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Trends and drivers of transitions in California wild capture fisheries and marine aquaculture

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by

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ABSTRACT

Trends and drivers of transitions in California wild capture fisheries and marine aquaculture

by

Mae Rennick

Commercial fisheries worldwide face growing demand, changing markets, resource limitations, and climate challenges, which makes them susceptible to perturbations and sudden declines. Historical reforms and diversification have stabilized fisheries, but increasing shock events threaten future adaptability. Marine aquaculture is emerging as a way to bolster dwindling fishery resources and satisfy the increasing seafood demand. This study examines trends in marine wild capture fisheries and aquaculture in California, addressing the impact of fisheries shocks and policy changes on trends in seafood production. We found evidence that fisheries shocks can coincide with increased marine aquaculture growth, but aquaculture growth is likely influenced by policy landscapes. Particularly, an unbalanced regulatory framework favoring restrictive regulations has likely limited aquaculture growth in the state. However, data limitations and misclassification challenge the detection of aquaculture growth and interactions between fisheries and aquaculture. Additional factors such as technology, economics, market forces, and social acceptance can influence aquaculture growth, highlighting that trends in aquaculture expansion likely result from the interaction of multiple driving factors. This study underscores the importance of considering local and state-level dynamics in understanding aquaculture's role in seafood production resilience and stability.

Introduction:

Globally and in the United States (U.S.), commercial fisheries landings have remained relatively stable over the last 30 years, but may be challenged in the future by social and ecological disruptions due to increasing demand, market shifts, limited resource availability and global climate change (Barange et al. 2018; Love et al. 2020, FAO 2022). Specifically, fisheries may be increasingly vulnerable to 'shock events', defined as large, statistically significant declines in production (volume or value) driven by social, economic and/or environmental factors, including overfishing, climate change, market crashes, and disease (Cottrell et al. 2019; Gephart et al. 2017). Fisheries management reforms and fisheries adaptation and diversification are the main factors that have contributed to the stabilization of commercial landings over the last several decades, shaping the modern commercial seafood industry (Cottrell et al. 2021; Hilborn et al. 2020; Woods et al. 2022). However, because these shock events are projected to increase, some evidence suggests fishers may be less able to readily adapt into the future (Cottrell et al. 2019). Therefore, further diversification to alternative production systems may be necessary to maintain the stability of seafood production and meet growing demand (Tidwell and Allen 2012; Naylor et al. 2021; FAO 2020; FAO 2022; Rexroad 2021).

Aquaculture has supplemented wild capture production to meet growth in seafood demand (Cottrell et al. 2021; Longo et al. 2019), and is increasingly viewed as an opportunity to compensate for projected employment, production, and earning losses due to the increased instability of fishery resources (Campbell et al. 2021; Stoll et al. 2019). In fact, there is growing evidence of 'blue transitions,'or a change of production from fisheries to aquaculture, ideally helping rebuild wild stocks, in addition to improving seafood availability and access globally (World Bank and United Nations Departments of Economic and Social Affairs 2017; Belton et al. 2018, Anderson 1985). Importantly, the theory of blue transitions is often predicated on an initial decline, such as a shock event, of wild capture harvest that may facilitate initial aquaculture development (Nahuelhual et al. 2019). Where in some cases, aquaculture can even replace capture fishing as the primary form of production in an area (Nahuelhual et al. 2019). While overfishing and poor status of wild capture fisheries appear to be driving factors in the occurrence of blue transitions at the country-level, this hypothesis has not been evaluated at sub-national and local scales (Cottrell et al. 2019; Kuempel et al. 2021). The extent to which aquaculture development and expansion is dependent upon the performance of fisheries is poorly understood.

The United States as a whole has large commercial wild fisheries, a robust freshwater aquaculture sector and a comparatively small, but growing marine aquaculture–or mariculture– sector. The U.S. commercial fishing industry has approximately 461 commercial stocks, worth $5.6 billion (National Marine Fisheries Service 2021). Many marine stocks have experienced collapses largely due to overfishing (Worm et al. 2006, Jackson et al. 2001), and while most are now rebuilt, they are fished at or near their maximum capacity with limited scope for sustainable increases in landings (National Marine Fisheries Service 2021; Greene et al. 2020; Costello et al. 2020). In contrast, there has been continual growth in the marine aquaculture sector in the U.S. with a 66% increase in number of farms and a 2.2-fold increase in production value from 1998-2018 (Froehlich et al. 2022, USDA). However, it is unclear if or how marine fisheries dynamics may have influenced marine aquaculture emergence and growth, particularly at the scale of individual states. One difficulty of studying possible transitions from wild fisheries to aquaculture is that there is not always a clear production trade off, e.g., fishers becoming farmers and farming the same taxa at the same amount (Fong et al. 2022). One way to address this is to evaluate the historical trends of wild capture landings in addition to value alongside marine aquaculture production across broad taxonomic groups. This approach can aid in identifying patterns consistent with emergent properties of blue transitions across different scales.

Fisheries and marine aquaculture are heavily interdependent through shared markets, resources and space. Therefore, interactions between aquaculture and fisheries are both numerous and complex (Clavell et al. 2019), making the study of possible blue transitions complicated. In particular, policy is a major factor influencing aquaculture and fisheries production and sustainability (Campbell et al. 2016; Asche and Smith 2018; Kuempel et al. 2021; Cotrell et al. 2021). However, the way in which policy measures influence fisheries and marine aquaculture interactions and growth are sometimes theoretical and are often ignored in future planning and predictive scenarios for the seafood sector (Clavelle et al. 2019). It has been proposed that unclear and complex policy structures have stymied aquaculture development and consequently impacted industry growth globally (Garlock et al. 2020; Cotrell et al. 2021), and in the US (Knapp and Rubino 2016; Lester et al. 2021; Rubino et al 2022). Increases in restrictive aquaculture US regulations from 1970-2017 far exceeded regulations limiting any other protein supply sectors, including fisheries (Staples et al. 2021; Staples et al. 2022). However, policy varies across states (e.g., Lester et al. 2021) and there is a need to better account for policy feedbacks that may affect how fisheries and marine aquaculture influence each other.

California provides an ideal case study to examine patterns of fisheries and aquaculture over time. On the West Coast, a large number of commercially relevant fisheries have recovered from past overexploitation as the result of effective management (National Marine Fisheries Service 2021; Hilborn et al. 2020). Still, despite its expansive coastline, the state of California still fishes many commercially important stocks at or near their maximum capacity (CDFW 2021, National Marine Fisheries Service 2021), and the state has experienced a series of fisheries collapses since the mid-twentieth century, limiting the potential for production increases. For example, several pelagic species (e.g., sardine) collapsed in the mid-to late-1900s (Radovich 1982; Norton and Herrick 2010; Miller et. al. 2017). The state of California plays a substantial role in seafood production, trade and distribution nationally and globally, which means that the downstream effects of fisheries instability or shocks could span broadly if production or employment losses are not somehow supplemented (Kildow 2005, CDFW 2021). While aquaculture is viewed as a potential solution, it is unclear if or how these shocks corresponded with trends in aquaculture in the state. In contrast to global trends, California has seen comparatively little increase in marine aquaculture relative to the size of its coastline and seafood consumption patterns (Fong et al. 2022; CDFW 2020). Furthermore, the policies governing California aquaculture are perceived to be particularly convoluted and largely rooted in structures which prioritize and manage alternative seafood sectors (Bowden 1981, Fairbanks et al. 2019). Therefore, the extent to which marine aquaculture can or will meet its perceived potential in the state, and what mechanisms may influence the trajectory of future marine aquaculture growth, are unknown and remain unquantified.

Using a combination of quantitative time-series analyses and a qualitative case-study evaluation, we seek to assess the trends of marine wild capture fisheries and aquaculture in California, specifically addressing the following questions: 1) How have shocks in wild caught fisheries corresponded with marine aquaculture production, both within and between major taxonomic groups? and 2) Do policies over time appear to support or hinder the development of marine aquaculture following key shock events in fisheries? Additionally, to better understand the drivers of marine aquaculture development, with an eye towards factors that may contribute to blue transitions, we critically evaluate the emergence of oyster aquaculture, the most prevalent and lucrative form of marine aquaculture in the state. Given wild capture fisheries are likely to become more variable into the future due to climate change and other disruptions (Brander et al. 2010; Barange et al. 2018; White et al. 2020), these findings will help elucidate potential interactions between fisheries and marine aquaculture and how certain policies may modify the strength of these interactions. In turn, this can be used to guide decision making and policies regarding the California seafood sector in this changing landscape which could lead to overall strengthened seafood production and trade.

Methods:

Fisheries Data

We used commercial fishing production data (volume and value) collected by the state of California from 1970-2018 (Free et al. 2022 and CDFW). Value data were adjusted for 2018 inflation. The California Department of Fish and Wildlife (CDFW) synthesizes and stores data from landing receipts ("fish tickets") collected and submitted by fish buyers and processors, in addition to annual landings reports. Only data on species, weight, and price were able to be obtained from CDFW (*see* Free et al. 2022 for more detailed information). We aggregated the data into major taxonomic groups: pisces, invertebrata (excluding mollusks and crustaceans), mollusks, plantae aquatica, and crustacea. Due to likely inaccuracies in state reported data (Froehlich et al. 2022, Blasco et al. 2020), we assumed that summarized data at the major group-level may dampen the effects of misreported data or data gaps at the species level. While this aggregation limits the detail of our analysis, broader trends and transitions in production should still be apparent. Due to low production values and data gaps in the plantae aquatica major group, this group was not included in the analysis.

We manually corrected for some known issues in the data. We removed oyster production reported in commercial fisheries landings because, despite the CDFW reports, there has been no commercial fishing of oysters within the state from 1939 onward (Conte and Moore 2001). Similarly, we removed report data for commercial mussel landings after 2008 (no longer commercially harvested in the state due to quarantine closures) (CDFW 2011) and abalone after 1996 (moratorium on all abalone species took effect) (California Fish and Game Code § 5521). While we know anecdotally that clams are primarily farmed, but it was not possible to correct these data given that both farmed and wild harvest can occur, so we made no adjustments to the clam fisheries landings data.

In addition to the broader multi-species data described above, we also compiled more detailed and extensive times-series data for one of the most valuable, productive and data rich taxa in the state: oysters. We obtained historical commercial oyster fishing production data from the California State Tax records (royalty reports) Database, the Department of Aquaculture Harvest Survey, the California Department of Fish and Game (and as it was previously, the California Division of Fish and Game), and the US Department of Commerce for the years 1888-1950. These data were synthesized and vetted through literature review (methods in Barrette 1963).

Aquaculture Data

We used marine aquaculture production data collected by the state of California from 1996-2018 and provided in the form of annual California Marine Bivalve Production Reports with information on volume (number and weight) and value of production, as well as species and location information (Froehlich et al. 2022). To supplement missing marine aquaculture production data, we used data extracted from a CDFW Report (CDFW 2020) to account for abalone production and for production estimates prior to 2000 (1970-2000). Specifically, the data were extracted from Figure 2.2 of the 2020 CDFW Report on the Status of Commercial Marine Aquaculture in California (CDFW 2020) using WebPlotDigitizer and then vetted by two state representatives. These data included production (metric tonnes) of mussels, clams, abalone, and oysters (including: Olympia oysters, European flat oysters, Eastern oysters, Kumamoto oysters, and Pacific oysters) from 1970-2018. Because this data source omits value data, all aquaculture value estimates used in this study are limited as they do not include abalone or values prior to 1996. Additionally, many bivalve mollusk species have been historically misreported as commercial fishing landings rather than marine aquaculture (mentioned above) (Froehlich et al. 2022). Further, California State Tax records (royalty reports) and Department of Aquaculture Harvest Survey Database report even higher values of marine aquaculture production than the CDFW reports; all of the aquaculture data reported here are therefore likely underestimates. For visual representation, we combined values reported for wild oyster landings from 1939-1950 to the values reported for oyster aquaculture to devise a potential upper limit to the total farmed oyster production in the state after 1939.

This study specifically focuses on marine production in the state of California, because state marine aquaculture–or mariculture– production is slated for possible expansion in the coming years (e.g., OPC- Guiding Principles for Sustainable Marine Aquaculture in California; OPC- Strategic Plan to Protect California's Coast and Ocean 2020-2025). In conjunction with freshwater limitations (resulting from drought conditions and existing proprietorship and allocations in the state), we presume most aquaculture development in California will occur in the marine production system, which makes understanding marine development particularly important.

Regulatory Policy Data

For this study, policy data were collected and evaluated to track and categorize California state-level policy regulating marine aquaculture and to broadly contextualize the policy landscape (state and federal) pertinent to California oyster cultivation and production through time.

Active California codes pertaining to marine aquaculture were extracted from a publicly available list, curated by the CDFW, of 'Regulations Governing Marine Aquaculture' (The Natural Resources Agency of California and California Department of Fish and Wildlife 2017) and were tracked and categorized using MAXQDA software (VERBI Software 2021). There are several facets to California policy: regulations, statues, codes, and statutory codes. Statutes are the laws enacted by the California legislature, signed by the California Governor, which contain regulations that implement or interpret the statute.

Each statute is housed within a set of codes that organize the statutes into categories or acts. These codes are divided among 29 separate statutory codes (e.g. Fish and Game Code) in California, which covers one or more major subject areas and is usually regulated and/or enforced by a governing agency (e.g. Fish and Game Commission). From the collected data, regulations within the codes were separated into two categories: enabling policy, defined as any policy that provides funds, resources, trainings, initiatives, etc. to support aquaculture development and growth (Lester et al. 2021, Hishamunda Ridler and Martone 2014), and restrictive policy, defined as any policy which implements additional fees, restrictions, standards etc. that may slow or restrict aquaculture development and growth (Engle and Stone 2013; Anderson et al. 2019). Each code was carefully read to determine whether the regulations within the codes had properties that could facilitate or restrict marine aquaculture growth and development. We were not able to determine downstream efficacy or the extent of implementation and enforcement of each regulation. Therefore, we assume that no regulations considered were neutral, because, as they are written, policies are inherently designed to exert influence over the subjects they govern.

Enabling regulations included: exceptions for aquaculture/aquaculturists; government transparency of decision-making processes; research initiatives; facilitation of improved social license; aquaculturist rights; improved accessibility to farming through financial or location-based initiatives; and aquaculturist/farm protections. Restrictive regulations included: fees; standards; and restrictions. These subcategories (defined in Supplemental Table 5) were designed to reflect broad trends in the regulations and to improve the resolution of our results by coarsely relaying the composition of each major category. We focused on aquaculture specific policies and therefore our analysis does not include more general regulations that can apply to multiple industries (e.g. water quality regulations). Enabling and restrictive policies were tracked through time in an effort to understand how regulatory policy may correlate with marine aquaculture development, particularly the timing before and after significant fishery shock events.

We assessed two reviews and one recent state report that detail the emergence and growth of oyster aquaculture in the state of California to determine pertinent state and federal policies and regulations over time. First, we looked at the Resource Agency of California Department of Fish and Game's "Fish Bulletin 123: The California Oyster Industry" (Barrett 1963), which is a detailed review of the California oyster industry through 1963 and includes specific considerations for regulatory and political influence; it largely compiles state solicited data with the work of Charles Townsend (1893) and Paul Bonnot (Bonnot 1935), who both provide detailed accounts of the California oyster industry through time. Next, we reviewed "Oyster Culture: Fundamentals and Technology of the West Coast Industry," (Conte 1996) in order to include updated information on the political drivers of oyster aquaculture in the state of California. A California state-specific review of oyster aquaculture has not been conducted with the inclusion of political drivers or updated since 1996. Therefore, to understand the more current political landscape, we used a list, curated by the Aquarium of the Pacific, of state and federal policies impacting marine aquaculture (generally) in the state of California (Nelson, Schubel and Thompson 2019), which is primarily oyster aquaculture (CDFW 2020). All policies and regulations mentioned in the context of impacting oyster aquaculture operations across all of these sources were collated into a list to create a timeline of policies impacting oyster production and development in the state of California through time.

Analysis:

Descriptive Trends

We calculated several descriptive trends of aggregate commercial fishing and aquaculture data (value and volume) to characterize the overall growth and contraction of production for both sectors through time at the state level. We found maximum values for fisheries (value and volume) and aquaculture (volume) to determine when production was at its highest, calculated a yearly average of production, and determined the number of major groups per sector, for overall comparison of the two sectors, on aggregate. We then determined, on average, what percentage each major group contributed to the total production through time to qualify any major taxonomic shifts.

Statistical Models

We used multiple linear regression to compare the overall trends, including the mean rate of change and directionality, of fisheries production (value and volume) and aquaculture production (volume) in California.

For fisheries, we fit multiple linear models to the data (see Supplementary Table 1 and Supplementary Table 2) in order to determine if production significantly changed (increased or decreased) over time, and if this differed between major taxonomic groups. We performed these analyses on landings weight (lbs) and value (USD$) to evaluate similarities in trends.We examined weight and value to evaluate the strength and consistency of changes to fisheries over time, which helps inform further analyses (*see* shock analysis). A natural-log transformation was applied to the data in order to ensure the underlying assumptions of linear regression were met (Zurr 2007). Model assumptions were verified by plotting residuals versus fitted values to ensure absence of residual patterns. Model selection was performed using Akaike Information Criterion Corrected (AICc) to measure goodness-of-fit in relation to model complexity (Burnham and Anderson 2002, Akaike 1973). AICc accounts for sample-size and provides a more accurate estimate of the true model fit for smaller samples. Best fit was characterized by the highest coefficient of determination (R2adj) and lowest AICc value relative to ∆AICc.

To determine the strength and significance of aquaculture production trends through time, we compared two linear models (see Supplementary Table 3). Similarly to fisheries, a natural-log transformation was applied to the aquaculture production data in order to ensure the underlying assumptions of linear regression were met (Zurr 2007), model assumptions were verified using residual analysis, and model selection was performed using AICc. The model with the smallest delta AICc value was selected.

Lastly, we conducted a comparative analysis of four different models (see Supplementary Table 4) to gain a better understanding of the trends in regulatory policy over time. We used a two-factor polynomial model due the strong non-linearities of the data, with year and regulatory type as the predictor variables and cumulative number of those policies as the response. Our aim was to determine how the number of cumulative regulations have changed through time and if this differed based on policy type (enabling or restrictive). Model selection was performed as described previously.

While a more detailed time-series analysis would be ideal, as previously mentioned (*see* Data section) the data are not reliable enough to support a more in-depth approach. In addition, we are largely interested in the estimate of strength, magnitude and direction (positive/negative) of the relationship between production types which can be achieved through linear regression.

Shock Analysis

We used shock analysis to identify significant and sudden changes in commercial fisheries volume and value and aquaculture volume. We employed the statistical approach of Gephart et al. (2017) and Cotrell et al. (2019) to identify negative shocks in commercial fisheries and oyster production, indicating a decline in production. We ran the shock analyses on volume and value for commercial fisheries, assuming a shock detected in both would have a larger effect on the seafood industry and thus a higher chance of facilitating aquaculture emergence or growth. Alternatively, for aquaculture we identified 'inverse shocks' that indicated sudden increases in production and adoption, which could signify a growth response to commercial fisheries declines. Across all datasets, large shocks were identified as outlier deviations, or points with a Cook's D value >0.3 (Cottrell et al. 2019), and small shocks were identified by a Cook's D value >0.1 but </=0.3, in a regression of the residuals and lag-1 residuals from a LOWESS fit of the time series with a smoother span of 2/3. Although large fisheries shocks may be more likely to impact growth of aquaculture, smaller shocks could still be informative, in particular providing insight into the stability of the sector. We compared the Cook's D values for fisheries and ten, separate increasing annual lag periods of aquaculture—a typical span of time to increase production, particularly related to domestication (Teletchea and Fontain 2014). We were specifically looking for synchrony in trends among large and small shocks related to the negative fisheries shocks and

coincident positive aquaculture shocks, represented by a strong Pearson's correlation (Supplementary Figure 3).

Breakpoint Analysis

We used a breakpoint analysis to identify changes in the growth trajectory and rate of change in marine aquaculture production. The breakpoint identifies a sudden change in slope and fits segmented linear regression models to the data (Muggeo 2008). If a production transition was initiated by a fishery shock event, we would expect to see a breakpoint in marine aquaculture production occur after or near a large shock event in commercial fisheries production, and the slope of the segment following the breakpoint would be greater than the initial slope of marine aquaculture production through time. We provided initial estimates for the breakpoints that align with major shocks in fisheries in order to focus the analysis on a smaller range of possible breakpoint locations and test the response of aquaculture to shock events. A breakpoint analysis is useful in addition to the inverse shock analysis because it can determine changes for longer lasting trends rather than sudden shifts. This was also used as an alternative method to determine a potential lag period by measuring the time in between a major shock event in fisheries production and a subsequent breakpoint in aquaculture landings.

We also performed a breakpoint analysis to determine the growth trajectory and rate of change in cumulative restrictive and enabling regulations before and after major fisheries shock events using the same approach. Because trends in policy can dictate or alter the growth and development of aquaculture, we expect that if there is a breakpoint in restrictive policy following a shock event, an emergence or growth in aquaculture may be delayed or dampened and if there is a breakpoint in enabling policy following a shock event, aquaculture may develop faster and experience a larger change in its growth trajectory. In order to narrow down the potential locations of breakpoints and assess the response of regulations to significant fishery shocks, we supplied initial estimates for the breakpoints that aligned with major shock events. This approach allowed us to test the impact of fishery shocks on policy which will have implications for aquaculture production responses.

All data synthesis and analysis was conducted on R version 4.0.1 (R Core Team, 2022), dependent on ‘broom’ (Robinson et al. 2022), ‘janitor’ (Firke et al. 2021), ‘here’ (Müller and Bryan 2020), ‘ggpubr’ (Kassambara 2022), ‘ggeffects’ (Lüdecke et al. 2022) packages and the ‘tidyverse’ suite (Wickham et al. 2022), segmented (Muggeo 2013).

Results:

Fishery and aquaculture trends

We found that the California fisheries and aquaculture sectors differ in magnitude and composition of production (Figure 1). For fisheries, both total volume and value hit a peak around 1980 (max volume = 1 billion lbs; max USD value = $1.35 million) and have subsequently declined. Between 1970-2018, the commercial fishing industry landed a yearly average of 507 million lbs across four major taxonomic groups. Across the four major groups analyzed, approximately 73% of total commercial fisheries landings (lbs) were within pisces, 19% mollusks, 3% invertebrates and 4% crustaceans. However, 77% of the total value was pisces landings, whereas 13% was from crustaceans, and mollusks and invertebrates make up the remaining 10% of value. While total marine aquaculture has expanded in the state (max volume = 2 million lbs in 2011) and did not show a substantial peak in production like wild capture, fisheries landings were ca. 30,000x greater than the yearly average of marine aquaculture production between 1970-2018. During that time period, the marine aquaculture industry landed an average of 780,000 lbs per year within one major group (mollusks). Oysters were the largest contributor to production across all years, but this is likely an underestimate given data limitations.

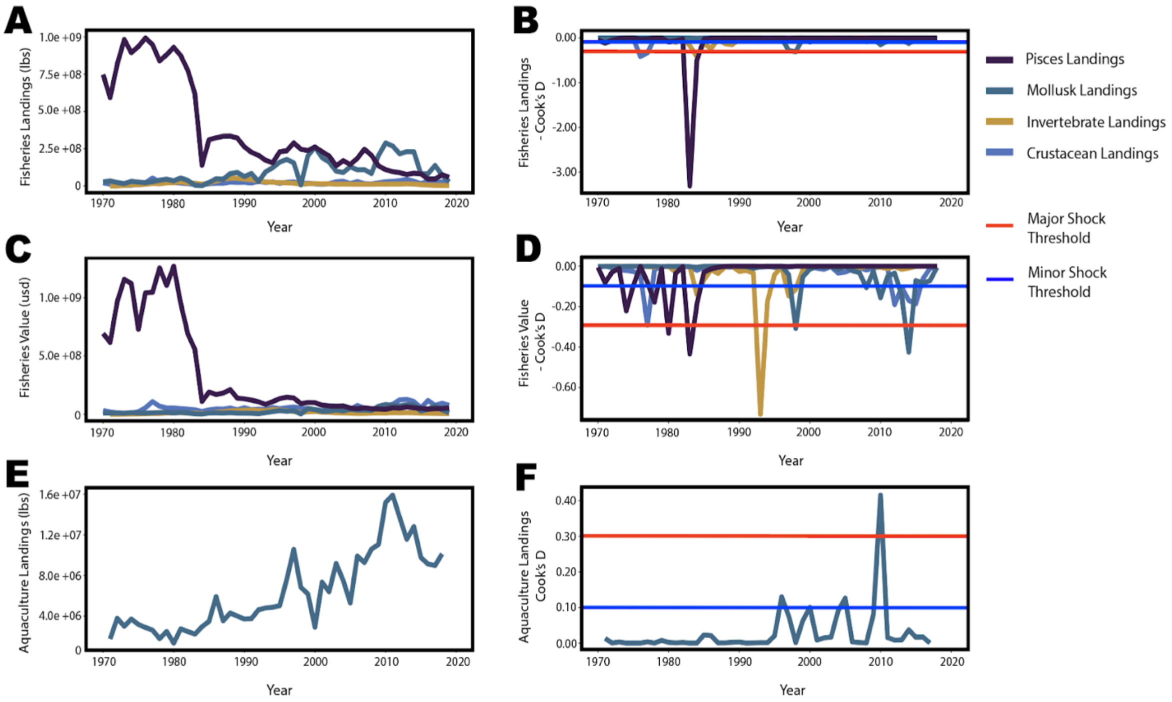


Figure 1: California state commercial fisheries **A)** landings (lbs) and **C)** value (USD) through time (1970-2018) for four major groups: crustaceans, invertebrates, mollusks, and pisces. **B)** Shock analysis of California state commercial fisheries landings through time (1970-2018) for four major groups: crustaceans, invertebrates, mollusks, and pisces. **D)** Shock Analysis of California state commercial fisheries landings value through time (1970-2018) for four major groups: crustaceans, invertebrates, mollusks, and pisces. **E)** California state aquaculture landings through time (1970- 2018). **F)** Inverse- Shock Analysis of California state aquaculture landings through time (1970- 2018). For all panels, the red line represents a major shock event in production (Cook's D > 0.3 or Cook's D < -0.3) and the blue line represents a minor shock event (Cook's D > 0.1 or Cook's D < -0.1).

Linear regression

We found fisheries landings significantly changed over time and by major taxonomic groups, with a combination of declines and increases (Figure 1A). Fisheries volume was best described by year and major group, accounting for the interaction between the two (F(7, 191) = 49.37, p < .001, R2adj = 0.63) (see supplement Table 1). Pisces had a large decline over time (-5.5% +/- 2.4 % per year), while crustaceans (1.6% +/- 1% per year), invertebrates (2.0% +/- 2.4% per year) and mollusks (4.6% +/- 2.4% per year) showed slightly increased production over time. Notably, the magnitude of percent change was ~3 times greater between fish and the other groups, on average, demonstrating that pisces – specifically tunas, bonitos and billfishes; miscellaneous pelagic fishes; and miscellaneous demersal fishes – drove much of the large-scale aggregate fisheries patterns over the time series.

Matching the patterns of volume, fisheries value significantly changed over time and across the major groups, again with significant differences in magnitude of percent change across the groups (Figure 1B). As was the case with volume, the temporal trends of fisheries value was best described by year and major group and their interaction, (F(7, 191) = 57.3, p < .001, R2adj = 0.66). Among the major groups, pisces exhibited a significant decline in value over time (-7.1% +/- 2.2% per year), while crustaceans (2.6% +/- 0.92% per year), invertebrates (4.5% +/- 2.2% per year) and mollusks (4.3% +/- 2.2% per year) showed small increases. Similar to volumetric trends, pisces - particularly miscellaneous demersal fishes and miscellaneous coastal fishes (see supplementary material Figure 2) - played a critical role in driving the overall patterns observed in the time series.

Between 1970-2018, aquaculture volume significantly increased over time (F(1, 46)= 149.60, p < .001, R2 = 0.76) (see Supplemental Table 3), increasing ca. 4% per year (+/-

0.32%). While there was growth in marine aquaculture production from 1970-2018 (absolute change: 1,047,638 lbs), the overall decrease in wild-caught fisheries was not replaced by aquaculture production in terms of taxa produced or volume of production (655:1 decrease in fisheries to increase in aquaculture).

Shocks & Breakpoints

Across our time series, all four wild capture taxonomic groups (crustaceans, invertebrates, mollusks and pisces) experienced statistically significant major (Cook's D> 0.3) and minor (Cook's D> 0.1) shock events for value and volume. However, only one major shock transcended both metrics. In 1983, pisces experienced a statistically significant shock event in volume (Cook's D=1.02; Fig 1B) and value (Cook's D=0.43; Fig 1D). Given the signal occurred across both metrics, we used 1983 to inform our breakpoint analysis. For volume, this shock was nearly six times larger than all other fluctuations across all major groups, and it was the second largest shock experienced in value. The species groups that primarily contributed to this shock event were tunas, bonitos and billfishes (Cook's D = 3.06), miscellaneous pelagic fishes (Cook's D= 1.42) and miscellaneous demersal fishes (Cook's D = 0.36) (see Supplemental Figure 1 and 2).

Examining the other, noncoincident and typically smaller fishery shock events across both metrics, we found that volume was slightly less variable than value over time for each group. For major volumetric shocks, there were two major events for crustaceans in 1976 (Cook's D= 0.41) and 1977 (Cook's D= 0.33), one for mollusks in 1998 (Cook's D= 0.31), and ones for invertebrates (Cook's D= 0.42) and pieces (Cook's D= 0.50) in 1984. In addition, we detected 9 minor volume shocks across all four groups. For major value shocks, there were two detected for mollusks in 1998 (Cook's D= 0.31) and 2014 (Cook's D= 0.43), one in invertebrates in 1993 (Cook's D= 0.73) and an additional one in pisces in 1980 (Cook's D= 0.33). We found a total of 15 minor shocks across all four groups.

Aquaculture experienced several statistically significant inverse shocks (i.e., sudden increases) following the majority of value and volumetric shocks in commercial fisheries (Fig 2B). We found one major inverse-shock in aquaculture landings in 2010 (Cook's D= 0.42) and three minor shocks in 1996 (Cook's D= 0.13), 2000 (Cook's D= 0.10) and 2005 (Cook's D= 0.13). However, none of these directly corresponded to any specific shocks in fisheries, suggesting any responses in aquaculture were likely lagged, dampened or non-existent. In addition, for a one year lag up to 10 years there was no significant correlation between aquaculture and fisheries shocks (see Supplemental Table 4), meaning that, in this case, rapid declines in fisheries does not beget rapid inclines in aquaculture, and that the aquaculture response rate is likely more gradual. The poor aquaculture data resolution and quality may also mute some, if any, more rapid changes in production.

While shocks in wild capture landings did not coincide with sudden sharp increases in aquaculture, using a breakpoint analysis we did find a statistically significant increase in total marine aquaculture production in close proximity to the major fishery shock event in 1983 (for volume and value), as well as several of the smaller events. Specifically, marine aquaculture production experienced a shift in its rate of change from -17,000 lbs/year before 1980 to +34,000 lbs/year after (Fig 2A); a complete reversal in slope direction.

Policies

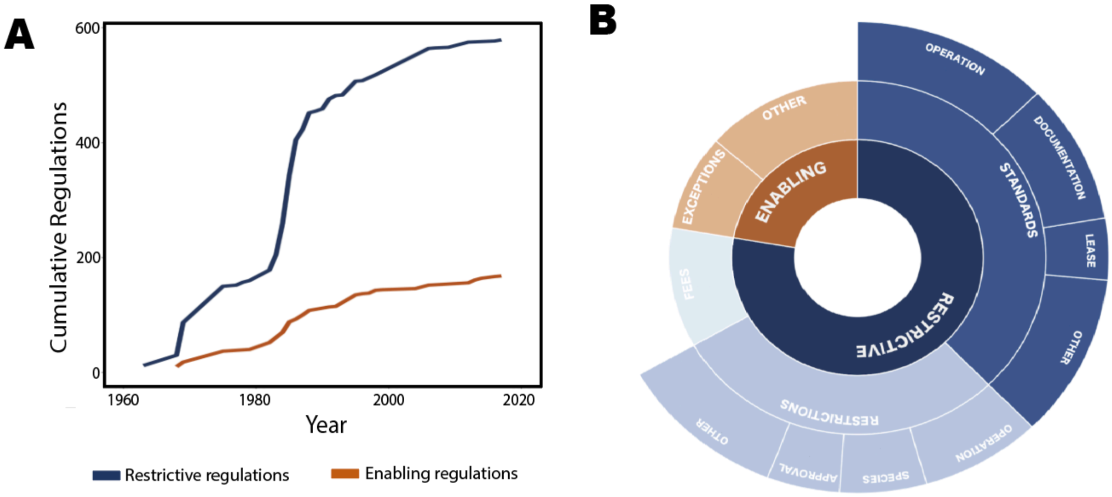
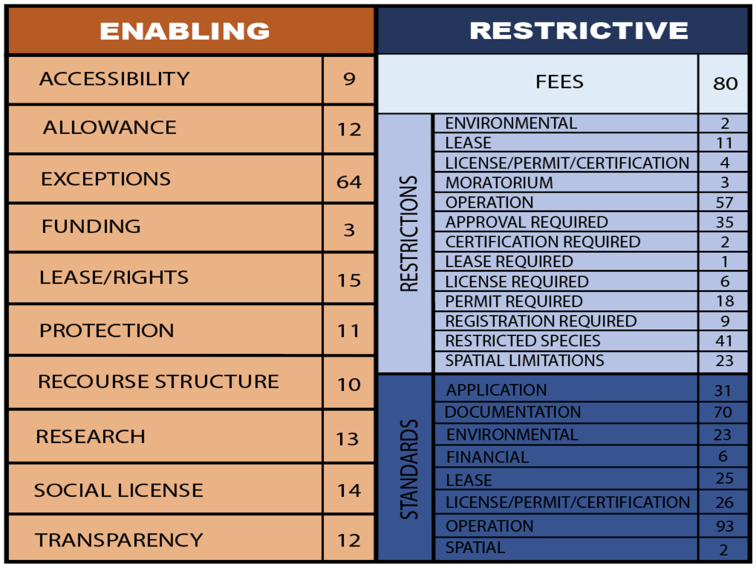


Figure 2: A) Cumulative regulatory policies B) Proportion and breakdown of policy type based on category and subcategory. For both panels, blue represents restrictive regulations, and the orange represents enabling regulations through time (1962-2018).

A total of 167 aquaculture-specific codes were assessed, which housed 747 actionable regulations, spanning 1962-2017. Collectively, the ratio of restrictive regulations to enabling regulations was approximately 3:1 (Figure 2B). The most prevalent categories of restrictive policy included: standards (50%) and restrictions (36%) with the standards and restrictions within the operation subcategory – governing how a farm is or is not allowed to operate – far exceeding any other subcategories (32% in standards and 25% of restrictions). The largest proportion of enabling regulations were exceptions for farmers (39%) in which having a farm or an active license grants them exemption from other regulations, such as take requirements or output standards.

Table 1: Proportion and breakdown of policy type based on category and subcategory. Blue represents restrictive regulations, and the orange represents enabling regulations established between 1962 and 2018.



ENABLING	
ACCESSIBILITY	9
ALLOWANCE	12
EXCEPTIONS	64
FUNDING	3
LEASE/RIGHTS	15
PROTECTION	11
RECOURSE STRUCTURE	10
RESEARCH	13
SOCIAL LICENSE	14
TRANSPARENCY	12

RESTRICTIVE		
FEES		80
RESTRICTIONS	ENVIRONMENTAL	2
	LEASE	11
	LICENSE/PERMIT/CERTIFICATION	4
	MORATORIUM	3
	OPERATION	57
	APPROVAL REQUIRED	35
	CERTIFICATION REQUIRED	2
	LEASE REQUIRED	1
	LICENSE REQUIRED	6
	PERMIT REQUIRED	18
	REGISTRATION REQUIRED	9
	RESTRICTED SPECIES	41
	SPATIAL LIMITATIONS	23
STANDARDS	APPLICATION	31
	DOCUMENTATION	70
	ENVIRONMENTAL	23
	FINANCIAL	6
	LEASE	25
	LICENSE/PERMIT/CERTIFICATION	26
	OPERATION	93
	SPATIAL	2

Cumulative restrictive and enabling aquaculture regulations both increased over time and experienced statistically significant breakpoints, but these changes occurred more than a decade after the fishery shock event in 1983 (fig 3A). We found that cumulative regulatory policy significantly changed over time and by type (enabling or restrictive) (F(5, 53) = 177.5, p < .001, R2adj = 0.94) (Figure 2A)(see supplement Table 4). Restrictive regulations had the largest increase over time (364.6% +/- 9.7% per year,) with a decreasing rate of change over time (~75.4%) whereas, enabling regulations increased but at a slower rate (100.9% +/- 9.2 % per year) with a decreasing rate of change over time (~9.9%). However, enabling regulations had a negative shift in rate of regulation adoption from 4 regulations/year until 1998 to 1 regulation/year. Restrictive regulations increased at a rate of 16 regulations/year until 1996 in which regulation adoption slowed to 3 regulations/year. Thus, as fisheries declined and aquaculture increased, aquaculture regulations proliferated until the mid- to late-90s, with a particularly dramatic growth in restrictive regulations.

Oyster Review:

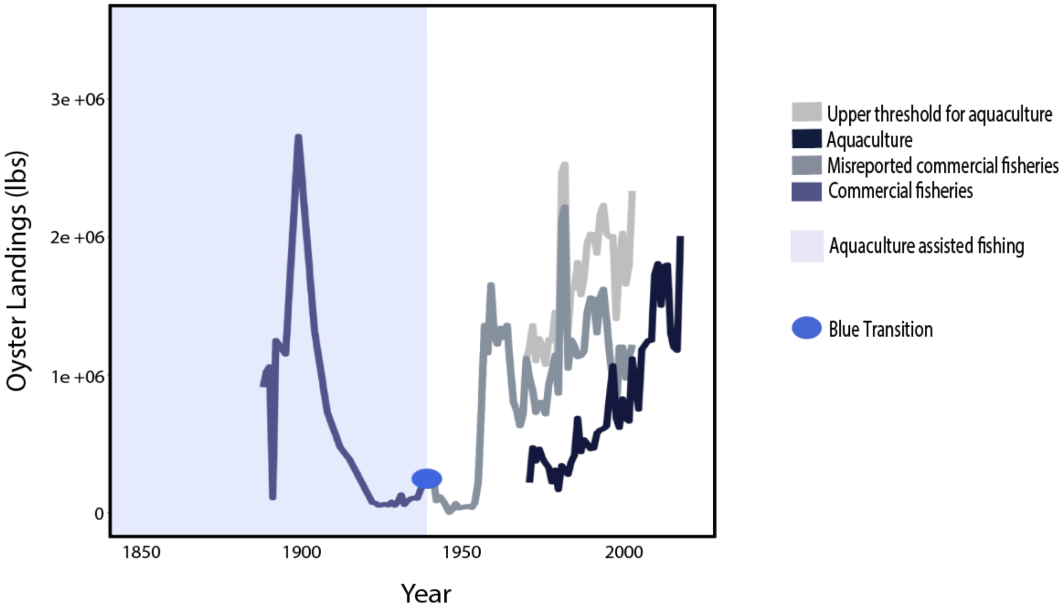


Figure 3: Historical California oyster production (1849-2003)

While it is not apparent in the formally reported data we analyzed above, a detailed review of the the primary oyster fishery – olympia oysters (*Ostrea lurida*) – in California uncovered that the oyster fishery collapsed numerous times as the result of overfishing and water quality issues, prompting the wild harvest of oysters to be fully replaced with aquaculture practices as a more stable alternative. The 1850s saw dramatic increases in the California population (US Census Bureau) correlating with decreases in oyster abundance as native oysters were fished to near extinction in order to support growing demand (Conte 1996, Barrett 1963, Bonnot 1935). In response to the declines of native oysters, fishers began outplanting hatchery-based oysters, importing non-native seed, and using farming methodologies and technologies to rebuild and strengthen the industry (Conte 2019). In 1909, the first leased oyster farm was established on the coast of California (Tomales Bay Oyster

Company) which solidified the establishment of the California aquaculture industry and began the trend of growing oysters in leased areas, signifying a full blue transition (Fig 3) (Conte 2019). However, progress was impacted in the 1980s with paralytic shellfish poisoning outbreaks (Conte 1984) and the passing of the California Aquaculture Development Act (Public Resource Code: 825-830), which limited leasable areas to only a few thousand acres. Despite making a complete blue transition, which revived the oyster industry, the increase in regulation appears to correspond with relatively stagnant oyster production; this is likely reflective of the patterns at large (i.e., disease and more restrictive policies slowing aquaculture growth). Further constraints to oyster farmers came in the form of fees and taxes, such as the Oyster Lease privilege tax, in which –in addition to the rent – every person operating under an oyster lease must pay a privilege tax of four cents ($0.04) per packed gallon, or fraction thereof, of shucked oysters harvested by the lessee (CDFW 15406.5). Additionally, the California Environmental Quality Act (CEQA) was introduced in the 1970s which placed sanitization, ecological disturbance, construction, and operation restrictions on farmers, making the acquisition of new leases and lease expansions an arduous process.

Discussion:

The California Shellfish Initiative has proposed that the state of California has the potential to “lead the nation to meet an ever-growing shellfish demand,” while creating environmentally sustainable “blue jobs" in coastal communities (AJR-43, California Shellfish Initiative, OPC- Aquaculture Guiding Principles). However, to meet these goals, it remains important to understand patterns and drivers of marine aquaculture development in the state.

Particularly, identifying influential drivers of aquaculture expansion will be necessary to determine the most suitable and sustainable path forward relative to other important sectors, including wild capture fisheries. In an effort to better understand the underlying mechanisms driving aquaculture development in California, our study found that production transitions from fisheries to marine aquaculture are not uniform across space and time and can occur to varying degrees depending on scale and taxonomic group. We found some support that major declines (i.e., shocks) of wild-capture fisheries may precede the emergence of more rapid marine aquaculture growth in California, but our policy review suggests that aquaculture growth is likely dependent on the policy landscape; these trends are a consistent finding with more global and US domestic studies (Keumpel et al. 2021, Cotrell et al. 2021, Gephart et al. 2021, Naylor et al. 2021). However, a better understanding of these dynamics will rely heavily on data quality and availability.

There was a significant increase in the rate of change of marine aquaculture production following the most prominent fisheries crash in 1983, providing empirical evidence that fisheries status may influence aquaculture growth. While we hypothesized larger shocks will have a larger influence on aquaculture growth, seafood shocks are common and can occur due to a variety of causes (Gephart et al. 2017). It is possible that significant, but smaller fisheries declines (i.e., the small shocks detected in our study) could perhaps cumulatively influence aquaculture emergence and growth overtime. The major shock in California fisheries value and volume in 1983 was preceded by the anchovy collapse in 1972 and the sardine crash of 1945, perhaps reducing the overall resilience of the wild capture sector. These circumstances, in addition to the declining groundfish fishery and environmental and market factors (e.g. cyclical changes in ocean temperatures and inflation), are likely what led to the large-scale shock (Fig 1A and Fig 1B) and added to the necessity of market diversification.

Qualitative accounts of fisheries declines spurring aquaculture in other regions support the findings of our more quantitative study. In Chile, a massive decline across all fisheries led to broad aquaculture development and growth, with aquaculture likely to surpass wild capture if diseases can be better managed long term (Naylor et al. 2021, Díaz et al. 2019). In Norway, a decline in wild Atlantic salmon stocks spurred the government and industry to increase cultured production of the same species, which now dominates the region's seafood sector (Naylor et al. 2021, Garlock et al. 2020, Liu et al. 2011). Finally, in the state of Florida, closures of the gillnet fishery led to active planning and government support for fishers to transition to farming clams (Colson and Sturmer 2000). However, while these regions saw aquaculture expanding in direct response to fisheries declines, the response of aquaculture we found is more complex, likely due to a number of important context dependencies. As predicted, the shock in 1983 forced many fishers, processors and wholesalers to diversify and switch markets (Errend et al. 2017), but was followed by the successful implementation of new fisheries management, including catch limits which mandated fishers to not exceed certain quotas (e.g. Magnuson-Stevens Fishery Conservation and Management Act 1976, NOAA 2021). The recovery and increase in catches in the various other wild harvest taxa (e.g., crustaceans) – governed by changes in state and federal policy – likely constrained the opportunities for aquaculture growth. That appears to be the case for historical California oyster fisheries that completely transitioned to become solely cultured when wild populations were unable to rebound prior to the implementation of the restrictive regulations analyzed in this study. In fact, oyster reefs globally have declined by

85% (Kirby et al. 2004, Beck et al. 2011) and oyster aquaculture has become one of the dominant forms of production around the world.

Our study found the proliferation of regulatory aquaculture policies co-occurred with the major fishery shock and increase in aquaculture. The high proportion of restrictive regulations likely played a key role in how slowly marine aquaculture production grew in California. At the federal-level, marine aquaculture production is small relative to its potential, likely in part because of a non-enabling political landscape (Rubino et al. 2022, Kaiser et al. 2011; Knapp and Rubino 2016), paralleling what we found in California. Still, within the US there are several states that have more robust mariculture industries as the result of prioritized state-led governance and management (Lester et al. 2021). For example, Florida has a comparatively large mariculture industry (no. of farms = 178) and appears to have one of the most enabling policy environments for marine aquaculture development in the country (Lester et al. 2021). Proactive government involvement through state-led training programs, the development of state-wide best practices for marine aquaculture, and the development of Aquaculture Use Zones (AUZs) in Florida demonstrates that a substantial regulatory environment can still be enabling. Given this context, it is not just the number of regulatory policies that matters, but also the type (restrictive or enabling) and content. Fees, for example – making up 11% of reviewed regulations in this study – can disproportionately affect small-scale aquaculture practices and farmers (van Senten et al. 2020, Engle and van Senton 2022) due to limited financial resources (Singh et al. 2018), economies of scale (Tveteras et al., 2012) and higher administrative burdens (van Senten et al. 2020). This may be particularly important in a state like California, where the majority of aquaculture operations are relatively small-scale (< 160 acres).

Additionally, our study corroborates that California prioritizes the environmental management of economic activity, which has translated to the implementation of many environmental restrictions (e.g., California Environmental Quality Act (CEQA) (Bowden 1981, Gualco-Nelson 2017), in addition to federal environmental regulations (Engle et al. 2013, Rubino et al. 2022). In California, oyster production emerged and fully transitioned prior to the implementation of many state and federal environmental management strategies and regulations and several of the current farms were established prior to the National Environmental Policy Act (NEPA) and CEQA. However, bivalve and seaweed aquaculture are now recognized for their potential positive environmental benefits, such as improving water quality (Theuerkauf et al. 2022, Barrett et al. 2022). As a result, regulations will likely affect the establishment and farming of different taxonomic groups unequally as new science emerges (e.g., the regulatory ban on finfish farming (Sustainable Oceans Act, SB 201)).

We found that the detection of shock responses and our ability to understand these drivers is the product of data quality and availability. As seen in the oyster case study, a lot of the data were not accurate mainly due to misreporting/misclassification between what is farmed versus fished. While we know and can contextualize the history of full blue transitions through literature review, they are not always well reflected in the data, which is certainly the case with incomplete or partial blue transitions. Though native oysters have not been commercially wild caught in California since the 1800s, the oysters landed from cultured seed continued to be categorized as commercial landings until the 1980s, and not all of the reporting was fully reclassified until around 1985 (personal correspondence, Conte 1996). As the official data record only begins in the 1970s, a large portion of fisheries dynamics leading to marine aquaculture are missed. Current fisheries and aquaculture data still lack specificity that could elucidate additional drivers of production transitions and interactions (Froehlich et al. 2022). For example, it is likely that the long-standing use of aquaculture assisted fishing practices (i.e., hatchery-based fisheries) contributes to production transitions, as seen in oysters, but the presence and reporting of such practices is not currently distinguished within state-level data. This makes partial transitions, such as the use of hatcheries for fisheries conservation or enhancement practices (Taylor et al. 2017) and ranching operations, extremely challenging to identify and track over time and space. In the cases of striped bass (Striped Bass Policy 1996, Delta Fisheries Management Policy 2019) and Pacific salmon (Priority Action Coho Team (PACT) initiative, Pacific Coastal Salmon Recovery Fund (PCSRF)), large-scale restorative operations and programs have been implemented to support natural populations through the use of hatcheries and other marine aquaculture practices; therefore, marine aquaculture may be expanding in response to fisheries shocks in ways that cannot be detected through current production data. Determining the extent of marine aquaculture being used in these partial-transition or co-production settings is important in order to fully understand the seafood production sector's resilience and how it responds to disturbance (Anderson 2002). In the absence of improving fisheries and aquaculture data collection and criteria (see Froehlich et al. 2022 for details) more qualitative assessments – such as the oyster example in our study – and data-limited, scenario modeling approaches may provide additional insights to understand these dynamics.

There are likely interactive effects across multiple drivers, in addition to fisheries' declines and regulatory policy, that are causing feedbacks and shaping aquaculture growth in the state that were not assessed in this study. It is recognized that technology has changed through time across production forms, shaping the current aquaculture industry globally (Zhang and Gui 2023, Afewerki 2023, Kumar 2018, Kumar 2016) and in California. In fact, technological advancements have been outlined in narrative accounts of oyster culture in the state (Conte 1996). In particular, the development of the transcontinental railroad and the ability to transport oyster seed from Japan played a significant role in increased development (Barrett 1963). Studies have shown that technological improvements can expedite aquaculture growth (Kumar and Engle 2016; Afewerki 2022). In California, the ability to quantify this is again limited by data, but could be assessed through other data sources such as social narrative accounts or patents. However, the comparatively slow aquaculture growth in California that runs counter to general technological advancement and knowledge sharing may suggest that innovation is not an important driver of aquaculture in the state. Similarly, economic and market factors are likely to influence the trajectory of aquaculture growth (Asche et al. 2022), but apart from tracking the value data of fisheries, we were unable to infer the effect size in California. Further, the influence of federal and global policy trends, market developments (i.e. certification and labeling standards), and increasing seafood demand can influence state-level drivers and can sway social license for aquaculture, which is considered to be a pivotal factor in determining the trajectory of aquaculture growth across multiple scales (Zajicek et al. 2023; Weitzman et al. 2023). Regardless, aquaculture production (forms and quantity) is highly variable across states (Olin 2001, OECD 2021) and despite growing federal interest in aquaculture development (i.e. the Federal Aquaculture Development Act (1980), the development of Aquaculture Opportunity Areas (Executive Order 13921)), this variability suggests that trends are heavily influenced by state-level drivers.

With variability of food production systems projected to increase with time, it is important to explore how aquaculture may grow and contribute to the stability and resilience of the seafood production sector. However, the contribution and role of aquaculture will likely be variable. Notably, aquaculture growth and development in the United States differs from other aquaculture producing countries because of its dependency on imports, restrictive regulatory structures, high labor costs, high coastal property values and historical deprioritization of marine aquaculture (NMFS 2016; Gephart et al. 2019; Garlock et al. 2020). Therefore, it is important that studies, such as this one, consider these mechanisms in local and domestic contexts rather than only relying on global and national assessments; this is particularly true as it pertains to fisheries stability and success. Delving into the bureaucracy surrounding a food system and identifying mechanisms which have hindered and facilitated its growth and development are important steps in improving food security, and improving sustainable food production (Gephart et al. 2021; Tigchelaar et al. 2022).

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Supplement:

Linear Regression Tables:

Table 1: Fisheries volume

MODEL	DF	AICc	Adjusted R^2	Δ AICc
log(weight_lb) ~ year + factor(major_group) + factor(major_group):year	9	579.2187	0.631	0
log(weight_lb) ~ year + factor(major_group)	6	625.7136	0.527	46.4949
log(weight_lb) ~ year	3	772.4085	0.5503	193.1898
log(weight_lb) ~ factor(major_group)	5	624.7726	0.5269	45.5539
log(weight_lb) ~ 1	2	770.7698	0	191.5511

Table 2: Fisheries value

MODEL	DF	AICc	Adjusted R^2	Δ AICc
log(value) ~ year + factor(major_group) + factor(major_group):year	9	545.7186	0.6575	0
log(value) ~ year + factor(major_group)	6	632.2127	0.4632	86.4941
log(value) ~ year	3	752.9778	0.0004881	207.2592
log(value) ~ factor(major_group)	5	632.7243	0.4592	87.0057
log(value) ~ 1	2	752.0826	0	206.364

Table 3: Aquaculture Volume

MODEL	DF	AICc	Adjusted R^2	Δ AICc
log(weight) ~ year	3	27.84131	0.7597	0
log(weight) ~ 1	2	95.31878	0	67.47747

Table 4: Aquaculture Policy

MODEL	DF	AICc	Adjusted R^2	Δ AICc
cumulative ~ poly(year, 2) * factor(d_e)	**7**	**633.2661**	**0.9383**	**0**
cumulative ~ poly(year, 2)	4	774.5168	0.292	141.2507
cumulative ~ factor(d_e)	3	761.7555	0.4204	128.4894
cumulative ~ 1	2	792.9583	0	159.6922

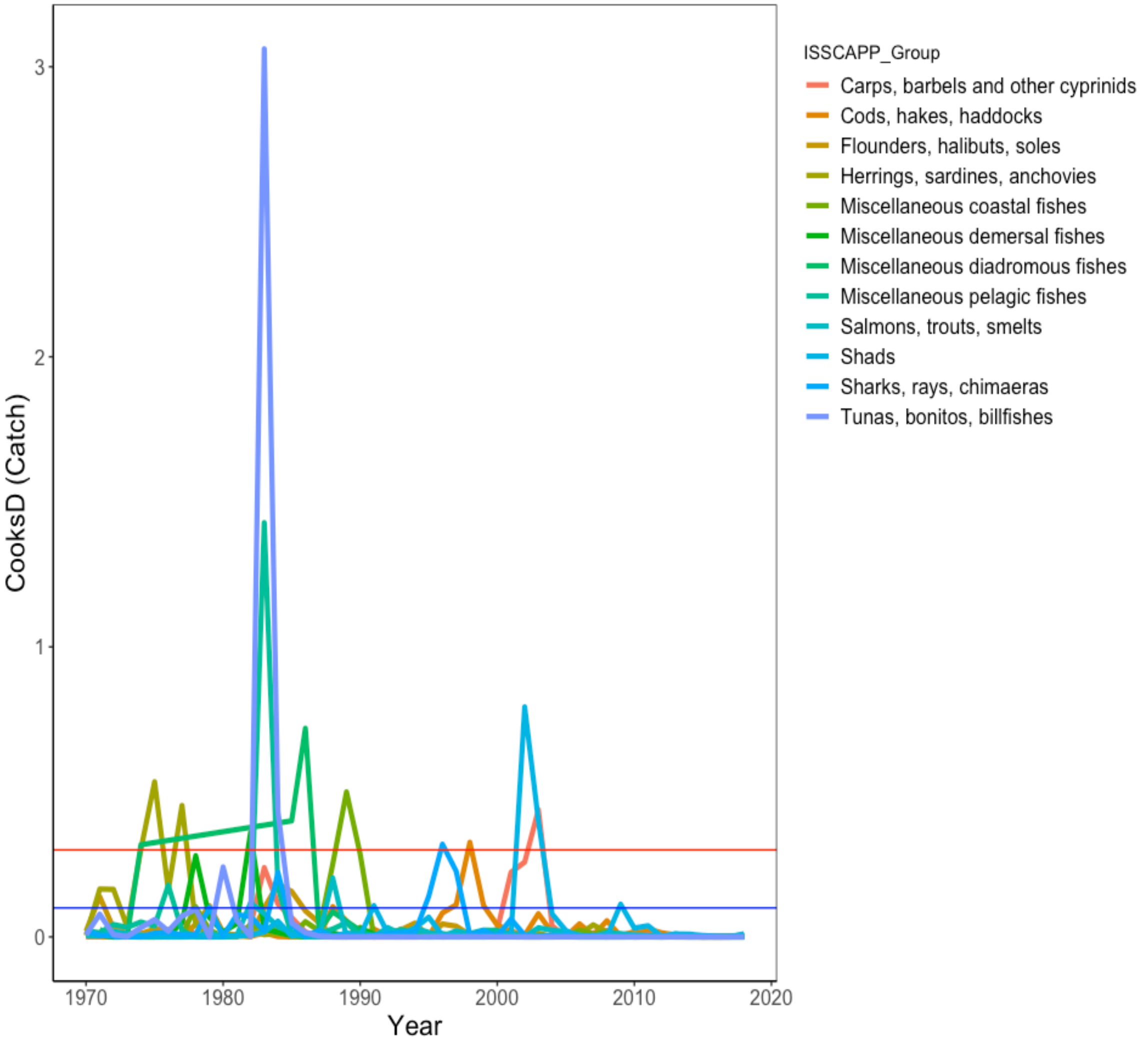

Figure 1: Fisheries production catch (lbs) shocks measured across ISSCAPP groups within major group Pisces. The red line represents a major shock event in production (Cook’s D > 0.3) and the blue line represents a minor shock event (Cook’s D > 0.1).

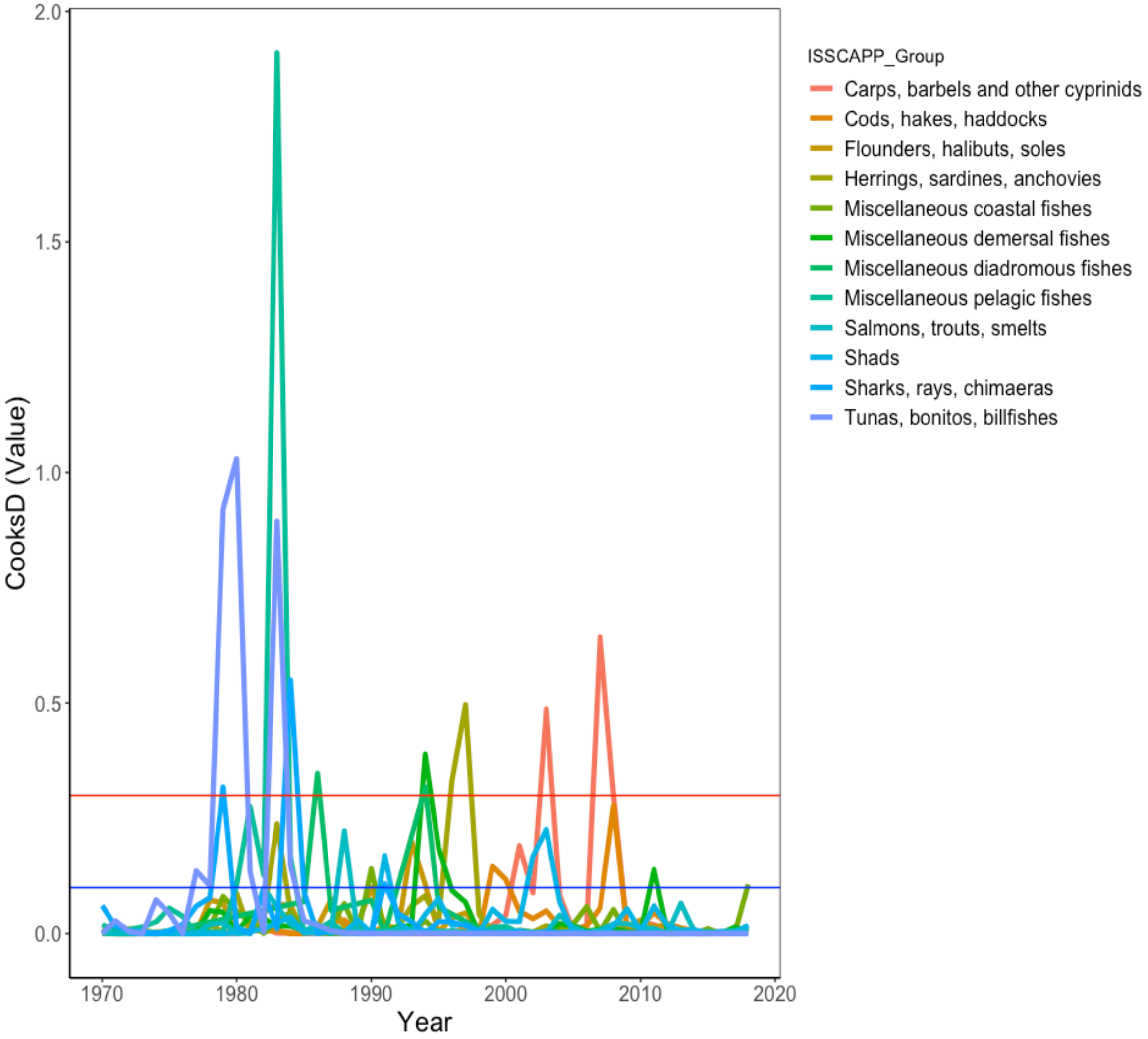

Figure 2: Fisheries production value (USD) shocks measured across ISSCAPP groups within major group Pisces. The red line represents a major shock event in production (Cook’s D > 0.3) and the blue line represents a minor shock event (Cook’s D > 0.1).

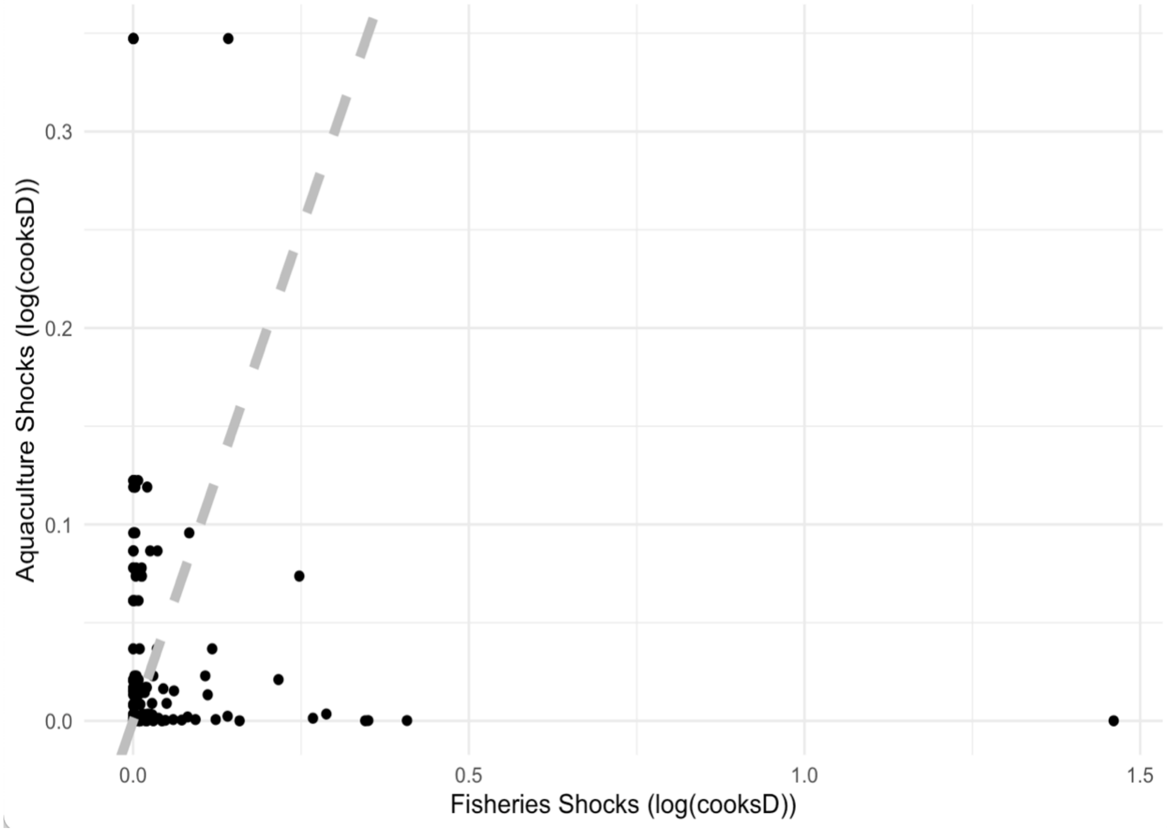

Figure 3: Correlation between aquaculture shocks and fisheries shocks through time. Dashed grey line represents a 1:1 ratio.

Table 4: Model results exploring the relationship between aquaculture and fisheries shocks through time with a lag period up to 10 years: R^2 Values and p-values from linear regression analysis

Year lag	R^2	p-value
0	0.0013991425	0.3284
1	0.0002915676	0.6103

2	0.0020034341	0.5441
3	0.0017941873	0.567
4	0.0008840487	0.6887
5	0.0012565284	0.6338
6	0.0018065699	0.5689
7	0.0022284832	0.528
8	0.0036432497	0.4209
9	0.0064606923	0.2848
10	0.0054282632	0.3284

Table 5: Subcategory definitions

Category	**Type**	**Subcategory**	**Definition of subcategory**
restrictive	fees		Fees on aquaculture operations
	Restrictions	approval required	In order to participate in aquaculture activities and/or production specifically,

			additional approval from a governing body is required. Aquaculture is restricted until approval is achieved.
		environmental	Aquaculture production is restricted or limited based on environmental concern or in order to limit environmental degradation.
		lease	Lease restrictions.
		license/permit/certification	Restrictions within licenses/permits/certifications.
		moratorium	The restriction of the cultivation of specific species or taxa.
		operation	Restrictions in how a farm or farmer is allowed to operate.
		certification required	Aquaculture activity is restricted without certification
		requires lease	Aquaculture activity is restricted without lease

		requires license	Aquaculture activity is restricted without license
		requires permit	Aquaculture activity is restricted without permit
		requires registration	Aquaculture activity is restricted without registration
		restricted species	Additional restrictions associated with certain species (not a full moratorium).
		spatial	Aquaculture activity is restricted spatially
	Standards	application	Standards required to submit an application
		documentation	Standards required for documentation of aquaculture operations and production
		environmental	Standards for environmental protections.

		financial	Standards regarding sale and value of production.
		lease	Standards required for lease holding, renewal and obtainment.
		license/permit/certification	Standards required for license/permit/certification holding, renewal and obtainment.
		operation	Standards and regulations that aquaculture operations must uphold.
		spatial	Site selection and ongoing spatial considerations and standards to be upheld by aquaculture operations.
enabling	accessibility		Improved access to prospective and current farmers through government funded programming, spatial planning etc.

	allowance	Farmers are entitled to or allowed to operate in a given way.
	exception	Exceptions allotted to farmers that are not extended to non-farmers.
	funding	Financial support of aquaculture operations.
	lease/rights	The legal ability to obtain a lease and the inherent rights that are associated with having a lease.
	protection	Legal protections for farmers, farms and operations.
	recourse structure	Legal recourse structure for farmers to challenge a regulatory decision or structure.
	research	Government supported research initiatives into aquaculture production.

	social license	Explicit programs, activities or initiatives to improve aquaculture social license and acceptance.
	transparency	Improved government transparency in decision making and governing.