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Spatial diversification as a mechanism to adapt to environmental changes in small-scale fisheries

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ABSTRACT

Small-scale fisheries' actors increasingly face new challenges, including climate driven shifts in marine resource distribution and productivity. Diversification of target species and fishing locations is a key mechanism to adapt to such changes and maintain fisheries livelihoods. Here we explore environmental and institutional factors mediating how patterns of spatial diversification (i.e., utilization of alternative fishing grounds) and target species diversification change over time. Using small-scale fisheries in Baja California Sur (Mexico) as a case study, we adopt a social-ecological network approach to conduct a spatially explicit analysis of fisheries landings data (2008–2016). This approach quantifies relative patterns of diversification, and when combined with a qualitative analysis of existing literature, enables us to illuminate institutional and environmental factors that may influence diversification strategies. Our results indicate that interannual changes in spatial diversification are correlated with regional oceanographic change, while illustrating the heterogeneity and dynamism of diversification strategies. Rather than acting in isolation, we hypothesize that environmental drivers likely operate in combination with existing fisheries regulations and local socioeconomic context to mediate spatial diversification. We argue that small-scale fisheries policies need to better account such linkages as we move towards an increasingly variable environment. Overall, our results highlight spatial diversification as a dynamic process and constitute an important step towards understanding and managing the complex mechanisms through which environmental changes affect small-scale fisheries.

1. Introduction

Shocks in food production are becoming more frequent (Cottrell et al., 2019), with climate change impacting the availability and distribution of many natural resources (Perry et al., 2005; Pinsky et al., 2013). These changes may affect fisheries actors' spatial and temporal patterns of fishing effort, as they adapt to increasingly variable and extreme environmental conditions, globalizing markets and shifting institutional contexts (Kittinger et al., 2013; Pershing et al., 2019). As projected climate changes alter the distributions of target species (Cheung et al., 2010), which prompt changes in fishing strategies and operations (e.g., Nunan, 2010; Pinsky and Fogarty, 2012; Young et al., 2019), the need for policies that enhance the flexibility of fisheries actors is growing increasingly acute.

Small-scale fisheries (SSF) are characterized by high spatial and temporal variability which necessitates the constant adaptation of fisheries actors (Naranjo-Madrigal and Salas Márquez., 2014; Wilson, 2017). Diversification is an important adaptation mechanism in fisheries that helps sustain livelihoods and revenue while diminishing risk in the face of change (Cline et al., 2017; Finkbeiner, 2015; Kasperski and Holland, 2013). Some of the most common diversification strategies employed within fisheries are targeting diverse species, moving to fish

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elsewhere, or pursuing alternative livelihoods (Allison and Ellis, 2001; Badjeck et al., 2010). However, there is a need to better understand fisheries actors' diversification strategies in data-poor SSF and how they are influenced by institutional, economic and environmental factors (McCay, 2012). This would aid in the development of governance policies that are better suited to account for the diversity and dynamism of activities that are essential for millions of people.

We focus on two diversification strategies prominent in SSF worldwide: species diversification (switching target species) and spatial diversification. The latter refers to seasonal mobility, internal migration, *translocal* livelihoods (*sensu* Islam and Herbeck, 2013) and/or spatial displacement of fishery actors that allow them to operate at geographical scales that extend beyond their local fishing areas or communities. Thus, spatial diversification requires actors to shift between alternative fishing grounds or change their usual landing sites. It may also encompass fisheries actors whose extractive activities are spread over large spatial scales. Spatial diversification (*sensu* mobility) has been described as an adaptation mechanism across diverse SSF systems, and as an important characteristic of many communities reliant upon marine resources (e.g., Badjeck et al., 2010; Njock and Westlund, 2010; Overå, 2005). Fisheries actors' may have diverse motivations and capabilities that constrain or enhance their mobility (Islam and Herbeck, 2013; Sievanen, 2014; Wanyonyi et al., 2016), and policies and institutions can play an important role in influencing diversification processes (Nunan, 2010; Nunan et al., 2012). Though diversification has historically been part of SSF activities, it is expected to play an increasingly important role as climate change progresses (c.f. Young et al., 2019).

Spatial diversification in particular poses specific governance challenges –It can lead to conflicts between actors (Crona and Rosendo, 2011; Dubik et al., 2019); and is frequently associated with overexploitation (Binet et al., 2012; Wilson, 2017). The phenomena of sequential exploitation and the serial depletion of fishing grounds, has been described in numerous study cases across the globe (c.f. Berkes, 2006). In this context, regulations that associate access rights with geographically defined boundaries have been proposed as solutions to the overexploitation problem, but these management approaches do not necessarily account for spatial diversification as an adaptation mechanism, nor do they address underlying socioeconomic, political and environmental drivers (Finkbeiner et al., 2017). Such policies may lead to unintended consequences such as inducing effort displacement (Abbott and Haynie, 2012; Kroetz et al., 2019) or reducing diversification capacities (Kasperski and Holland, 2013) while increasing individual vulnerability and rule-breaking (Stoll et al., 2016). A better understanding of spatial diversification patterns and how they have changed over time is of critical importance for improved fishery management that better accounts for actors' diversification across large scales (e.g., Cudney-Bueno and Basurto, 2009; Nunan et al., 2012).

In this study we aim to better characterize the diversification strategies of fisheries actors by analyzing the inter-annual patterns of fisheries diversification in SSF across the state of Baja California Sur (Mexico), addressing two specific research questions: i) How do patterns of species and spatial diversification change over time? and ii) what environmental and institutional factors likely influence the observed diversification patterns within the SSF system? To answer these questions, we conducted a detailed and spatially explicit analysis of fisheries landings data from 2008–2016, differentiating between the strategy of switching species without changing fishing locality (hereafter named *local diversification*), from the strategy of spatial diversification. Such detailed analysis was made possible by official fisheries data furnished at a higher spatial resolution than previously available (e.g., daily georeferenced landings by fishery actor).

We apply a social-ecological network model that allows analyzing multi-species diversification patterns across time and space, focusing on the observed relationships between social nodes (fisheries actors) and ecological nodes (spatially explicit species groups). To explore potential drivers of spatial diversification, we first compare observed patterns with oceanographic changes commonly associated with El Niño Southern Oscillation (ENSO) and other large-scale climate drivers. Next, we investigate the potential role of institutional factors such as the regulatory and institutional forms governing the harvest of each species functional group, in shaping patterns of diversification. Therefore, in answer to question ii we suggest multiple causes and conditions that may underlie the observed patterns of spatial diversification and together provide possible explanatory factors that can be tested through further research. We justify our hypotheses through our mixed method analysis that comprises a comparison with other studies and literature from across the study area (Section 4.4). We acknowledge that such hypotheses are only a first step towards establishing causal relationships, which is inherently difficult in complex SES such as fisheries (Ferraro et al., 2019). It is, however, an important first step in that it synthesizes a solid set of evidence derived through multiple quantitative and qualitative methods that serves as a basis for further investigation. Finally, we discuss the implications of our findings for the development of policy and future research (Sections 5.3 and 5.4).

2. Study case: fisheries in Baja California Sur, Mexico

The state of Baja California Sur (BCS), Mexico, is located on the Baja California peninsula on the Northwest Mexican Pacific coast. Given the significant variation in sea surface temperatures and levels of primary production across space within and between years, this region is well-suited to study the effects of seasonal and interannual environmental change. In addition to the large temporal and spatial variability of BCS fisheries (Pellowe and Leslie, 2017), El Niño Southern Oscillation (ENSO) events are known to trigger significant changes in the distribution and abundance of marine resources (Lluch-Cota et al., 1999) and represent an important driver affecting fisher's diversification strategies (Finkbeiner, 2015; Pellowe and Leslie, 2017). The regional manifestations of the ENSO, such as the warmer sea surface temperatures and lower primary productivity associated with El Niños, and the colder sea surface temperatures and higher primary productivity associated with La Niñas, have well-documented impacts on regional fisheries (Frawley et al., 2019a; Martín et al., 2017).

Understanding fishers' diversification in BCS requires consideration of how different fisheries policies can trigger, enable or constrain different diversification strategies. Fisheries management in Mexico is based on a limited entry permit system (Basurto et al., 2012; Cinti et al., 2010). Fishing permits vary in their specificity. Some are limited to a single species, while others refer to generic groups of species (e.g., sharks, finfish) (DOF, 2018). Some species are also managed through concessions that grant a user an exclusive access to the resource within a clearly defined area (McCay et al., 2014). For other fisheries, permits comprise larger geographic boundaries such as one municipality or the state of BCS.

In Mexico fishing permits can be granted to private or collective actors, named permit-holders or fishing cooperatives respectively (Basurto et al., 2020, 2013). They are referred to as *Unidades Económicas* (herein economic units) in official landing records. In our analysis, economic units represent the fisheries actors, and define our smallest unit of analysis. Each economic unit can hold a diverse number of permits for one or several fisheries, operating with one or multiple fishing boats and specific gears for each permit, which will influence their capacity to diversify. Economic units have access to landing sites that are usually the first point of commercialization (i.e., the beach). While some economic units are sole fishers, others "employ" fishers working for them (e.g., Frawley et al., 2019c; González-Mon et al., 2019). Therefore, spatial diversification may represent economic units (e.g., permit-holders) employing fishers that fish in distant fishing communities, and not only direct mobility. Notably moving to distant locations can take place by sea or land, as the boats (7–9 meter open-air, fiberglass boats) can be transported on land, and such mobility can be facilitated by permit-holders (Cinti et al., 2010; González-Mon et al., 2019).

3. Methods

We use a network approach to analyze patterns of spatial and local diversification (Section 3.3). This approach measures the network *connectivity*, which here implies there are economic units that deploy diversification strategies, either locally (species diversification within a region) or spatially (diversification across regions). This approach required delineating landing regions to define spatial diversification (Section 3.1) and the synthesis of the fisheries landings database (Section 3.2). To interpret observed patterns of spatial diversification, we identify drivers of change based on published information and qualitative data (Section 3.4).

3.1. Delineation of spatial units: landing regions

We defined a landing site as the location where fish is first landed (Fig. 1), and identify them based on “The SSF Database” (described in section 3.2) as reported by the National Fisheries Commission (CONAPESCA) and subsequently georeferenced by M. Nenadovic based on the official compilation of landing sites (Ramírez-Rodríguez et al., 2004). Given the data available, we use landing sites (N > 200) because they are most likely to represent a location closer to where fishing took place and often represent the first point of commercialization. We clustered the landing sites by using the BDSCAN spatial algorithm (Ester et al., 1996) in Python/scikit-learn (version 0.20.1), which groups data points according to their proximity measured as Euclidean distance, and defined landing regions as groups of landing sites with the extremes separated by a minimum linear distance (as described below). We only included landing sites in coastal areas (removing the few landing sites were reported inland) and landing sites that were reported every year. See supplementary material 1.1 for details and limitations of the clustering process.

We used 25 km as a minimum distance threshold to define the landing regions (clusters). Fishers in the region are known to travel for their daily fishing operations a mean of 50 km (Johnson et al., 2017; Leslie et al., 2015; Moreno-Báez et al., 2012). Based on this empirical information, we assume that changes in landing site separated by more than 25 linear km (which would require travelling at least 50 km back and forward) are not part of the regular daily fishing activities. Following this criterion, we divided the study area into six spatial *landing regions* (Fig. 1), and denoted instances of an economic unit reporting landings in different landing regions during the same year, as representative of a spatially diversified fishing strategy (see supplementary material 1.1). Note that we apply a conservative criterion that may underestimate spatial diversification, in order to distinguish connectivity between regions from regular, daily fishing operations. To validate the defined landing regions, we consulted with members of fishing communities and researchers working in BCS (supplementary material 1.1). Overall, this was considered the optimal spatial representation of the system given the decentralization of landing sites and our goal to isolate large-scale mobility patterns, however we acknowledge the findings of this study are bound to the spatial scale we selected.

3.2. Synthesis of fisheries data

The social-ecological network models (described further down) were built from “The SSF Database”, a version of the official trip-ticket database curated by the Coasts and Commons Co-Lab at Duke University, comprising the years 2008–2016 (see supplementary material 1). Economic units in Mexico are required to report trip-tickets (‘arribos de pesca’) of their fishing trips at the official fishing offices of the National Fisheries Commission (CONAPESCA) on a number of variables including volume and value of the resources catch, landing site, etc. (Ramírez-Rodríguez, 2011). Each fishing trip ticket typically reports catch information from 3 to 7 fishing trips due to feasibility constraints, providing an imprecise estimation of fishing effort (Ramírez-Rodríguez, 2011). For that reason, our analysis is only based on the presence/absence and frequency of fishing events by economic units. In addition, limitations of self-reported data apply, including incentives economic units might have to misreport their landing sites and capture. However, we believe the size and breadth of this dataset allows accurate investigation of trends and patterns.

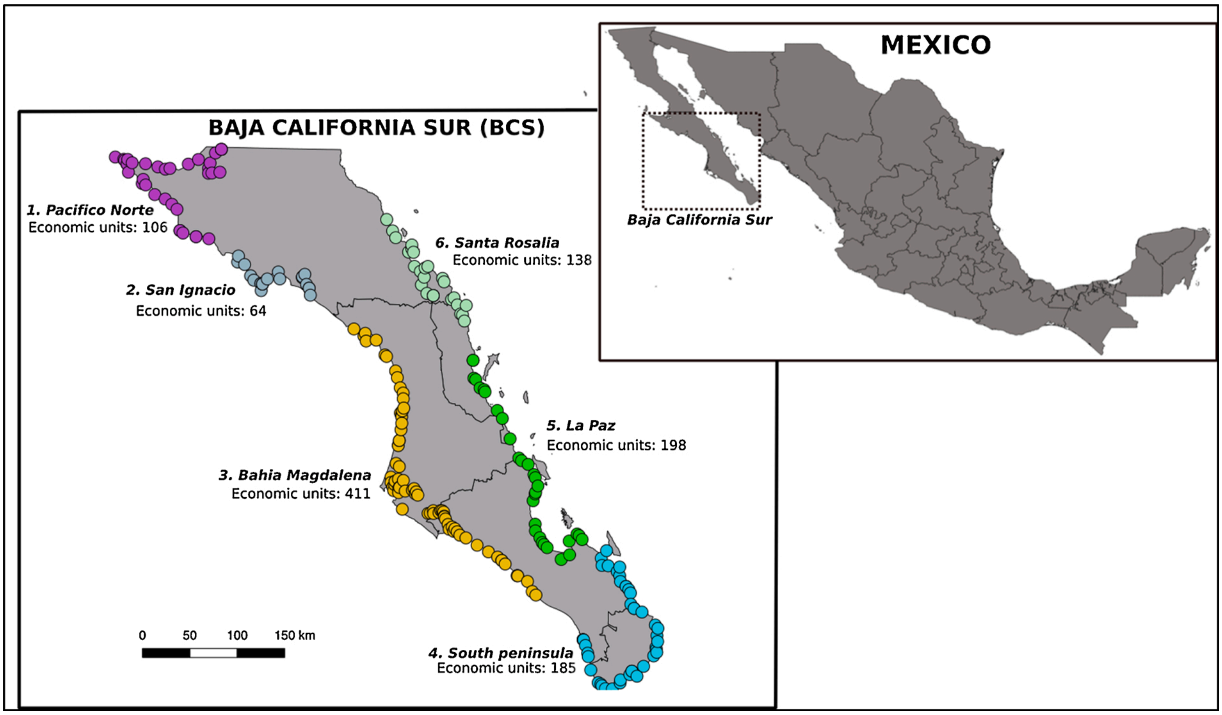

Fig. 1. Landing regions in study area based on time series (2008-2016) of landing sites of SSFs. Circles represent landing sites. Black lines in the map represent municipal boundaries in BCS (left) and states of Mexico (right). Data source: “The SSF Database”.

We report on 37 species groups contained in the database over time (2008–2016) and representing 95 % of the total catch in each landing region. These are mainly commercial species groups as reported by CONAPESCA, which group species that generally have similar biological and market characteristics, and are fished by similar institutional arrangements and gears (see Table 1). See supplementary Material 1.2 for details on how species groups were constructed. The 37 species groups were considered as distinct species groups in each of the landing regions where they were reported, creating 208 landing-region-specific Fisheries Spatial Units (FSU), summing every species group targeted in each landing region (Giron-Nava et al., 2018). These FSUs were used as input for the network analysis (see Section 3.3).

3.3. *Analysis of fisheries networks*

3.3.1. *Definition of the networks*

We built 9 social-ecological networks (one for each year between 2008–2016), following an approach recently applied to fisheries datasets in the United States (e.g., Fuller et al., 2017; Kroetz et al., 2019), to analyze patterns of spatial diversification and their changes over time. We constructed “projected” social-ecological networks (c.f. Sayles et al., 2019), where FSUs are the nodes (with landing region as its attribute), and links between any two nodes are the number of economic units targeting both FSUs in a given year. We considered an economic unit targeting an FSU only if this was reported in more than 2 trip-tickets and thus eliminating potentially accidental events (2 trip-tickets would imply minimum one fishing week considering that each trip-ticket might comprise 3–7 fishing days). Out of the 657 economic units present in the raw data, we removed economic units with less than 2 trips per year and those that targeted only species groups not included in our analysis. See supplementary material 1 for a detailed description of the construction of these networks.

3.3.2. *Network analysis*

We applied different network metrics to measure patterns and changes of diversification: relational contingency-table analysis, and External-Internal index (E.I. index) analysis. These metrics are implemented in UCINET 6 (Borgatti et al., 2002), and only measure presence/absence of links. We performed all other analysis to build the network matrixes and graphs and obtain descriptive network measures in R (R Core Team, 2018), using the package igraph (Csardi and Nepusz, 2006); and the tidyverse packages (Wickham et al., 2019).

First, we use a relational contingency-table analysis to measure spatial and local diversification. This is a model that calculates the frequency of links within and between landing regions in the observed network compared to the frequency expected by chance in a random network. The model provides a Pearson Chi-squared statistic to measure significance as compared to a random model with 10,000 iterations (Hanneman and Riddle, 2005). Thus, this analysis quantifies the level of spatial diversification for each year by measuring connectivity between FSUs from different landing regions, and local diversification by measuring the connectivity between FSUs within the same landing region. We use a random network model as a baseline for each year analyzed to allow comparing between years.

The E.I. index analysis provides a quantitative measure of the relative spatial diversification versus local diversification strategies. The E.I. index developed by Krackhardt and Stern (1988) is a simple measure based on the relative number of links between nodes of a different group (External) and between nodes of the same group (Internal) (Hanneman and Riddle, 2005), defined as: E.I. = (*N° external links* – *N° internal links*) */ Total n° links*. We define “groups” as the landing regions and use the E.I. index in our projected social-ecological networks to define the relative degree of spatial diversification (external links) versus the degree of local diversification (internal links). The index results in a gradient from only spatial diversification (E.I. = 1) to only local diversification (E.I. = −1) (see supplementary material 1.3). We calculate the index at the network level and for each individual FSU (Hanneman and Riddle, 2005). For each individual FSU, the E.I. index indicates its relative number of connections with FSUs from other landing regions in respect to FSUs from their own landing region (comparing the amount of external and internal links for each FSU). It therefore measures FSU’s relative participation in spatial and local diversification strategies.

3.4. *Analysis of environmental and institutional factors*

We use yearly average values of the Oceanic Niño Index (ONI) retrieved from NOAA (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php), as an indicator of oceanographic variability. The ONI is a measure of sea surface temperature anomalies across the equatorial pacific and is highly correlated with other regionally sensitive ENSO indicators. A linear regression model is used to test the relationship between changes in ONI and adaptation strategies (E.I. index), using the *lm* function in R (R Core Team, 2018). To visualize regional changes in Sea Surface Temperature (SST) anomalies (a factor associated to ENSO), we accessed remotely sensed environmental data online through NOAA’s CoastWatch server (Multi-scale Ultra-high Resolution SST Analysis Anomaly fv04.1, 2002-Present, 0.01°), aggregated it on an annual basis, and plotted it spatially using the “raster” v2.5 package in R (Hijmans, 2015). Anomalies represent observed SST values minus the long-term mean.

To analyze some of the institutional and economic factors potentially influencing spatial diversification, each species group is characterized by: i) regulatory characteristics informed by the Mexican fisheries regulation (DOF, 2018); ii) fishing gears used for each species group informed by the same regulations and previous literature (DOF, 2018; Finkbeiner, 2015); iii) market characteristics extracted from the database (mean price/kg) and informed by previous studies (e.g., González-Mon et al., 2019 for finfish); and iv) habitat affiliation which is related to their biological, regulatory and fishing characteristics. In addition, we draw on previous literature to further understand the role of different species groups in spatial diversification. The qualitative analysis of these factors helped interpret the results in order to answer question ii by identifying factors and conditions that may influence the observed patterns of spatial diversification.

4. Results

4.1. *Diversification patterns in BCS*

Diversification patterns differ between landing regions and across years. Some regions are strongly connected while others are less so, yet these tendencies change over time. The changes in spatial diversification are not uniformly distributed across all regions, but rather show distinct patterns (Fig. 2). For example, Santa Rosalia and San Ignacio were not connected or slightly connected during 2009–2012, but later became more connected, thus indicating an increase in spatial diversification connecting the regions 2013 and onwards (Fig. 2). We also observe that Pacifico Norte is less connected to other regions over time, and becomes isolated in 2014 and 2015 (Fig. 2). However, we caution that the northern area in Pacifico Norte region likely experiences more migration to and from the state of Baja California (North of BCS) that was not captured in our analysis.

We also found consistent patterns across years between some regions. Landing regions like Bahia Magdalena and the Southern peninsula have more connectivity than expected by chance during all years (Fig. 2). A consistent but weaker connectivity also exists between other regions such as Bahia Magdalena and La Paz.

Overall, local diversification is more prevalent than spatial diversification for all years, indicating that switching between species groups’ within landing regions is more common than fishing across landing regions (E.I. < 0, Fig. 3a). This is generally true for all regions, but the magnitude and changes of local diversification differ between regions (Fig. 2). For example, Bahía Magdalena has higher levels of local

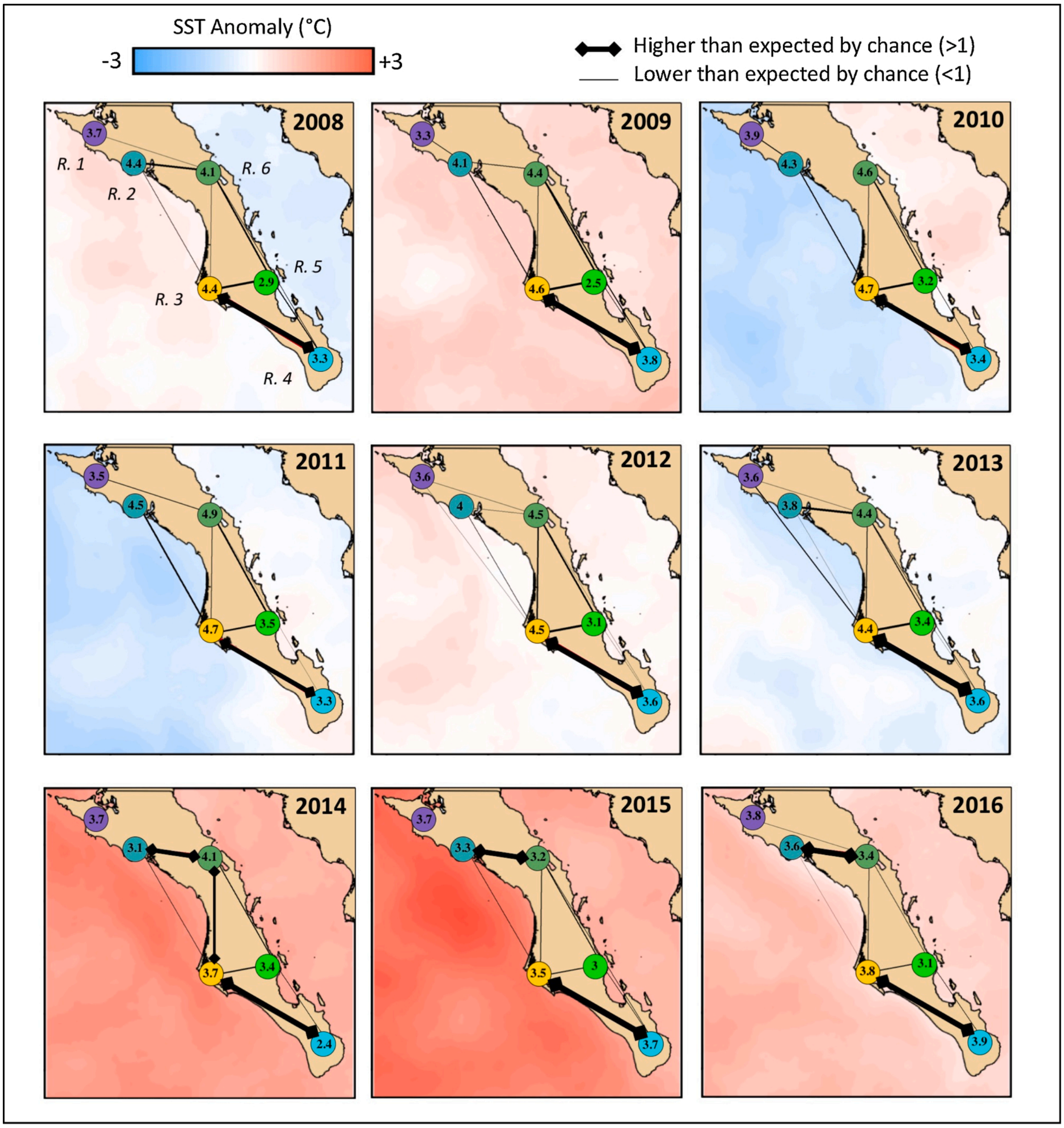

Fig. 2. Spatial and local diversification in Baja California Sur across years. Nodes indicate the landing region; value in the nodes the tendency for local diversification in each landing region (>1 if higher than expected by chance). Thickness of links represent relative prominence of spatial diversification between regions (amount), and no links indicates the absence of connections (0 or approx. 0). See supplementary material 2.3 for numerical and absolute values. Map colors are based on sea surface temperature anomalies (SST), where red represents anomalously warm temperatures while blue represents anomalously cold temperatures. R.1, Pacifico Norte; R.2, San Ignacio; R.3, Bahía Magdalena; R.4, South peninsula; R.5, La Paz; R.6, Santa Rosalía.

diversification than La Paz region (Fig. 2), and has some of the highest levels of local diversification during the years we analyzed.

Even if local diversification is more prevalent, changes in the E.I. index mainly represent changes in spatial diversification, as we observe when comparing the E.I. index (Fig. 3a) with the absolute number of internal links (local diversification) and external links (spatial diversification) that are the two components of the E.I. index (Fig. 3a).

The sensitivity analysis (see supplementary material 1.4) indicates that the changes in spatial diversification patterns (Fig. 3) are influenced by a number of network links that are maintained by one economic unit each (“weak” links). Eliminating such weak links decreases the amount and variability of the data and do not show significant changes over time. This result suggests that when diversification strategies change, each economic unit may adopt unique and/or different diversification patterns. The patterns found seem largely created by economic units who fish both FSUs with 1–3 boats per trip-ticket on average (supplementary material 1.4).

4.2. *Correlation with patterns of oceanographic change*

The changes in spatial diversification strategies are strongly correlated with oceanographic changes (Fig. 3b, positive correlation with $R^2 = 0.7342$, $F_{1,5} = 19.33$, $P < 0.01$). For example, in 2011, a moderate La Niña event in BCS lead to cooler water temperatures (Fig. 2). In 2015, a strong El Niño event led to warmer water temperatures (Fig. 2). In addition, 2015 was the year with the highest spatial diversification (E.I. = - 0.046) and 2011 with the lowest (E.I. = - 0.365, Fig. 3). This relationship is less pronounced when considering changes in the overall network connectivity (density) or in the number of FSUs alone (which generally increase from 2012), indicating the specific importance of spatial diversification in driving this correlation (see supplementary material 1.3).

4.3. *Participation of different species groups in diversification strategies*

Each species group shows distinct levels of participation in species

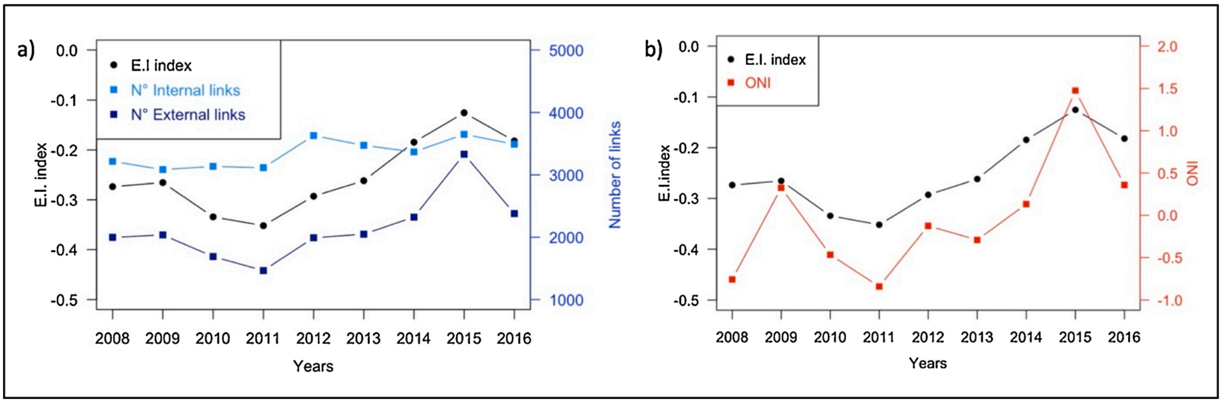

Fig. 3. Changes in species and spatial diversification compared to El Niño Southern Oscillation. In black, changes in the E.I. index per year. a) In blue, changes in the number of internal links (local diversification, light blue) and in the number of external links (spatial diversification, dark blue) that compose the E.I. index. b) In red, Oceanic Niño Index (ONI).

and spatial diversification strategies (Fig. 4). Some species groups are more commonly linked to spatial diversification strategies than others, and show a more consistent participation in spatial diversification across landing regions and across years (Fig. 4). Those are some of the most commercially important finfish species in terms of value, volume or availability (e.g., snappers, jacks, triggerfish), in addition to elasmobranches and shrimp. Shrimp is the only benthic fishery that is strongly and consistently associated with spatial diversification across time and landing regions (Fig. 4). On the opposite end, some species show low association with spatial diversification strategies, including several benthic species (e.g., abalone, lobster, snail) and finfish that are of lower commercial importance in BCS (e.g., croaker and pompano). We also find species groups such as crabs, clams, pen shell, or squid that are specifically targeted as part of spatial diversification strategies, but only in specific landing regions or during certain years, as indicated by the high variability of their E.I. index (Fig. 4, see supplementary material 2.4). Some of these cases are further discussed in Section 4.4.

4.4. The potential role of oceanographic dynamics and institutional factors

Species groups can be associated with specific regulatory and ecological characteristics (Table 1), and distinct fishery dynamics revealed by previous literature in BCS. Next we engage in an in-depth analysis of several of the above-mentioned species groups, to explore some of the environmental and institutional factors that may contribute to the observed patterns.

4.4.1. The dynamics of squid

Environmentally driven changes in resource abundance may be one factor impacting observed patterns of spatial diversification. In particular, a well-described mechanism linking environmental change and shifts in in the abundance and distribution of the squid fishery may have influenced the changes in spatial diversification shown in connection to Santa Rosalía region (Fig. 2, Section 4.1). Drastic changes in fishery production were observed following the warming of surface and subsurface water temperatures in the Gulf of California (Frawley et al., 2019a) during the latter portion of our study period. The squid fishery declined from 90 % (by weight) of landed catch in Santa Rosalia in 2008 to 55 % in 2012 before collapsing completely in 2015. In the years prior to this collapse, as traditional fishing grounds grew increasingly unproductive, large quantities of squid were landed in other fishing grounds along the Pacific Coast in the Bahia Magdalena and the Pacifico Norte regions (Medellín-Ortiz et al., 2016; Schneller et al., 2014) and in the Northern Gulf outside of BCS (Frawley et al., 2019a). These changes triggered diverse responses amongst fisheries actors, including local diversification of target species (Frawley et al., 2019b), spatial diversification to fish squid across regions (Schneller et al., 2014), and spatial diversification to target alternative species (T. H. Frawley, personal observation). We suggest that spatial diversification to follow squid occurred in specific years and landings regions (explaining squid's high variability in Fig. 4, see supplementary material 2.4). For example, the increased connectivity in 2011 and 2012 between Santa Rosalía and Pacifico Norte regions (Fig. 2) was partially caused by the squid fishery (see supplementary material 2.4), which corresponds to years during which squid aggregations were located in the region. However, the collapse of the squid fishery may have also led to movements to target other species such as finfish. This is suggested by the increased spatial diversification between San Ignacio and Santa Rosalía regions between 2012–2013, which may be linked to an increase in the spatial diversification associated with finfish (see supplementary material 2.4).

4.4.2. The finfish fishery

The finfish fishery seems to play an important role fostering spatial diversification for commercially important species, while simultaneously and more generally stimulating local diversification (Fig. 4). The high variability and uncertainty in catches of some finfish species affected by both seasonality and inter-annual changes (Pellowe and Leslie, 2017; Sievanen, 2014), may on the one hand increase the importance of flexible and diverse fishing strategies when targeting these species. In fact some economic units may move across the peninsula following the seasonal life history patterns of species like jacks or red snapper (*unpublished data*). On the other hand, diversification involving finfish species is widely spread and there are no strong regulations in place which constrain diversification strategies for this permit type. The finfish permit is one of the most common permits held by economic units (*CONAPESCA permits data*), and grants access to more than 200 species that are most often fished with hook and line or gillnets (Table 1). In the last years, the regionalization of permits led to a restriction mandating that fishers target finfish species only in waters considered part of their home municipality (Leslie et al., 2015; Sievanen, 2014). However, some municipalities comprise several landing regions which enables spatial diversification between them (see Fig. 1). These flexible institutional conditions may enable economic units to diversify and change their diversification strategies in response to environmental or market changes. In addition, economic incentives for certain finfish species may incentivize spatial diversification, given that most commercially important species show the highest levels of spatial diversification.

4.4.3. Benthic species groups

Species groups from benthic fisheries regulated by species-based or group-based permits (Table 1) are generally not associated with spatial diversification to the same degree as finfish species (Fig. 4). The

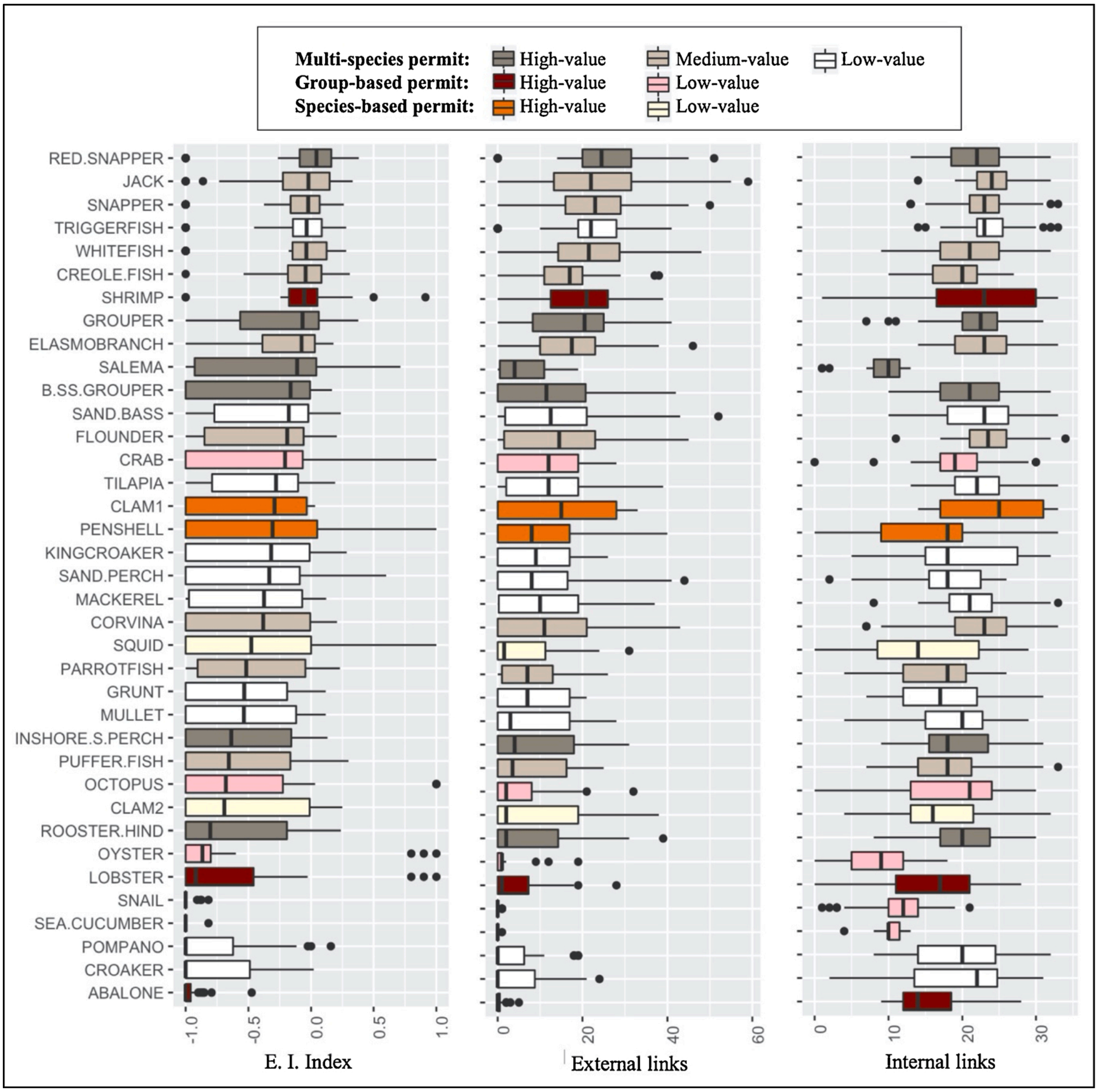

Fig. 4. Importance of each species group for diversification strategies. Box and Whisker plots showing the variation in the role of species groups. Variability between FSUs and between years is represented by the size of Box and Whiskers, and points are outliers. Species groups role based on: a) E.I. index indicating their relative participation in spatial vs. local diversification, ordered from highest spatial diversification (top) to lowest (bottom); b) number of external links (participation in spatial diversification); c) number of internal links (participation in local diversification). See supplementary material 2.4. for plots disaggregated per year and landing region, and Table 1 for color codes and non-abbreviated names.

association of some fisheries in spatial diversification strategies can be very limited, as is the case with abalone (Fig. 4). Abalone is one of the species of highest economic value in BCS, where institutions likely contribute in limiting spatial diversification through which non-resident fishers can access the resource. Well-organized economic units (e.g., fishing cooperatives) that hold concessions (spatially-explicit fishing rights) for high-value benthic resources such as lobster and abalone may have higher capacity to self-organize locally and restrict the entry of non-local actors (McCay et al., 2014).

Other benthic species can show high participation in spatial diversification, either overall (i.e., shrimp), or during specific years (Fig. 4 and supplementary material 2.4). The shrimp fishery is regulated through a temporal closure and it is commonly associated with seasonal migration, where fishers are drawn (often enabled by informal institutional arrangements) to productive shrimp fishing grounds from different parts of the peninsula and mainland Mexico (García Martínez and Chávez Ortiz, 2007; Young, 2001). In addition, ENSO events have been suggested to affect the shrimp fishery (Lluch-Cota et al., 1999; Santamaría-del-Ángel et al., 2011), which may affect inter-annual changes in spatial diversification, yet to our knowledge there is no literature describing such changes within the regional SSF. For other benthic species groups, the variability in diversification strategies (Fig. 4) may be explained by spatial diversification following diverse processes (see supplementary material 2.4).

5. Discussion

5.1. The role of spatial diversification in SSF diversification strategies

We found that local diversification is generally a more common diversification strategy than spatial diversification. This may not be surprising since there are often constraints associated with spatial diversification related to the economic and social costs of travelling beyond one's home region (Islam and Herbeck, 2013; Sievanen, 2014). In addition, all targeted species groups contributed to local diversification strategies (Fig. 4), indicating that fisheries actors in BCS largely

Table 1

Characteristics of species groups. Species groups classified according to their institutional and ecological characteristics. Ecological role based on species' habitat, where "mix" are pelagic or demersal species including those associated to sandy bottoms, reefs or seamounts. Clams where grouped as clam 1 (high-value, >100MXN/kg) and clam 2 (low value, <10MXN/kg).

Species group	Permit extent	Market role	Main gear type	Ecological role
Clam 1, Penshell	Species-based permit: e.g. *Tagelus sp. Lyropecten sp.*	High-value (70−150MXN/Kg)	Hookah diving	Benthic
Clam 2	Species-based permit: e.g. *Anadara sp. Megapitaria sp.*	Low-value (5−40 MXN/kg)	Hookah diving	Benthic
Squid	Species-based permit	Low-value (2 MXN/kg)	Jigging	Pelagic
Abalone, Lobster, Shrimp	Each species group has permit with <5 species per permit	High-value (70−150MXN/Kg)	Hookah diving Artisanal trawls[†] Traps*	Benthic
Snail, Crab, Octopus, Oyster, Sea Cucumber	Each species group has permit with <5 species per permit	Low-value (5−40 MXN/kg)	Hookah diving Traps*	Benthic
Groupers, Broomtail and Star-studded grouper, Rooster hind, Red snapper, Salema, Inshore sand perch	Generic finfish permit (271 species)	High-value (30−113 MXN/Kg)	Gillnets Hook and line	Mix
Puffer fish, Creole fish, Flounder, Snapper, Parrotfish, Whitefish, Corvina, Jack	Generic finfish permit (271 species)	Medium-value (12−25 MXN/Kg)	Gillnets Hook and line	Mix
Triggerfish, Sand perch, Tilapia, Grunt, Croaker, Panama kingcroaker, Pompano, Spanish mackerel, Sand bass	Generic finfish permit (271 species)	Low-value (6−11 MXN/Kg)	Gillnets Hook and line Traps*	Mix
Mullet	Species-based permit	Low-value (6−11 MXN/Kg)	Gillnets	Pelagic
Elasmobranches (sharks and rays)	Generic sharks permit (45 species)	Medium-value (8−22 MXN/Kg)	Artisanal longline Gillnets	Mix

*For lobster, crabs, octopus; possible for snail, triggerfish, and sand bass. [†]For shrimp.

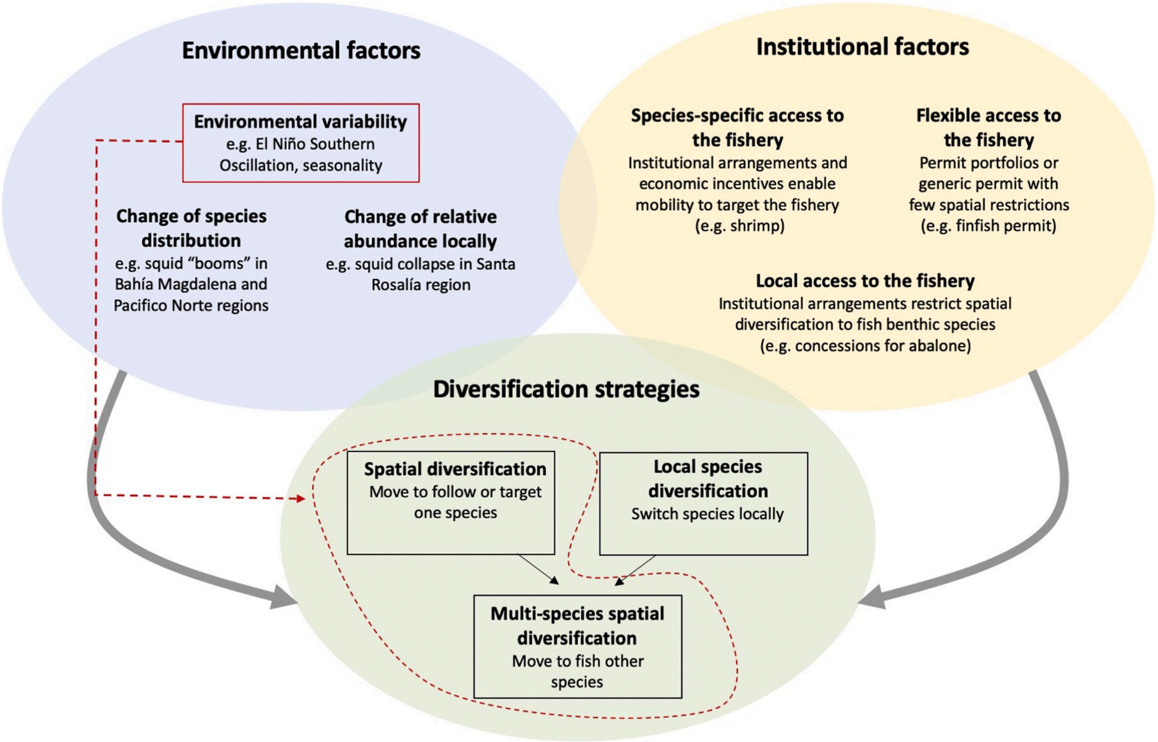

Fig. 5. Multiple factors may influence fisheries diversification strategies. Changes in diversification strategies can be mediated by both environmental and institutional factors. Red arrow represents the correlation between El Niño Southern Oscillation (ENSO) and changes in spatial diversification found in this study.

engage in multi-species fisheries through multi-species permits and/or rely upon portfolios comprised of multiple fishing permits (see Table 1). We also observed several spatial diversification patterns that occurred consistently across years (for example, between Bahia Magdalena region and the South peninsula, Fig. 2), which may reflect processes of recurrent seasonal migration (e.g., Sievanen, 2014; Wanyonyi et al., 2016), or the existence of economic units owning fishing boats in multiple locations. Finally, marked inter-annual changes in spatial diversification were evident in our analysis. Previous research in BCS and elsewhere has reported changes in target species diversification over time (e.g., Finkbeiner, 2015), and here we add to this literature by providing a characterization of changes in spatial diversification in SSF at a sub-national scale.

5.2. Environmental and institutional factors that may shape spatial diversification patterns

The patterns of spatial diversification observed in BCS are likely the result of a combination of environmental and institutional factors, that constrain or enable diversification strategies (Dubik et al., 2019; Young et al., 2019). We hypothesize a set of factors, that when considered collectively may help explain when and why spatial diversification occurs. These factors emerged upon analyzing which landing regions and species groups dominated local versus spatial diversification strategies (Figs. 2 and 4). While our aim is to identify and synthesize several potential factors influencing spatial diversification, we acknowledge that there may be other factors and dynamics affecting each species group in the different fishing localities in which they operate.

Fig. 5 summarizes the main factors identified by interpreting the observed patterns of diversification (Section 4.4). We suggest that oceanographic changes affecting some species like squid, likely incentivize diversification. This may involve spatial diversification strategies where actors target squid in other regions, but also other species (Section 4.4. and references therein). We refer to the latter as multi-species spatial diversification, which results from the simultaneous utilization of species and spatial diversification strategies (Fig. 5). In addition, some institutional factors may facilitate or enable spatial diversification, which can be the case for fisheries with flexible regulations, but also for fisheries where different institutional arrangements incentivize shifting fishing grounds to target specific species. For instance, economic units acting as "patrons" can mandate the mobility of fishers working for them (Frawley et al., 2019b; González-Mon et al., 2019), and/or employ outsider fishers to fish high-value resources (Cinti et al., 2010). Finally, we hypothesize that institutions can directly limit spatial diversification, such as in the case of locally-regulated benthic species (Fig. 5).

5.3. Methodological limitations

Although our social-ecological network approach was very useful for answering our research questions, it nonetheless comes with several limitations. In this paper we present a relatively simple analysis of projected (one-level) networks. This does not take into account the role of different economic units and their individual diversification patterns, which is only referred to in the additional results provided by the sensitivity analysis (supplementary material 1.4) and could be further analyzed through multi-level networks (e.g., Bodin and Tengö, 2012).

Other methods could be used to further investigate the dynamics of this fishery system and/or add alternative mechanisms and explanations to the ones proposed. For instance, while we have focused on environmental dynamics and structural constrains, additional research is required to examine the role of actors' agency and motivations. Likewise, there is a need to further investigate the role of social and cultural norms, as well as gear availability, as they relate to diversification. Analyses at finer geographical scales, would allow for a better understanding of the social and political nuances relevant for geographically appropriate management strategies. While our analyses were limited by the resolution of available information, we encourage the pursuit of more detailed investigations when and where they are feasible.

5.4. Implications for fisheries policy in the era of global change

Spatial diversification can be an especially important strategy to deal with changes in the relative availability of species across different geographic areas within and across years. Given the current and projected changes in species distributions due to climate change (Free et al., 2019; Pinksy et al., 2013) and surprising oceanographic changes such as marine heatwaves (Lonhart et al., 2019; Pershing et al., 2019), the spatial diversification of fisheries actors will likely be of increasing importance in adapting to new and unfamiliar conditions. Governance systems and regulatory frameworks may have important implications for such adaptation mechanisms in a changing climate (Badjeck et al., 2010; Dubik et al., 2019). For instance, more flexible fishing licenses in terms of the number of species and the spatial extent of the permits can enable spatial diversification (e.g., finfish), whereas more exclusive fishing permits managed through spatial concessions (e.g., abalone) can inhibit it. Therefore even if policies that limit fisheries access have contributed to successful resource management (McCay et al., 2014), they also risk promoting specialization and restricting the options fisheries actors have to deal with environmental changes (Cinner et al., 2018; Kasperski and Holland, 2013). This wicked problem warns against ignoring spatial diversification specifically, and diversification strategies in general, when designing and implementing fisheries policies.

Furthermore, management strategies aiming to limit the extent of fishing permits (spatially and through species-based permits), may lead to unintended consequences. These management approaches can lead to displaced fishing effort (i.e., “spillover effects”) and may require a deeper understanding of the social-ecological linkages influencing effort reallocation in order to accomplish their objectives (Cudney-Bueno and Basurto, 2009; Kroetz et al., 2019). In addition, certain environmentally-driven changes such as the collapse of the squid fishery may also lead to spillover effects as effort is reallocated to other fishing regions (Fig. 5), which may increase user conflicts and incentivize overharvesting. The analysis of social-ecological interdependencies between fisheries and the spatial locations in which they operate can help us better account for the existing diversification strategies and evaluate potential implications of policy and environmental changes across scales.

Finally our analysis shows that diverse fishery actors influence changes in spatial diversification. Economic units in Mexico can own several fishing boats and/or permits and distribute them across different localities, enabling a type of spatial diversification that could be a consequence of changes in actors’ organizational capacities and not only mobility, which has not been sufficiently addressed in the literature. Diversification strategies and their policy implications are likely to differ across the many actors that participate in fisheries systems and the institutional arrangements in which they are embedded (Finkbeiner, 2015; Frawley et al., 2019b; Pellowe and Leslie, 2019). There is an important research gap in the role of these actors for diversification processes in SSF, which is key for policies to address diversification strategies while recognizing the power dynamics and inequalities between different actors.

6. Conclusion

In this study we emphasize that diversification is a dynamic process, showing how diversification patterns of SSFs actors at a sub-national scale change between years, and how they differ by landing region and fishery. We also show that changes in spatial diversification are correlated with oceanographic changes and suggest that they may also be constrained or enabled by different regulatory and institutional forms that mediate fisheries access. Our analyses and data do not allow us to precisely determine the relative contribution of specific factors to observed patterns of spatial diversification. However, by carefully parsing our analysis linking it to other regional research, we compile evidence to advance environmental and institutional factors that warrant further investigation.

There is limited research considering both spatial and species diversification strategies in tandem, and evaluating their dynamics as well as factors that may influence their adoption. This is one of the first studies that allows such nuanced understanding at the resolution of commercial species groups considering nearly all species fished at a subnational scale in this type of SSF context, as previous analyses using a similar approach are based on datasets from the United States (e.g., Fuller et al., 2017; Kroetz et al., 2019). The collection and aggregation of high-resolution SSF landings data, like those used in this study, when combined with network approaches, represent a unique opportunity to systematically synthesize and understand the patterns and dynamics of diversification in fisheries.

A better understanding is needed concerning how projected environmental changes might result in complex and cascading responses in SSF, where the reallocation of fishing effort is an important adaptation mechanism. This will be critical for the design of policies that balance the need for restricting spatial diversification to maintain fisheries sustainability, with the need to allow for spatial diversification as an adaptation mechanism to support the resilience of fisheries livelihoods. This study represents a first step in understanding the interdependencies and dynamism of multi-species SSF fisheries systems, which we hope will trigger future research unpacking the mechanisms influencing the dynamics of adaptation in SSF.

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CRediT authorship contribution statement

Blanca Gonzalez-Mon: Conceptualization, Methodology, Validation, Formal analysis, Writing - original draft, Visualization, Writing - review & editing. **Örjan Bodin:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Emilie Lindkvist:** Conceptualization, Methodology, Writing - review & editing. **Timothy H. Frawley:** Conceptualization, Methodology, Visualization, Writing - review & editing. **Alfredo Giron-Nava:** Conceptualization, Methodology, Writing - review & editing. **Xavier Basurto:** Conceptualization, Writing - review & editing. **Mateja Nenadovic:** Conceptualization, Data curation, Writing - review & editing. **Maja Schlüter:** Conceptualization, Supervision, Funding acquisition, Writing - review & editing.

Declaration of Competing Interest

The authors declare no conflicts of interest

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2020.11.006.

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