from the bottom-up requires explicit attention to how different self-governance forms influence vulnerability and response to extreme events and increasing environmental variability.

CRediT authorship contribution statement

Timothy H. Frawley: Conceptualization, Funding acquisition, Project administration, Data curation, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing. **Blanca González-Mon:** Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Mateja Nenadovic:** Data curation, Funding acquisition, Project administration, Writing – original draft, Writing – review & editing. **Fiona Gladstone:** Validation, Writing – original draft, Writing – review & editing. **Keiko Nomura:** Methodology, Writing – original draft, Writing – review & editing. **José Alberto Zepeda-Domínguez:** Validation, Writing – original draft, Writing – review & editing. **Salvador Rodriguez-Van Dyck:** Validation, Writing – original draft, Writing – review & editing. **Erica M. Ferrer:** Validation, Writing – original draft, Writing – review & editing. **Jorge Torre:** Validation, Writing – original draft, Writing – review & editing. **Fiorenza Micheli:** Funding acquisition, Writing – original draft, Writing – review & editing. **Heather M. Leslie:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Xavier Basurto:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary material

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