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Original Article

Fisheries connectivity measures of adaptive capacity in small-scale fisheries

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Small-scale fisheries (SSFs) around the world are increasingly facing pressures from a range of environmental, economic, and social sources. To sustain SSFs, it is imperative to understand how fishing communities adapt to these pressures. In particular, to manage economic risks fishers often catch many different species; diversifying harvest portfolios creates multiple income sources in case one species becomes less abundant, less valuable, or otherwise unavailable. Here, we apply fisheries connectivity network analysis to assess the portfolios and potential adaptive capacity of small-scale fishing communities in the Baja California Peninsula (BCP), Mexico. We found that network metrics like modularity and density varied by region and through time. The Pacific coast region of Baja California displayed increasingly modular fisheries connectivity networks, indicating fisheries landings became increasingly asynchronous with each other and the potential adaptive capacity increased. The remaining three regions of Baja California showed the opposite trend, where the temporal covariance between fisheries increased over time. Overall, this study shows that the potential adaptive capacity of fishing communities varies substantially throughout the BCP, and highlights how fisheries connectivity networks can offer a way to quantify and advance our understanding of adaptive capacity within small-scale fishing communities.

Keywords: adaptive capacity, fisheries, network theory, resilience, risk management, social–ecological systems, vulnerability.

Introduction

Small-scale fisheries (SSFs) provide livelihoods and food security for millions of people worldwide, comprising over 90% of global fisheries employment and producing nearly half of the seafood destined for human consumption (FAO, 2019; Troell *et al.*, 2019). SSFs are diverse in terms of the people that comprise them, the gear types that they use, and the species they target. They are typically low-impact operations that use small outboard motorboats and non-destructive gear (Berkes, 2001), though the sheer numbers of SSFs translate into a cumulatively high sectoral importance (Schuhbauer and Sumaila, 2016). Since SSFs employ so many people and are broadly distributed geographically, governance is typically decentralized or unregulated (Finkbeiner, 2015). Recent studies have prioritized needs to understand how such resource-reliant populations, whose occupations are also globally beneficial, may brace themselves amidst changing social–ecological conditions driven by climate variability, climate change, or market shocks (Cinner *et al.,* 2018; Barnes *et al.,* 2019; White *et al.,* 2020).

Several factors can influence a fishing community's overall vulnerability to stressors. The vulnerability of human communities is defined as the susceptibility to be harmed by a given perturbation. The key parameters of vulnerability are exposure, sensitivity, and adaptive capacity (Adger, 2006). Exposure is the magnitude and frequency of a perturbation, while sensitivity is the level to which the system is affected by said perturbation. Adaptive capacity is defined as the ability to cope with stress and counteracts these components. The various parts of this framework can be assessed separately to look at specific facets and drivers of vulnerability. Increasingly, this vulnerability framework has been applied as a theoretical tool to study the abilities of people whose livelihoods depend on the environment to cope with environmental, social, and economic changes (Allison *et al.*, 2009; Leslie *et al.,* 2015; Blasiak *et al.,* 2017). Fishers commonly adapt to changes in weather conditions, species availability, market fluctuations, and fisheries closures (Cinner *et al.*, 2008; Yletyinen *et al.*, 2018). But fishers must also adapt to longer-term changes. As ocean conditions fluctuate with climate change, the geographic distributions of target marine organisms and the resultant community compositions of species may change (Badjeck *et al.,* 2010; Barange *et al.,* 2014). Social processes like economic demand, geopolitical instability, and technological innovations can also influence fishers' target species or fishing success. Adapting to these processes helps fishers avoid becoming vulnerable to losses in their livelihoods and income.

Adaptive capacity from a livelihoods perspective contends that diversification is an important strategy for increasing options and flexibility to respond to disturbances and maintain income (Allison and Ellis, 2001; Marschke and Berkes, 2006; Finkbeiner, 2015). In fact, the concepts of diversification and turnover in fisheries have long been considered key components of social-ecological resilience (Cline *et al.*, 2017). Diversifying a harvest portfolio, or the group of species caught, can alleviate economic hardships and enhance fishers' abilities to cope with idiosyncratic risks in specific fisheries (e.g. fishery closures, decreased demand, and seasonality; Kasperski and Holland ,2013; Stoll *et al.,* 2017; Oken *et al.,* 2020). Although specializing can be lucrative, it is highly risky to lose flexibility in the event that the fishery were to crash (Steneck *et al.*, 2011). In particular, a diverse portfolio of species whose abundances are uncorrelated or disassociated from one another throughout time should lower a fisher's risk by providing a steadier, less variable income (Kasperski and Holland, 2013; Cline *et al.,* 2017; Stoll *et al.,* 2017). Knowledge of the diversification and synchrony of fishing portfolios is therefore a fundamental step toward characterizing fisheries' potential adaptive capacity. Adaptive capacity can vary at the scales of individuals, households, communities, states, and nations (Siders, 2019). Consequently, being able to characterize the portfolios of fishing communities or port groups is useful when strengthening regional policies that target enhanced adaptive capacity of fisheries livelihoods.

Network theory is a prominent approach for analyzing the vulnerability (or resilience more broadly) of human–natural systems (Janssen and Ostrom, 2006; Baggio *et al.,* 2016; Levin, 2019). Networks represent systems in terms of their individual components (i.e. nodes) and their interactions with each other (i.e. edges or links). Further, a network analysis approach enables the assessment of important system characteristics by examining the network's topology. Recent studies have applied networks to livelihoods research. For example, connections between occupations like farming, fishing, and ecotourism can be analyzed with networks to understand how people diversify their livelihoods (Cinner and Bodin, 2010). A rich body of literature specifically examines fisheries livelihoods using various network approaches (Dee *et al.,* 2017; Beaudreau *et al.,* 2018, 2019; Fisher *et al.*, 2021). Yletyinen *et al.* (2018) characterize a social–ecological network based on fishing strategies and trophic linkages (Yletyinen *et al.*, 2018). Other studies examine adaptation by creating cross-fisheries participation networks between various "métiers," or fishing strategies based on compositions of gear types and species compositions (Fuller *et al.,* 2017). Similar studies have constructed networks based on how fishers connect multiple permits (Addicott *et al.*, 2018) or species landings (Kroetz *et al.,* 2019), which is useful for exploring fisheries spillover, or how fishers may redistribute their fishing effort into other fisheries. Networks are useful for examining community-level adaptation since they can elucidate connections at smaller individual-level scales as well as the overall properties of the social–ecological system.

Here, we construct fisheries connectivity networks to describe how fisheries are connected through regional catch portfolios and timing of landings. Our networks characterize communities' fishing portfolios and apply network theoretic metrics to measure how synchronous or asynchronous the species landings are. Network theoretic metrics such as edge density and modularity (Newman, 2003; Janssen and Ostrom, 2006) relate the network's topology to the timing of landings, where asynchronous portfolios are represented by highly dense or less modular networks. In this study, we consider potential adaptive capacity to be higher when fishers have access to asynchronous fisheries that complement each other.

Methods

SSFs in the Baja California Peninsula (BCP), Mexico, are used as a case study for fisheries connectivity analysis to understand community-level harvest portfolios and potential adaptive capacity. We focused on this region because it supports productive and diverse SSFs. Fisheries landings ticket data reported to fisheries offices around the Peninsula were used to create fisheries connectivity networks. Regional values and linear models elucidated spatial and temporal trends in portfolio diversity and network metrics. These landings summaries were used to determine how diversification and network structure changed over the 2001–2017 time period in each region.

The BCP is part of the Northwest Mexico region that contributes nearly half of the national fisheries production (Cisneros-Mata, 2010). Its two states, Baja California and Baja California Sur, have abundant and diverse SSF communities for which fishing is central for their livelihood, cultural identity, and food security (Lluch-Cota *et al.,* 2007; Pellowe and Leslie, 2017; Giron-Nava *et al.,* 2019). SSFs typically operate using pangas, small outboard motorboats (Pellowe and Leslie, 2017), and a variety of gear to target various species including finfish, mollusks, crustaceans, and elasmobranchs (Finkbeiner, 2015). As a whole, Mexican SSFs produce nearly the same volume of food for human consumption as the industrial sector while employing many more people (Cisneros-Montemayor and Cisneros-Mata, 2017). Despite their benefits, several factors threaten SSFs here, such as overfishing, shifting ocean regimes, and lack of enforcement and government support (Lluch-Cota *et al.*, 2007; Cinti *et al.,* 2010; Espinoza-Tenorio *et al.,* 2011).

SSFs in the BCP region commonly diversify their catch portfolios as a risk-reduction strategy (Sievanen, 2014; Finkbeiner, 2015). Previous studies have noted the difficulties with characterizing SSFs here given the diversity of species that they typically harvest (Leslie *et al.,* 2015), yet this information is critical for promoting resilient multi-species fisheries. The harvesting patterns of fishing communities around the BCP are highly variable, with dozens of fisheries operating at different times and places due to various ecological and social conditions. Ecologically, both coasts of the Peninsula support high levels of biodiversity and fisheries production but are driven by different physical and oceanographic processes (e.g. primary productivity and sea surface temperature). Socially, there are two primary types of fisheries governance: fishing cooperatives with fishing territories or permits and individuals using permits and patron-client relationships (Cota-Nieto *et al.*, 2018). Fisheries management also varies by state, since the National Commission of Fisheries and Aquaculture (CONAPESCA) establishes federal fisheries policies such as gear restrictions and catch quotas, which are then allocated to states who have some flexibility to operate within these guidelines (McCay *et al.,* 2014). Social–ecological variations partially affect when, where, and which species can be harvested. Our analysis takes a regional perspective of fisheries connectivity to examine broader-scale spatial variations in portfolios and potential adaptive capacity around the Peninsula. Temporally, seasonal portfolio diversification around the BCP is relatively well-documented (Sievanen, 2014; Pellowe and Leslie, 2017; Gonzalez-Mon *et al.,* 2021) compared to interannual portfolios despite longer-term influences on fisheries like El Niño and La Niña oscillations (Lluch-Cota *et al.,* 2010; Frawley *et al.,* 2019a), resource degradation, and management regimes (Espinoza-Tenorio *et al.,* 2011). Therefore, we focus on interannual timescales to examine year-to-year portfolio fluctuations.

Fisheries connectivity networks were created for four regions in the BCP using an existing dataset of fisheries ticket landing reports from CONAPESCA (Ramírez-Rodríguez, 2011). These data are available online for interactive analysis at https://doi.org/10.13022/m3mw2p (Ramírez-Valdez *et al.*, 2014). Commercial small-scale and industrial fishers submit fish tickets to a fisheries office reporting the date, location, type of species caught, weight of catch, and revenue of catch. The data spans twenty-one fisheries offices in the BCP from 2001 to 2017. Data was grouped by species group, location, and year to yield annual catches of species at each location and excludes industrial fisheries, as characterized by CONAPESCA. Anchovy landings were removed because they are primarily an industrial fishery in Mexico. Algae landings were also removed since these are typically associated with algae production for agar and other non-fisheries-related uses (Vázquez-Delfín *et al.*, 2019). In total, 43 commercially landed fisheries were assessed (Table 1). It is important to note that fisheries are aggregated under the broader "General Species Name" field in the CONAPESCA database rather than at individual species levels (i.e. there are 43 general fisheries categories containing 288 scientific species names). A "fishery" in our analysis may therefore actually contain multiple species and even gear types. Seven additional offices were also removed because they did not consistently report landings over the study time period. We assigned the remaining fourteen offices to one of four regions based upon each location's state and coast in order to reflect large-scale differences in environmental conditions and fisheries management (Figure 1). Region 1 has three offices, Region 2 has six offices, Region 3 has two offices, and Region 4 has three offices.

Table 1. Fisheries used to create fisheries connectivity networks in the BCP. Names of fisheries derive from CONAPESCA's broad categorization of landings ("General Species Names"). Therefore, each fishery may contain several species. English names are translated from Spanish.

Spanish Name	English Name
Abulon	Abalone
Almeja	Clam
Bagre	Catfish
Barrilete	Skipjack Tuna
Berrugata	Gulf Croaker
Besugo	Sea Bream
Cabrilla	Grouper
Calamar	Squid
Camarón	Shrimp
Cangrejo	Crab
Caracol	Snail
Carpa	Carp
Charal	Silverside
Cintilla	Cutlassfish
Corvina	Gulf Weakfish
Dorado	Dolphinfish
Erizo	Sea Urchin
Esmedregal	Yellowtail
Jurel	Mackerel
Langosta	Lobster
Lebrancha	Mullet
Lenguado	Flounder
Lobina	Sunfish
Marlin	Marlin
Mojarra	Mojarra
Ostion	Oyster
Otras	Other
Pampano	Pompano
Pargo	Snapper
Pepino de Mar	Sea Cucumber
Pez Espada	Swordfish
Pez Gallo	Roosterfish
Pez Vela	Sailfish
Pierna	Ocean Whitefish
Pulpo	Octopus
Raya	Rays
Robalo	Snook
Ronco	Grunt
Rubio	Sea Robin
Sábalo	Milkfish
Sardina	Sardine
Tiburón	Shark
Túnidos	Tuna

For this study, fisheries connectivity represents temporal relationships between fisheries landings. Network nodes represent fisheries and edges indicate that the fisheries operate at the same time and place as one another. Fisheries connectivity networks were created for each of the fourteen offices using fisheries landings reported from 2001 to 2017, using the R package *igraph* (Csardi and Nepusz, 2006). Each network was built with a 6-year window of landings, resulting in 12 timesteps from 17 years of data (Supplementary Table S1). Undirected and unweighted edges were drawn between network nodes when the two nodes shared the same activity profiles over the 6-year timespan. Grouping at an interannual timescale aligns with our goal to examine multi-year rather than seasonal changes in fisheries connectivity.

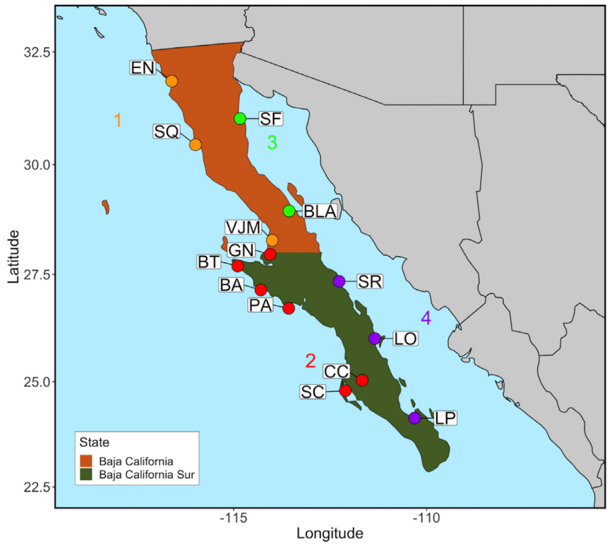

Figure 1. Map of the 14 fisheries offices in the BCP. Baja California is in orange and Baja California Sur is in green. The offices are divided into four regions based upon which state (Baja California and Baja California Sur) and coast (Pacific or Gulf) they are located. Offices are coloured to match their region. Office names are abbreviated as follows: EN (Ensenada), SQ (San Quentin), VJM (Villa de Jesus Maria), GN (Guerrero Negro), BT (Bahia Tortugas), BA (Bahia Asuncion), PA (Punta Abreojos), CC (Ciudad Constitución), SC (San Carlos), SF (San Felipe), BLA (Bahia de Los Angeles), SR (Santa Rosalia), LO (Loreto), and LP (La Paz).

Temporal relationships were calculated using Hamming distance, which is used in information and coding theory to measure differences or similarities between binary strings (Norouzi *et al.*, 2012). Here, we use the Hamming distance to measure the similarities between fisheries based on when and where they were landed. Landings data were converted from kilograms to binary strings to denote the fishery as either active or inactive at a particular time and location. A fishery's activity status was determined using a relative percentile cutoff value based on the typical landings of that fishery in a particular office location. For each species at a particular office, the 20th percentile of the landed amount was calculated and used as the cutoff value. If the value of actual landings at any given time fell below the 20th percentile cutoff, the fishery was deemed inactive and coded as 0; otherwise, it was coded as 1 and considered active. This cutoff was chosen to account for large amounts of zeroes in the dataset and to qualify a fishery as active only if it has considerable landings in a particular year. Hamming distances measured the differences between each species' landings. The distances were subtracted from 1 to convert into similarities. The resulting adjacency matrix was then transformed to a fisheries connectivity network.

Each office's fisheries connectivity network was measured for its species diversity and network metrics *edge density* and *modularity*, and then averaged across regions. Network metrics edge density and modularity evaluate different types of network arrangements: density measured connectedness and modularity measured clustering. Edge density analyzes network connectedness, calculated as a proportion from 0 to 1 based on the ratio between the actual edges and the maximum potential number given a particular network layout (Figure 2 and Table 2). Network modularity is essentially the opposite of connectedness, calculating the amount of clustering present in a network by identifying dense communities (Figure 2 and Table 2). A modularity value ranging from −1 to 1 was calculated for each network. Shannon's Diversity Index was used to measure the richness and evenness (Maurer and McGill, 2011) of species landed each year in each office. While useful for analyzing species richness and evenness, it does not convey information about species composition. To address this, we assessed which species made up the greatest proportions of catches in each region.

Diversity, modularity, and density can provide insights about the adaptive capacity of fishing portfolios. Since diverse portfolios lead to lower income risk (Kasperski and Holland, 2013), we equate more diverse networks with higher adaptive capacity. Additionally, fisheries connectivity networks are clustered together based on similar fluctuations in landings, allowing inferences about the timing of landings based on the network's topology. When fishers' target species fluctuate at different times, the species are economic complements, and fishers are highly adaptable because they can switch between species from season to season or year to year (Oken *et al.*, 2020). Because we defined nodes as inactive and not connected if species were landed at different times, less dense (or more modular) fisheries connectivity networks would represent this asynchronous, complementary scenario (Figure 2d). Conversely, stocks that fluctuate simultaneously are economic substitutes and may leave fishers vulnerable and unable to fish during times of inactivity. Because we defined nodes as active and connected if species were landed at the same time, denser (or less modular) networks reflect this latter, less adaptive scenario (Figure 2a). Therefore, we equate stronger potential adaptive capacity with higher diversity, higher modularity, and less dense networks.

We evaluated the effects of time, region, and their interaction on the two network metrics (edge density and modularity) and catch diversity using Generalized Linear Models (GLMs). It should be noted that density and modularity are expected to be inversely related since they measure opposing aspects of network connectance, with density assessing connectance over the entire network and modularity assessing connectance within network subgroups (Newman, 2003; Table 2). The diversity of catch, however, does not necessarily correlate to network topology; regions may be similar in diversity but different in modularity and density. In the GLMs, we tested for an interaction between region-specific fixed effects and a time trend to account for unobserved heterogeneity and enable comparisons of individual regional trends in diversity, density, and modularity over time. To address temporal autocorrelation from the construction of timesteps, we utilized a Newey–West estimator to account for covariance in the regression parameters. All analyses were performed in R (R Core Team, 2020) and Matlab (MATLAB, 2018).

Results

Fisheries connectivity networks varied with location and time, reflecting the heterogeneity of fishing portfolios. The number of fisheries in a region ranged from 11 to 35 with an average of 26.40 fisheries across all regions. The top fisheries varied by region, but certain fisheries such as squid and shark appeared to be relatively prominent everywhere (Figure 3). Sessile, high-value species such as lobster, clam, urchin, and oyster were more prominent on the Pacific coast (Regions 1 and 2), whereas the Gulf coast (Regions 3 and 4) recorded more mobile fish species. The average Shannon's Diversity was lower in Baja California than in Baja California Sur, with Region 1's catch considerably less diverse than the others (Table 3,

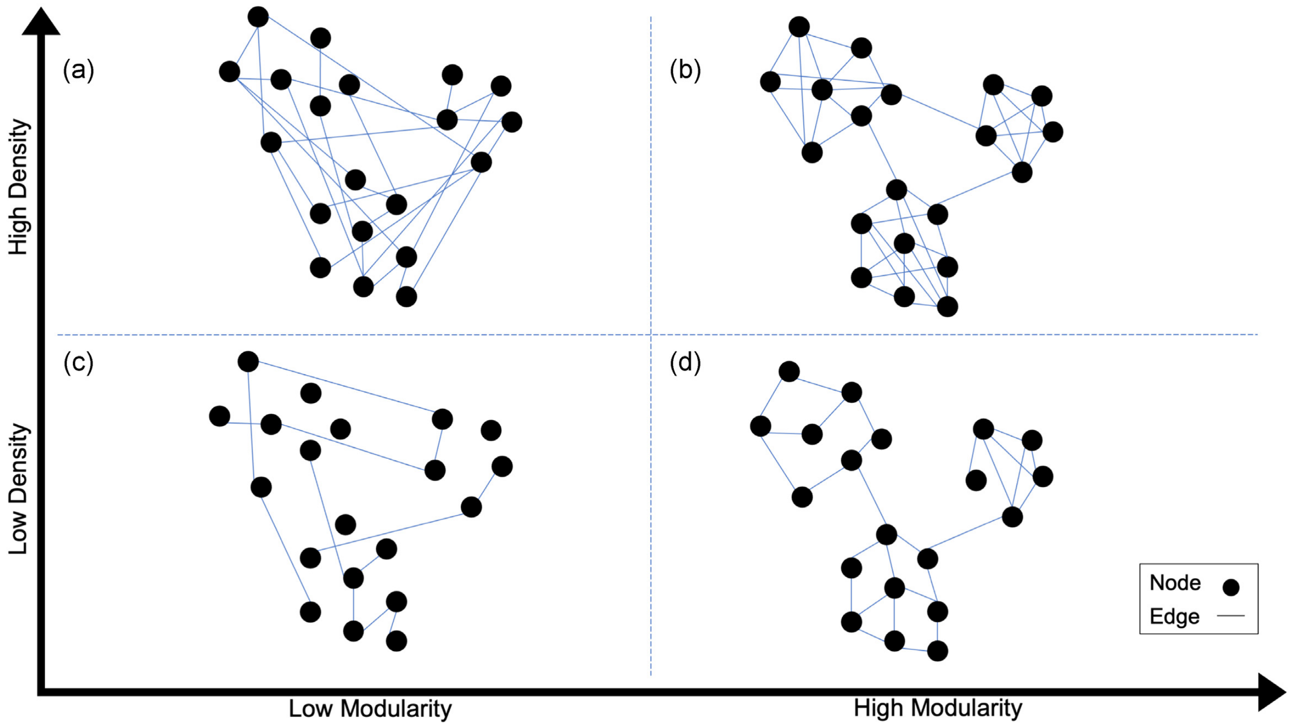

Figure 2. Networks with varying levels of Modularity (*x*-axis) and Density (*y*-axis). Modularity measures the amount of clustering and density measures the overall connectedness in a network. The networks in the left column are less modular and therefore more randomly interconnected than the highly modular networks in the right column that possess more distinct clusters. The low density networks on the bottom row have less connections between nodes than the highly dense networks on the top row. Fishing portfolios with synchronous species landings translate into less modular networks, while portfolios of distinct, asynchronous fishing activities are represented by highly modular networks. Similarly, denser networks indicate that more numerous species are in synchronicity with one another, and less dense networks represent independent, asynchronous species landings.

Table 2. Equations for network metrics edge density and modularity.

Metric	Equation	Variables
Edge density	$\frac{m}{\frac{n*(n-1)}{2}}$	m = number of edges n = number of nodes
Modularity	$\frac{1*m}{2} * \Sigma\left[A_{ij} - \frac{d_j d_i}{2}\right] * \delta_{ij}$	m = number of edges A_{ij} = value in row *i* and column *j* of the adjacency matrix d_i, d_j = degree of nodes i and *j* δ_{ij} = 1, if *i* and *j* are in the same community; 0 if they are not

$p < 0.001$) and Region 2 more diverse (Table 3, $p < 0.01$). Regions 3 and 4 had similar diversity values despite variation in the number and proportions of species, highlighting the importance of examining species proportions in catch compositions. While Region 4 was dominated by squid, Region 3 possessed more even proportions of several species including squid, croaker, mackerel, shrimp, and crab. Based solely on its low diversity value, it appears that Region 1 is less adaptive than the other regions.

Network edge density and modularity also varied regionally (Figure 4). Averaged across the entire time period, Region 4 had denser fisheries connectivity networks than the other regions. Since network modularity is partially opposite to density in terms of network connectance, we expected Region 4 to be low in modularity. Indeed, Region 4 also had the lowest modularity while Regions 1 and 2 (the Pacific coast) had the highest modularity (Table 3). Therefore, fisheries in Region 4 were caught relatively in sync with one another compared to Regions 1, 2, and 3 that exhibited more asynchronous landings. On average, then, fishing portfolio timing along the Gulf coast of Baja California allows for less complementarity in fishing activity, potentially leaving it with lower adaptive capacity than other regions studied. Although here we study regional trends, diversity and network metrics also varied greatly between individual office locations (Supplementary Figure S1).

Catch diversity and network metrics also varied through time (Figure 5). GLMs indicated that Region 1 showed a weak, non-significant trend toward less diversified fisheries ($p < 0.1$) while the Gulf coast Regions 3 and 4 showed weak, nonsignificant trends of becoming more diversified ($p < 0.1$; Table 4). Individual regional fixed effects allowed us to examine temporal trends in modularity, density, and diversity. As expected, network modularity and density had inverse linear relationships with each other in all regions over the 2001–2017 time period (Supplementary Figure S2). This is partly due to the topological relationships between modular and dense networks. For fishing portfolios, this implies that regions with high modularity and low density have different subgroups of target species that alternate over the time period, while high density implies species are being caught simultaneously. Specifically, network density in Regions 2, 3, and 4 increased over time while in Region 1 it decreased over time ($p < 0.05$). In contrast, modularity in Region 1 showed a slight, significant increase over time ($p < 0.01$) while the

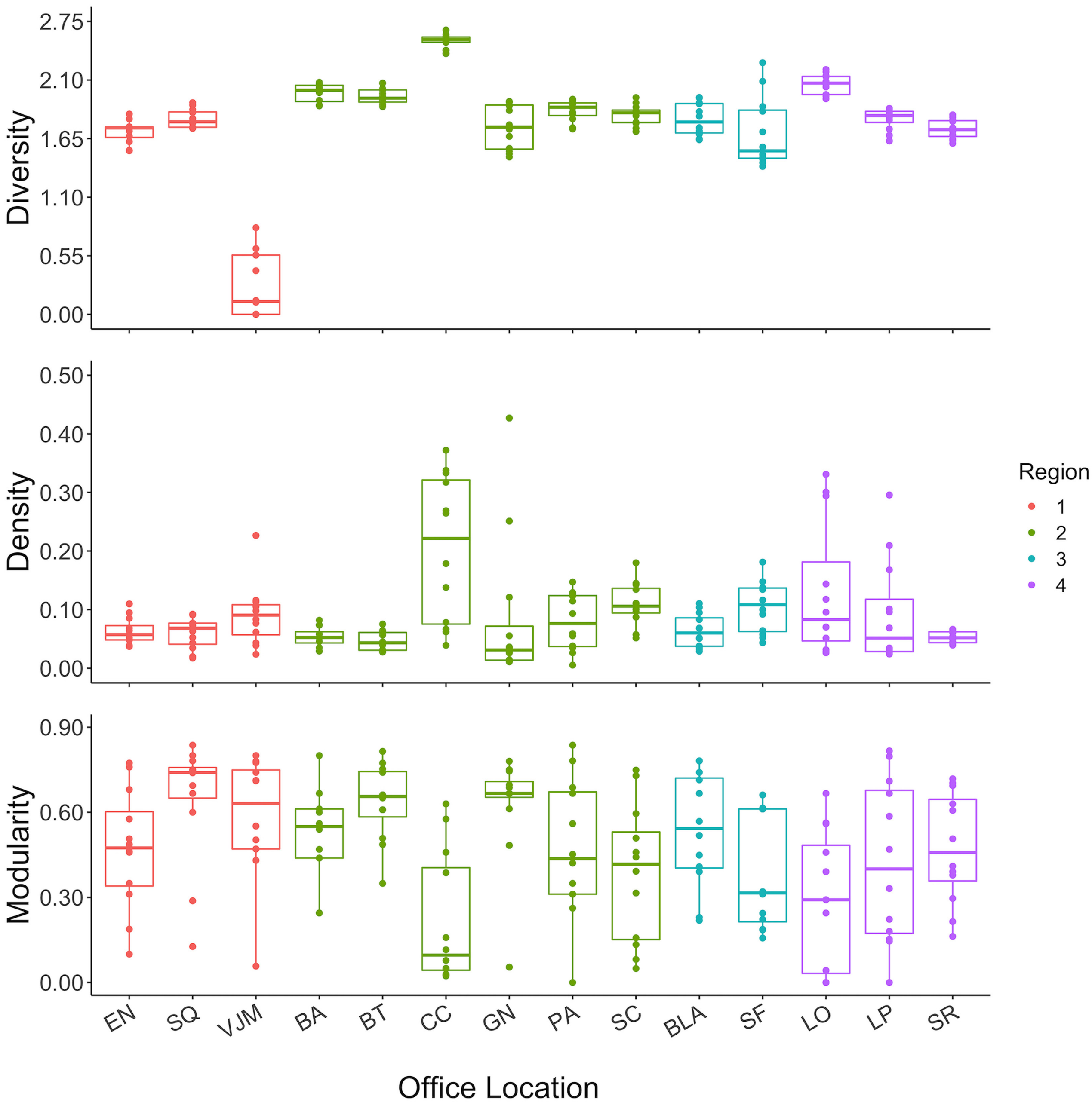

Figure 3. Boxplots of fisheries connectivity network diversity, density, and modularity values by office location. Each value is from a different 6-year window timestep from 2001 to 2017. Offices are colored by their region as shown in Figure 1. Office names are abbreviated as follows: EN (Ensenada), SQ (San Quentin), VJM (Villa de Jesus Maria), GN (Guerrero Negro), BT (Bahia Tortugas), BA (Bahia Asuncion), PA (Punta Abreojos), CC (Ciudad Constitución), SC (San Carlos), SF (San Felipe), BLA (Bahia de Los Angeles), SR (Santa Rosalia), LO (Loreto), and LP (La Paz).

other regions decreased significantly over time ($p < 0.001$). These results imply that most of the regions' fisheries connectivity networks became more connected, signaling a trend towards more synchronous fisheries landings over time (e.g. Figure 6). While temporal trends in network metrics were evident, temporal trends in diversity were insignificant (Table 4), implying that diversity of landings does not necessarily correspond with timing of landings. However, model coefficient values indicate that the directions of regional trends for diversity align with directions of regional trends for density (Table 4). This qualitative correspondence would suggest that fishing portfolios tend to become more synchronous and diverse, though we do not have quantitative, statistical support for this conclusion. Overall, Region 1 is the only region with landings that appear to be becoming more asynchronous as indicated by a positive modularity and negative density trend. From a timing perspective, this means that the fisheries portfolio in Region 1 may be increasing in adaptive capacity. However, this inference does not align qualitatively with the region's declining diversity measures, which imply a decreasing potential adaptive capacity. This diversity trend was not significant, though, and the region's low diver-

Table 3. Summary statistics for fisheries connectivity network modularity, density, and diversity at each region. Regions consist of *N* number of offices as displayed in Figure 1.

	Metric	Mean	*SD*	*N*
Region 1	Modularity	0.56	0.22	3
	Density	0.07	0.04	
	Diversity	1.27	0.75	
Region 2	Modularity	0.52	0.25	6
	Density	0.09	0.09	
	Diversity	2.04	0.28	
Region 3	Modularity	0.47	0.21	2
	Density	0.08	0.04	
	Diversity	1.76	0.26	
Region 4	Modularity	0.40	0.25	3
	Density	0.09	0.09	
	Diversity	1.91	0.20	

sity values may be due to one particular fisheries office, Villa de Jesus Maria (Figure 4). Adjusting the GLMs with the Newey–West covariance matrix estimators to account for autocorrelation did not much affect these qualitative results (Supplementary Table S2).

Discussion

To be sustainable, it is imperative for fisheries to adapt to several environmental, anthropogenic, and climatic factors that are altering fisheries landings. The adaptive responses of fishers are critical for supporting fisheries productivity and associated income and food security . There are several ways that fishers can choose to adapt based on their responses to social–ecological conditions. Knowledge about the dynamics of diverse fishing portfolios, including when and where certain fisheries are active, is crucial both for fishers navigating their own income risks and managers supporting fisheries livelihoods. For fishers, strategically diversifying one's catch with complementary, asynchronous landings can lead to a more stable income (Kasperski and Holland, 2013). For managers, strategically supporting fishing communities' diverse portfolios through time (e.g. by identifying central fisheries or reducing barriers to entry) can enhance livelihood opportunities and community-wide adaptive capacity (Oken *et al.*, 2020). This may be especially important for SSF communities that often operate complex multi-species fisheries as their livelihoods.

Combined analysis of fisheries connectivity networks and catch compositions reflect regional fishing patterns related to governance and ecology in the BCP. Large cooperatives that own territorial use rights along the Pacific coast have historically focused on high-value sessile species like spiny lobster, sea cucumber, and turban

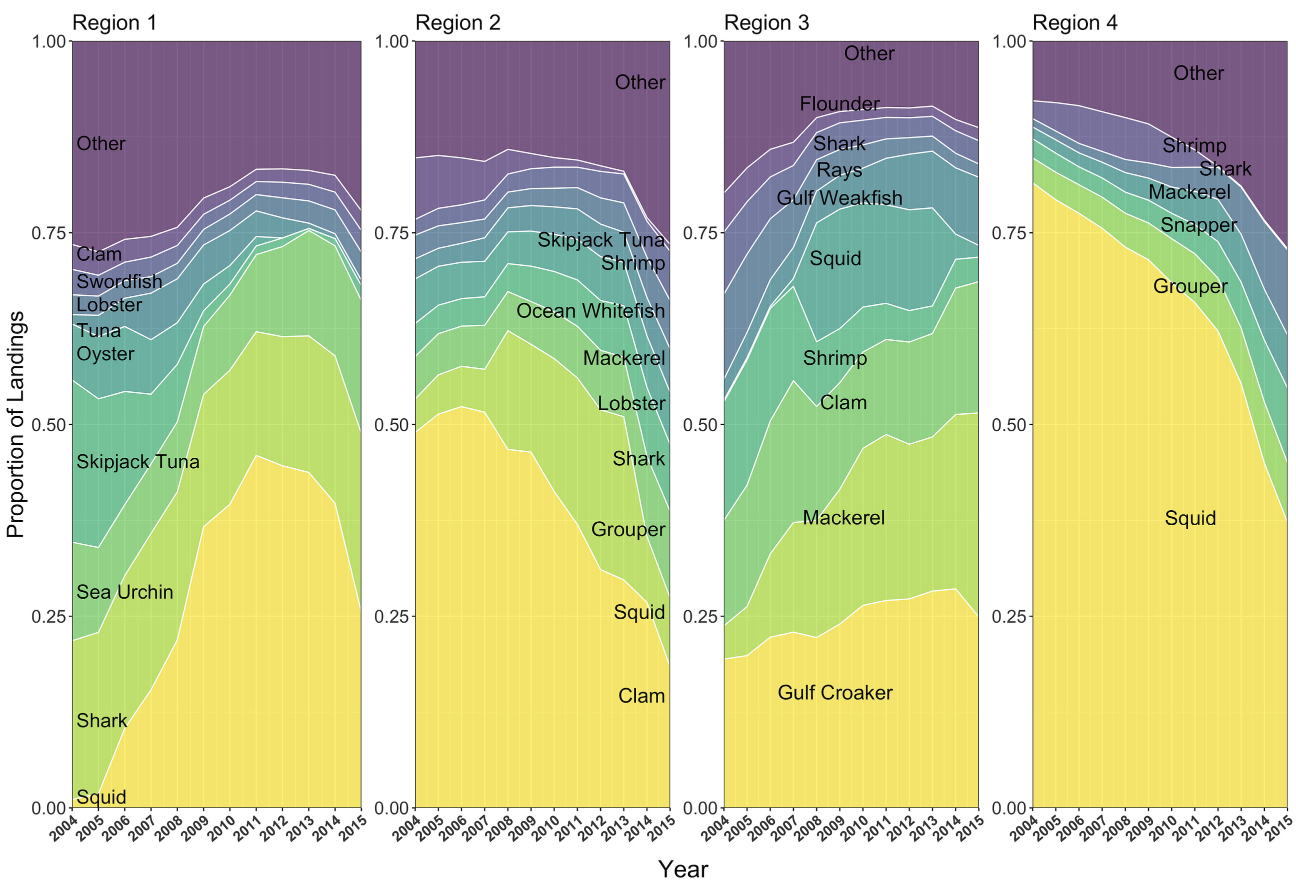

Figure 4. The topmost landed species in each region over the 2001–2017 time period. Graphs either show the 10 most common species or the species that make up approximately 90% of the catch, with species at the bottom comprising the largest proportions for that region. Remaining species are categorized as "Other." Catches were grouped into twelve 6-year timesteps that are represented by a central year along the *x*-axis (i.e. 2004 represents the 2001–2006 period, 2005 represents the 2002–2007 period, and so on). Regions are based on office locations as shown in Figure 1.

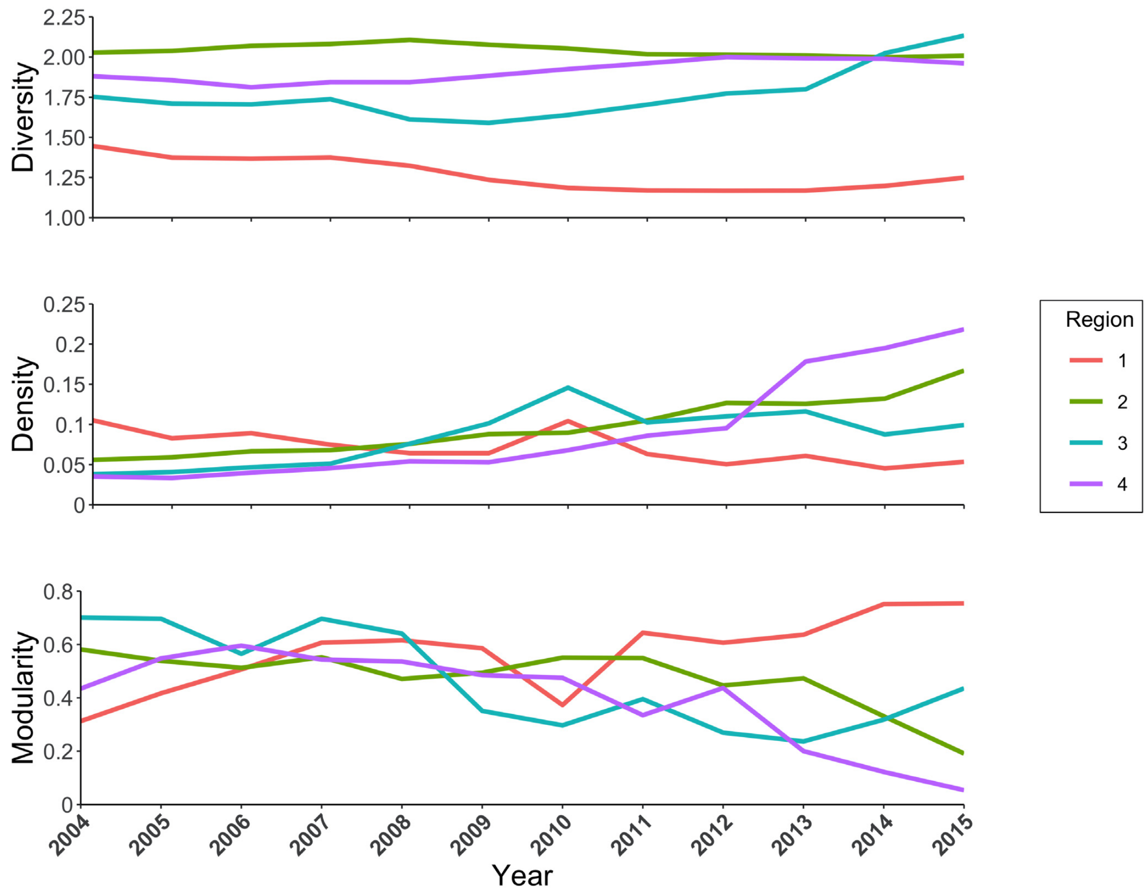

Figure 5. Regional diversity, density, and modularity values from fisheries connectivity networks from 2001 to 2017. Years were grouped into twelve 6-year timesteps to create the networks. The timesteps are represented along the *x*-axis by a central year (i.e. 2004 represents the 2001–2006 period, 2005 represents the 2002–2007 period, and so on). Lines are colored by regions as displayed in Figure 1.

Table 4. Generalized linear model results for regional time series of fisheries connectivity network modularity, density, and diversity. Regions are divided into offices as displayed in Figure 1. The table displays region fixed effects (FE) and region trends for each of the variables. Values are coefficient estimates followed by standard errors in parentheses, and significance is denoted by: $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

	Dependent Variables		
	Modularity	**Density**	**Diversity**
Region 1 (FE)	0.30*** (0.054)	0.09*** (0.020)	0.87*** (0.07)
Region 2	0.19** (0.005)	−0.06* (0.025)	0.25** (0.08)
Region 3	0.25** (0.08)	−0.06* (0.09)	0.08 (0.11)
Region 4	0.21** (0.08)	−0.10*** (0.005)	0.16 (0.10)
Region 1 Trend	0.02** (0.007)	−0.004* (0.003)	−0.02 (0.01)
Region 2 Trend	−0.04*** (0.009)	0.01*** (0.001)	0.02 (0.01)
Region 3 Trend	−0.05*** (0.01)	0.01* (0.02)	0.03 (0.02)
Region 4 Trend	−0.05*** (0.01)	0.02*** (0.004)	0.02 (0.01)
Observations	168	168	168
Log Likelihood	82.65	243.49	33.19
AIC	−147.29	−469.98	−48.38
Family, Link	Gaussian, Identity	Quasibinomial, Logit	Gaussian, Log

snail (Cunningham *et al.*, 2013; Aburto-Oropeza *et al.*, 2017). Other governance arrangements include cooperative permit-driven fishers or patron-client relationships. The Pacific coast ecosystem is characterized by temperate kelp forest habitat with relatively little interannual variation (Checkley and Barth, 2009). Conversely, fishers on the Gulf coast primarily operate in a patron-client fashion where fishing is more heterogeneous across species groups, including squid, shrimp, clams, snails, croakers, mackerels, and snappers (Cisneros-Mata, 2010). Supporting this, the Gulf is a highly biodiverse semi-enclosed sea area that is regulated by seasonal and tidal influences and aggregates pelagic biomass (Lluch-Cota *et al.*, 2007; Checkley and Barth, 2009). Our analyses reflected these social and ecological variations, with Pacific coast regions catching higher proportions of clam, lobster, oyster, and other less mobile organisms, and Gulf coast regions containing more pelagic species of fishes and elasmobranchs that reflect the more complex and pelagically-dominant Gulf ecosystems (Figure 3).

Longitudinal changes in fisheries activities can also be observed through changing catch compositions and fisheries connectivity networks. For instance, historical catches of the environmentally-dependent Gulf of California jumbo squid have fluctuated with anomalous climatic and oceanographic conditions, namely the 2009–2010 El Niño that collapsed the fishery by severely decreasing population abundances and individual sizes (Frawley *et al.*, 2019b).

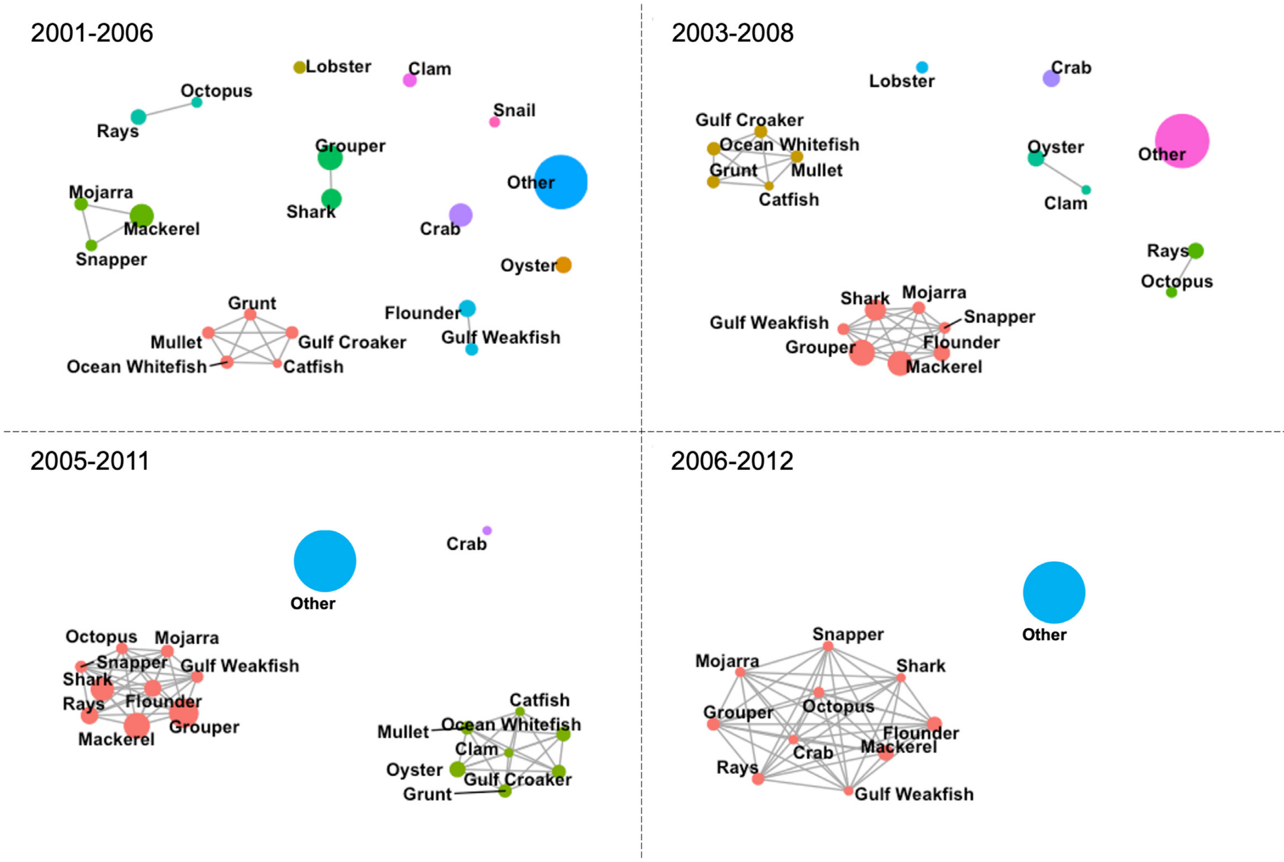

Figure 6. Example fisheries connectivity networks at four timesteps (1: 2001–2006, 3: 2003–2008, 5: 2005–2011, and 6: 2006–2012) for the office located in Tijuana, which was not included in the analysis. Each node represents a fishery and is sized according to the total weight landed at that location and timestep. The edges connect fisheries with similar fisheries activities as measured by Hamming similarities. The nodes are colored based on their modules. In this time series, network modularity decreases and density increases as the fisheries connectivity network rapidly becomes more uniformly connected. In terms of harvest portfolios, this indicates that species landings became more synchronized with one another and the adaptive capacity decreased.

During anomalously warm years, squid catch volume declines but value increases as the resource becomes scarcer (Elsler *et al.*, 2021). For most fishers, this means catching proportionally less squid and diversifying to other species. Regional catch compositions reflected this collapse as jumbo squid became less prominent in Region 3 and 4's portfolio after the year 2009 (Figure 3). Fisheries connectivity results also indicated that landings became more synchronous (i.e. more densely connected) in the Gulf during and following these El Niño years (Figure 5), potentially from a response to simultaneously fish for more species as squid became less abundant. On the other hand, Region 1 of the Pacific coast is trending towards more asynchronous and homogenous fishing portfolios despite squid still comprising a considerable portion of regional catch (Supplementary Figure S2). This may be because more moderate ocean temperature fluctuations buffered by the California Current allow fishers to continue targeting some squid with less need to diversify to other species. Importantly, social processes can also influence how fishers respond to resource scarcity. For instance, in areas of high cooperation between fish buyers, fishers may receive less value for their squid catch as buyers collude to fix prices (Elsler *et al.*, 2021). Depending on existing cooperative or competitive relationships with buyers, fishers may respond differently to squid shortages by either focusing on scarce but valuable squid or diversifying effort into other fisheries. However, despite this expected response, our analysis did not detect any major increases in portfolio diversity following the squid fishery collapse (Figure 4). Still, differing social relations may have also played a role influencing different catch compositions following environmentally driven squid declines. While direct recovery of such an environmentally-dependent fishery such as squid may be difficult with long-term ocean changes, fisheries managers could prioritize the productivity of secondarily important fisheries that fishers diversify into as a result of squid fluctuations and new policies could discourage buyer manipulation of price points. Future work to understand what type of management strategies can help recovery of fisheries like jumbo squid considered here will be increasingly important under climate change.

Fisheries connectivity networks can be useful for understanding complex multi-species fisheries, which is a central tenet for ecosystem-based fisheries management. These networks can clarify combinations of synchronous and asynchronous species that support communities over time. This approach might be particularly suitable given the complex multi-species nature of many Mexican SSF communities. Finfish permits, for instance, are broad and often allow non-selective gear, meaning that a wide range of species are landed under these permits (Cartamil *et al.,* 2011; Ojeda-Ruiz *et al.,* 2019). Fisheries connectivity networks can be used to clarify the species landings within these broad fisheries permit groups to evaluate complementarity of fishing practices with an eye to toward bolstering fishers' adaptive capacity. Additionally, a key property of fisheries connectivity networks is that they connect species that may not be connected ecologically (Fuller *et al.*, 2017). As such, they can be useful for studying fisheries spillover that may occur if management or environmental factors impede access to primary target species, potentially forcing fishers to adjust their fishing strategies and portfolios (Pinsky *et al.*, 2013; Rogers *et al.,* 2019). For example, many BCP shark fisheries are declining from overfishing, and it has been suggested that fishing effort be redirected to certain more valuable fishes and invertebrates whose abundances are synchronous with existing shark fishing effort (Cartamil *et al.*, 2011). Fisheries connectivity networks can help confirm this or identify similar complementary opportunities to sustain fisheries income. Future work could explore spillover pathways and the factors shaping portfolios, such as gear, permits, product value, or the environment. Clarification of how and why portfolios change can help managers better understand fishing pattern dynamics to build sustainable fisheries.

Fisheries connectivity networks contribute to vulnerability and adaptation research in coastal livelihoods. Many studies have applied portfolio theory to multispecies stocks and life history stages to enhance fisheries resilience (Edwards *et al.*, 2004; DuFour *et al.,* 2015; Jin *et al.,* 2016). Fisheries connectivity adds to this literature by using networks to analyze the covariance of portfolios and relating it to economic resilience through the ideas of complements and substitutes. Fishers who switch between multiple species throughout the year depending on the season have an asynchronous fishing portfolio with many complements. Conversely, fishers targeting species whose abundances are synchronized have many substitutes at any given time, but risk not having reliable sources of fisheries-related income during the off-seasons. While a synchronous portfolio can allow for rapid income accumulation over a short time period, an asynchronous portfolio may better mitigate risks associated with long-term income stability. We interpret networks with many substitutes (high density networks) to be more vulnerable, and those with many complements (high modularity) to be less vulnerable. However, one could argue that ideally networks would have both high density and high modularity, so that a community has many substitutes within years as well as complements across years. Our fisheries connectivity approach explores these ideas of using networks to interpret the temporal structures of community fishing portfolios. Future work to explore the relationships between portfolio timing and diversity across seasonal, interannual, and other temporal scales, and direct empirical measures of adaptive capacity remains an important area of inquiry. Similarly, fisheries connectivity adds to our understanding of social–ecological systems by assessing complex harvesting patterns. It can also contribute to the sustainable livelihoods approach, a framework that seeks to support policy development by recognizing the seasonal, spatial, and adaptive complexity associated with fishing livelihoods (Allison and Ellis, 2001; Schuhbauer and Sumaila, 2016). Incorporating fisheries connectivity with these ideas could be useful for characterizing the economic viability of SSFs. The place-based focus of our approach here enables us to account for regional variations in ecology and management to identify priority fisheries in each geographic area.

The fisheries connectivity analysis presented here could be used to complement other studies of adaptation to lead to a more robust understanding of adaptive capacity. Common adaptations besides diversifying include increasing fishing effort, changing gear types, moving fishing sites, temporarily suspending operations, and/or quitting fishing altogether (Cinner *et al.*, 2008; Yletyinen *et al.,* 2018). Accounting for these behaviors would help further clarify coastal communities' full range of abilities to cope with change. Each strategy has tradeoffs, so fishers' choices may be influenced by their goals, capabilities, and risk preferences. One study in Baja California Sur found that while diversification was important for maintaining a stable income, the ability to specialize and take advantage of opportunities is important for accumulating wealth (Finkbeiner, 2015). Consistent, predictable fishing from a diversified portfolio yields more stability, but the value of certain lucrative species can prompt fishers to engage in riskier but potentially more rewarding specialization strategies (i.e. gilded trap; Steneck *et al.*, 2011). Another common adaptation is acquiring a different job outside of fishing, or diversifying one's livelihoods. Similar to many global coastlines, Mexico's coastal economies have been transitioning away from natural-resource based livelihoods like fishing or farming and towards tourism and service industries (Gamez and Angeles, 2010). Mexican fishers also adapt spatially by migrating to new locations for days to even months at a time, often to fish for more abundant or more valuable species than are available locally. Heavily influenced by seasonal variations in fish abundances, moving between fishing spots is such an important adaptation for local fishers that there are fishing camps established to support this seasonal strategy (Sievanen, 2014). Indeed, ethnographic studies have already revealed the importance of spatial mobility, livelihood diversification, and portfolio diversification as intertwined adaptive mechanisms in Baja (Lluch-Cota *et al.*, 2007; Sievanen, 2014; González-Mon *et al.,* 2019). Alongside fisheries connectivity networks, alternative livelihoods networks (e.g. Cinner and Bodin, 2010) and spatial mobility networks could further complement our understanding of fishers' adaptations from a shared network perspective.

The goal of our study was to examine adaptive capacity through fisheries connectivity, although several challenges with measuring adaptive capacity remain, such as choices of scale, context, and drivers (Siders, 2019). In our study, we aimed to capture adaptive capacity at the scales of fishing communities and interannual timelines by measuring fisheries connectivity along the entire BCP coastline over nearly two decades. Spatially, aggregating fisheries offices by region provides insight into community-level adaptive capacity but may obscure fisheries connectivity on an individual office level, which may more accurately reflect fishers' fishing locations. Temporally, assessing annual landings is useful for measuring interannual variations but may not detect important seasonal fishing patterns in BCP fisheries. Similarly, the decision to study groups of species rather than individual species could have concealed connectivity and diversity within species groups. Higher resolution species data could be used for future studies of specific multi-species fisheries. Overall, the optimal scales to assess adaptive capacity through fisheries connectivity might still be unknown, and future work may adjust analytical scales for the appropriate context.

Beyond Mexico, most developed and developing countries maintain databases of regional fisheries landings. Though the CONAPESCA dataset in our study and those elsewhere have limitations, network analysis of the spatiotemporal covariation in landings across species still allows inferences about potential adaptive capacity for fishing communities. In turn, such insights about potential adaptive capacity can increase our understanding and prediction of vulnerability of complex social–ecological systems to climate change and other perturbations. As global pressures on SSFs intensify, it is becoming ever more important to seek an understanding of how risks propagate through the complex social–ecological networks that actors are embedded in, and to discover the long-term ability of communities to maintain (individual and collective, and economic and ecological) well-being in the coming decades.

Data availability statement

The data underlying this article were provided by dataMares by permission. Data will be shared on request to the corresponding author with the permission of dataMares.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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