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Small-scale fisheries around the world are increasingly facing pressures from a range of environmental, economic, and social sources. In order to sustain the societal benefits of small-scale fisheries, it is imperative to understand how fishing communities adapt to disturbances. Fishermen often catch multiple different species as an adaptation technique because diversifying one's harvest portfolio like this creates multiple sources of income in case one species becomes unavailable. Here, we apply fisheries connectivity network analysis to characterize the harvest portfolios and timing of landings of dozens of small-scale fisheries in the Baja California Peninsula, Mexico. We found that network metrics like modularity and density varied by region and through time. The Pacific coast of Baja California displayed increasingly modular fisheries connectivity networks over the study period. This indicates that fisheries landings became less covaried with one another, implying an increased capacity to adapt by targeting species that are uncorrelated with each other through time. The remaining three Regions showed the opposite trend, where the covariance between fisheries increase over time. Differences in regional catch compositions also reflected

the diversity of species caught around the Baja California Peninsula. A network perspective of small-scale fisheries landings provides insight into the resilience of multi-species fishing communities.

Fisheries Connectivity Networks to Measure the Adaptive Capacity of Small-Scale Fisheries in the Baja California Peninsula, Mexico

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Keiko Nomura

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Major Professor, representing Marine Resource Management

Dean of the College of Earth, Ocean, and Atmospheric Sciences

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Keiko Nomura, Author

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

Chapter 1: Small-Scale Fisheries in the Baja California Peninsula, Mexico

Globally, small-scale fisheries comprise more than 90% of fisheries employment (Berkes et al. 2001). They also provide livelihoods and food security for millions of people worldwide (FAO 2018). Small-scale fisheries face increasing pressures from a range of environmental, economic, and social processes operating on both local and global scales (Frawley, Crowder, and Broad 2019; Kittinger et al. 2013). For instance, global market conditions can value certain species over others, and this incentivization to participate in the international seafood trade has restructured many small-scale fisheries operations (Kittinger et al. 2013; Frawley, Crowder, and Broad 2019). Similarly, many management approaches have restricted fishing portfolios (Stoll, Fuller, and Crona 2017). Further, increased uncertainty over environmental and climatic conditions threatens to make fishing communities vulnerable by altering marine species' habitat ranges (Pinsky et al. 2013; Rogers et al. 2019).

Particular threats to specific small-scale fishing communities depend on a variety of social-ecological factors. Small-scale fisheries operating in tropical or semi-tropical environments are thought to be especially vulnerable (Allison et al. 2009; Badjeck et al. 2010). Their susceptibility to sea level rise, ocean warming, and extreme weather events puts their fishing grounds and infrastructure at risk. These tropical small-scale fisheries are also increasingly incorporated into global institutions and trade networks (Crona et al. 2016). Typically combined with a high resource dependence and low governance capacity, small-scale fisheries and those who rely on them can be highly vulnerable.

Small-scale fisheries in Baja California and Baja California Sur, Mexico, are similarly productive yet threatened. The two states have long been major contributors to Mexico's national fisheries production. For many small-scale fishing communities in Northwestern Mexico, fishing is central for their livelihood, cultural identity, and food security. Artisanal, or small-scale, fisheries employ many more people and produce nearly comparable landings. Small-scale fishermen typically operate using pangas, small outboard motorboats that are 6 to 8 meters in length (Pellowe and Leslie 2017). They target a range of species including finfish, molluscs, crustaceans, and elasmobranchs using diverse gear types (Finkbeiner 2015). Commercial fisheries tend to focus on sardines, tuna, and shrimp, and land much higher amounts of these species than their small-scale counterparts. However, as a whole, artisanal fisheries produce nearly the same amount volume of food for human consumption as the industrial sector (Cisneros-Montemayor and Cisneros-Mata 2017). Despite this, small-scale fisheries have received relatively little attention from the federal government compared to industrial fisheries (Cinti et al. 2010; Sievanen 2014).

Baja is a dynamic location with a variety of environmental conditions and processes. The Gulf of California, also known as the Sea of Cortés, lies to the east of Baja and separates the peninsula from mainland Mexico. This eastern coast of Baja primarily consists of rocky shorelines intermixed with sandy beach stretches (Lluch-Cota et al. 2007). Along the west coast of Baja, the California Current is a primary driver of oceanographic conditions, bringing cold water from the north and facilitating upwelling along the coast. Wetlands and sandy beaches are common. The environment around the peninsula is highly variable. Weather varies between the north and south end of the peninsula. On interannual timescales, El Niño Southern Oscillation events also greatly impact Baja. Other perturbations include episodes of hypoxic waters due to upwelling events along the Pacific coast of Baja (Micheli et al. 2012).

These environmental nuances support various types of fisheries at different times and places around Baja. Fishermen in Baja react to these ocean changes by moving around and/or diversifying their fishing portfolios (Sievanen 2014; Leslie et al. 2015). Many fishermen, both small-scale and industrial, temporarily move from the Gulf to the calmer Pacific coast during the winters because the waters are not as cold and windy and the fishing is better (Sievanen 2014). The fish species also tend to be more valuable on the Pacific coast during the winter, so market forces may also be influencing fishermen's behaviors throughout the year. Another way that fishermen deal with this environmental variability is by catching several different species (Finkbeiner et al. 2015). Fishermen who diversify their catch portfolios are better prepared to adapt in the case of unexpected changes. Baja small-scale fishermen have long employed this strategy (Cisneros-Montemayor and Cisneros-Mata 2017).

History of Small-Scale Fisheries Formation

Small-scale fisheries in Baja have undergone several changes over the past century. Historically, many people in Baja make their livelihoods from the natural environment. The 1917 Constitution aimed to give Mexico's working class rights and opportunities by returning lands that had been taken from communities (Greenberg et al. 2012). It designated natural resources as publicly owned resources and maintained that these resources are to be distributed and managed by the state (Young 2001). In efforts to distribute exclusive fishing rights to fishermen, the

Mexican government decided in 1935 that all fisheries would be administered through a system of cooperatives (Frawley, Crowder, and Broad 2019). The reform encouraged more permanent development, but working conditions were still bad for Mexican fishermen.

The federal government also still continued to contract to outside developers and capitalists who could earn more fisheries profit (Mccay et al. 2013). People traveled to Baja to work in the newly established fisheries. Many of these workers came from mainland Mexico (Young 2001), and a significant portion also traveled from the United States and across the Pacific from East Asian countries to participate in the growing fisheries operations. Fishing had become a major economic driver in Baja by the 1950's (Frawley, Finkbeiner, and Crowder 2019). Amidst growing unrest, a 1960's labor movement ensured that by the 1970's, Mexican fishermen had essentially taken over fisheries operations from foreign owners. Groups of fishermen owned the fishing rights and the processing plants. This vertical integration of operations along with exclusive access rights to lobster, abalone, and other species, meant that cooperatives and the federal government were the main actors at this time. A series of laws in the 1970's solidified these cooperatives rights and encouraged participation in international markets by supporting fisheries exports (Frawley, Crowder, and Broad 2019). In 1992, sweeping reforms in Fisheries Law granted cooperatives exclusive access rights to certain species (abalone, lobster, turban snail), while also decreasing government subsidies and opening up fishing permits to private interests. This increased individuals' access to permits, and many fishermen have since begun operating through individually permitted patron-client arrangements. Both types of fisheries operations are presently common around Baja.

Current Fisheries Policies

Today, the Fisheries Law and the Regulation to the Fisheries Law are the main laws governing the use of aquatic resources in Mexico. The laws were most recently updated in 2001 and 2004, respectively (FAO 2018). A new General Law for Sustainable Fisheries and Aquaculture was passed in 2006 to replace the Fisheries Law. This new General Law reorganized federal fisheries agencies (Cisneros-Montemayor and Cisneros-Mata 2017) and provides more decision-making power to states and municipalities in an attempt to promote cooperative management among user groups (Espinoza-Tenorio et al. 2011). It also mandates periodic assessments of resources under concession and fishery management plans to include bycatch rates (Cisneros-Montemayor and Cisneros-Mata 2017).

The primary agency currently tasked with overseeing fisheries and aquaculture legislation is the Secretariat of Agriculture, Livestock, Rural Development, Fisheries and Food (*Secretaría de Agricultura, Ganadaría, Desarrollo Rural, Pesca y Alimentación,* SAGARPA) (FAO 2018). Housed within SAGARPA, the National Commission on Aquaculture and Fisheries (*Comisión Nacional de Acuacultura y Pesca,* CONAPESCA) is the administrative entity responsible for overseeing fisheries management and policy development (FAO 2018). Another body of SAGARPA is the National Fisheries Institute (*Instituto Nacional de Pesca,* INP) that is tasked with providing scientific and technical expertise regarding the sustainable use of fisheries. INAPESCA is responsible for producing the annual National Fisheries Chart (*Carta Nacional Pescaquera*), which provides stock assessment updates for fisheries in federal waters. In efforts to further decentralize fisheries management and support, there are also Regional Centers for Fisheries Research (*Centros Regionales de Investgaciones Pesqueras*, CRIPs) throughout Baja to provide smaller-scale technical support and expertise around stock management.

CONAPESCA has 21 fisheries offices around Baja that collect records of self-reported fish landings and certifies proof of product to accompany products to market (Ramírez-Rodríguez 2011). Fishermen are required by law to report their landings to their local CONAPESCA office within 72 hours of coming ashore (Espinosa-Romero et al. 2017). However, illegal, unregulated, and unreported fishing activities often result in inaccurate documentation of actual small-scale fish landings. Fishermen may fish without correct permits, use excessive or inappropriate gear, target species that are not legally in season, or engage in other types of illicit extraction activities (Espinosa-Romero et al. 2017).

Civil society conservation organizations (CSOs) including national and international non-governmental organizations also played a substantial role in advancing Mexican fisheries management (Cisneros-Montemayor and Cisneros-Mata 2017). For example, the red rock lobster fishery on Baja's Pacific coast became certified by the Marine Stewardship Council in 2004 for its ecological sustainability and role in supporting community livelihoods (Cisneros-Montemayor and Cisneros-Mata 2017). The certification has prompted increased government support to coastal communities participating in the red rock lobster fishery, resulting in infrastructure improvements like the distribution of reliable electricity, modernization of fishery processing plants, and construction of new holding facilities (Chaćon 2013).

Current Fisheries Management

Fisheries management occurs at the state level under the national General Fisheries Law (Pellowe and Leslie 2017). The law includes language to permit greater decentralization of governance on more local or regional scales to promote more place-based management, but the enacting of this law has not been fully realized yet (Pellowe and Leslie 2017). However, there is some variation in the types of fisheries governance along the coast of Baja. Two main governance arrangements include fishing cooperatives who operate under shared territorial user rights and individual fishermen who utilize permitting systems (Cota-Nieto et al. 2018). Fishermen are either affiliated with cooperatives (2 to 5-year spans) or work for private companies or fishbuyers that operate based on licenses or concessions granted per resource (5 to 20-year spans) (Ramírez-Rodríguez and Ojeda-Ruíz 2012; Finkbeiner 2015). CONAPESCA currently operates under a permitting system that requires all existing permits to be transferred to other fishermen in an effort to control the size of the fishing fleet and normalize fishing effort (Espinosa-Romero et al. 2017)Concessions may also be issued directly to cooperatives for lucrative, less mobile fisheries species such as lobster and abalone (Finkbeiner 2015), although this management style is much less common. The concessions last for 20-year periods and provide cooperatives with exclusive access rights to particular species or areas. Renewal of these concessions to cooperatives depends upon the fishermen's participation in self-governance and the status of stocks (Pellowe and Leslie 2017). Fishermen have autonomy to implement their own enforcement, monitoring, and internal decision-making around the concession.

A number of governance styles have evolved in fisheries around Baja within this management and policy framework. Patron-client relationships and fishing cooperatives are two common governance arrangements in Baja's small-scale fisheries. A patron-client relationship is a horizontal governance structure where individual fishermen work with individual fishbuyers, where cooperatives are vertically structured groups of fishermen who pool their resources to fish together (Lindkvist, Basurto, and Schlüter 2017). The Mexican government has been promoting self-governance through the formation of cooperatives since the 1930's (Young 2001; Cinti et al. 2010). Patron-client relationships were not legalized until 1947 and were less abundant. However, in 1992, constitutional reforms allowed some rights previously reserved for cooperatives to be obtained by private corporations and individuals, such as access to certain permits, loans, and subsidies (Young 2001; Cinti et al. 2010). These changes increased accessibility to permits and subsequently the number of patron-client relationships increased. It was recently estimated that approximately 30% of fishermen in Northwest Mexico operate via patron-client relationships (Leslie et al. 2015). Cooperatives tend to be found in more rural coastal communities, while patron-client relationships typically exist in areas of high population densities (Frawley, Crowder, and Broad 2019).

Patron-client relationships consist of working contracts between a fisherman and fishbuyer. Fishbuyers, also called *permisionarios*, own the permits and equipment that fishermen need to harvest, such as gear, bait, and gasoline (Cinti et al. 2010; Lindkvist, Basurto, and Schlüter 2017; Frawley, Crowder, and Broad 2019). In exchange, fishermen are obligated to sell their catches to the permit-holding fishbuyer. Patron-client relationships tend to be fairly informal and influenced by social norms, as the *permisionario* already holds the relevant permits from CONAPESCA. A major factor in PC relationships is trust. Fishbuyers take a risk by contracting with any fishermen, as the fishermen have power to cheat the fishbuyer out of the repayment of the loan or income from the catch (Lindkvist, Basurto, and Schlüter 2017). Studies from the Sea of Cortez in Northwest Mexico demonstrate that fishbuyers will often cease working with a fishermen if that fishermen behaves unreliably (Cinti et al. 2010; Leslie et al. 2015; Basurto 2016). Fishbuyers often end up working with a small group of highly reliable fishermen (Cinti et al. 2010). Notably, most *permisionarios* are not even from the local area. Because of their status as permit holders, they also often represent small-scale fisheries interests at regional and national fisheries and conservation meetings (Cinti et al. 2010; Frawley, Crowder, and Broad 2019). Neoliberal restructurings have been able to influence the roles of fishbuyers through aggregation of economic and political powers (Frawley, Finkbeiner, and Crowder 2019). In certain areas of Baja California Sur, monopolies have formed where fishermen continually work with only one fishbuyer, decreasing fishermen's abilities to negotiate prices when selling their landings (Frawley, Finkbeiner, and Crowder 2019).

Groups of fishermen also form cooperatives around Baja. Fishermen pool together their resources such as gear, vessels, permits, and processing and distribution infrastructure in order to achieve common goals. One well-known cooperative system is the Baja California Regional

Federation of Fishing Cooperative Societies (FEDECOOP) located on the Pacific coast of Baja California Sur, an area also called Pacífico Norte. FEDECOOP is known for being a long-standing group catch share arrangement between 13 cooperatives utilizing a property-based territorial use rights in fisheries (TURFs) system to collectively manage resources (Cunningham et al. 2013). The cooperatives range in size from 80 to 190 members (Cunningham et al. 2013) who operate within 10 area-based concessions along the Pacífico Norte coastline. The assemblage strikes an interesting balance between top-down and bottom-up governance by allowing local fishing communities a fair amount of autonomy to use their natural resources as they please while also imposing catch limits and other regulations from the federal Fisheries Agency (Cota-Nieto et al. 2018). The assemblage has undergone several restructurings over the past century. Throughout this time, the landscape of actors, objectives, discourses, laws, and other elements have evolved to create the fishing cooperative arrangement that we observe today.

Present day Pacífico Norte fisheries have adopted a nested co-management structure that balances top-down and bottom-up governance. FEDECOOP was created to serve as a liaison between the cooperatives and state and federal governments. FEDECOOP actively co-manages the TURF system with the National Commission on Aquaculture and Fisheries (CONAPESCA) to establish catch limits and manage fishery harvests (Cunningham et al. 2013). Entities like Mexico's national fisheries agency Centro Regional de Investigaciones Pesqueras (CRIP; Regional Center for Fisheries Science) are responsible for conducting joint scientific monitoring of the area in partnership with the cooperatives. CONAPESCA maintains a presence of top-down control by establishing overarching regulations that cooperatives must operate within. Still, in this nested co-management arrangement, fishermen retain considerable authority over the type and amount of fishing practiced within their concessions. There are even cases of federated cooperatives collecting their own scientific monitoring data to propose changes to national fisheries law (Cunningham et al. 2013). Today, the cooperatives are well-known for their sustainable fisheries management and ability to maintain local fishing livelihoods.

Conclusion

Many of the threats and challenges facing Baja's small-scale fisheries are representative of those facing small-scale fisheries globally. Mexico's fisheries are largely considered overexploited (FAO 2018). However, there are also several examples of successful fisheries governance in

Mexico. Competition with industrial fishing fleets is increasing as fish stocks decrease. As in many coastal areas globally, Mexico's coastal economy has been steadily transitioning towards the tourism and service industries and away from fishing and agriculture (Lauterio and Arizpe 2012). Mexico's fisheries have absolutely been influenced by neoliberal transformations that do not often benefit small-scale fishermen (Frawley, Finkbeiner, and Crowder 2019; Espinosa-Romero et al. 2017). Warming oceans, rising sea levels, and other effects of climate change will also pose various risks to fishermen as the viability of fish stocks is influenced by unprecedented environmental shifts.

Future fisheries management will need to acknowledge the multiple stressors that small-scale fisheries face today. Fisheries plans in Baja are shifting towards more integrated, ecosystem-based approaches. Climate change and its impacts on ocean ecosystems are now being prioritized in policy so that fisheries adaptation and mitigation measures can be implemented. There is also an acknowledgement that fisheries support human well-being, so sustaining healthy fisheries has social and cultural benefits. In addition to policy action, actual implementation needs to occur on the ground. Small-scale fisheries in Baja provide important social, cultural, and economic benefits to coastal communities in Baja and several other areas worldwide. Understanding the threats to small-scale fisheries and how to address these issues moving forward is critical to sustaining healthy human and natural well-being.

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Chapter 2: Fisheries Connectivity Networks to Measure the Adaptive Capacity of Small-Scale Fisheries in the Baja California Peninsula, Mexico

Introduction

Small-scale fisheries are ubiquitous along coastlines around the world, comprising over 90% of fisheries employment globally (Berkes 2001). They also provide livelihoods and food security for millions of people worldwide (FAO 2018). Small-scale fisheries are extremely diverse in terms of 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). Such large numbers of people are employed through small-scale fishing that governance is typically decentralized across many people (Finkbeiner 2015). Additionally, small-scale fisheries tend to be dynamic since fishermen often switch their target species, fishing locations, gear types, and other strategies in order to maintain their income. These fisheries are complex, and recent studies have prioritized the needs to understand how these resource-reliant populations may brace themselves for an evolving world in the age of the Anthropocene (Finkbeiner 2015). They are vulnerable to threats like overfishing and changing ocean conditions.

Vulnerability of human communities is defined as the susceptibility to be harmed by a given perturbation (Adger 2006). The key parameters of vulnerability of a social-ecological system are its exposure, sensitivity, and adaptive capacity (Adger 2006). Exposure is the magnitude and frequency of a perturbation, while sensitivity is the amount that the system is affected by said perturbation. Adaptive capacity counteracts these components and is defined as the ability to cope with stress (Adger 2006). The three components of vulnerability may be assessed together to come up with a single vulnerability metric, or they may be analyzed separately to investigate 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; Morzaria-Luna, Turk-Boyer, and Moreno-Baez 2014; Leslie et al. 2015; Finkbeiner 2015).

Fishermen who rely on the ocean for a living constantly adapt their fishing behaviors to weather conditions, species availability, market fluctuations, technological innovations, and policy changes (Cinner, J.E., T. Daw 2008; Yletyinen et al. 2018). This adaptive capacity is essential to lowering their vulnerability to losing income over these risks. However, unprecedented changes in global marine social-ecological systems pose novel risks to fishermen by disturbing fisheries in previously unseen ways. As ocean conditions fluctuate with unprecedented climate changes, the geographic distributions of marine organisms and the community of target species may change (Pinsky et al. 2013; Morley et al. 2018). Landings may deviate from historical landings in terms of size and composition of species, especially as climatic and anthropogenic pressures increase (Oremus et al. 2020). Social factors like economic demand, fisheries closures, and cultural preferences can also influence fishermen's fishing strategies and their target species. Such dynamics may leave fishermen vulnerable to losses in their income or livelihood options. This emphasizes the importance of adaptive capacity in responses to such changes to maintain their abilities to continue fishing for a living.

Fishermen can use many strategies to improve their adaptive capacity. Common ones are increasing their fishing effort, changing gear types, moving fishing sites, fishing for different species, temporarily suspending operations, and/or quitting fishing altogether (Cinner, J.E., T. Daw 2008; Yletyinen et al. 2018). Adaptive capacity from a livelihoods perspective contends that livelihood diversification is important for increasing options and flexibility to respond to disturbances (Allison and Ellis 2001; Finkbeiner 2015; Marschke and Berkes 2006). In fact, the concepts of diversification and turnover in fisheries have long been considered key components of social-ecological resilience (Cline, Schindler, and Hilborn 2017). Similarly, diversifying one's harvest portfolio, or the types of species one is able to fish, can alleviate economic hardships and enhance fishermen's abilities to cope with unforeseen circumstances (Cline, Schindler, and Hilborn 2017). Indeed, most fishermen harvest a variety of species to create multiple sources of income. Fishermen often gain the ability to diversify their catches by maintaining access rights to multiple species through permits, quotas, or territorial use rights. This generalist approach buffers against the idiosyncratic risks in specific fisheries (e.g., fishery closures, decreased demand, seasonality) by enabling fishermen to opportunistically switch their efforts to fisheries that are the most abundant or valuable at any given time (Cline, Schindler, and Hilborn 2017; Yletyinen et al. 2018). In particular, a harvest portfolio of species whose abundances are uncorrelated or disassociated from one another over time should provide more options for a fisherman to maintain a steadier, less variable income (Kasperski and Holland 2013; Stoll, Fuller, and Crona 2017). Conversely, fishermen who focus on a single lucrative fishery risk falling into a vulnerable "gilded trap" as they lose their adaptive capacity and become highly sensitive to any perturbations to that fishery (Steneck et al. 2011). Knowledge of the fishing portfolios of fishermen is therefore a fundamental step toward characterizing fisheries' adaptive capacities.

Network theory is becoming much more prominent for analyzing the resilience or vulnerability of natural resource-based livelihood systems (Janssen and Ostrom 2006; Baggio et al. 2016). The network approach enables assessment of social-ecological connections between (and among) resource users and the resources themselves. Conclusions about the stability of resource-dependent communities can be drawn based on the arrangement of network structure using network metrics. The interpretations of these measurements vary depending on how the network is constructed. For example, livelihoods research uses networks to examine the layout of natural resource-based livelihoods available to people. Connections between several livelihoods like farming, fishing, and ecotourism can be analyzed with networks to understand how people diversify their livelihoods in a "landscape" (Cinner and Bodin 2010). A rich body of literature specifically examines fisheries livelihoods using various network approaches. Fuller et al. (2017) creates connectivity networks between various "métiers," or fishing strategies based on compositions of gear types and species compositions, in order to illustrate cross-fisheries participation between métiers along the U.S. West Coast (Fuller et al. 2017). Yletyinen et al. (2018) use a similar approach that characterizes a social-ecological network based on switching between fishing strategies that also includes ecological linkages with target species (Yletyinen et al. 2018). Network analysis is also useful for illustrating and exploring ideas of fisheries spillover, where fishermen may redistribute their fishing effort into other fisheries. For instance, some studies have constructed networks based on how individuals connect multiple permits (Addicott et al. 2018) or reported fish landings (Kroetz et al. 2019).

Here, we create fisheries connectivity networks to describe how fisheries are connected through catch portfolios. Our approach builds upon work by Fuller et al. 2017 but differs in that we examine the network connectivity of fisheries landings via timeseries rather than via vessel participation. Network theoretic metrics such as modularity and density (Newman 2003; Janssen and Ostrom 2006) can be used to relate the network's structure to fishermen's behaviors and the vulnerability framework (Adger 2006), particularly adaptive capacity. Network modularity is essentially the opposite of connectedness and measures the amount of clustering present in a network (Figure 1). It is often used to measure a system's resilience, since a network is less likely to be disrupted if there are many separate and densely connected clusters (Newman 2003; Levin

2019). Edge density describes the overall connectedness of the network, calculated as a proportion of the maximum number of edges that could be present in a network with a certain number of nodes (Table A.1). Additionally, the diversity of components in a system also contributes to its overall resilience (Levin 1998, 1999) and, in the context of fisheries connectivity networks, informs about the diversity of catch compositions (i.e., the catch portfolio). Fishing communities' catch compositions change from year to year. This network and time series perspective can provide insight into the evolution of fishing portfolios over time and the roles of various species in small-scale fishing communities. By measuring network metrics and diversity, we quantify the structures of fisheries connectivity networks using the Baja California Peninsula, Mexico, as a case study to help understand small-scale fisheries harvest portfolios and adaptive capacities.

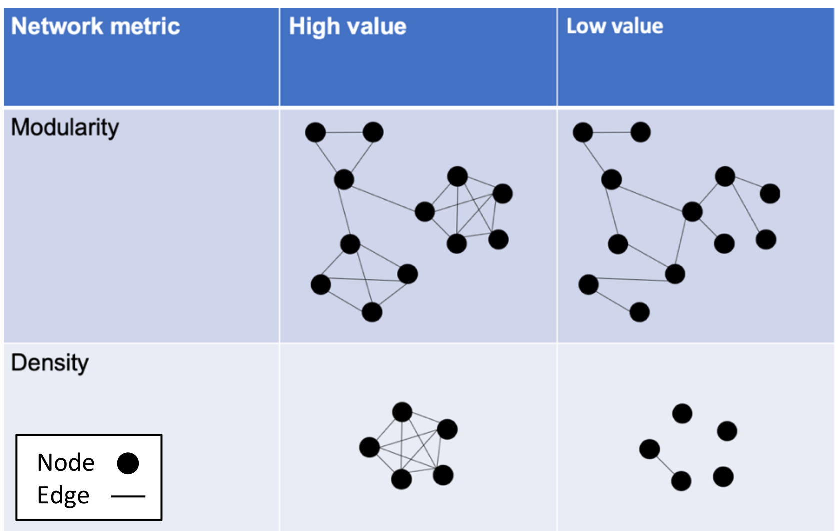

Figure 1. Example network layouts of high and low modularity and density values. A highly modular network has groups of densely connected nodes, while a less modular network is more uniformly connected. A highly dense network contains many edges while a less dense network has fewer edges.

Methods

Case Study: Baja Small-Scale Fisheries

The four states that encompass Northwest Mexico (Baja California, Baja California Sur, Sonora, and Sinaloa) contribute nearly half of the national fisheries production (OECD 2006; Cisneros-Mata 2010). Baja California and Baja California Sur comprise the Baja California Peninsula, an area that has substantial presence of diverse small-scale fisheries. For many small-scale fishing communities in Baja California Peninsula, fishing is central for their livelihood, cultural identity, and food security (Pellowe and Leslie 2017; Giron-Nava et al. 2019; Lluch-Cota et al. 2007). Small-scale fishermen typically operate using pangas, small outboard motorboats between 6 to 8 meters in length (Pellowe and Leslie 2017). They target a range of species including finfish, mollusks, crustaceans, and elasmobranchs using diverse gear types (Finkbeiner 2015). Industrial fisheries use larger vessels and tend to focus on sardines, tuna, and shrimp, landing much higher amounts of these species than their small-scale counterparts. However, as a whole, small-scale fisheries produce nearly the same amount volume of food for human consumption as the industrial sector, while also employing many more people (Cisneros-Montemayor and Cisneros-Mata 2017). Many factors threaten the sustainability of small-scale fisheries along the Baja California peninsula, such as overfishing, shifting ocean regimes, and lack of enforcement (Lluch-Cota et al. 2007; Espinoza-Tenorio et al. 2011). Despite these threats and their contributions to the national sector, small-scale fisheries have received relatively little attention from the Mexican federal government compared to industrial fisheries (Cinti et al. 2010; Sievanen 2014).

Management of small-scale fisheries occurs at the state level under the national General Fisheries Law (Pellowe and Leslie 2017). The types of fisheries governance along the coast of the Baja California peninsula varies between two main governance arrangements: fishing cooperatives who operate under shared territorial user rights, and individual fishermen who utilize permitting systems and patron-client relationships (Cota-Nieto et al. 2018). Fishermen are either affiliated with cooperatives (2 to 5-year spans) or work as individuals for private companies or fishbuyers that operate based on permits or concessions granted per resource (5 to 20-year spans) (Ramírez-Rodríguez and Ojeda-Ruíz 2012; Finkbeiner 2015). Permits may also be issued directly to cooperatives, rather than individuals, for lucrative, less mobile fisheries species such as lobster and abalone (Finkbeiner 2015), although this is much less common. These concessions last for 20-year periods and provide cooperatives with exclusive access rights to particular species or areas. Fishermen have autonomy to implement their own enforcement, monitoring, and internal decision-making around the concession.

A patron-client relationship is a horizontal governance structure where individual fishermen work with individual fish buyers, whereas cooperatives are vertically structured groups of fishermen who pool their resources to fish together (Lindkvist, Basurto, and Schlüter 2017). The Mexican government has been promoting self-governance through the formation of cooperatives since the 1930's (Young 2001; Cinti et al. 2010). It was recently estimated that approximately 30% of fishermen in Northwest Mexico operate via patron-client relationships (Leslie et al. 2015). Cooperatives tend to be found in more rural coastal communities, while patron-client relationships typically exist in areas of high population densities (Frawley, Crowder, and Broad 2019).

The Baja California peninsula's physical and oceanographic processes support highly productive and diverse fishing grounds for small-scale fisheries. The environment around the peninsula is highly variable. The Gulf of California, also known as the Sea of Cortés, lies to the east of the peninsula and separates the peninsula from mainland Mexico. This eastern coast of the peninsula primarily consists of rocky shorelines intermixed with sandy beach stretches (Lluch-Cota et al. 2007). Along the west coast of the peninsula, the California Current is a primary driver of oceanographic conditions, bringing cold water from the north and facilitating upwelling along the coast. In the Gulf, sea surface temperatures vary seasonally, with warmer waters at the gulf and mouth during the summer and cooler waters in the north and around mid-Gulf islands. Wetlands and sandy beaches are common along the Gulf. Weather around the peninsula varies seasonally due to changes in atmospheric forcing, with weak southeasterly winds in the summer and stronger northwesterlies in the winter. Rainfall primarily occurs in the summer, with tropical storms in the late summer to fall (Salinas-Zavala 1998). On interannual timescales, El Niño Southern Oscillation events also greatly impact the region by altering sea surface temperatures and rain patterns (Lluch-Cota et al. 2007). Other environmental processes include summertime episodes of hypoxic waters due to upwelling events along the peninsula's Pacific coast (Micheli et al. 2012).

The social-ecological characteristics of fishing communities around the Baja California peninsula are highly variable, with dozens of small-scale fisheries at different times and places. Given environmental variability the presence of popular target species fluctuates depending on the season and location. The types of governance (e.g., individuals or cooperatives) can also influence which fisheries are accessible via permits or profitable to target. Because the fishermen on the Baja California peninsula commonly diversify their catch portfolios by catching several different species, it is a useful case for studying livelihood diversification, particularly compared to industrial fishers who tend to specialize on fewer species (Sievanen 2014; Finkbeiner 2015). Previous studies in the region have also noted the difficulties with characterizing social-ecological systems of small-scale fisheries given the diversity of species they typically harvest (Leslie et al.

2015). In order to address this, we use a network approach to understand small-scale fisheries portfolios and adaptive capacities along the Baja California Peninsula. The network perspective allows us to view dozens of fisheries species as individual parts of a larger small-scale fisheries system.

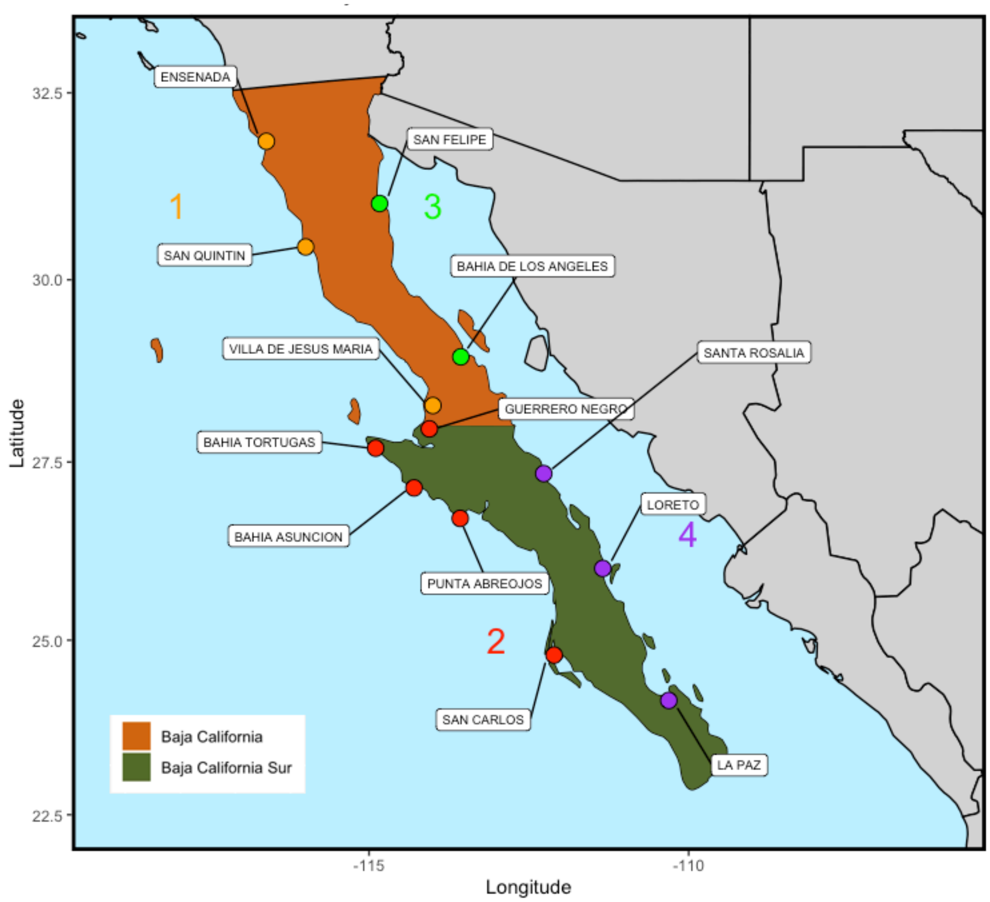

Figure 2. Map of the thirteen fisheries offices in the Baja California Peninsula used in our analysis. The offices are divided into four regions based upon which state (Baja California and Baja California Sur) and coast (Pacific or Gulf) they are located. Regions and offices are colored.

Analysis

Fisheries connectivity was quantified for thirteen fisheries offices across four Regions in the Baja California peninsula (Figure 2) using an existing dataset acquired from the Gulf of California Marine Program at Scripps Institute of Oceanography. The dataset derives from Mexico's National Commission of Fisheries and Aquaculture (CONAPESCA) and includes information about commercial fisheries landings, or the amount of fish caught (Ramírez-Rodríguez 2011). Tickets contain information on twenty-one fisheries offices in the Baja California peninsula from 2001 to 2017 and includes information such as the date, location, number of days at sea, type of species caught, weight of catch, and revenue of catch. Data was grouped by species, location, and year to yield annual catches of species at each location. Industrial fisheries were excluded from the dataset because the focus of this study is on small-scale fisheries. The data was filtered to exclude Anchovy landings since anchovies are primarily an industrial fishery in Mexico. Algae landings were also removed since these reports are often comprised of algae production for agar and other non-fisheries-related uses (Vázquez-Delfín et al. 2019). Four office locations were removed from analysis since they are located inland and do not accurately represent coastal small-scale fishing activities; four additional offices were also removed (two from each state) because they did not consistently report landings over the study time period. A total of thirteen offices and forty-three commercially landed fish species were assessed.

Temporally, we focus on annual and multiannual timescales appropriate for observing changes in harvest portfolios due to annual and decadal oscillations. Other studies of Baja California peninsula fisheries vulnerability have focused on monthly timescales to assess seasonal variability in fishing behaviors (Pellowe and Leslie 2017). While this is important to shed light on fishermen's adaptations throughout the year, here we are interested in longer-term patterns that may take several years to emerge. Geographically, both coasts of the peninsula support high levels of biodiversity and fisheries production but are driven by different environmental (e.g., primary productivity, sea surface temperature) processes. The socioenvironmental contexts along the Pacific and Gulf coasts of the Baja California peninsula present an opportunity to compare fisheries connectivity under contrasting ecological conditions but relatively coherent social systems. By looking at the regional level, we allow for spatial comparisons between the coasts.

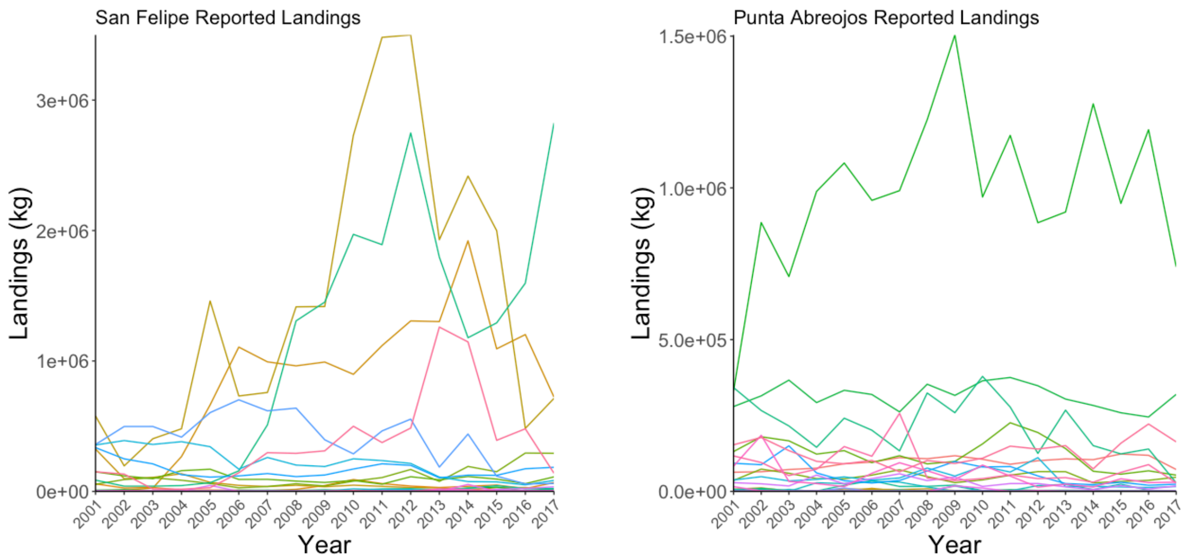

Figure 3. Examples of annual landings (kg) from 2001-2017 reported to two fisheries offices, San Felipe and Punta Abreojos. Each colored line represents a different fishery. The species composition and diversity landed at each fisheries office varies.

Networks were created for each of the thirteen offices using fisheries landings (kg) reported from 2001 to 2017. The diversity and composition of landings varies by office. Some office locations have a more even richness of species landings while other areas' catches are dominated by a particular species (Figure 3). The networks were constructed and analyzed using the R package *igraph* (Csardi and Nepusz 2006). In this study, fisheries connectivity represents temporal relationships between annual fisheries landings measured using Hamming distances. Hamming distances are used in information and coding theory to measure the differences between data (Norouzi, Fleet, and Salakhutdinov 2012); in this case, fisheries landings at a place over a particular time period. Landings data can be converted from kilograms to binary strings (i.e., 0 or 1) to denote the fishery's activity status (i.e., inactive or active) at that time and location. To determine the activity status, the 20th percentile of the number of kilograms landed was calculated and used as a cutoff value for each species. If the value of actual landings fell below the 20th percentile cutoff, the fishery was deemed inactive and coded as 0; if the landings exceeded the cutoff value, the fishery was considered active and coded as 1. Fisheries connectivity networks were constructed out of these fisheries activity data by measuring Hamming distances between each species. All Hamming distance values were subtracted from 1 to convert the distances into similarities. The resulting adjacency matrix was then converted to a network. The network nodes represent fisheries and the edges indicate the similarity between fisheries activity statuses at particular time and region. In other words, fisheries that are active and inactive at the same location and years will be connected in the network as nodes. Edges in the networks were undirected and unweighted as they represent a mutual similarity between fisheries activities. Each network was built using 5 years of activity status data, resulting in 12 networks created from 17 years of fisheries landings per office. Examining network topologies through these timesteps helps us understand changing fishing portfolios over the 2001-2017 study period (Figure 4).

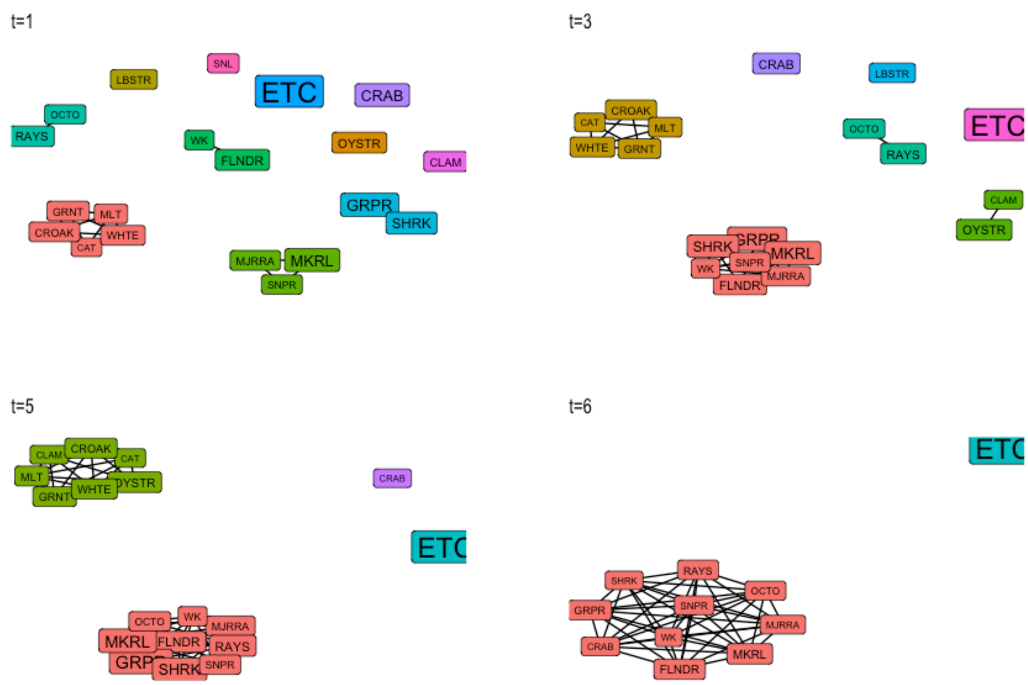

Figure 4. Fisheries connectivity networks at four timesteps (t=1, 3, 5, 6) for one fisheries office, Tijuana. Each node represents a fishery and is sized according to the total weight landed at that location and timestep. The edges connect fisheries with similar fisheries activities as measured by Hamming distances. The nodes are colored based on their clusters, or groups of more densely connected fisheries. In this time series from timestep 1 to 6, network modularity is rapidly decreasing and density is increasing as the fisheries connectivity network becomes more uniformly connected. At timestep 1, fisheries activities are more disjointed from each other, whereas most of the fisheries have identical activities in timestep 6 (except for "Etc").

Network metrics modularity and density were measured from the fisheries connectivity networks. Each metric represents a different arrangement of fisheries connectivity networks, and it is important to interpret these measures within the context of our specific network design. Here, we use modularity as a proxy for socioeconomic adaptive capacity, as it essentially separates groups of fisheries based on when they are landed. A modularity value ranging from -1 to 1 was calculated for each network and nodes were assigned to clusters. A highly modular fisheries connectivity network contains many clusters of densely connected fisheries, while one with low modularity would have more uniformly connected fisheries. Because fisheries nodes within clusters exhibit similar activities to each other through time, a more modular network means that there are several different fisheries activities profiles, implying higher adaptive capacity. Network density ranges from 0 to 1 and measures the proportion of edges in the network. A highly dense fisheries connectivity network is a network with more uniformly connected nodes. High density indicates that several fisheries are active at the same time and, which would suggest a lower ability to cope. Looking at time series of network metrics allows us to understand how these fisheries interactions evolved over time.

In this study, we determine adaptive capacity to be equated with scenarios where fisheries are active opposite of each other. This lines up with research stating that fishing portfolios made up of species whose abundances are uncorrelated with each other reduce a fisherman's overall risk (Kasperski and Holland 2013; DuFour et al. 2015). However, an argument can also be made for the opposite interpretation. Scenarios where fisheries landings fluctuate with one another (i.e., a more uniform fisheries connectivity network with low modularity) offer more diversity at specific points of time. We decide to go with the former. Additionally, while we equate diversity with higher adaptive capacity for this study, there are certainly instances where this is not the case, such as in a fishing down situation (Sala et al. 2004). Signs that an ecosystem has been fished down include a loss of top predators and biodiversity (Myers and Worm 2003; Pauly et al. 1998). In cases where fishermen do not have options to catch their typical target species, they may target a wide diversity of species in order to cover their losses. There are also tradeoffs associated with diversification or specialization. Diversification is important for risk mitigation, but specialization is important for wealth accumulation and poverty reduction (Sievanen 2014). Therefore, diversification may not always be advantageous or indicative of adaptive behaviors, although we conceptualize it as such. To measure diversity associated with each network, we applied a Shannon's Diversity Index to the landings data.

Time series of network metrics and diversity were created for the 13 fisheries offices and then grouped into four regions based on their locations in Baja California or Baja California Sur and on the Pacific or Gulf coast (Figure 2). Region 1 has three offices, Region 2 has five offices, Region 3 has two offices, and Region 4 has three offices. Regional trends in fisheries networks and diversity were compared using Generalized Linear Models (GLM), Locally Estimated Scatterplot Smoothing (LOESS), analysis of variance (ANOVA), and Tukey-HSD tests to test for spatial differences in trends of fisheries connectivity networks and diversity. All analyses were performed in R (R Core Team 2020) and Matlab.

Results

Changes in fisheries connectivity networks indicate changes in the timing of fisheries activities. More dense fisheries connectivity networks mean that fisheries are active at fewer times, while more modular networks mean that fisheries are active at more numerous times. Because areas with more times to fish at should have a higher adaptive capacity, more modular networks represent areas of higher adaptive capacities.

The network metrics vary by location and through time (Figure 5). The average modularity and density values across all offices were 0.46 and 0.093, respectively. Regions 1 and 2 (Pacific coast) have the highest modularity values around 0.49, while Region 3 is approximately 0.45 and Region 4 is low around 0.41 (Table A.2). This means that Regions 1 and 2's networks contain more numerous separate clusters, and therefore more fisheries with distinct activities profiles; this would indicate a higher adaptive capacity. Regions 1, 2, and 3 have average density values around 0.09, while Region 4 is the highest at 0.11. This result indicates that Region 4's fisheries are more uniformly connected than the other Regions, so fisheries are landed at the same times in Region 4, implying a lower adaptive capacity.

The average Shannon's Diversity Index (Herfindahl-Hirschman Index) for all regions is 1.72. The average Shannon's Diversity Index value is the highest for Region 2 at 1.94, followed by 1.91 for Region 4, 1.76 for Region 3, and 1.27 for Region 1. Baja California Sur therefore had a more diverse catch portfolio than Baja California. It should be noted that Shannon's Diversity Index is a useful measure of species richness and evenness, but it is difficult to compare communities that vary greatly in richness. For instance, Regions 3 and 4 have similar Diversity values despite the amount and spread of species (Figure 6). It also does not convey information about the actual species composition. To address this, we also assessed the top most landed fishery in each Region. The top fisheries varied by Region, but certain fisheries such as squid and shark appear to be prominent in all regions (Figure 6). Diversity of an office does not necessarily relate to its network modularity or density. Offices or regions may have similar diversity measures but different modularity and density values.

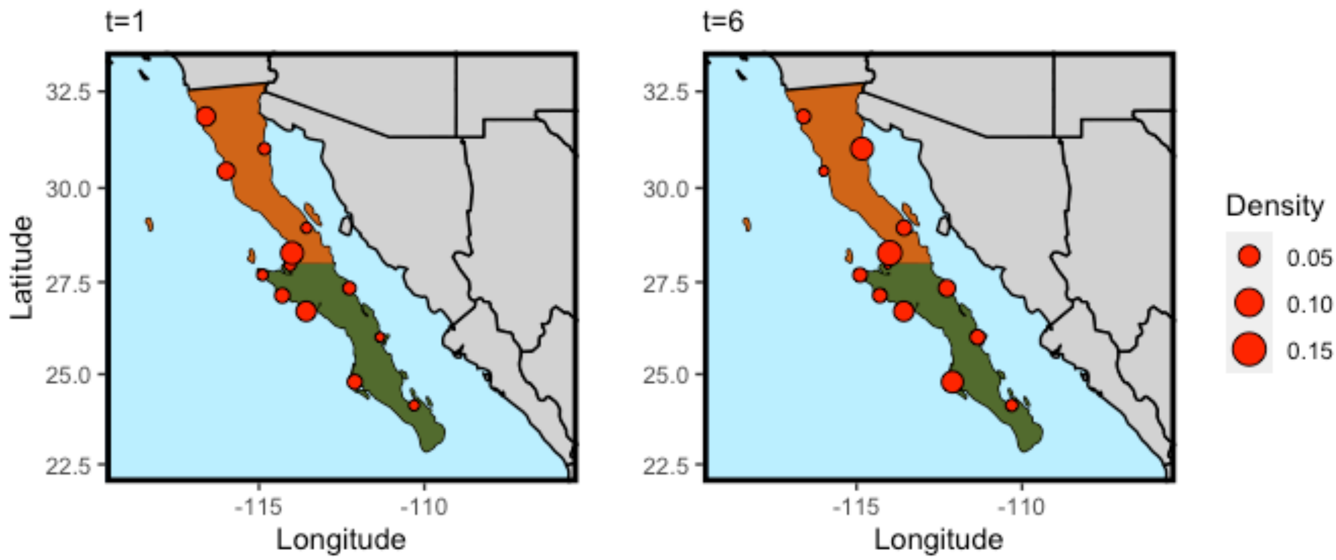

Figure 5. Map displaying spatial and temporal variation of network density from fisheries connectivity networks at Baja fisheries offices at two timesteps, t=1 and t=6. Larger circles indicate larger density values.

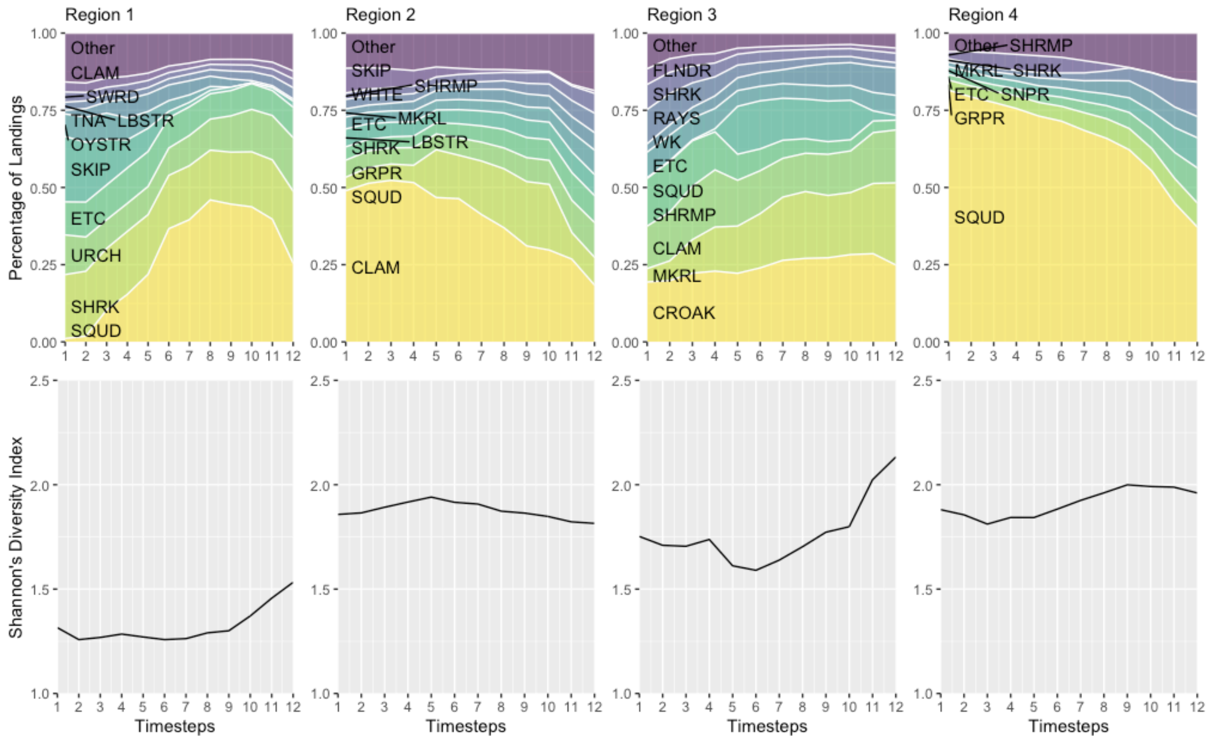

Figure 6. The top most landed species and the overall Shannon's Diversity Index of each region's catch compositions by weight (kg). The remaining species are categorized as "Other." The landings data was smoothed over a 5-year window to match the timescales of the fisheries connectivity networks created.

Generalized linear models (GLMs) were fit to the three regional timeseries of modularity, density, and diversity (Figure A.2, Table A.3). In all regions, network modularity and density had inverse linear relationships with each other. Region 1 increased in Modularity over time while the other regions decreased. For Density, Regions 2, 3, and 4 increased while Region 1 decreased. Lastly, Shannon's Diversity Index slightly decreases over time in Regions 1 and 2 and increases in over Regions 3 and 4, though the significance is weak. The network modularity and density results imply that Region 1 became more adaptive while the other Regions decreased. However, the diversity values indicate that Region 1 became less adaptive while Regions 2 and 3 became more adaptive. Smoothed local regressions (LOESS) were also created for all three timeseries in order to elucidate trends not captured by the parametric GLM approaches (Figure 7). They show similar trends to the GLMs and confirm that high density appears to line up with low modularity.

The linear trends in network and diversity metrics were compared across Regions using ANOVAs and Tukey-HSDs post-hoc tests (Table A.4 and Table A.5). The ANOVA tests indicated there are significant differences between Regions for all of the variables – modularity, density, and diversity. A Tukey post-hoc test tested for pairwise differences between the Regions. It revealed that Region 1 is significantly different from each of the other regions for Diversity ($p < 0.0001$, Table A.5).

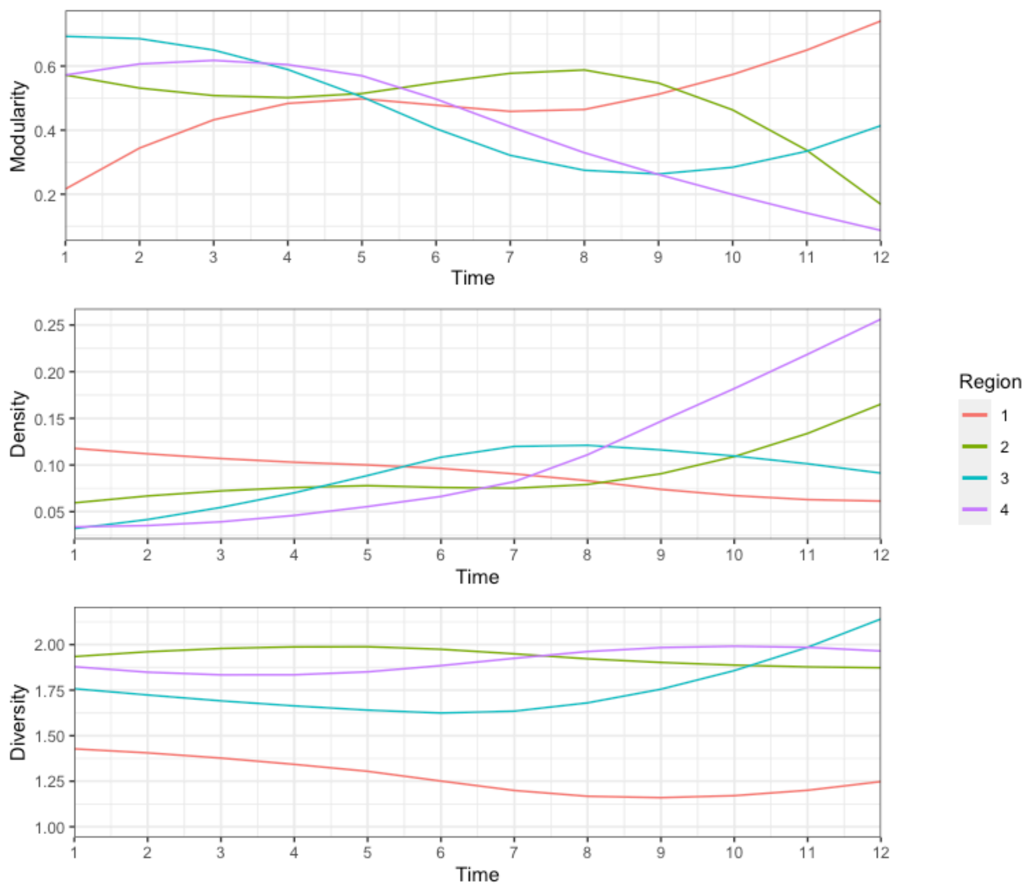

Figure 7. Smoothed local regressions (LOESS) for regional trends in modularity, density, and diversity of fisheries connectivity networks from 2001-2017. Twelve Timesteps were created using data from 2001-2017. Lines are colored by Region.

Discussion

Overall, regional fisheries connectivity networks in the Baja California Peninsula vary in terms of their topologies and the fisheries that comprise them. Regional differences in small-scale fishing portfolios and timing of fisheries activities imply that adaptive capacities vary regionally. Specifically, Baja California's Pacific coast showed an increasing adaptive capacity as measured by network metrics, while the rest of the coast showed decreasing adaptive capacity. Measuring the layouts of fisheries connectivity networks is important because it informs our understanding of the ways in which fishing patterns may leave communities more or less vulnerable to stresses like changing management practices or ocean conditions. The vulnerability framework is important for connecting network theoretic metrics to concepts related to adaptation.

Fisheries connectivity relates to adaptation through several existing ideas including portfolio theory, sustainable livelihoods, and fishing strategies. Fisheries connectivity essentially applies portfolio theory by analyzing the covariance of the portfolio's components (i.e., fisheries species) through time. Studies have applied portfolio theory to multispecies stocks and life history stages to enhance fisheries management (Edwards, Link, and Rountree 2004; DuFour et al. 2015; Jin, DePiper, and Hoagland 2016; Link 2017). Similarly, fisheries connectivity adds to our general understanding of fisheries social-ecological systems. Fishing is a harvesting pattern representing a direct interaction between people and the natural environment, and therefore a critical link in marine social-ecological systems. The sustainable livelihoods approach is a similar framework that seeks to support policy development by recognizing the seasonal, spatial, and adaptive complexity associated with fishing livelihoods (Allison and Ellis 2001). The framework incorporates ideas of vulnerability, marginalization, and poverty, key aspects when characterizing the economic viability of small-scale fisheries (Schuhbauer and Sumalia 2016) and can be used to frame fisheries connectivity analysis. It also relates to the idea of fishing strategies, which describes the group of fisheries that fishermen participate in (Boonstra and Hentati-Sundberg 2014). Each of these ideas relates to ways in which fishermen can adjust their behaviors in order to maintain their well-being and livelihoods while minimizing their vulnerabilities to social or ecological threats.

There was hardly any trend in diversity in any of the regions. Fisheries in Mexico have been continually overexploited for decades (Sala et al. 2004; Sáenz-Arroyo et al. 2005), and major fishing down events that would have substantially decreased diversity occurred earlier. Species that may not have initially been target species become popular when stocks are overexploited (Sala et al. 2004). Catch per unit effort (CPUE) has also declined in the Baja area as fishing pressure increases (Pellowe and Leslie 2015). Additionally, being a part of a cooperative that holds multiple species permits may allow fishermen more flexibility to fish for multiple species (Sievanen 2014), so there should be a higher diversity of catches along the Pacific coast (Regions 1 and 2). However, we did not find any significant differences between any of the regional diversity measures. This may be due to the scale of the analysis. Diversity may vary by individual office locations but were overlooked by aggregating the catch at the regional level. Furthermore, our analysis spanned 2001-

2017. Perhaps if the analysis had gone farther back, historical differences in diversity would have emerged.

Specific differences in catch compositions may reflect differences in regional fisheries management or efforts to prioritize certain fisheries over others. It is known, for example, that fishing communities that manage through area-based territorial fishing approaches tend to focus on less mobile species (Cunningham et al. 2013; Aburto-Oropeza et al. 2017; Nomura et al. 2017). Indeed, large Baja cooperatives who run territorial use rights in fisheries (TURFs) primarily catch abalone, spiny lobster, sea cucumber, and turban snail (Cunningham et al. 2013; Aburto-Oropeza et al. 2017). The catch compositions indicate sessile, high-value species such as lobster, clam, urchin, and oyster are more prominent on the Pacific coast (Regions 1 and 2) where FEDECOOP and other cooperatives operate. Additionally, some of these high-value sessile species have not been harvested in the Gulf of California for over 50 years due to initial overharvesting and dwindling populations. Currently, Gulf of California small-scale fisheries tend to harvest several species of bony fish, elasmobranchs, crustaceans, and mollusks (Lluch-Cota et al. 2007), which can be seen in the landings for Regions 3 and 4. The prominence of the Gulf of California jumbo squid fishery can also be seen, which began in the 1970's and fluctuated before becoming one of the country's largest fisheries (Lluch-Cota et al. 2007). However, the 2009-2010 El Niño led to smaller sized individuals and so the fishery has become less important to the region (Frawley et al. 2019). This trend can be seen in Region 4's fisheries connectivity networks becoming denser and more uniformly connected among several species. Squid was no longer such a central fishery along the Gulf coast. Looking at the evolution of network topology along with the specific composition of the network nodes can help explain small-scale fishing patterns like this.

Although we focus on portfolio diversification to measure adaptive capacity, fishermen have several adaptation options besides fishing in multiple fisheries. Indeed, several studies have used various approaches to measuring fisheries adaptive capacity around the Baja California Peninsula. One study found that some fishermen who want to diversify their portfolios may be unable to due to loss of fishing ground access from economic development or regulations such as MPAs (Sievanen 2014). To combat this, fishermen commonly relocate to new locations throughout the year to take advantage of different fishing seasons in different places (Lluch-Cota et al. 2007; Sievanen 2014). Fishing camps are established around the peninsula for this reason as fishermen visit regions for days to months at a time, often to target higher value species (Sievanen

2014; González-Mon et al. 2019). In this scenario, mobility and portfolio diversification are intertwined as adaptive mechanisms. One study in Baja California Sur found that while diversification was important for maintaining a stable income, being able to specialize and take advantage of opportunities is important for accumulating wealth (Finkbeiner 2015). This alludes to the tradeoffs between diversification and specialization. Which strategy a fisherman chooses may be influenced by individual risk preferences. Consistent, predictable fishing from a well-diversified portfolio leads to more stability. However, there are surely instances where the amount and value of the fisheries landings is more important than the diversification itself. The Maine lobster fishery is an example of such a gilded trap. Lobster was predictable, abundant, and valuable, leading many fishermen to invest heavily in lobster fishing (Steneck 2001). Although specializing in lobster is lucrative, it is highly risky to lose flexibility to target other species if lobster were to crash. Our fisheries connectivity analysis can add context by providing a timeline of when and where communities may be trending more towards either specialization and income accumulation (i.e., a gilded trap scenario) or diversification and income maintenance. Another adaptation is to acquire a different job outside of fishing, or diversifying one's livelihoods. Similarly to other coastlines around the world, Mexico's coastal economies have been transitioning away from natural-resource based livelihoods like fishing or farming and towards tourism and service industries since the 1970's (Gamez and Angeles 2010). In Baja, tourism, carpentry, maintenance, and painting are popular alternative jobs for fishermen (Sievanen 2014). Accounting for other common adaptive strategies in the Baja California Peninsula would help us further understand coastal communities' full range of abilities to cope with change. For instance, tracking the spatial distributions of fishing boats in the area would be helpful to understand how fishermen pair mobility with diversification to adapt to ecosystem and market changes. Assessment of alternative livelihoods networks (e.g., Cinner and Bodin 2010) outside of fishing, alongside the fisheries connectivity network constructed here, could further broaden our understanding of fishing-related livelihood strategies in coastal communities.

This type of adaptation research is important for identifying potential vulnerabilities in management and policy. An analysis of literature on Mexican fisheries over the past few decades reveals that more research is being conducted about sustainable fisheries management approaches (Espinoza-Tenorio et al. 2011). There are increasing amounts of interdisciplinary academic programs in Mexico that acknowledge fisheries and coastal communities as coupled human-natural systems. Generating this type of knowledge domestically is important for capacity building within Mexico (Espinoza-Tenorio et al. 2011). Indeed, there have been calls for a need for research on climate change at the local level so that communities can proactively monitor and address smaller-scale impacts (Morzaria-Luna, Turk-Boyer, and Moreno-Baez 2014). Several studies have used the social-ecological systems framework to indicate important vulnerabilities in natural resource systems (Malakar 2013, Henly- Shepard et al. 2015, Cisneros-Montemayor and Cisneros-Mata 2017; Whitney et al. 2018). However, there is still a need for these insights to be fully integrated into fisheries management plans (Peña-Puch, Pérez-Jiménez, and Espinoza-Tenorio 2020).

Adaptive capacity is a broad concept that can be challenging to describe for vulnerability assessments. Fisheries connectivity is one approach for quantifying adaptive capacity. Differences in network metrics such as edge density and modularity provide information about fisheries adaptive capacities. Adaptive capacity is affected to some extent by the ways that species landings fluctuate in relation to one another. Network metrics provide a useful lens to view this fisheries variability by viewing small-scale fisheries as a single complex system. By applying network theory to a long-term dataset of self-reported fisheries landings, we analyze spatiotemporal trends in fishermen's harvesting strategies using network theories of resilience. Modularity is a commonly used measure of resilience that we applied here. However, it is also possible to expand to other network measures such as centralization, which can also be used to determine resilience or sensitivity, or centrality, which can identify specific fisheries important to the catch portfolios. Nonetheless, it is important to remember that there are myriad tools for assessing adaptive capacity beyond the network analyses used here. Here, we use cross-regional comparisons of quantitative adaptive capacity indicators using fisheries connectivity networks (Whitney et al. 2018). While this scale is useful to examine regional differences, our approach might overlook variations in adaptive capacity that exist between or even within communities (Cinner et al. 2013).

As a measure of adaptive capacity, fisheries connectivity lends itself well to further analysis using the vulnerability framework (Adger 2006). Another natural next step is to compare variations in fisheries connectivity networks to potential explanatory variables that may be influencing catch compositions, such as sea surface temperature or chlorophyll-a concentrations. Fisheries connectivity networks could also be made more spatially explicit with the addition of fishing vessel location data, which would provide a better picture of fishermen's adaptation by including their mobility. Furthermore, future work using networks to measure fisheries resilience can explore fisheries connectivity as part of a mixed-methods approach to studying adaptive capacity alongside surveys or interviews. Fisheries connectivity networks are broadly applicable to existing datasets that many fisheries agencies already have. Even in our study, the CONAPESCA dataset comes with certain limitations. The dataset consists of self-reported landings by the fishermen themselves, so the data may be less accurate than if reporting landings was mandatory and enforced. It also does not include any complete measure of fishing effort that can be used to characterize the relative fisheries production across the locations. It is therefore difficult to confidently attribute changes in landings to true changes in fishing pressures. However, despite this, we are still able to draw conclusions about community-level adaptive capacity in the Baja California Peninsula, demonstrating the flexibility and utility of fisheries connectivity to complement other studies of fisheries vulnerability (Ekstrom et al. 2015). In the long-term, improving upon fisheries connectivity research could prove fruitful for resilient fisheries management.

Vulnerability assessments of all kinds are important to identify areas of fisheries social-ecological systems that could become more robust. Integrating fisheries connectivity networks into studies of vulnerability could be useful for fully describing adaptive capacity. First, small-scale fisheries are often complex social-ecological systems made up of dozens of fisheries varying spatially and temporally. A network perspective explicitly acknowledges this complexity. Viewing small-scale fisheries as a multi-species complex system that varies with space and time is a central tenet to ecosystem-based management. Importantly, fisheries connectivity networks vary in terms of their network metrics and species compositions, meaning that different regions have differential fisheries adaptive capacities and priorities. Having an understanding of the entire portfolio of fisheries that communities target is important for thinking about small-scale fisheries will adapt systemically. Many analyses of adaptation and fishing portfolios are performed at the level of the permit holder, usually an individual fisherman or a vessel. Examining the dynamics of regional portfolios focuses on the adaptive capacity of communities rather than individuals, and may be useful for spatial approaches to fisheries management. Importantly, a key property of fisheries connectivity networks is that they can connect fisheries species that may not otherwise be connected ecologically (Fuller et al. 2017). For instance, fisheries spillover, or redistribution of fishing effort into different fisheries, can occur in the event that management or environmental factors alter the community's access to their primary target species. Fisheries connectivity network connections can be useful for anticipating changes in fishing participation and strategies. Such information is useful when aiming towards integrated multi-species fisheries management rather than a single-species perspective.

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Chapter 3: Vulnerability and Adaptive Capacity in Baja Small-Scale Fisheries

The dynamic nature of marine social-ecological systems can leave fishing communities vulnerable. Vulnerability of human communities is defined as the susceptibility to be harmed by a given perturbation. The key parameters that define vulnerability of a social-ecological system are its exposure and sensitivity to stress, along with its capacity to adapt to the stress (Adger 2006). Exposure is the magnitude and frequency of a perturbation, while sensitivity is the amount that the system is affected by said perturbation. Adaptive capacity counteracts these components and is defined as the ability to cope with stress (Adger 2006). The three components of vulnerability may be assessed together to come up with a single vulnerability metric, or they may be analyzed separately to investigate specific facets and drivers of vulnerability. Increasingly, the framework has been applied as a theoretical tool to study the abilities of resource users to cope with environmental, social, and economic changes (Barnes et al. 2020). Resilience is a similar concept used across disciplines (Levin 2019). Resilient fisheries are those that minimize exposure and sensitivity while maximizing opportunities to increase adaptive capacity.

Small-scale fisheries are important globally. However, small-scale fisheries in many places are experiencing pressures such as overfishing (Schuhbauer and Sumaila 2016), climate change, illegal fishing, etc. Small-scale fisheries livelihoods may be vulnerable to these environmental, political, and economic pressures (Schuhbauer and Sumaila 2016). Fishermen who rely on the ocean for a living continually adapt to weather conditions, species availability, market fluctuations, technology innovations, and policy changes. Fishermen can increase their fishing effort, change gear types, move fishing sites, fish for different species, and/or quit fishing altogether (Cinner and Bodin 2010; Yletyinen et al. 2018). Indeed, most fishermen harvest a variety of species to create multiple sources of income. This approach buffers against the idiosyncratic risks in specific fisheries. Conversely, some fishermen focus on a single lucrative fishery and risk falling into a "gilded trap". Diversity increases the variety of responses to disturbance and the likelihood that fishing communities are able to continue fishing. Small-scale fishermen often employ this generalist strategy, catching several different species, using various gear types, and travelling around to locations where the fishing is most productive (Yletyinen et al. 2018). In order to increase their physical and social capital, fishermen can also enter cooperatives arrangements where they pool their resources like gear, vessels, knowledge, tenure rights, and more. Globally, it is common for groups of fishermen to employ this method to form fishing cooperatives. From a sustainable livelihoods perspective, fishermen may also acquire other jobs to complement their fishing income with other sources of income (Allison and Ellis 2001). Such a strategy may be particularly useful if fishing is not lucrative throughout the entire year.

It is important to note that these individual behaviors occur within the larger social-ecological context. People adapt within their means. Humans do not act rationally and do not always behave in ways that maximize their gains and minimize their losses. Social norms, cultural practices, access to capital, management, and policy are all processes that fishermen operate in that influence their abilities to adapt. For instance, it may be ideal for a fisherman to adapt by targeting a different species, but that fisherman must first at least have adequate knowledge about the species and the appropriate gear to catch it. Management and policy can also greatly affect the species that fishermen are legally allowed to catch. Limited entry into certain fisheries may inhibit fishermen's attempts to diversify their portfolio. Fishing communities may not target the most valuable species but may instead focus on culturally or historically important species. Researchers have employed a variety of methods to analyze a system's adaptive capacity (Whitney et al. 2018; Barnes et al. 2020; Naylor et al. 2020).

Adaptive Capacity in Baja Fisheries

Characteristics of Baja's small-scale fisheries can be assessed through an adaptive capacity lens. Understanding the social processes that support or inhibit fisheries adaptation is pertinent to identifying potential vulnerabilities in fisheries operations. Institutional support, governance strategies, scientific capacity building, and fishermen engagement are all processes that affect the abilities of fishermen, fishing communities, and decision-makers to react to and recover from the inherent variability in fisheries. Here, I explore ways these processes and characteristics might lead to differential adaptive capacities in Baja's fisheries.

Differences between small-scale versus industrial commercial fisheries result in different adaptive capacities. From the diversification perspective, for example, the tendencies of small-scale fishermen to diversify their portfolios provides them more adaptive capacity compared to industrial fishermen who typically focus on the few lucrative species. Often times, discrepancies in adaptive capacities between the sectors can arise from differing access to resources and institutional support. Legal and institutional fisheries frameworks may support industrialized fisheries since this is where a large portion of income and official catch statistics are accrued (Cisneros-Montemayor and Cisneros-Mata 2017). On the other hand, small-scale fisheries employ far more people and account for most of the fishing vessels in Baja's waters. However, in Mexico, promoting the creation of jobs associated with small-scale fisheries is not clearly defined in development policies (Ramírez-Rodríguez and Ojeda-Ruíz 2012). Industrialized fisheries receive more government support in the forms than industrialized ones (Cisneros-Montemayor and Cisneros-Mata 2017). The National Fisheries Charter acknowledges that there are only limited opportunities to increase fishing effort, yet fishing communities continue to request fishing licenses. Expanding small-scale fishing capacity around Baja may also be difficult due to poor infrastructure and few market opportunities, particularly in more rural areas (Ramírez-Rodríguez and Ojeda-Ruíz 2012). The emphasis on industrial fisheries could potentially reflect inequalities of political power or influence between the sectors (Cisneros-Montemayor and Cisneros-Mata 2017). Institutional support makes fisheries more vulnerable or more resilient.

Fishermen who operate in cooperatives versus patron-client relationships should have access to different types of adaptive behaviors. Patron-client arrangements are capable of buffering fishermen against environmental uncertainties by providing fishermen with insurance when catches are low (Lindkvist, Basurto, and Schlüter 2017). In this sense, patron-client relationships provide fishermen higher adaptive capacities. However, cooperatives are also able to cope with environmental changes and constraints (Sievanen 2014). Shared physical capital (e.g., gear), economic outcomes, knowledge, and self-governance allow groups of fishermen to cooperatively develop adaptive rules. Indeed, cooperatives in Baja have shown abilities to adapt to El Niño through these self-governance mechanisms (Mccay et al. 2013). An agent-based model of patron-client and cooperative styles of self-governance found that cooperatives were better prepared for seasonal variability (Lindkvist, Basurto, and Schlüter 2017). Other cooperatives may diversify their livelihoods to also include ecotourism during off-seasons or times of particularly low catches (Finkbeiner 2015).

Decentralizing power to give resource users decision-making abilities over their fisheries operations helps to engage them in governance and adaptation efforts. In cooperatives, for instance, fishermen are more inclined to fish responsibly since they directly depend on the sustainability of the resources. Similarly, working with fishermen to exchange or generate knowledge can also promote good monitoring, enforcement, and overall management. This can entail acknowledging the importance of traditional ecological knowledge for thoroughly understanding a resource system. Relationship-building between academics and fishermen can provide useful insights about the fisheries and effective ways to manage them. Indeed, having multiple sources of knowledge should make a system more resilient to shocks. For instance, participatory research approaches in collaboration with local fishermen produced cross-validated maps about where small-scale fishermen fished (Moreno-Báez et al. 2011). Partnerships between fishermen and other institutions can also be effective. Over recent years, the creation of management plans, involvement of civil society conservation organizations and CONAPESCA, and the role of the INP has produced groups of fishermen around Baja and the Gulf of California who are relatively highly trained and invested in fisheries enforcement and monitoring (Cisneros-Montemayor and Cisneros-Mata 2017). Communities where fishermen are involved in protecting their resources can experience less conflict with other fishermen such as illegal fishing. This sort of preparation can enable fishing communities to be better prepared to adapt to external pressures like illegal fishing. Fishermen have the abilities and incentives to make the fisheries social-ecological more resilient. Indeed, a lack of enforcement can lead to resource and institutional degradation (Frawley, Finkbeiner, and Crowder 2019), so facilitating enforcement is important for social-ecological resilience.

Mexico's marine fisheries have undergone several neoliberal reforms since the 1980's (Frawley et al. 2019) that have affected small-scale fishing communities' abilities to cope in several ways, primarily by affecting their social and economic capital. Firstly, many neoliberal policies stated their goals as stimulating economic growth and improving well-being in poorer classes; however, much of the wealth has been accumulated by elites and to the detriment of small-scale fishermen's livelihoods (Greenberg 2006; Frawley, Finkbeiner, and Crowder 2019). For example, in patron-client arrangements, many fishbuyers and permitholders not actually from local fishing communities. They are often foreign investors who are removed from the community. As such, much of the revenue from fishing often leaves the community. The lack of financial capital in the community affects its ability to deal with shocks to fishermen's incomes. Having a baseline income is indeed a critical asset in the event of a fish stock collapse.

The rising influence of markets and the decentralization of state control over fisheries resources could well affect the species that fishermen target. Permitholders can influence when fishermen are able to fish by only contracting out their permits at certain times of the year. Some fishermen's livelihoods and incomes are thus inconsistent and unstable. Neoliberal reforms also often influence fishermen towards catch specialization in order to maximize their income according to which species the market deems valuable at that time (Frawley, Finkbeiner, and Crowder 2019). In this way, national and international market policies can make fishermen more vulnerable by constructing a gilded trap situation.

The boom in economic opportunities have also undermined social cohesion by incentivizing competition and conflict over fisheries resources (Frawley, Finkbeiner, and Crowder 2019). Fishermen motivated by short-term economic incentives are more likely to fish destructively or illegally (e.g., overfishing or poaching) (Cinti et al. 2010). These illicit activities undermine cooperation and therefore the likelihood that communities would come together to adapt. Indeed, this outcome may be more likely to emerge in governance arrangements that already support competition, such as patron-client relationships. Within cooperatives, competition over resources may be less common.

Vulnerability Assessments for Resilient Baja Fisheries

Vulnerability assessments are important to identify areas that fisheries social-ecological systems could become more robust. Although the factors outlined here are primarily social processes concerned with fisheries adaptive capacity, it is important to consider how environmental and climatic factors might also be at play considering that fisheries are built upon a biophysical environment. In the vulnerability framework, the natural variation in the marine environment could be considered an Exposure (Adger 2006). Notably, these environmental exposures occur at various temporal and spatial scales. For instance, Baja is expected to experience considerable ocean warming over the coming decades, although the rate of warming and therefore type of disruption to fishing communities will vary geographically (Micheli et al. 2012; Sáenz-Arroyo et al. 2005). El Niño Southern Oscillation (ENSO) events also greatly affect the region on longer interannual time scales. Warming ocean temperatures, delayed upwelling, and increased precipitation associated with ENSO events are likely to variably affect important Mexican fisheries species' distributions, growth rates, and reproductive success (Sala et al. 2004; Sievanen 2014). Sea level rise is expected to make wetlands vulnerable, which are important nursery habitats for commercially important species (Morzaria-Luna, Turk-Boyer, and Moreno-Baez 2014). Many recent Mexican policy changes have acknowledged the need to study climate impacts on the ocean and develop climate adaptation strategies (Morzaria-Luna, Turk-Boyer, and Moreno-Baez 2014).

Adaptation research is important for identifying potential vulnerabilities in management and policy. An analysis of literature on Mexican fisheries over the past few decades reveals that more research is being conducted about sustainable fisheries management approaches (Espinoza-Tenorio et al. 2011). There are increasing amounts of interdisciplinary academic programs in Mexico that acknowledge fisheries and coastal communities as coupled human-natural systems. Generating this type of knowledge domestically is important for capacity building within Mexico (Espinoza-Tenorio et al. 2011). Indeed, there have been calls for a need for research on climate change at the local level so that communities can proactively monitor and address smaller-scale impacts (Morzaria-Luna, Turk-Boyer, and Moreno-Baez 2014). Several studies have used the social-ecological systems framework to indicate important vulnerabilities in natural resource systems (Malakar 2013, Henly- Shepard et al. 2015, Cisneros-Montemayor and Cisneros-Mata 2017; Whitney et al. 2018). These types of governance studies allow for science-based management and policy recommendations to emerge, such as a call for secure access rights rather than a permitting system (Cinti et al. 2010). More constant and iterative research about small-scale fisheries in Baja can provide knowledge to inform resilient fisheries development.

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Appendix

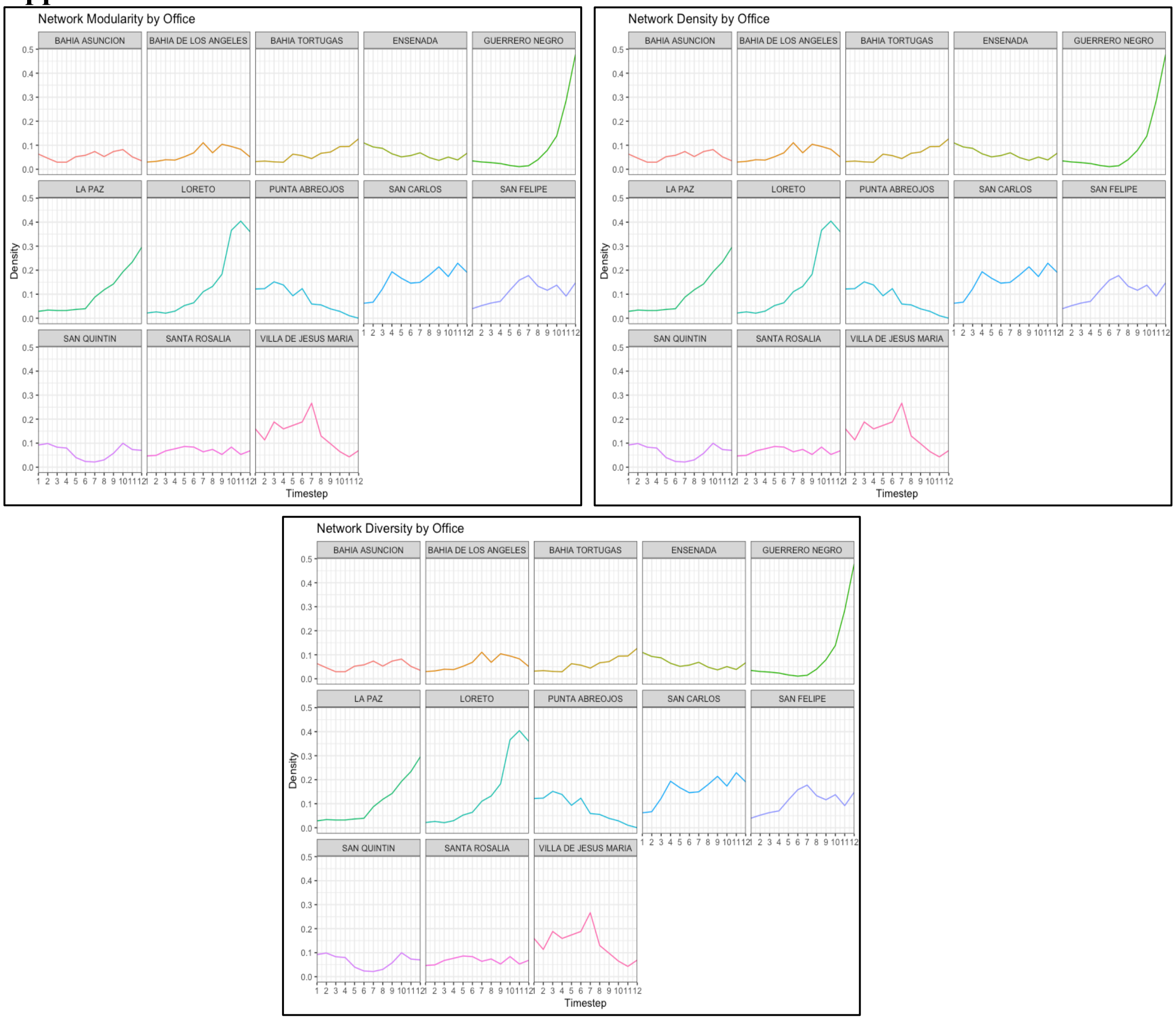

Figure A.1. Network metrrics through time at each fisheries office. Each timestep represents a network comprised of a 5-year window of species landings (kg).

Table A.1. Network metric modularity and density equations.

Metric	Equation	Variables
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
Density	$\frac{m}{\frac{n*(n-1)}{2}}$	m = number of edges n = number of nodes

Table A.2. Summary statistics for modularity, density, and diversity at each region.

	Measure / Metric	Mean	Standard deviation	N
Region 1	Modularity	0.4923092	0.2130169	3
	Density	0.08882587	0.05432969	
	Diversity	1.271536	0.7461055	
Region 2	Modularity	0.4879192	0.2343477	5
	Density	0.09010839	0.08060125	
	Diversity	1.935611	0.1672199	
Region 3	Modularity	0.45542	0.2228121	2
	Density	0.08648916	0.04307257	
	Diversity	1.764841	0.2582797	
Region 4	Modularity	0.40827	0.2465961	3
	Density	0.1069706	0.1031015	
	Diversity	1.911964	0.2039326	

Table A.3. Generalized linear model results for regional time series of modularity, density, and diversity. Values are coefficient estimates followed by standard errors in parentheses, and significance is denoted by: *p<0.1; **p<0.05; ***p<0.01.

	Dependent Variables		
	Modularity	**Density**	**Diversity**
Region 1 (constant)	0.240*** (0.050)	0.117*** (0.020)	0.868*** (0.073)
Region 2	0.246*** (0.063)	-0.072*** (0.026)	0.230** (0.092)
Region 3	0.306*** (0.078)	-0.075** (0.032)	0.078 (0.115)
Region 4	0.341*** (0.070)	-0.133*** (0.029)	0.163 (0.103)
Time	0.023*** (0.007)	-0.005* (0.003)	-0.018* (0.010)
Region 2:Time	-0.039*** (0.009)	0.011*** (0.003)	0.015 (0.013)
Region 3:Time	-0.051*** (0.011)	0.011** (0.004)	0.028* (0.016)
Region 4:Time	-0.062*** (0.010)	0.023*** (0.004)	0.024* (0.014)
Observations	156	156	156
Log Likelihood	88.934	228.267	28.876
AIC	-161.869	-440.535	-41.752
Family, Link	Gaussian, Identity	Quasibinomial, Logit	Gaussian, Log

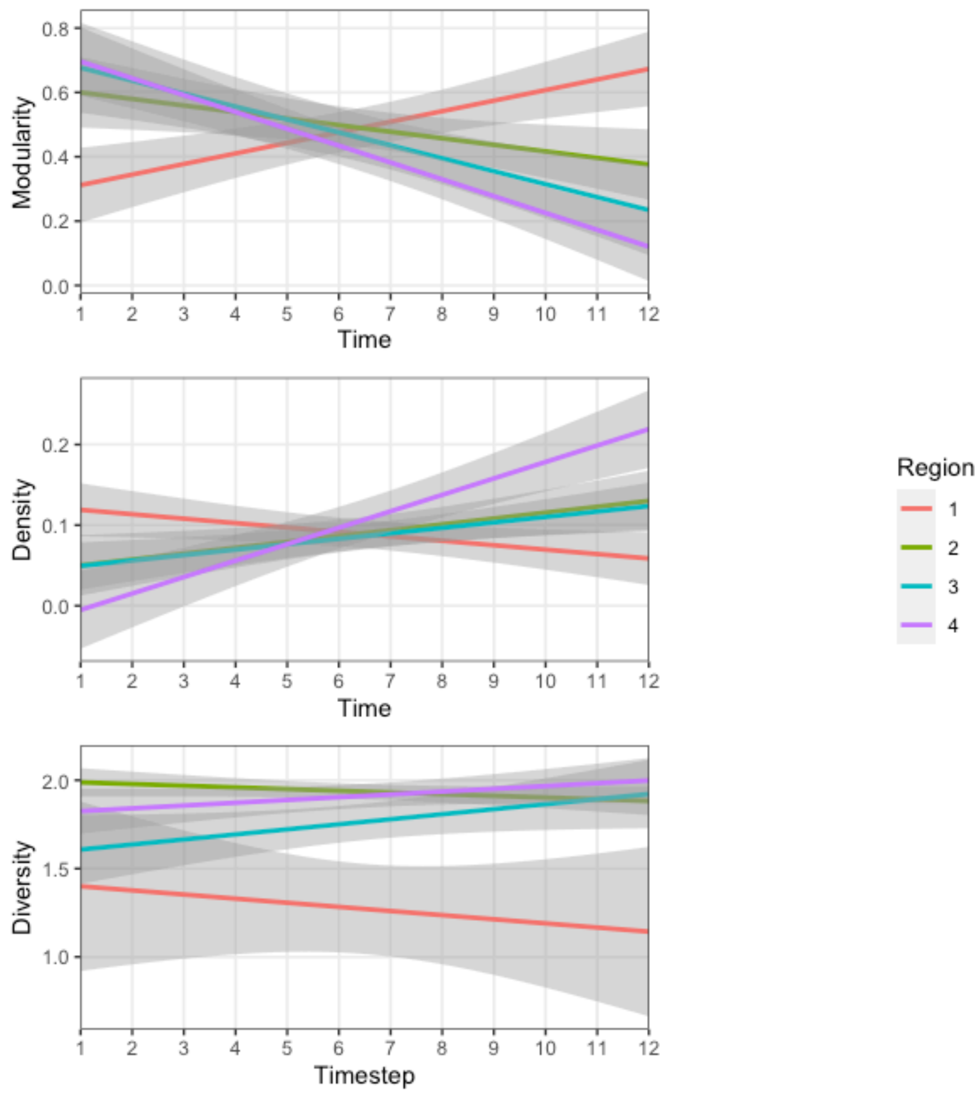

Figure A.2. Generalized linear models for regional trends in network modularity, density, and diversity.

Table A.4. ANOVA results.

	Df	**Sum of Squares**	**Mean Square**	**F-value**	**Pr(>F)**
Modularity					
factor(Region):Time	4	0.829	0.20734	9.129	1.24e-6 ***
Residuals	151	3.429	0.02271		
Density					
factor(Region):Time	4	0.1165	0.029116	7.941	7.76e-6 ***
Residuals	151	0.5537	0.003667		

Diversity					
factor(Region):Time	4	2.638	0.6594	15.29	1.62e-10 ***
Residuals	151	6.514	0.0431		

Table A.5. Tukey-HSD comparisons between regional trends.

	Mean	Group
Modularity		
Region 1	0.4923092	a
Region 2	0.4879192	a
Region 3	0.45542	a
Region 4	0.40827	a
Density		
Region 1	0.08882587	b
Region 2	0.09010839	b
Region 3	0.08648916	b
Region 4	0.1069706	b
Diversity		
Region 1	1.271536	c
Region 2	1.935611	d
Region 3	1.764841	d
Region 4	1.911964	d