



Climate adaptation in the market squid fishery: fishermen responses to past variability associated with El Niño Southern Oscillation cycles inform our understanding of adaptive capacity in the face of future climate change

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Received: 9 December 2021 / Accepted: 14 June 2022 / Published online: 4 July 2022
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Abstract

Evaluating the strategies fishermen have used to respond to short-term climate variability in the past can help inform our understanding of the adaptive capacity of a fishery in the face of anticipated future change. Using historic fishery landings, climate records, and fishermen surveys, we document how market squid fishermen respond to high seasonal and interannual climate variability associated with the El Niño Southern Oscillation (ENSO) and responses to hypothetical future scenarios of low abundance and range shift. Overall, fishermen have been able to adapt to dramatic shifts in the geographic range of the fishery given their high mobility, with fishermen with larger vessels expressing a willingness to travel greater distances than those with smaller vessels. Nearly half of fishermen stated that they would switch fisheries if market squid decreased dramatically in abundance, although fishermen who were older, had been in the fishery longer, were highly dependent on squid for income, and held only squid and/or coastal pelagic finfish permits were less likely to switch to another fishery in a scenario of lower abundance. While market squid fishermen have exhibited highly adaptive behavior in the face of past climate variability, recent (and likely future) range shifts across state boundaries, as well as closures of other fisheries, constrain fishermen's choices and emphasize the need for flexibility in management systems. Our study highlights the importance of considering connectivity between fisheries and monitoring and anticipating trans-jurisdictional range shifts to facilitate adaptive fishery management.

Keywords California Current · Diversification · Fishing strategy · Flexibility · Mobility · Range shift

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1 Introduction

Temporal variability is inherent in natural resource-based sectors, including commercial fisheries (Stoll et al. 2017), and is driven by human-induced global environmental change (Halpern et al. 2015), naturally occurring climate phenomena (e.g., El Niño Southern Oscillation [ENSO] and Pacific Decadal Oscillation [PDO]) (Hollowed et al. 2001; Perretti and Sedarat 2016), and socioeconomic pressures (e.g., migration to coastal communities and/or changes in market dynamics/demand) (Bennett et al. 2016; Reddy et al. 2013). In social-ecological systems, escalating environmental changes interact across scales with social and economic changes, which can lead to feedback loops, abrupt change, and heightened exposure to new types of risk (Reyers et al. 2018). Thus, it has become increasingly important to understand whether and how communities and/or individuals dependent on natural resources can adapt to change (Bennett et al. 2016; Cinner et al. 2012; Whitney et al. 2017). Despite the importance of understanding adaptation to change, there are few examples of concrete adaptation actions in marine and fishery systems (Lindegren and Brander 2018; Miller et al. 2018). This limits our ability to predict the capacity of fishermen and other marine resource users to respond to future change (Coulthard and Britton 2015) as well as our understanding of the potential for adaptation that can be incentivized through policy (van Putten et al. 2017).

The ways in which fishermen respond to climate change can be understood within the broader perspective of resilience thinking, where responses fall along an adaptation continuum — remaining/coping (e.g., no behavioral change), adapting (e.g., changing fishing strategies or location), and transforming (e.g., switching fisheries or exiting a fishery) (Coulthard 2009; Ojea et al. 2020; Rubio et al. 2021). One of the most common adaptive strategies fishermen employ is diversification (Anderson et al. 2017), buffering income variability by targeting multiple species or fisheries and allowing fishermen to shift between fisheries based on what is most convenient, abundant, or valuable at a particular moment in time (Anderson et al. 2017; Kasperski and Holland 2013; Robinson et al. 2020). Another common strategy involves changes in fishing activities, including how, where, and when to fish (Wilson 2017). Fishermen may change method of harvest (Cinner et al. 2015), engage in seasonal fishing effort (Sievanen 2014), change the intensity of fishing effort/activity (Stoll et al. 2017), and/or diversify fishing grounds (Young et al. 2019). Furthermore, in order to offset potential losses associated with local declines in abundance and/or range shifts, fishermen can migrate to operate out of new ports (Savo et al. 2017; Sievanen 2014; Young et al. 2019). Lastly, and generally the least desirable option, fishermen may choose to exit the fishery and leave fishing altogether and pursue alternative employment (Coulthard 2009; Johnson et al. 2014). Focusing on these responses at the level of the individual fishermen is particularly important (but uncommon) because ultimately, adaptive responses occur at this scale (Stoll et al. 2017).

From an ecological standpoint, ongoing climate change is causing unprecedented changes in ocean and coastal conditions. In the California Current System (CCS), there is considerable evidence of significant ocean warming (Schwing et al. 2010) and associated changes in ocean stratification over the past century (Palacios et al. 2004). A recent study found a robust increase in future Eastern Pacific ENSO sea surface temperature (SST) variability due to greenhouse warming-induced intensification of upper-ocean stratification, as well as an increase in the number of strong Eastern Pacific El Niño events (Cai et al. 2018). Projections show a robust and unambiguous signal of future surface warming in the CCS, with predicted increases in SST between 2.5 and 5 °C by 2090 (Pozo Buil et al. 2021), along with changes in the timing and intensity of upwelling, which affects nutrient and oxygen concentrations (Checkley and Barth 2009; Pozo Buil et al. 2021; Xiu et al.

2018). These changes impact many commercial fisheries in the region such as market squid (*Doryteuthis opalescens*), which has routinely ranked as the state of California's top commercial fishery in terms of volume (tons) and value (US dollars) (NMFS 2018).

Market squid abundance exhibits substantial interannual variability due to variable recruitment, growth, and survival of populations in response to fluctuating oceanographic conditions associated with ENSO (Jackson and Domeier 2003; Perretti and Sedarat 2016; Zeidberg et al. 2006). Market squid populations decline drastically in unfavorable environments associated with El Niño events, characterized by warm SST and low productivity, and rebound rapidly during favorable conditions associated with La Niña events, characterized by cool SST and high productivity (Reiss et al. 2004; van Noord and Dorval 2017). Such large-scale population variability and periodic collapses of the fishery not only have a large economic toll on fishing communities, but they also greatly disturb ecosystem food web dynamics given that market squid are one of the state's most important forage species (Alder and Pauly 2006; Morejohn et al. 1978).

In addition to volatility in landings and abundance, the fishery is subject to spatial and phenological changes. Landings in the northern range of the fishery (north of Point Conception, primarily out of Monterey Bay) traditionally take place from April through November, while landings in the southern range of the fishery (south of Point Conception, predominantly around the Channel Islands) traditionally take place from October through March, due to regional and temporal differences in peak spawning (Porzio and Brady 2008). Typically, only about 20% of the annual statewide squid catch comes from the northern fishery, with the remainder caught in the southern fishery (Cavole et al. 2016). However, the availability of market squid to the fleet can vary tremendously from year to year due to regional oceanographic processes (Ralston et al. 2018). Numerous reports of market squid in Oregon, Washington, and Alaska in 2015 and 2016 (Chambers 2016; Columbia Basin Bulletin 2018, Miller 2015) support the prediction that the market squid population along the US west coast shifted north in response to warm water events such as the "Blob" (Cavole et al. 2016), and models based on fishery independent data show that squid has become increasingly abundant in northern latitudes in the California Current over the past two decades (Chasco et al. 2022). In terms of changes in phenology, warmer ocean temperatures cause squid to mature faster (Forsythe 2004) and recruit to spawning grounds earlier (i.e., before the seasonal peak in prey availability) (Sims et al. 2001). Accelerated maturation could thus cause a "match-mismatch" scenario that alters critical trophic interactions (van Noord and Dorval 2017). Concomitant shifts in species distributions, changes in phenology, and reductions in abundance will redistribute resources available to local fishing communities, possibly leading to revenue losses, disruptions in the processing and supply chain, and less effective fishery management measures (e.g., Mills et al. 2013; Pinsky and Fogarty 2012).

Globalization of the seafood industry has also influenced fishery dynamics over time through shifts in market dynamics and demand. In particular, the rapid expansion of seafood markets to China (Crona et al. 2020; FAO 2020; Porzio and Brady 2008) caused the market squid fishery to expand tremendously in scale. The majority of the commercial catch (~80%) is exported to Asian and European markets, with China being the largest market (Porzio and Brady 2008). Given the market squid fishery's global market, it is also highly susceptible to economic and market volatility associated with changes in international demand and/or tariffs (Ess 2020; FAO 2020). For example, COVID-19-related market volatility was associated with an 80% decline in total landings from ~66,678 metric tons in 2017–2018 to ~13,607 metric tons in both the 2019–2020 and 2020–2021 seasons. Furthermore, in the 2018–2019 season (pre-COVID-19), squid exported to China carried a 27% tariff, whereas in 2019–2020 season, the USA imposed an additional 25% for a total of 52% (value-added charges and duty combined) (Ess 2020), resulting in very low prices offered to squid fishermen.

The growing international demand coupled with subsequent increases in effort and landings facilitated by newer, larger, and more efficient vessels and greater processing capacity (PFMC 2008) prompted the California Department of Fish and Wildlife (CDFW) to develop the Market Squid Fishery Management Plan (MSFMP) in 2005. The MSFMP established several static management measures including a fixed seasonal catch limit of 118,000 t, two-day weekend closures, light and gear restrictions, a restricted access program, and monitoring programs (port sampling and logbooks) (CDFW 2005). While current management measures prevent excessive fishing effort and allow for critical periods of uninterrupted spawning (CDFW 2005), the static, equilibrium-based fishery control rules do not account for or address climate-driven interannual variability in stock dynamics and productivity. Furthermore, despite the mobility afforded by the large vessels in the squid fleet, the implications of a more permanent northerly range shift could have cascading ecological and economic impacts and may require a shift from a state-based to a regional fishery management approach.

The magnitude of ongoing change (both climatic and socioeconomic) raises important questions and concerns regarding market squid fishermen's capacity to adapt to predicted future climate change (Chavez et al. 2017; Stoll et al. 2017) and the implications of their adaptive capacity for the future of the fishery. Whether due to cyclical climate variability or market and regulatory influences on fishing dynamics, market squid fishermen have a long history of adapting to challenging conditions. Here, we assess market squid fishermen's responses to past short-term climatic events associated with the ENSO cycle, particularly the regional warming conditions associated with El Niño events, as a proxy to reflect likely response to future, more permanent warming trends. Using landings data and fishermen interviews, we present trends based on fishermen's responses to previous ENSO events as well as their stated responses to potential future scenarios including reductions in species' abundance and range shifts. We also evaluate how characteristics of individual fishermen (e.g., age, boat size, dependence on squid, and access to additional permits) influence decision-making and adaptive responses. We conclude with a discussion of the implications of our findings for the adaptive capacity of the market squid fishery, as well as management considerations that will be critical in ensuring fishery sustainability and adaptation in a changing climate.

2 Methods

To understand how fishermen respond to changing conditions in the market squid fishery, we used a convergent mixed methods framework and methodological triangulation (Olsen 2004). We conducted parallel analyses of quantitative fishery-dependent and climate data and qualitative survey data to identify drivers of change relevant to the fishery, examine how fishermen adapt in response to the aforementioned changes, and explore whether fishermen's responses differed based on relevant demographic and socio-economic characteristics. By comparing information obtained from diverse sources, triangulation approaches ensure greater validity and reliability (e.g., Islam et al. 2014; Whitney et al. 2017), and can generate a deeper, contextual, and more comprehensive understanding of complex social-ecological systems (Bennett et al. 2016; Frawley et al. 2021).

2.1 Fishery landings data and Oceanic Niño Index

Fishery-dependent landings data were analyzed to explore patterns relating to fishermen's responses to change. Forty seasons (1980–2019) of market squid landings data were obtained

through a confidential, non-disclosure agreement with CDFW. This type of data, known as fishery-dependent data, is derived from the fishing process itself and is collected through self-reporting by fishermen. Landing receipts provide detailed daily information on both quantity (lbs) and location (CDFW fishing block) of catch. These blocks (10×10 nautical miles) correspond to a three-digit database code that CDFW uses to record and aggregate all “fish ticket” and landings data. Each entry corresponds to a unique fishing trip ($N=102,001$ total trips/unique observations). We primarily focused on information pertaining to quantity and location of catch. Given that data is self-reported by fishermen, it is prone to human error and requires data cleaning. This entailed excluding catch data that was not in a recognized CDFW fishing block and eliminating duplicate entries (in which every column was identical).

In order to understand how ENSO-related variability alters fishing patterns, catch data were aggregated spatially (by fishing block) and temporally (by ENSO phenomenon). To explore spatial changes in fishery landings during different ENSO phases, the percentage of total catch obtained from each fishing block was calculated for each season. Each fishing season was assigned to a group corresponding to the strength (weak, moderate, or strong) and type (El Niño, La Niña, or neutral) of event that occurred during that season based on the Oceanic Niño Index (ONI) (see Electronic Supplemental Material [ESM], Table S1). The National Oceanic and Atmospheric Administration’s (NOAA) Climate Prediction Center defines ONI as the 3-month running mean of SST anomalies in the Niño-3.4 region (i.e., 5°N – 5°S , 120° – 170°W), based on centered 30-year base periods updated every 5 years (NOAA 2019). Events are defined as five consecutive overlapping 3-month periods at or above the $+0.5^{\circ}\text{C}$ anomaly for warm (El Niño) events and at or below the -0.5°C anomaly for cold (La Niña) events. The threshold is further broken down into weak (0.5 to 0.9° SST anomaly), moderate (1.0 to 1.4°), and strong ($\geq 1.5^{\circ}$) events. Neutral events indicate seasons with no statistically significant SST anomaly (i.e., those that did not exceed the $\pm 0.5^{\circ}\text{C}$ anomaly).

We explored both spatial and temporal variability in landings data in relation to past ENSO events. To maintain consistency with fishermen interviews and because extreme events tend to show the clearest signal of change, we focused our analysis on strong El Niño and La Niña events, as well as neutral events. For the spatial component of our analysis, we averaged the percent catch from each block across all seasons that fell into the same event strength grouping. For seasons between 1980 and 1999, the given block may indicate landing location versus fishing location due to discrepancies in data reporting between earlier and later seasons, but still corresponds with the general latitude of fishing activity. All spatial processing was conducted using the *sf* package (Pebesma 2018) in R. Mapped data products were projected using the California Teale Albers (NAD83) (Patterson 2018). In order to investigate temporal changes in landings as a function of ENSO, we calculated the percentage of total season catch per month for each season, and then averaged monthly percentages across seasons that fell into the same event strength grouping.

2.2 Fishermen surveys

Surveys were conducted with active squid fishermen between January 2017 and November 2018 with the goal of surveying an owner or boat operator representing as many active squid vessel permits as possible. Permits were considered “active” if the vessel participated in the fishery (landed and reported catch) in at least one of the previous three fishing seasons (i.e., 2014–2015, 2015–2016, 2016–2017) based on a list of permits and landings data obtained from the CDFW. Surveys were conducted at Ventura Harbor, the primary landing port for squid, as well as non-port locations or by phone (if preferred or if fishermen were

based outside of southern California). A total of 54 squid fishermen were interviewed, representing 48% of total active vessels (both squid and squid lightboat) during the survey period. The survey consisted of a series of multiple choice, Likert scale, and open-ended questions related to changes in the fishery (i.e., timing, location, abundance, and other) due to ENSO or other regional climate patterns in the last 5–10 years, responses to past warm-water events, and responses to hypothetical lower abundance and species' range shift scenarios. The survey also included a series of multiple-choice and open-ended questions relating to demographic and socio-economic characteristics that might influence fishermen's responses to change.

After familiarizing ourselves with the interview data, open-ended responses were coded using an iterative, inductive approach (e.g., Maguire and Delahunt 2017) to identify themes relating to observed changes, adaptive strategies, and responses to hypothetical scenarios. We reviewed and coded the data until no new themes emerged. Following identification of themes, fishermen's adaptive strategies and responses were analyzed using descriptive (i.e., frequency, mean, and standard deviation) statistics. In order to determine whether responses to hypothetical scenarios were associated with fishermen's demographic or socio-economic characteristics, we used inferential statistics (unpaired two sample t tests, non-parametric two-sample Wilcoxon rank test, and two proportion z tests) within the R environment (R Core Team 2020). Fishermen's responses were coded into three distinct groups: continuing to participate in squid (including fishermen who did not change fishing strategies or behavior and those who did), switching to another fishery, and exiting fishing (e.g., selling their permit or taking up non-fishing employment). We selected t tests under the assumption that both samples are random, independent, and come from normally distributed populations (confirmed using the Shapiro–Wilk test) with unknown but equal variance. If samples were not normally distributed, we used the Wilcoxon rank test. When dealing with categorical data (e.g., resource dependence and type of additional fishery permit(s)), we used the two proportion z test to determine if the proportions of categories in two group variables significantly differed from each other. We considered fishermen to be primarily dependent on squid if > 60% of their total annual income was from squid. As we were interested in understanding whether certain types of permits facilitate flexibility in response to change, we grouped fishermen into two groups based on feasibility/ease of switching — those holding only squid or coastal pelagic finfish permits (i.e., mackerel, anchovy, sardine, bonito) in addition to squid and those holding other types of permits (e.g., salmon, lobster, longline, crab, etc.) in addition to squid.

In order to visualize and explore spatial responses to change as reported by market squid fishermen, participants were asked to identify and delineate fishing grounds during an ENSO neutral season and during an El Niño phase of ENSO. Fishermen either stated specific CDFW fishing blocks or provided ranges (minimum/maximum latitude or northern/southern location) of fishing areas, which we then converted to fishing blocks. All coastal fishing blocks within a stated range were included. We then generated choropleth maps using the *sf* package (Pebesma 2018) in R to display the percentage of respondents who reported fishing in a given block during El Niño and neutral phases of ENSO. Lastly, in order to determine whether distance traveled to fishing grounds varies between El Niño and neutral phases of ENSO, we calculated the distance traveled (after accounting for land and the curvature of California's coastline) from a fishermen's home port to the centroid of each specified fishing block for each ENSO phase independently. Distance data for each individual fisherman were averaged and then compared for differences between each ENSO neutral and El Niño event years.

2.3 Fishermen feedback session

Following completion of data analysis, we held a feedback session with squid fishermen to present preliminary findings in order to get their feedback on data analysis and interpretation and answer outstanding questions that arose from preliminary data analysis. The session was held in November 2019 with 11 fishermen in Ventura, CA, the primary port for squid and where most fishermen are based during that time in the fishing season. Participants were recruited based on an opt-in question at the end of the survey (asking fishermen if they wanted to participate).

3 Results

Results from both the fishermen surveys and landings data are presented thematically in order to corroborate and compare findings.

3.1 Observed changes in fishery

There was substantial consensus among fishermen regarding observations of changes in the fishery in relation to regional climate variability (particularly ENSO cycles) in the past 5–10 years. Eighty-seven percent of fishermen acknowledged that they had noticed changes, while only 2% had not. The remaining fishermen were not sure or had been in the fishery for less than 5 years. Of the fishermen who had noticed changes, 79% noted changes in abundance, 72% noted changes in location/range of squid, and 28% noted changes in the seasonal availability of squid or timing of spawning events.

For each category of change, fishermen were asked to elaborate on the changes they observed. Of the fishermen who observed changes in location/range of squid, 82% stated that squid spawned farther north during El Niño events, resulting in a more productive fishery in the northern range (i.e., north of Point Conception, primarily Monterey), and 41% of respondents believed that squid spawned at deeper depths during El Niño. Several fishermen noted that the most recent El Niño event (2015–2016, the “Blob”) resulted in the most drastic range shifts, with large quantities of squid found in Humboldt, Oregon, Washington, and Alaska.

Fishermen’s observations of a fairly recent northward range shift are consistent with trends in fishery landings data. While the proportion of catch in the southern fishery historically has been much greater than that of the northern fishery (except during strong El Niño events and sometimes during the year immediately after the event), since 2014–2015, the proportion of catch in the northern fishery has increased (ESM, Fig. S1). Percentage catch in the northern fishery increased from an average of 20.2% between 1990–1991 and 2013–2014 seasons to an average of 49.2% between 2014–2015 and 2018–2019 seasons.

Of the fishermen who noted changes in abundance, all agreed that there were fewer squid during El Niño events; however, fishermen attributed this decrease in abundance to different factors. Seventy-six percent noted a decrease in abundance of squid as warm temperatures and reduced prey availability (from decreases in upwelling) result in higher mortality rates at each life history stage of squid. Several of these fishermen specifically noted that El Niño-induced declines in abundance continue to affect the fishery for 1 to 2 years after the event. Twenty-seven percent of fishermen who noticed changes

in abundance reported that squid were unharvestable, believing they were likely spawning in atypical locations where they could not be easily accessed (i.e., further north or in deeper offshore waters than what is commercially fished).

Finally, of the fishermen who observed changes in the timing and seasonality of fishery events in recent years and during past El Niño events, 82% said that peak fishery landings occurred months earlier, while 18% mentioned that the catch was less seasonal (i.e., occurring year-round versus peaking late in the season). Landings data also showed that during ENSO neutral and strong La Niña seasons, the majority of catch takes place in the southern fishery, whereas during strong El Niño events, catch is concentrated in the northern fishery. The proportion of catch in the northern fishery during El Niño seasons (0.71 ± 0.18) was, on average, significantly greater than both ENSO neutral seasons (0.21 ± 0.09) ($t(7) = 5.56$, $p = 8.5 \times 10^{-4}$) and strong La Niña seasons (0.05 ± 0.09) ($t(6) = 6.55$, $p = 6.1 \times 10^{-4}$) (Fig. 1). These spatial shifts in the fishery also affect the timing of peak catch. During ENSO neutral and La Niña seasons, the majority of catch occurs between October and March, which coincides with the timing of peak spawning in the southern portion of their range. During strong El Niño seasons, however, peak landings occur much earlier in the season, between April and September (Fig. 2).

3.2 Fishermen's responses to change

3.2.1 Previous El Niño events

Seventy-six percent of fishermen said that they had changed their fishing strategies in response to previous El Niño events. Of the respondents who altered their fishing strategies, 59% shifted their effort north and fished primarily in the northern range of the fishery, 24% fished deeper, 17% fished further offshore, and 15% temporarily exited the fishery (either tying up their boat for the season or switching to another fishery) (ESM, Fig. S2). In addition to changes in the location of fishing activity, fishermen also reported traveling significantly farther from their home ports during El Niño events versus ENSO neutral fishing seasons (Fig. 3). During El Niño events, fishermen traveled, on average, 171.6 km (106.6 mi) further to fish than during ENSO neutral seasons ($t(61.9) = 2.9$, $p = 0.005$).

When self-reported changes in fishing location are viewed spatially (by CDFW fishing block), the latitudinal patterns in fishing activity during El Niño and neutral phases of ENSO show clear differences (Fig. 4). In an ENSO neutral fishing season, the fishery is distributed in coastal waters from San Francisco to the California-Mexico border, with the majority of participants fishing south of Point Conception and throughout the Channel Islands. During strong El Niño events, the total fishing area expands and effort is concentrated in central/northern California. Eight fishermen noted that they had traveled well beyond the border and into southern/central Oregon during historically strong El Niño events. Fishermen's reported changes in fishing location/effort (i.e., northward) during El Niño events are consistent with spatial trends in fishery landings data (Fig. 1).

3.2.2 Range shift

In addition to understanding how fishermen have responded to past climate variability, we also sought to understand how participants would respond to a hypothetical scenario in which the fishery range shifted north beyond the historical species distribution. Responses

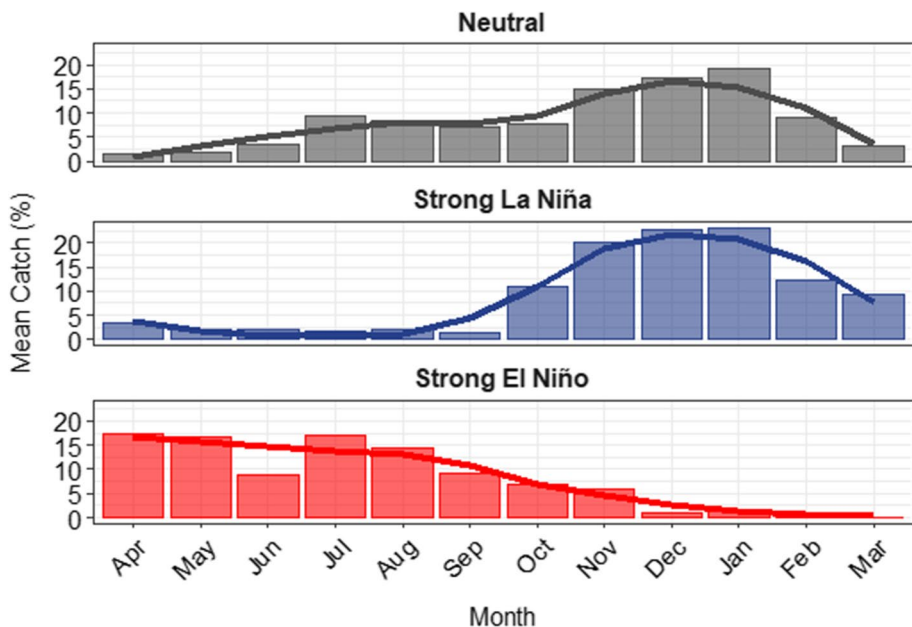
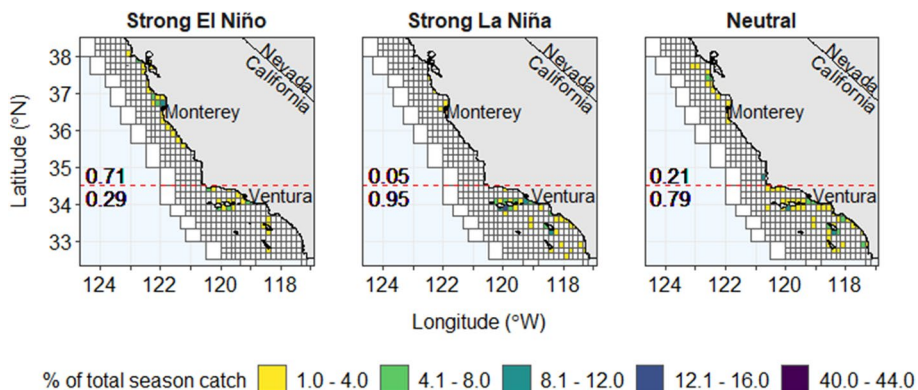


Fig. 2 Percentage of total market squid catch per month averaged across seasons (1980–2018) that fell into the same strength/event grouping (based on the Ocean Niño Index characterization). Lines represent smoothed estimates obtained from a loess smoother. Note that fishing season runs from 1 April to 31 March of the subsequent year

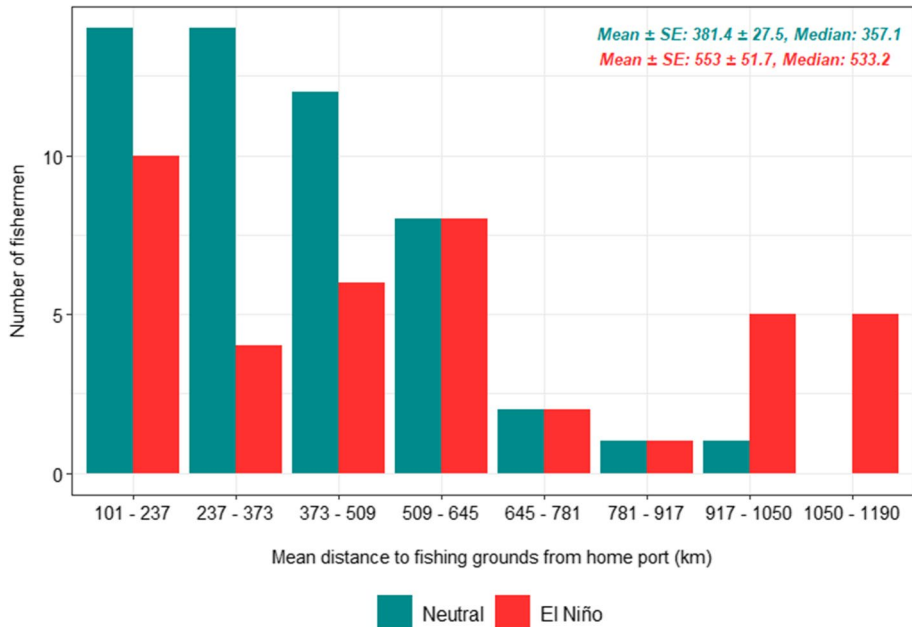


Fig. 3 Mean distance to reported market squid fishing locations during neutral ($n=52$ fishermen) and El Niño ($n=41$ fishermen) phases of the El Niño Southern Oscillation (ENSO). The distance from a fisherman's home port to the centroid of each reported California Department of Fish and Wildlife (CDFW) fishing block was calculated for each ENSO phase. Individual distance data were averaged and sorted into non-overlapping bins of equal length

to this scenario were highly consistent, with 94% of fishermen saying that they would travel to catch squid in other locations (ESM, Fig. S3). Of these fishermen, 87% stated that they would travel an unlimited distance, mentioning Oregon, Washington, and/or Alaska as potential fishing locations due to the mobility afforded by their large vessels. However, 18% of those fishermen provided other contingencies that might affect their willingness to pursue squid, including economic feasibility and consistency of fishing, market price/value, and availability or proximity of offloading facilities. The remaining 14% of fishermen who were willing to travel said they would travel with limitations on distance, generally setting Monterey and/or San Francisco as their northern limit. The fishermen who stated that they would travel with limitations or not travel at all in response to a hypothetical range shift had significantly smaller vessels on average than the fishermen who stated that they were willing to travel an unlimited distance (mean difference 23.7 ft [7.22 m]) ($t(42)=6.5$, $p=7.7 \times 10^{-8}$).

3.2.3 Lower abundance

Fishermen were also posed with a hypothetical scenario of lower abundance of squid in the future. In the event of low squid abundance, 46% of the participants said that they would switch to another fishery (ESM, Fig. S4). Alaskan salmon was the most commonly mentioned fishery that fishermen would switch to, and it was the second most commonly held permit in addition to squid. While coastal pelagic species permits (i.e., sardine, anchovy,

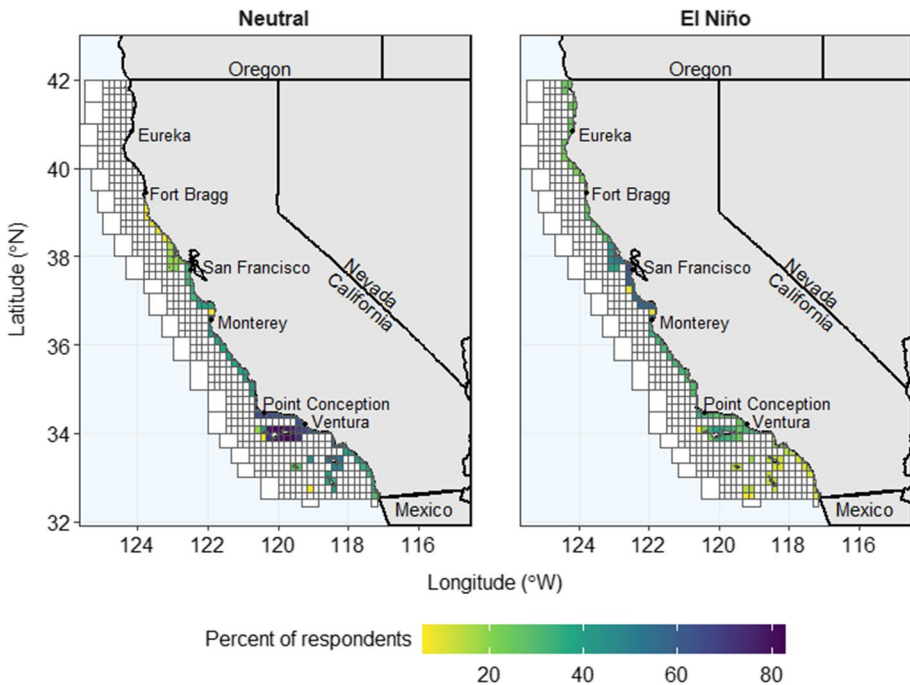


Fig. 4 Market squid fishing grounds during neutral ($n=52$ fishermen) and El Niño ($n=40$ fishermen) phases of the El Niño Southern Oscillation (ENSO). Values indicate the percentage of fishermen who reported fishing in a given California Department of Fish and Wildlife fishing block (10×10 nautical miles) for each ENSO phase. Note that blocks with less than 2 entries were excluded

mackerel, bonito) were the most commonly held additional permits, this was the least commonly mentioned alternative fishery choice (Fig. 5). Approximately 41% of fishermen stated that they would continue to participate in the squid fishery, with 35% of fishermen reporting they would do so with altered fishing strategies (e.g., increasing distance traveled, increasing effort, or fishing a longer season) and 6% stating they would continue without changes in effort and/or behavior (ESM, Fig. S4). Additional responses to a hypothetical reduction in abundance include permanently exiting the fishing industry and/or seeking non-fishing employment (~7%) and temporarily dropping out of fishing for the remainder of the season (or until conditions improve) (~6%). Seventeen fishermen gave first and second resorts (i.e., for low abundance and very low abundance scenarios); however, overall trends remained the same, but with an increase in the number of fishermen who stated they would quit fishing or sell their permit and/or seek non-fishing employment (as a second resort) (ESM, Fig. S5).

We found that fishermen's age, the number of years they had participated in the fishery, the percent of total income derived from squid, and the type of additional fisheries permits held all influenced fishermen's stated responses to hypothetical low squid abundance. On average, fishermen who stated they would exit the fishing industry were significantly older than those who stated that they would switch to another fishery (mean difference 17.6 years), ($t(27)=3.08$, $p=0.005$). Similarly, fishermen who stated that they would switch to another fishery had participated in commercial squid fishing for fewer years than

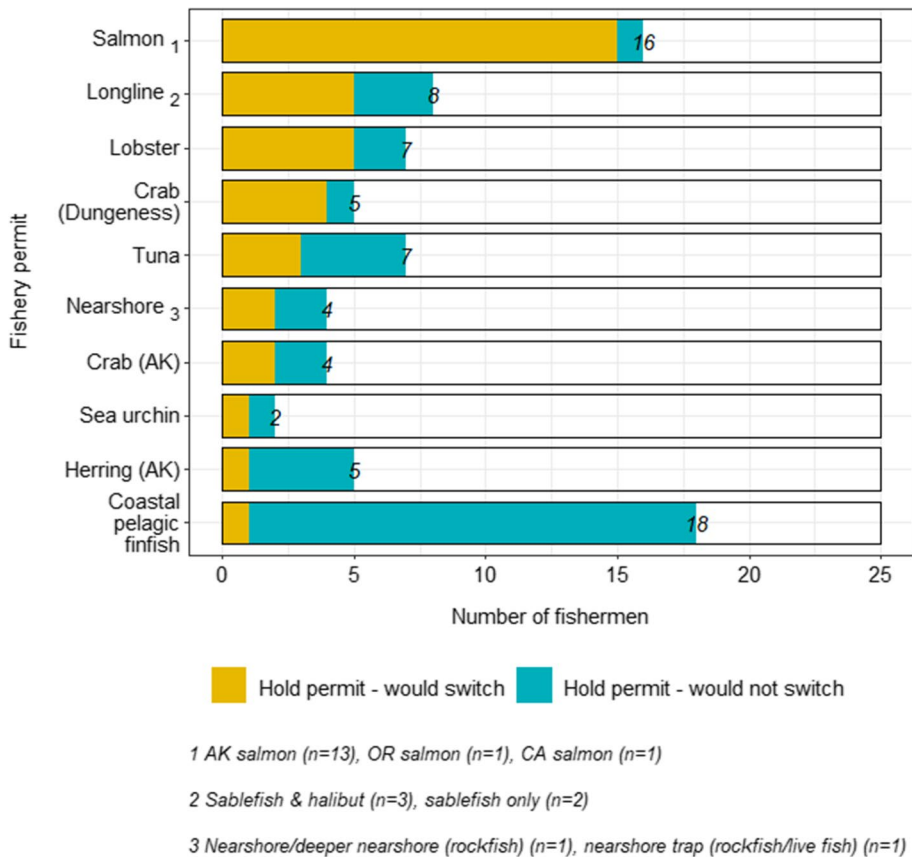


Fig. 5 Stacked barplot showing the number of market squid fishermen who hold permits for additional fisheries (total number indicated by italicized value) out of those who stated they would switch to an alternative fishery in response to hypothetical lower abundance ($n=25$). The yellow bar indicates the number of fishermen who stated they would switch to each fishery, and the turquoise bar shows the total number of fishermen who hold a given fishery permit, but would not choose to switch to it as an alternative to squid

those who stated that they would quit/exit fishing ($W=90$, $p=0.008$). Resource dependence, or percent of total income from commercial squid fishing, also differed between response groups. Fishermen who are primarily dependent on squid (i.e., > 60% of total annual income) were significantly more likely to state that they would continue to participate in the squid fishery (0.95) given a hypothetical decline in abundance than switch to another fishery (0.3) ($z=3.92$, $p=8.9 \times 10^{-5}$). Fishermen primarily dependent on squid were also significantly more likely to state that they would exit the fishing industry (1) than switch to another fishery (0.3) ($z=2.04$, $p=0.02$). The type of additional fishery permits that fisherman held also significantly influenced fishermen's stated response to hypothetical lower abundance. Fishermen who only held squid and coastal pelagic finfish permits (versus those holding other additional permits) were significantly more likely to state that they would either continue to fish for squid or exit the fishing industry (0.92) than switch to another fishery (0.27) ($z=4.44$, $p=9.2 \times 10^{-6}$).

4 Discussion

Our mixed-methods approach employed complementary data sources to investigate fishermen's responses to climate variability in the market squid fishery. Findings were consistent between quantitative and qualitative data sources, strengthening the validity of our results. This mixed-methods approach also provided a more in-depth, contextual, and comprehensive understanding of fishermen's adaptive capacity in regards to how they have responded to past change as well as considerations for how they might respond to future change.

Short-term variability in ocean and climate conditions associated with ENSO has resulted in notable changes in the market squid fishery over the past several decades. During past El Niño events, fishermen have observed marked reductions in squid abundance and/or availability, northward and possibly depth-related changes in spawning location, and changes in timing of peak fishery landings. Given projections of an increase in the frequency and intensity of strong eastern Pacific El Niño events (Cai et al. 2018) coupled with the species' high sensitivity to fluctuating environmental conditions (van Noord and Dorval 2017), the market squid fishery will likely be subject to significant changes in the future. As climate change continues to shift the distribution of squid northward and potentially deeper, fishermen will experience economic and logistical challenges associated with shifting fishery operations, including learning about and fishing in geographically new areas and traveling further to reach more favorable grounds, likely raising safety concerns and increasing fuel, bait, and crew costs (e.g., Chavez et al. 2017; Pinsky and Fogarty 2012). Additionally, due to the very high perishability of the product as well as the limited infrastructure for offloading, processing, and cold freezer storage in northern ports, potential expansion in areas where the fishery is emerging is currently limited.

4.1 Implications for adaptive capacity in the market squid fishery

4.1.1 Mobility

Market squid fishermen have exhibited highly adaptive behavior when faced with past ENSO-related changes in the fishery, and they expressed confidence in their ability to continue to adapt to hypothetical future scenarios of species' range shifts and low abundance. The majority of participants were able to cope with changes in the fishery associated with past El Niño events by shifting the location (north) or depth (deeper) of fishing, which was facilitated by large and mobile vessels characteristic of the market squid fleet. This is in line with other studies that found that high mobility can buffer fishing communities from the effects of environmental change (Sievanen 2014; Young et al. 2019). When posed with a hypothetical future scenario in which the fishery range shifted north beyond the historical focus, nearly all fishermen were willing to travel great distances to target market squid in other locations. While attachment to a particular place can limit fishermen's willingness to travel far from their home fishing grounds (Cinner et al. 2018; Seara et al. 2016; Shaffril et al. 2015), highly mobile fleets may be less likely to express strong attachment to fishing in a particular place (NOAA 1993), and squid fishermen already cover large ranges while fishing. During the feedback session, fishermen noted that this willingness to travel has increased dramatically over the last 5 years due to higher demand for squid. They also noted that many individuals had quickly responded to previous challenges relating to limited offloading infrastructure in northern California by using mobile pumps.

While greater mobility enables fishermen to adapt to fluctuations in stock distribution and abundance, short- or long-term migration could have significant socio-economic consequences for fishing communities. In addition to economic and logistical consequences to the fishermen themselves (discussed above), shoreside services that support market squid fisheries, including traditional ports, processors, dealers, and supply houses, could experience reduced revenue and income flow as fishermen migrate from their traditional grounds to land and process their catch in new locations (Chavez et al. 2017).

Given that fishermen with larger vessels are more mobile, fleet composition could shift toward larger vessels if the range of squid continues to expand. Such a shift would have implications for catch efficiency as larger vessels can capture and store greater quantities of squid with less effort than smaller vessels. In addition, larger vessels with greater engine power will likely have higher total catch due to their ability to exploit distant (and potentially less exploited) fishing grounds and deal with adverse weather and ocean conditions, thus potentially increasing fishing days (e.g., Robinson et al. 2020). A shift toward larger vessels could also push smaller vessel owners and operators, typical of those with lightboat and brail/scoop permits, out of the fleet. Fishermen noted during the feedback session that market squid permits are increasingly owned by large corporations rather than by the fishermen operating the boats, as large seafood processing companies have bought out independent fishermen to secure their supply over competing buyers (Rahaim 2016). This recent trend toward consolidation, coupled with a potential shift toward larger vessels as the fishery expands northward, may push the remaining smaller-scale owner operators out of the fishery. To date, fishermen based in northern California who wanted to participate in the emerging squid fishery have been restricted by the extremely high cost of entry, incompatible vessels (and gear), inflexible permitting which was based on historical participation in the fishery, and a lack of offloading, storage, and processing infrastructure (Chambers 2016; Chavez et al. 2017).

4.1.2 Diversification

As ocean systems continue to be affected by climate change, the fishing industry and associated management systems must adapt and develop novel ways to ensure sustainable fisheries into the future. In the USA, many fisheries are managed by limited entry permit systems that restrict access to help prevent overexploitation. However, the high cost of permits and overall lack of flexibility in permitting and quota allocation also prevents fishermen from diversifying their target stocks as changes in the climate, ecosystem, and fishery occur, ultimately reducing their adaptive capacity (Gourlie 2017; Mills et al. 2013). To viably continue to participate in fishing in light of ongoing climate change, fishermen need the flexibility to adjust where, when, and what they catch, which necessitates flexibility in the management system.

While the majority of market squid fishermen held permits for multiple fisheries, we found that the degree of flexibility afforded by holding additional permits is contingent on the type of additional permit(s) held, as well as the status of the stock and economic value of the fishery. The most frequently held additional permit for market squid fishermen is for coastal pelagic finfish fisheries (i.e., Pacific sardine, Pacific mackerel, and northern anchovy), given their overlapping ranges, gear and vessel requirements (i.e., round haul gear such as purse seines and drum seines), and personnel (i.e., crew, buyers, and shoreside receivers and processors) (Pomeroy et al. 2002). This interconnected fishery system has historically enhanced flexibility, as fishermen have shifted effort among these fisheries in response to fluctuations in

resource availability or demand associated with climate (given that the species favor different ENSO phases), market, and regulatory changes (Aguilera et al. 2015; Pomeroy et al. 2002). However, the closure of the Pacific sardine fishery in 2015, as well as reductions in demand and thus value of anchovy and mackerel fisheries, now undercut the advantages of having a coastal pelagic finfish permit, meaning the most complementary and commonly held additional permit that market squid fishermen hold no longer increases flexibility. While most market squid fishermen stated that they would move or shift target species in response to climate perturbations, a smaller group, primarily older fishermen who had been in the fishery longer, were highly dependent on squid for income, and who held only squid and/or coastal pelagic finfish permits, stated they would resort to temporarily or permanently exiting fishing in response to climate-induced declines in market squid abundance.

4.1.3 Adaptive permit allocation

Adaptive, responsive, and proactive management and decision-making frameworks are essential to mitigate impacts of climate change on fisheries (FAO 2020). Distributive conflicts and policy revisions are already occurring in states where stocks straddle management boundaries but are undergoing a spatial redistribution. For example, warming ocean temperatures along the East Coast of the USA have resulted in large-scale northward shifts in fishery stocks for the summer flounder (*Paralichthys dentatus*) and black sea bass (*Centropristis striata*) fisheries. Fishermen in northern regions of these species' ranges either do not have permits for landing and processing the fish, or quotas, which are based on historical fishery catch, are allocated primarily to southern states (Dubik et al. 2019; MAFMC 2021). The misalignment between fish allocations and their geography, which has generated frustration in the fleets and conflict between management authorities, led to policy revisions seeking to equitably reallocate quota; however, the process has been highly contentious (Suatoni 2020). This will be an emerging issue on the West Coast as species shift beyond the jurisdictions in which they are traditionally managed, which is already occurring with market squid.

To facilitate access to market squid for fishermen based out of northern California ports, new legislation has recently been passed to initiate an Experimental Fishing Permit (EFP) program for small-scale operators from Point Arena to the California/Oregon border (Marine fisheries: experimental fishing permits 2018). This trial EFP could provide new opportunities for local fishermen in these northern California ports (e.g., Eureka, Fort Bragg, and Crescent City) who are currently dealing with closures and/or declines of previously abundant and commercially important species (e.g., salmon, groundfish, herring, abalone, and sea urchin) (Bates and Hildebrand 2018; Pomeroy et al. 2010). Proponents of this trial EFP state that it would enable collection of real-time fishing reports on northern California market squid stocks and resource availability, which could be utilized to test and develop more dynamic management strategies within a smaller fleet or cooperative. Programs such as this have the potential to facilitate adaptive permit allocation (on a small scale), promote collaborative and cooperative fisheries research, and decrease the likelihood of conflict with fishermen in northern parts of the state as fisheries migrate northward.

4.1.4 Trans-jurisdictional fishery management

The northward shift in market squid catch also has implications for trans-jurisdictional fishery management. Historically, the market squid fishery has been managed by the state

of California, given that the vast majority of catch occurs within state waters. As such, geographic movement of resources across political boundaries in a state-managed fishery raises important discussions regarding whether and how fishermen follow the fish, the allocation of permits to potential new fishery entrants, the social impacts of shifts in fishery resources, trans-jurisdictional institutional coordination, and sustainable fishery management.

With warming ocean temperatures, market squid have been increasingly found in large aggregations outside of California, such as in Oregon, Washington, and Alaska (Chambers 2016; Columbia Basin Bulletin 2018; Soley 2018). This trend was corroborated during surveys and follow-up sessions, where fishermen mentioned that people had traveled well beyond the California state line and into southern/central Oregon to land squid during recent strong El Niño events. In fact, from 2016 to 2020, nearly 25.4 million pounds of market squid were landed in Oregon ports (ODFW 2021), with a catch value of approximately \$6 million in 2020 (Tims 2021). In 2021, in response to these recent increases, the Oregon Department of Fish and Wildlife (ODFW) implemented new regulations specific to market squid fishing in state waters, including a weekend closure (similar to California to allow for uninterrupted spawning), rib line requirements (to reduce bycatch and destruction of benthic habitat), and logbook requirements for lightboats (to track participation and effort). Given the consistency of squid landings in Oregon since 2016, ODFW has plans to establish a control date for a limited entry fishery in the near future, although information regarding qualifying criteria, permit allocation, and quota have yet to be determined (T. Buell, personal communication, September 29, 2021).

A more permanent and northward range shift across fixed jurisdictional or management boundaries (e.g., to Oregon, Washington, Alaska, or Canada) would likely lead to conflicts over property rights and resource access, raising complex discussions regarding coordination and equity (Pinsky and Mantua 2014; Pinsky et al. 2018). Given the high mobility of the current fleet of California permit holders, it is likely that these individuals will advocate for continued fishing rights as stocks shift north. Still, decisions regarding who would have access to emerging fisheries and how quota and permits would be allocated are likely to be contentious given the extremely high value nature of the fishery, as vested stakeholder interests vie with new regional interest groups. However, a shift in species range could also create a unique opportunity to work to develop more flexible and adaptive trans-jurisdictional management systems.

5 Conclusions

Given the high interannual variability in market squid stocks (driven by the species' high sensitivity to ENSO), the fleet has a long history of overcoming uncertainty and adapting to change. Market squid fishermen have employed diverse strategies to buffer against environmental and associated income variability, and have expressed confidence in their ability to continue to adapt to future change. However, as climate change intensifies, the capacity of fishermen, and associated fishery management systems, to adapt to novel conditions may be tested.

Our research revealed two key responses to historical shifts in market squid abundance and distribution: shifts in fishing grounds and shifts in target species. Due to the industrial

nature of the fishery, characterized by large and highly mobile vessels, the fleet has been able to track northward shifts in stock distribution, frequently traveling several hundred miles from their home ports to harvest market squid during historically strong El Niño events. Despite significantly greater costs associated with travel and increased effort, given the extremely high value of this fishery, many fishermen (particularly those with large vessels) are willing to travel an unlimited distance in the event of future range shifts. In recent years, however, market squid have appeared in large quantities in locations well beyond the fishery's historic focus, raising questions about whether current management systems and allocation policies will be sufficient to manage the stock in the future. While market squid fishermen are remarkably flexible when it comes to shifting fishing locations, shifting to alternative species can be more challenging. In the past, the interconnectedness of market squid and other coastal pelagic species facilitated shifting target species during unfavorable environmental and/or market conditions. However, regulations and markets now constrain market squid fishermen's ability to take advantage of coastal pelagic species, and access to other permit types is limited. Understanding how fishermen's connections to other fisheries, as well as the status and economic value of these fisheries, influence their response to change is critical to assessing a fishery's adaptive capacity.

Given observed and predicted changes in the market squid fishery, it is important to plan for fishery management under future climate conditions. Monitoring stocks and tracking potential distribution shifts in areas beyond traditional market squid fishery boundaries can help inform future management considerations and challenges, anticipate potential conflicts over resource allocation, and evaluate the need to develop novel management approaches. Engaging in preliminary discussions with fishermen and managers and planning ahead for cooperative management in regions where the fishery is emerging could also help to prevent conflicts associated with trans-jurisdictional species range shifts. Continued and planned engagement with fishermen to understand what facilitates or inhibits adaptation can increase both the effectiveness of policies and the resilience of fishing communities to climate change.

Fishermen's responses to past change serve as a valuable tool for anticipating their capacity to adapt to future change. While there is extensive literature on adaptive capacity and vulnerability frameworks in fishery systems, this study provides concrete examples of observed and implemented adaptation actions evidenced from historic catch records and fishermen's own stated adaptive responses. The challenges and potential opportunities associated with species' range shifts that are highlighted in this study serve as a preview of the types of changes and associated responses that are likely to occur or are already occurring in other fisheries. Identifying cases and examples of successful adaptation is critical for developing adaptation strategies and policies that will enhance existing capacities to sustain fisheries under ongoing climate change.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10584-022-03394-z>.

Acknowledgements We would like to acknowledge our funding source (National Science Foundation Coastal SEES Collaborative Research Grant, Award #1600149).

Data availability The datasets generated and analyzed during the current study are not publicly available as catch data were obtained through a non-disclosure agreement with the CDFW and interview data are confidential.

References

- Aguilera SE, Cole J, Finkbeiner EM et al (2015) Managing small-scale commercial fisheries for adaptive capacity: insights from dynamic social-ecological drivers of change in Monterey Bay. *PLoS ONE* 10:e0118992. <https://doi.org/10.1371/journal.pone.0118992>
- Alder J, Pauly D (2006) On the multiple uses of forage fish: from ecosystems to markets. <https://doi.org/10.14288/1.0074759>
- Allison EH, Ellis F (2001) The livelihoods approach and management of small-scale fisheries. *Mar Policy* 25:377–388. [https://doi.org/10.1016/S0308-597X\(01\)00023-9](https://doi.org/10.1016/S0308-597X(01)00023-9)
- Anderson SC, Ward EJ, Shelton AO et al (2017) Benefits and risks of diversification for individual fishers. *Proc Natl Acad Sci USA* 114:10797–10802. <https://doi.org/10.1073/pnas.1702506114>
- Bates K, Hildebrand L (2018) Proposal for a small-scale trial squid fishery north of Point Arena, California: offered as an amendment/addition to the California Fishery Management Plan. <https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=156321&inline>. Accessed 18 Feb 2020.
- Bennett NJ, Blythe J, Tyler S, Ban NC (2016) Communities and change in the anthropocene: understanding social-ecological vulnerability and planning adaptations to multiple interacting exposures. *Reg Environ Change* 16:907–926. <https://doi.org/10.1007/s10113-015-0839-5>
- Cai W, Wang G, Dewitte B et al (2018) Increased variability of eastern Pacific El Niño under greenhouse warming. *Nature* 564:201–206. <https://doi.org/10.1038/s41586-018-0776-9>
- Cavole L, Demko A, Diner R, et al (2016) Biological impacts of the 2013–2015 warm-water anomaly in the Northeast Pacific: winners, losers, and the future. *Oceanography* 29. <https://doi.org/10.5670/oceanog.2016.32>
- CDFW [California Department of Fish and Wildlife] (2005) Market squid fishery management plan. California Department of Fish and Game Marine Region. <https://www.wildlife.ca.gov/Conservation/Marine/MSFMP>. Accessed 3 Nov 2019.
- Chambers S (2016) California's squid show up in Oregon where 6 vessels are fishing, meeting on regs set for June. *SeafoodNews.com*. <https://www.seafoodnews.com/Story/1018390/Californias-Squid-Show-up-in-Oregon-where-6-Vessels-are-Fishing-Meeting-on-Regs-Set-for-June>. Accessed 18 Feb 2020.
- Chasco BE, Hunsicker ME, Jacobson KC et al (2022) Evidence of temperature-driven shifts in market squid *Doryteuthis opalescens* densities and distribution in the California Current Ecosystem. *Mar Coast Fish* 14:e10190. <https://doi.org/10.1002/mcf2.10190>
- Chavez FP, Costello C, Aseltine-Neilson D, et al (2017) Readyng California fisheries for climate change. California Ocean Science Trust, Oakland, CA.
- Checkley DM, Barth JA (2009) Patterns and processes in the California Current System. *Prog Oceanogr* 83:49–64. <https://doi.org/10.1016/j.pocean.2009.07.028>
- Cinner JE, McClanahan TR, Graham NAJ et al (2012) Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries. *Glob Environ Chang* 22:12–20. <https://doi.org/10.1016/j.gloenvcha.2011.09.018>
- Cinner JE, Huchery C, Hicks CC et al (2015) Changes in adaptive capacity of Kenyan fishing communities. *Nat Clim Change* 5:872–876. <https://doi.org/10.1038/nclimate2690>
- Cinner JE, Adger WN, Allison EH, Barnes ML, Brown K, Cohen PJ, Gelcich S, Hicks CC, Hughes TP, Lau J, Marshall NA (2018) Building adaptive capacity to climate change in tropical coastal communities. *Nat Clim Change* 8(2):117–123
- Columbia Basin Bulletin (2018) El Nino, 'Warm Blob' expected to supercharge storms, redistribute marine species. *Chinook Observer*. https://www.chinookobserver.com/news/local/el-nino-warm-blob-expected-to-supercharge-storms-redistribute-marine/article_14f3ac3f-4632-5229-98ce-9c9161a3b870.html. Accessed 2 Jul 2019.
- Coulthard S (2009) Adaptation and conflict within fisheries: insights for living with climate change. In: Adger WN, Lorenzoni I, O'Brien KL (eds) *Adapting to Climate Change*. Cambridge University Press, Cambridge, pp 255–268
- Coulthard S, Britton E (2015) Waving or drowning: an exploration of adaptive strategies amongst fishing households and implications for wellbeing outcomes. *Sociol Ruralis* 55:275–290. <https://doi.org/10.1111/soru.12093>
- Crona B, Wassénius E, Troell M et al (2020) China at a crossroads: an analysis of China's changing seafood production and consumption. *One Earth* 3:32–44. <https://doi.org/10.1016/j.oneear.2020.06.013>
- Dubik BA, Clark EC, Young T et al (2019) Governing fisheries in the face of change: social responses to long-term geographic shifts in a U.S. fishery. *Mar Policy* 99:243–251. <https://doi.org/10.1016/j.marpol.2018.10.032>

- Ess C (2020) Pacific squid: trade hurdles to China remain, but prices are steady. National Fishermen Forum <https://www.nationalfisherman.com/pacific-squid-trade-hurdles-to-china-remain-but-prices-are-steady>. Accessed 13 Dec 2020.
- FAO [Food and Agriculture Organization] (2020) The State of World Fisheries and Aquaculture 2020: Sustainability in action. FAO, Rome, Italy
- Forsythe JW (2004) Accounting for the effect of temperature on squid growth in nature: from hypothesis to practice. *Mar Freshwater Res* 55:331–339. <https://doi.org/10.1071/MF03146>
- Frawley TH, Muhling BA, Brodie S et al (2021) Changes to the structure and function of an albacore fishery reveal shifting social-ecological realities for Pacific Northwest fishermen. *Fish Fish* 22:280–297. <https://doi.org/10.1111/faf.12519>
- Gourlie D (2017) Reeling in uncertainty: adapting marine fisheries management to cope with climate effects on ocean ecosystems. *J Environ Law* 47:179–224
- Halpern BS, Frazier M, Potapenko J et al (2015) Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nat Commun* 6:7615. <https://doi.org/10.1038/ncomms8615>
- Hollowed AB, Hare SR, Wooster WS (2001) Pacific Basin climate variability and patterns of Northeast Pacific marine fish production. *Prog Oceanogr* 49:257–282. [https://doi.org/10.1016/S0079-6611\(01\)00026-X](https://doi.org/10.1016/S0079-6611(01)00026-X)
- Islam MdM, Sallu S, Hubacek K, Paavola J (2014) Vulnerability of fishery-based livelihoods to the impacts of climate variability and change: insights from coastal Bangladesh. *Reg Environ Change* 14:281–294. <https://doi.org/10.1007/s10113-013-0487-6>
- Jackson GD, Domeier ML (2003) The effects of an extraordinary El Niño/La Niña event on the size and growth of the squid *Loligo opalescens* off Southern California. *Mar Biol* 142:925–935. <https://doi.org/10.1007/s00227-002-1005-4>
- Johnson TR, Henry AM, Thompson C (2014) Qualitative indicators of social resilience in small-scale fishing communities an emphasis on perceptions and practice. *Hum Ecol Rev* 20:97–115
- Kasperski S, Holland DS (2013) Income diversification and risk for fishermen. *Proc Natl Acad Sci USA* 110:2076–2081. <https://doi.org/10.1073/pnas.1212278110>
- Lindegren M, Brander K (2018) Adapting fisheries and their management to climate change: a review of concepts, tools, frameworks, and current progress toward implementation. *Rev Fish Sci Aquac* 26:400–415. <https://doi.org/10.1080/23308249.2018.1445980>
- MAFMC [Mid-Atlantic Fishery Management Council] (2021) ASMFC and MAFMC approve changes to state allocations of commercial black sea bass quota. <https://www.mafmc.org/newsfeed/2021/asmfc-and-mafmc-approve-bsb-commercial-allocation-changes>. Accessed 26 May 2021
- Maguire M, Delahunt B (2017) Doing a thematic analysis: a practical, step-by-step guide for learning and teaching scholars. *AISHE-J* 9:3
- Marine fisheries: experimental fishing permits, A.B. 1573, 2017–2018 Reg. Sess. (Cal. 2018) (enacted). https://leginfo.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB1573. Accessed 10 Jan 2020
- Miller M (2015) Warm-water fish increasingly spotted in Alaska waters. In: Alaska Public Media. <https://www.alaskapublic.org/2015/09/15/warm-water-fish-increasingly-spotted-in-alaska-waters/>. Accessed 3 Jan 2021
- Miller DD, Ota Y, Sumaila UR et al (2018) Adaptation strategies to climate change in marine systems. *Glob Chang Biol* 24:e1–e14. <https://doi.org/10.1111/gcb.13829>
- Mills K, Pershing A, Brown C et al (2013) Fisheries management in a changing climate: lessons from the 2012 ocean heat wave in the Northwest Atlantic. *Oceanography* 26:191–195. <https://doi.org/10.5670/oceanog.2013.27>
- Morejohn GV, Harvey JT, Krasnow LT (1978) The importance of *Loligo opalescens* in the food web of marine vertebrates in Monterey Bay, California. *Fish Bull* 169:67–98
- NMFS [National Marine Fisheries Service] (2018) Fisheries economics of the United States 2016. NOAA, US Department of Commerce
- NOAA [National Oceanic and Atmospheric Administration] (1993) *Atlantic Sea Scallop Fishery, Fisheries Management Plan (FMP): Environmental Impact Statement*.
- NOAA [National Oceanic and Atmospheric Administration] (2019) Cold & Warm Episodes by Season. In: National Weather Service Climate Prediction Center. https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php. Accessed 17 Nov 2021
- ODFW [Oregon Department of Fish and Wildlife] (2021) Agenda item summary - exhibit f attachment 1. Oregon Department of Fish & Wildlife
- Ojea E, Lester SE, Salgueiro-Otero D (2020) Adaptation of fishing communities to climate-driven shifts in target species. *One Earth* 2:544–556. <https://doi.org/10.1016/j.oneear.2020.05.012>

- Olsen WK (2004) Triangulation in social research: qualitative and quantitative methods can really be mixed. In: Holborn M (ed) *Developments in Sociology: An Annual Review*. Causeway Press, Ormskirk, UK, pp 103–121
- Palacios DM, Bograd SJ, Mendelssohn R, Schwing FB (2004) Long-term and seasonal trends in stratification in the California Current, 1950–1993. *J Geophys Res Oceans* 109^{https://doi.org/10.1029/2004JC002380}
- Patterson W (2018) CDFW projection and datum guidelines. California Department of Fish and Wildlife.
- Pebesma E (2018) Simple features for R standardized support for spatial vector data. *The R Journal* 10:439. ^{https://doi.org/10.32614/RJ-2018-009}
- Perretti CT, Sedarat M (2016) The influence of the El Niño Southern Oscillation on paralarval market squid (*Doryteuthis opalescens*). *Fish Oceanogr* 25:491–499. ^{https://doi.org/10.1111/fog.12167}
- PFMC [Pacific Fishery Management Council] (2008) Status of the Pacific Coastal Pelagic Species Fishery and Recommended Acceptable Biological Catches. Pacific Fishery Management Council
- Pinsky ML, Fogarty M (2012) Lagged social-ecological responses to climate and range shifts in fisheries. *Clim Change* 115:883–891. ^{https://doi.org/10.1007/s10584-012-0599-x}
- Pinsky ML, Mantua N (2014) Emerging adaptation approaches for climate-ready fisheries management. *Oceanography* 27:146–159. ^{https://doi.org/10.5670/oceanog.2014.93}
- Pinsky ML, Reygondeau G, Caddell R et al (2018) Preparing ocean governance for species on the move. *Science* 360:1189–1191. ^{https://doi.org/10.1126/science.aat2360}
- Pomeroy C, Hunter MS, Los Huertos M (2002) Socio-economic profile of the California wetfish industry. In: Pleschner D (ed) *California's "Wetfish" Industry: Its Importance Past, Present and Future*. California Seafood Council, Santa Barbara, CA, p 46
- Pomeroy C, Thomson CJ, Stevens MM (2010) California's North Coast fishing communities historical perspective and recent trends. California Sea Grant College, La Jolla, CA, p 340
- Porzio D, Brady B (2008) Status of the fisheries report: market squid. California Department of Fish and Game
- Pozo Buil M, Jacox MG, Fiechter J et al (2021) A dynamically downscaled ensemble of future projections for the California Current System. *Front Mar Sci* 8:612874. ^{https://doi.org/10.3389/fmars.2021.612874}
- R Core Team (2020) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Australia. ^{https://www.R-project.org}. Accessed 17 Nov 2021
- Rahaim N (2016) California's confidential fishing rights leave millions of dollars in mystery. *Monterey County Weekly*. ^{https://www.montereycountyweekly.com/news/cover/californias-confidential-fishing-rights-leave-millions-of-dollars-in-mystery/article_32047aba-43b4-11e6-8d8d-cfb0fd7f9c6.html}. Accessed 15 Jul 2019
- Ralston S, Dorval E, Ryley L et al (2018) Predicting market squid (*Doryteuthis opalescens*) landings from pre-recruit abundance. *Fish Res* 199:12–18. ^{https://doi.org/10.1016/j.fishres.2017.11.009}
- Reddy SMW, Wentz A, Aburto-Oropeza O et al (2013) Evidence of market-driven size-selective fishing and the mediating effects of biological and institutional factors. *Ecol Appl* 23:726–741
- Reiss CS, Maxwell MR, Hunter JR, Henry A (2004) Investigating environmental effects on population dynamics of *Loligo opalescens* in the Southern California Bight. *CalCOFI Reports* 45:87–97
- Reyers B, Folke C, Moore M-L et al (2018) Social-ecological systems insights for navigating the dynamics of the Anthropocene. *Annu Rev Env Resour* 43:267–289. ^{https://doi.org/10.1146/annurev-envir-110615-085349}
- Robinson JPW, Robinson J, Gerry C et al (2020) Diversification insulates fisher catch and revenue in heavily exploited tropical fisheries. *Sci Adv* 6:0587. ^{https://doi.org/10.1126/sciadv.aaz0587}
- Rubio I, Hobday AJ, Ojea E (2021) Skippers' preferred adaptation and transformation responses to catch declines in a large-scale tuna fishery. *ICES J Mar Sci* fsab065. ^{https://doi.org/10.1093/icesjms/fsab065}
- Savo V, Morton C, Lepofsky D (2017) Impacts of climate change for coastal fishers and implications for fisheries. *Fish Fish* 18:877–889. ^{https://doi.org/10.1111/faf.12212}
- Schwing FB, Mendelssohn R, Bograd SJ et al (2010) Climate change, teleconnection patterns, and regional processes forcing marine populations in the Pacific. *J Mar Syst* 79:245–257. ^{https://doi.org/10.1016/j.jmarsys.2008.11.027}
- Seara T, Clay PM, Colburn LL (2016) Perceived adaptive capacity and natural disasters: A fisheries case study. *Glob Environ Change* 38:49–57
- Shaffril HAM, D'Silva JL, Kamaruddin N et al (2015) The coastal community awareness towards the climate change in Malaysia. *Int J Clim Change Strateg Manag* 7:516–531. ^{https://doi.org/10.1108/IJCCSM-07-2014-0089}
- Sievanen L (2014) How do small-scale fishers adapt to environmental variability? Lessons from Baja California, Sur. *Mexico Marit Stud* 13:9. ^{https://doi.org/10.1186/s40152-014-0009-2}

- Sims DW, Genner MJ, Southward AJ, Hawkins SJ (2001) Timing of squid migration reflects North Atlantic climate variability. *Proc Biol Sci* 268:2607–2611. <https://doi.org/10.1098/rspb.2001.1847>
- Soley T (2018) As Alaskan waters warm, market squid move north. *Undark Magazine*. <https://undark.org/2018/03/14/market-squid-alaska-climate-change/>. Accessed 20 Feb 2020
- Stoll JS, Fuller E, Crona BI (2017) Uneven adaptive capacity among fishers in a sea of change. *PLoS One* 12 <https://doi.org/10.1371/journal.pone.0178266>
- Suatoni L (2020) On the move: how fisheries policy can address shifting fish stocks - fact sheet. NRDC. <https://www.nrdc.org/sites/default/files/fisheries-policy-shifting-fish-stocks-fs.pdf>. Accessed 2 Feb 2020
- Tims D (2021) Changing ocean conditions create fishery for “market” squid off Oregon coast, already more valuable than commercial salmon catch. *YachatsNews.com*. <https://yachatsnews.com/23997-2/>. Accessed 25 Aug 2021
- van Noord JE, Dorval E (2017) Oceanographic influences on the distribution and relative abundance of market squid paralarvae (*Doryteuthis opalescens*) off the Southern and Central California coast. *Mar Ecol* 38:e12433. <https://doi.org/10.1111/maec.12433>
- van Putten IE, Jennings S, Hobday AJ et al (2017) Recreational fishing in a time of rapid ocean change. *Mar Policy* 76:169–177. <https://doi.org/10.1016/j.marpol.2016.11.034>
- Whitney C, Bennett N, Ban N et al (2017) Adaptive capacity: from assessment to action in coastal social-ecological systems. *Ecol Soc* 22:22. <https://doi.org/10.5751/ES-09325-220222>
- Wilson J (2017) Learning, adaptation, and the complexity of human and natural interactions in the ocean. *Ecol Soc* 22 <https://doi.org/10.5751/ES-09356-220243>
- Xiu P, Chai F, Curchitser EN, Castruccio FS (2018) Future changes in coastal upwelling ecosystems with global warming: the case of the California Current System. *Sci Rep* 8:1–9. <https://doi.org/10.1038/s41598-018-21247-7>
- Young T, Fuller EC, Provost MM et al (2019) Adaptation strategies of coastal fishing communities as species shift poleward. *ICES J Mar Sci* 76:93–103. <https://doi.org/10.1093/icesjms/fsy140>
- Zeidberg LD, Hamner WM, Nezlin NP, Henry A (2006) The fishery for California market squid (*Loligo opalescens*) (Cephalopoda: Myopsid), from 1981 through 2003. *Fish Bull* 104:46–59

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