Portfolio Substitution between Coastal Pelagic Species under Shifting Target Species Distributions and Policy Constraints

Felipe Quezada[1,2,*] Desiree Tommasi[1,2] Stephen Stohs[2] Timothy Frawley[1,2]
Jonathan Sweeney[4] Isaac Kaplan[3] Barbara Muhling[1,2]

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Abstract

Fishers for forage species typically face a set of possible species to choose that allow them to diversify their portfolio and reduce income risk. Switching among species is more feasible for vessels that share similar gear and methods for fishing. More diverse portfolios may increase fisher resilience to climate-driven changes in target species' spatial distributions and availability. However, regulations and other constraints (e.g., port constraints on where landings of a particular species may occur, or permit requirements) may reduce the degree of substitution we observe. This study analyzes how historical changes in forage species distribution and the closure of the Pacific sardine fishery affected landing substitution between two coastal pelagic species: Pacific sardine (*Sardinops sagax*) and market squid (*Doryteuthis opalescens*). Using a hurdle model, we also study how spatial distribution and closure affected the coastal pelagic species fisheries' participation decisions over the 2000-2019 period. Our preliminary results show strong substitution between market squid and Pacific sardine when both were available, while the Pacific sardine closure in 2015 was associated with reduced market squid landings suggesting lower fishers' participation in this fishery.

[1] Institute of Marine Sciences, University of California Santa Cruz

[2] NOAA Southwest Fisheries Science Center

[3] NOAA Northwest Fisheries Science Center

[4] NOAA Pacific Islands Fisheries Science Center

[*] Correspondence: Felipe Quezada <felipe.quezada@noaa.gov>

1 Introduction

Fishing portfolios are an essential mechanism to safeguard fishers' livelihood. Diversification strategies have been principally associated with reducing income variability [Kasperski and Holland, 2013]. For instance, when a species abundance is reduced due to environmental conditions, fishers can change targeted species to a species that requires similar gears. However, there is not always room for diversification. Switching between species can be costly if gears are different between species, or a new permit is required for legal fishing. Moreover, even though fishers may have flexibility switching between species, port infrastructure, markets, and regulations that limit access to fisheries to avoid collapse of fish stocks from overfishing may impose some restrictions on this flexibility [Kasperski and Holland, 2013]. Therefore, it is unclear how species distribution and regulation changes would be reflected in landings compositions and participation.

In this study, we analyze how changes in spatial distribution and the implementation of fisheries closures affect landings and fisher participation of the two most important coastal pelagic species (CPS) harvested on the U.S. West Coast: Pacific sardine (*Sardinops sagax*) and market squid (*Doryteuthis opalescens*). Fisheries closures are an interesting policy instrument when fishers target more than one species because they allow us to study how fishers change behavior by excluding one alternative. However, fewer studies have studied one fishery closure's effect on other fishery outcomes. An example is Vermard et al. [2008], which studies the effect of the European anchovy (*engraulis encrasicolus*) fishery closure in trip choices conducted by the Bay of Biscay pelagic fleet. Another example is Richerson and Holland [2017], who studied the effect of US West Coast salmon fishery closures on vessel participation. In this paper, we study the effect of the 2015 Pacific sardine closure implemented after the over-exploitation of the fishery and the effect of seasonal closures after reaching a catch limit target.

Studying the effect of closures and changes in species distribution is not straightforward as different responses can be observed in response to the same conditions, as fishers and vessels are heterogeneous [Zhang and Smith, 2011]. Moreover, vessel heterogeneity and port constraints will dictate the possible set of species that a fisher can choose. Species are also interconnected, at least economically, if not ecologically. Thus, any regulation or ecological disruption that affects one species would affect fishers' decision to target another species. Therefore, a multiple species targeting framework that considers interrelation between species is necessary to understand the CPS fishery further. Our research goes a step further and analyzes the CPS fishery as one where fishers can target multiple species in line with recent literature [Richerson and Holland, 2017]. Our goal is to understand how changes in species distribution, seasonal and total closures affect vessel responses with respect to landing amount and participation, and the substitution between species.

Our papers build on the model developed by Smith et al. [2021] for sardine landings. We expand their model, including a landing equation for the two species analyzed in this study and estimating a participation model simultaneously using a multilevel Bayesian hurdle model. The participation models (i.e., hurdle component) are built on the work of Richerson and Holland [2017] for the US West Coast salmon troll fishery. The Bayesian hurdle model incorporates heterogeneity between fleets and ports areas. We use the probability of presence obtained from Species Distribution Models (SDM) as an explanatory variable instead of landing by species. Including the spatial distribution of different species to explain landings allows us to understand how interactions between species availability would affect fishers target decisions. We expect these additions to better characterize how the fishers portfolio is composed and better understand the effects of species interactions on catch rates and participation. Moreover, an additional benefits of including SDM in our model as explanatory variable is that it could allow researcher and resource managers to project landing and participation over time using SDM predictions for different climate scenarios.

The remainder of the paper is organized as follows: Section 2 provides background on the CPS fishery on the U.S. West Coast. In Section 5 we discusses our data set and empirical strategy. Section 6 presents the results of the estimations, and we conclude in Section 7.

2 Coastal Pelagic Species fishery

The Pacific Fishery Management Council (PFMC) is responsible for the CPS species management through a Fisheries Management Plan (FMP). Before 2000, the only fishery under a FMP was the fishery for Northern anchovy (*Engraulis mordax*). The Northern anchovy FMP started to be developed in 1977, and the final draft was approved and implemented in 1978 [PFMC, 2021]. During these times, and for many years, the Northern anchovy was harvested for reduction. This fleet was referred to as the *wetfish* fleet, and also fished for other CPS such as Pacific sardine(*Sardinops sagax*), market squid (*Doryteuthis opalescens*), Pacific mackerel (*Scomber japonicus*), Jack mackerel (*Trachurus symmetricus*), Pacific bonito (*Sarda lineolata*), and Pacific bluefin tuna (*Thunnus orientalis*) [PFMC, 2020]. In March 1995, the PFMC decided to expand the FMP through Amendment 8 to include the entire CPS complex (Pacific sardine, northern anchovy, Pacific (chub) mackerel, jack mackerel, and market squid) along the U.S. west coast. The PFMC partially approved this amendment in June 1999, and they published the final regulations in December 1999. Finally, the PFMC implemented the FMP on January 1st, 2000.

In recent years, there is no reduction capacity for the Northern anchovy fishery in California, and it is principally harvested in the Monterrey area as a substitute for sardine and squid when both are not available [PFMC, 2020]. The Northern anchovy fishery has lost its importance within the CPS complex after the decline of the reduction market. However, in some particular ports like Monterrey, it is the only species that fishers can harvest when market squid is unavailable and the Pacific sardine fishery is closed [PFMC, 2020]. In Oregon, the Northern anchovy fishery was categorized as “developmental fishery” between 1995 and 2009. Only 4 of the 15 developmental permits were issued for this fishery. The developmental program was suspended in 2009, as there were no funds to support it [PFMC, 2020]. The Oregon Northern anchovy fishery is currently under an open-access regime but limited by gear [PFMC, 2020]. A significant fishery started to grow in 2015 and 2016, but no landings was observed in Oregon during the year 2018. In Washington, the Northern anchovy fishery is restricted from developing to a high-volume fishery to protect the traditional bait fishery. Some of these regulations limit catch and limit the catch percentage allocated to reduction.

In the 60s, the Pacific sardine fishery in California closed due to the fishery’s collapse. The fishery reopened in 1986 with a precautionary quota of 906 metric tons. The Pacific sardine fishery was considered as fully recovered in 1998 with an estimated biomass of over one million metric tons [PFMC, 2020]. Since 2000, after implementing the CPS FMP, the Pacific sardine has been managed under a limited entry (LE) permit with a quota management system, or Harvest Guideline (HG), that controls commercial catch of sardine biomass. If harvests are over the HG, then the commercial fishery is closed for the rest of the season. Permits are transferable and cumulative, but they are required to match the vessel tonnage, and it is uncommon to see vessels and permits sold separately. LE permits are only required if a vessel lands more than 5 tons of all CPS finfish combined in a trip. The CPS LE fleet is composed of 65 permits and 55 vessels. The LE permits program is federal but only applies south of Point Arena, California (39°N). This geographical point divides the coast into two areas which were used to allocate the total HG for the Pacific sardine during a season (changed from 35°40'N to 39°N in 2003). In 2005, the quota allocation for Pacific sardine was modified from area-based to coast-wide seasonal release that follows an allocation formula:

1. 35% of the HG to be allocated coastwide on January 1st.
2. 40% of the HG, plus any portion not harvested from the initial allocation, will be reallocated coastwide on July 1st.
3. 25% of the HG, plus any portion not harvested from earlier allocations, will be reallocated coastwide on September 15th.

The commercial fishery has been closed for the whole U.S. west coast since 2015 as the spawning stock biomass (SSB) is estimated to be below the cutoff point of 150,000 metric tons. This total closure came after many years of seasonal closures.

North of 39°N, vessels do not require federal permits. However, Oregon and Washington have implemented state permits for sardine. In Oregon and Washington, the fishery did not develop until the 2000s. In 1999, a fishery for the Pacific sardine started to operate in both states targeting larger sardines to be sold as bait to Asian longline tuna fisheries [PFMC, 2020]. Then, in 2006 the fishery expanded in both states to supply the market for human consumption. In Oregon, the Pacific sardine fishery was categorized as a "developmental fishery" until 2005, and the first LE permits were issued in this state in 2006, capped at 26 (currently, there are 24 LE permits for this fishery in Oregon). In Washington, the Pacific sardine fishery was a "trial fishery" from 2000-2002 with a state HG of 15,000 metric tons (i.e., no limits on the number of participants). Later, from 2003 to 2009, the fishery was under an "experimental fishery" category, with experimental permits capped at 25. Finally, in 2009, Washington's Pacific sardine fishery was designated as a "commercial fishery" with a LE program that allocated 16 permanent permits and ten temporary ones. In Washington, fishing for sardine is prohibited from January 1st to March 31st, and directed commercial harvest is prohibited within state waters (0 to 3 miles).

The market squid fishery was unregulated and open access until permits became required in California in 1998. However, there were no limits to the number of permits issued by the authorities. In 2001, a HG was implemented at 125,000 U.S. tons for this fishery. Later, in 2005, the California Fish and Game Commission (CFGC) implemented the Market Squid Fisheries Management Plan, which reduced the fleet to a maximum of 73 vessels, limits the number of light boats to 34, reduced the HG to 118,000 U.S. tons and incorporated a weekend closure to allow for a period of uninterrupted spawning [PFMC, 2020].[1] Oregon's market squid fishery started in 2014 with few vessels targeting squid (15 in 2016

[1] Vessel permits allow vessels to attract squid with light and use purse seine for harvest, Brail permits allow vessels to attract squid with light and use brail gear, and light boat permits only allows to attract squid with lights

and 11 in 2018), while in Washington, there are no directed landings of market squid. In 2019 two permits were issued to allow market squid catch from Oregon to be delivered to Washington ports.

Pacific sardine fishing season in California has a peak in landings during the early summer to fall in the Monterrey area, specifically in Moss Landing, while in Southern California, specifically in San Pedro and Terminal Island, peak landings occur during the winter. Fishing seasons for Pacific sardine are shown in Panel (a) of Figure 1. In Oregon and Washington state, specifically at Astoria and Ilwaco/Chinook ports, the fishing season is primarily during summer and early fall. Panel (b) shows that market squid fishing season in Southern California, specifically in San Pedro, Terminal Island, and Ventura, goes from fall to winter, while in Northern California, specifically in Moss Landing and Monterrey, the season goes from late spring to summer.

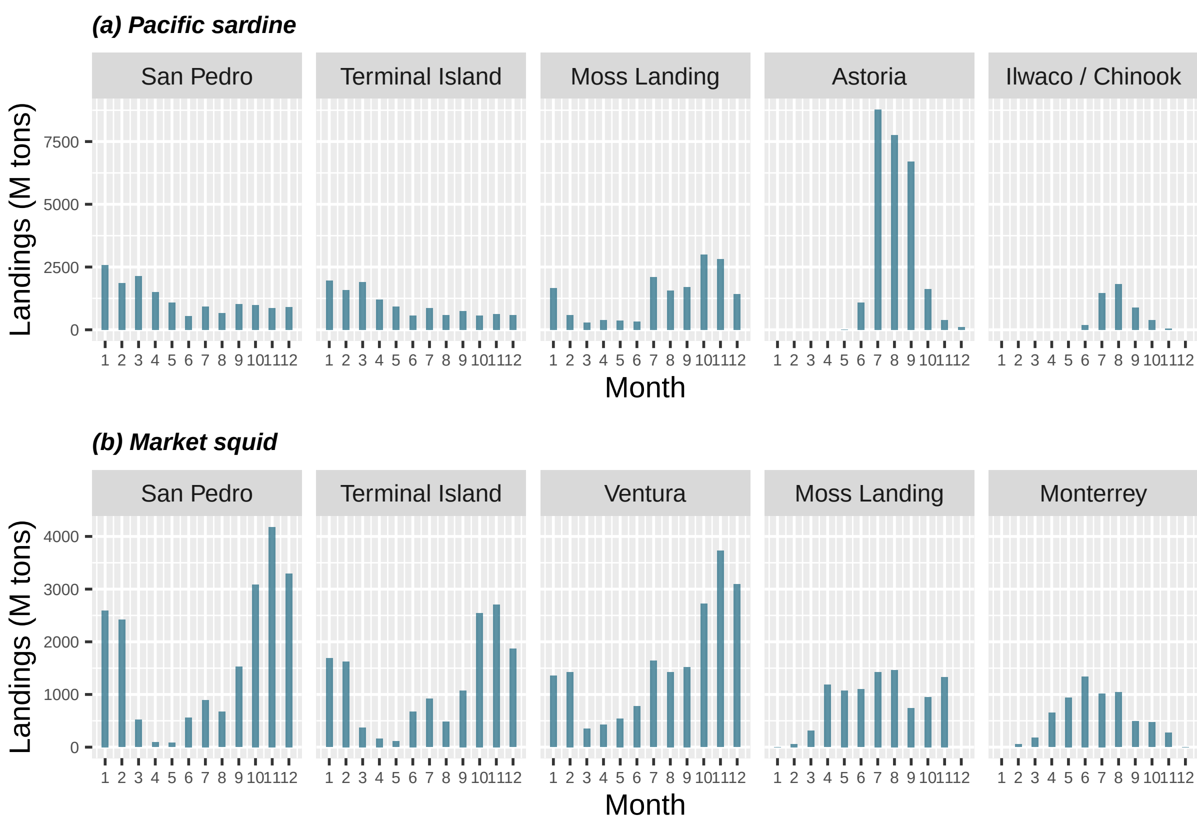

Figure 1: Fishing season for Pacific sardine and Market squid (average monthly total harvest for the period 2000-2014, before the Pacific sardine closure).

3 Data analysis

3.1 Landing, prices and revenue

Pacific sardine and market squid, followed by Pacific Mackerel and the Northern anchovy, mainly dominated the CPS fishery in terms of landings and revenue during the period 1981-2014, as is shown in Panel (a) and Panel (b) in Figure 2, respectively. Panel (c) shows average annual prices. Average prices are low for all CPS species, below 1 USD per kilogram. This lower average price suggests that fish availability instead of prices determine landings.

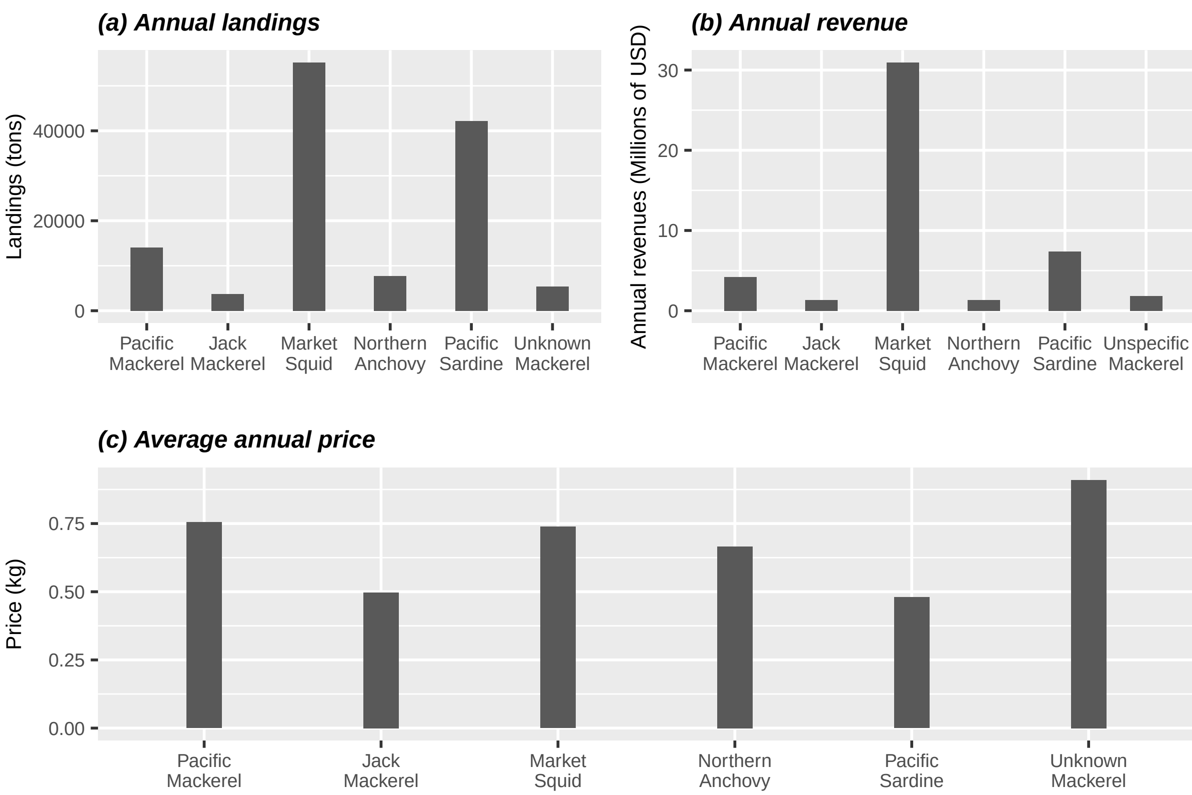

Figure 2: Average annual landings, prices and revenues by species (1981-2014).

The composition of the catch varies geographically. We show in Figure 3 the average annual landings by ports. We can observe that market squid is mostly landed in the southern ports of California located around Los Angeles, Santa Barbara, and Monterrey areas. In contrast, Pacific sardine is mainly landed in California in Los Angeles and Monterrey areas and Oregon in the Columbia River area. As we mentioned before, a fishery in Oregon started developing for market squid recently. Within California boundaries, landing constraints comes from infrastructure capacity. For instance, between Coos Bay and San Francisco, there are ports with little opportunity to handle large volumes of market squid landings due to a lack of infrastructure. It is possible to truck landings to processors from these ports, but this is unlikely to be profitable due to transport costs.

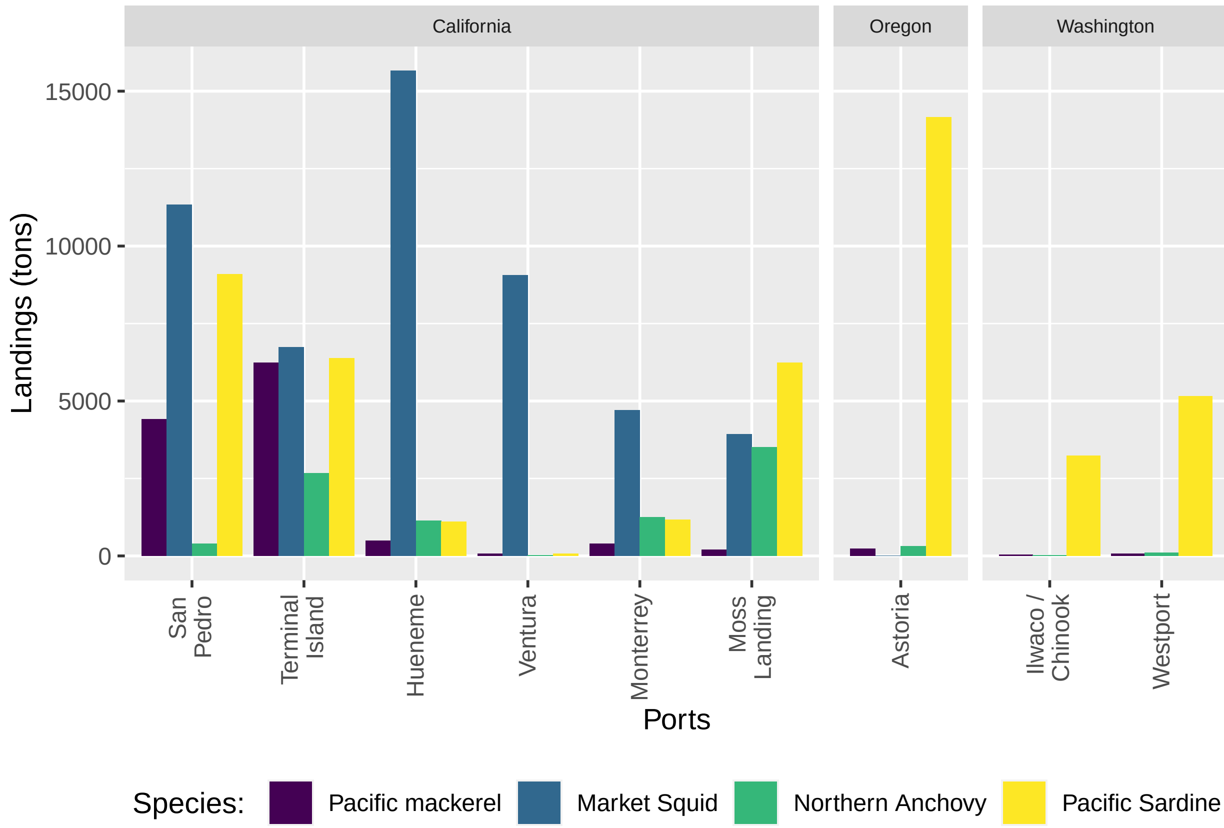

Figure 3: Annual average landings by port area.

Let us now analyze our data ver time. In Figure 4 we show the total annual landing by selected ports during the 2000-2020 period for market squid and Pacific sardine. The ports selected are the ones with the highest average annual landings and substitution is likely, identified in Figure 3 . There is a general conception that vessels that harvest Pacific sardine switch to market squid when the other is unavailable. However, we can notice from Figure 4 that landings of market squid have been decreasing in the last five years together with Pacific sardine landings. We would expect that the Pacific sardine fishery's closure would have increased the level of market squid landing, but the graphs show some complementary instead of substitution. Complementary does not coincide with stakeholders' perceptions about switching behavior. They claim that many vessels in California switched to market squid after the Pacific sardine closure.[2]

[2]Stalkholders state this during their participation in a workshop that reunited U.S. West Coast fishery.

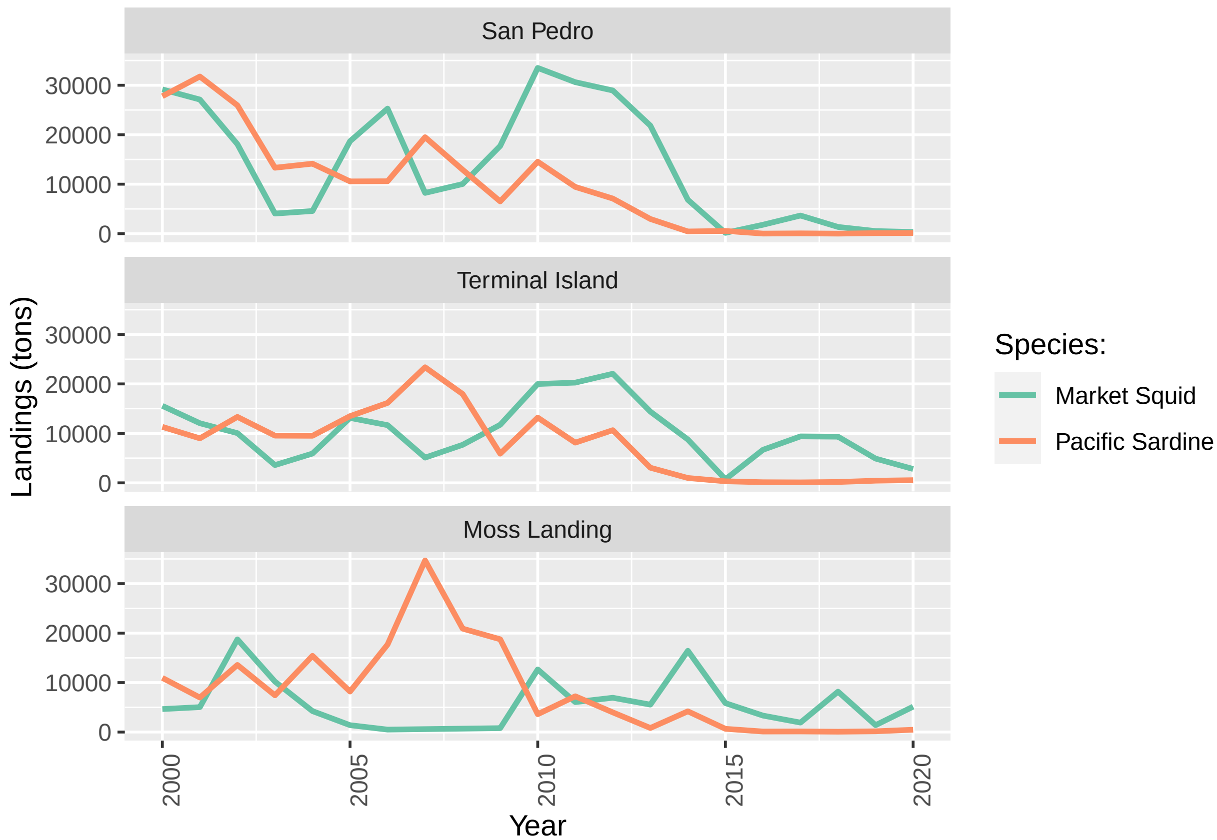

Figure 4: Total annual landing by port area. 2000 - 2020.

A potential hypothesis is that unfavorable market conditions (e.g., low prices) affected market squid landings in recent years, independently of the condition of the Pacific sardine fishery. Figure 5 shows the evolution of landings and prices by species during the period 1981-2020. In Panel (a), we can observe that real prices for market squid have been increasing during the last two decades. Incentives should be high for landing market squid, invalidating this hypothesis.[3]

[3]Prices for forage species are likely to be determined in the world market, as the California current landings for forage species correspond to a small share of the total landings in the world.

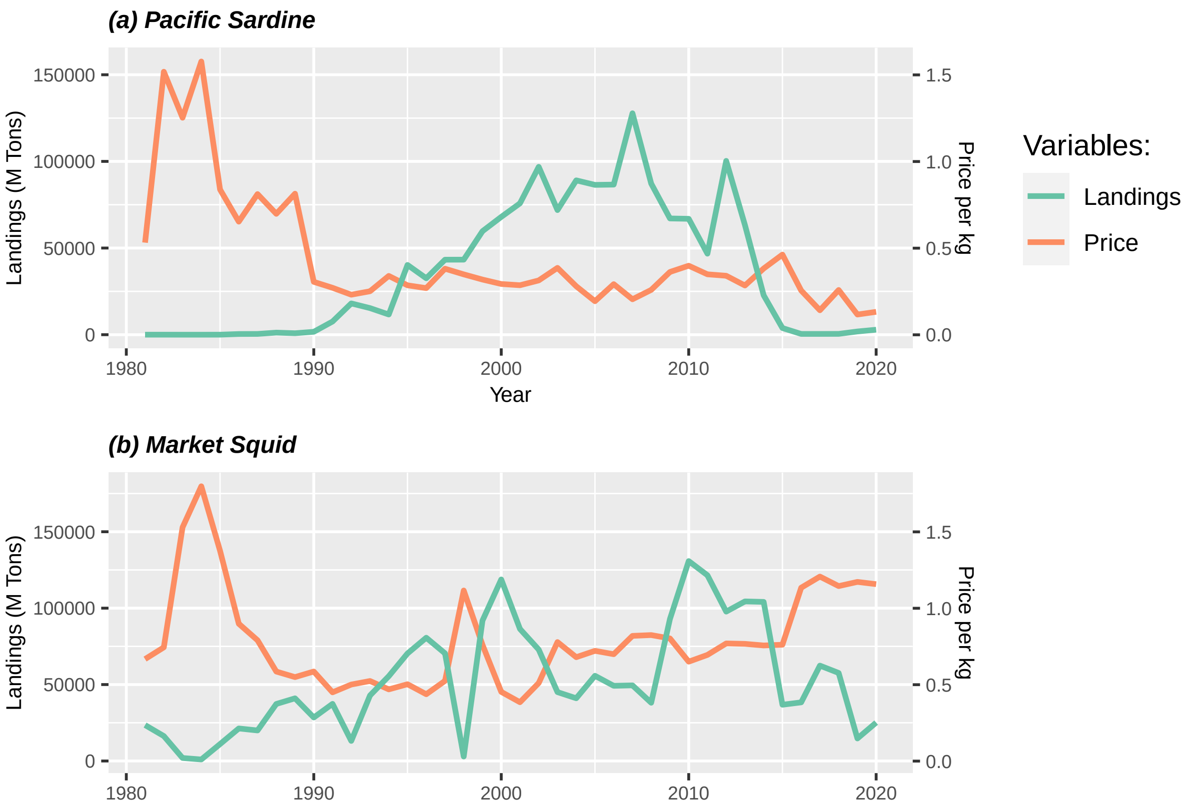

Figure 5: Yearly total landing v/s average price by CPS species (1981 - 2020).

Another hypothesis that could explain the lower landings levels observed for market squid in the last decade could be the reduction in market squid's species availability and, therefore, the substitution to another species more profitable than market squid. According to a workshop conducted with stakeholders, Pacific sardine's substitution may occur with other species such as mackerel, tuna, or anchovy. Figure 6 shows the relationship between the probability of presence (obtained from Species Distribution Models) and landings by species in three main ports: San Pedro, Terminal Island, and Moss Landing. The graph suggests that Pacific sardine landings positively correlate with the probability of presence of this species, similar to Smith et al. [2021] findings. However, in the case of market squid, we observe a high correlation between the probability of presence and landings in Moss Landing after 2003. However, this correlation is not observed in other ports, suggesting that other variables might, together with the probability of presence, be in play

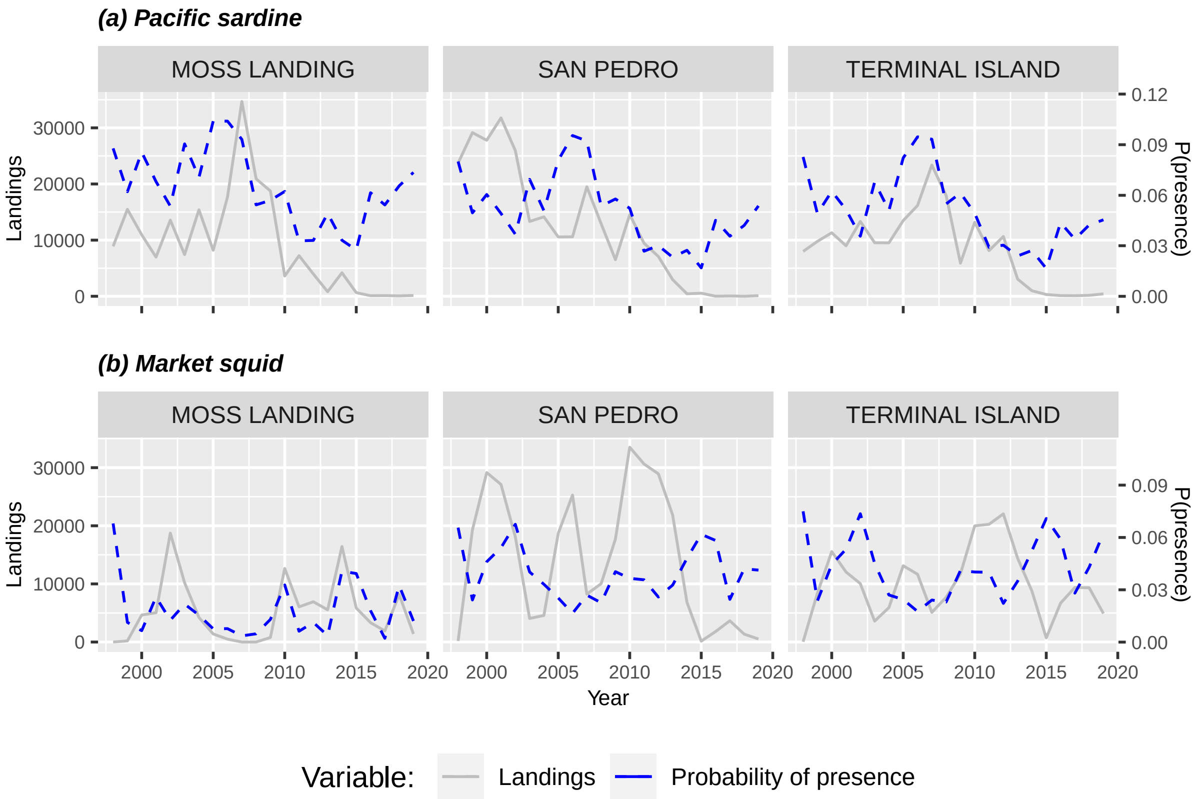

Figure 6: Landings v/s probability of presence by port area.

It could also be that the lower abundance and the consequent closure of the Pacific sardine fishery also affect vessels' decision to participate in the market squid fishery. Maybe fishers stop fishing at all as the exclusion of Pacific sardine from their portfolio reduces fisher's ability to overcome income risk through diversification [Kasperski and Holland, 2013]. This hypothesis suggests an unintended consequence from a policy that aims only to affect Pacific sardine, but its effect indirectly affects other fisheries [Richerson and Holland, 2017]. We have some suggestive evidence from this in Figure 7, which shows the evolution of Pacific sardine landings and the number of vessels landing market squid during the period 1981-2020. In the first year of the Pacific sardine closure, we observe that the number of vessels that lands Market squid decreased from 99 vessels in 2014 to 74 vessels in 2015. After this abrupt decline, we observe a slight recovery, reaching 109 vessels in 2020. Nevertheless, the level observed in 2020 is below the levels observed in 2012 with 139 vessels landings market squid during that year.

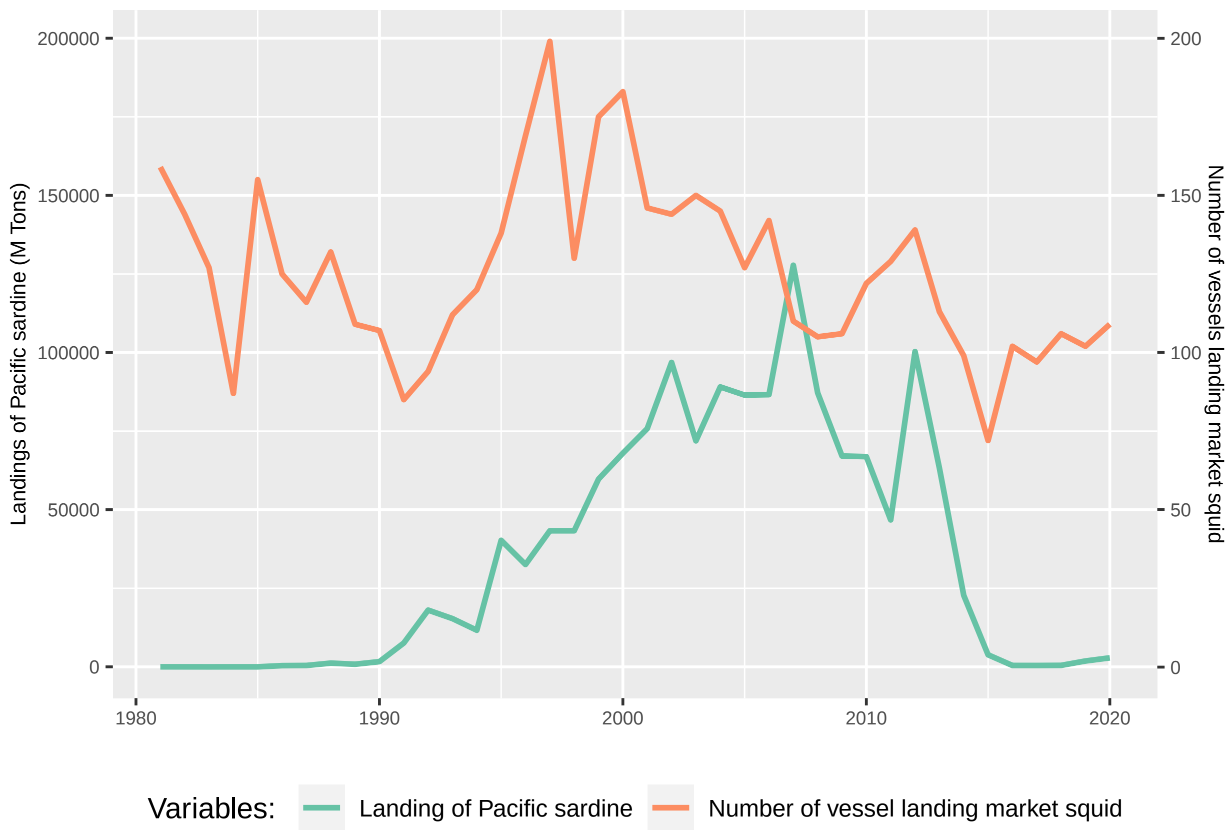

Figure 7: Landing of Pacific sardine v/s Number of vessel landing market squid.

A clear story about why market squid landings have decreased would require a more rigorous statistical analysis. We design our empirical strategy to address various concerns about omitted variables to obtain clean causal effects of a set of explanatory variables on both Pacific sardine and market squid landings.

4 Data sample

4.1 Subsample

In our model, we only use a subsample of vessels actively participating in the CPS fishery. We first have to define what we understand as participation to do this. Following Richerson and Holland [2017], we consider a vessel to participate in a specific fishery if they met the following criteria:

1. Harvest the species during 2000-2014 (before the Pacific sardine closure).
2. The species' total annual revenue averaged at least 1000 USD per year over 2000–2014. This calculation excludes years where the vessel did not fish.

3. Revenue from the species at least 5% of total vessel revenue per year over 2000–2014.
4. The vessel fished at least 3 of 15 years between 2000 and 2014.

From 2000 to 2014, 156 vessels participated in the market squid fishery according to our criteria, 100 in the Pacific sardine fishery, 18 in the Northern anchovy fishery, and 25 in the Pacific, and 1 in the jack mackerel fishery.

4.2 Cluster analysis

Before continuing our analysis, we have to verify whether there is switching behavior between CPS species. Moreover, categorizing vessel in different groups allows us to estimate differentiated coefficients to capture different responses to an explanatory variable. We conduct a cluster analysis to categorize the different portfolios fishers manage during a year. For this, we conduct our cluster analysis using a hierarchical clustering method. This method has been used before in fisheries to define *metiers* in discrete choice models [Vermard et al., 2008]. This approach does not require defining the number of clusters chosen within the algorithm. There are different methods to compute the distance between two clusters and conduct the algorithm. We use Ward's method in our study, similar to [Vermard et al., 2008]. The goal of this method is to reduce the within-cluster variance. The algorithm starts with all observation in a cluster and then merge in each step the two cluster with the minimum distance between cluster. We use a cluster variable, the percentage of total landings by species during 2000-2014. The analysis includes commercial vessels that have participated at least in one CPS fishery during 2000-2014, identified in the previous section.

Table 1 present the results for the clustering analysis. Many vessels belong to Cluster 1 winch describes a portfolio that focuses only on market squid. On average, 97.10% of the total landings in this cluster correspond to market squid. The other cluster shows substitution between species. For instance, in Cluster 4, 46.5% of the total landings correspond to market squid and 40.57% to Pacific sardine, on average. Cluster 2, 3, and 5 also show substitution, but one species has a considerable share of the total landings (more than 80%). 80.27% for Market squid in Cluster 2, 83.52% for Pacific sardine in Cluster 3, and 84.65% for Northern anchovy in Cluster 5. In the last two clusters, 6 and 7, vessels participate in other fisheries outside the CPS group. The cluster with the highest number of observations is Cluster 1 and Cluster 4. In the following subsections, we study gear used and port landed by vessel depending on the species landed and the vessel's cluster.

Table 1: Cluster by percentage of landings by species.

	Pacific mackerel	Market squid	Northern anchovy	Jack makerel	Pacific sardine	Other	Obs.
1	0.35	97.10	0.20	0.03	1.59	0.73	55
2	0.74	80.27	1.64	0.05	7.00	10.31	24
3	1.58	8.53	0.71	0.23	83.52	5.42	31
4	5.75	46.51	4.80	0.79	40.57	1.58	53
5	0.07	2.18	84.65	0.04	12.79	0.28	6
6	3.20	19.95	0.88	0.09	3.66	72.22	18
7	63.92	0.13	1.25	0.33	2.07	32.30	9

4.3 Switching behavior

Substitution between species is likely related to the gear that a vessel or fisher have invested in for their fishing activities and the port they commonly land. These two characteristics will dictate the potential species choices that a vessel has to choose. Richerson and Holland [2017] call species choices and other spatial patterns of ocean use as spatial constraints. Vessels with the same spatial constraints share local ecological knowledge and vessel mobility [Richerson and Holland, 2017]. Nevertheless, vessels are not restricted to a specific gear and port. In theory, they can switch between different gear alternatives and choose different ports to land. Therefore, they can modify the spatial constraints that they face. Nevertheless, switching between gears that are entirely different could be costly, and landing in a port without the infrastructure to land the targeted is unlikely.

In the case of CPS species, vessels that use nets as gear for harvest only require to change net sizes, which is an easy task. Therefore, we should observe higher substitution within these vessels that uses net gears. We can even observe landing on the same day of Pacific sardine and market squid as the former is a day fishery, while the latter is a night one. Regrading to ports, substitution between Pacific sardine and market squid is more likely in the south of the California Current System (CCS) as both species have a fishery running around this area. Specifically, substitution between market squid and Pacific sardine seems more likely in Los Angeles, Monterrey, and Santa Barbara area ports as positive values for market squid and Pacific sardine are observed. Meanwhile, there is less target switching in the north of the CCS (CPS Workshop).

Vessel traveling considerable distances to catch CPS species is unlikely. Because CPS spoils quickly, fishers stay close to ports and usually come back to port on the same day. Therefore, ports constraints could have consequences if species distribution shifts north due to climate conditions. Probably, fishers will not target market squid, independently of its biomass levels, if fishing grounds move north, as there is no close infrastructure for its landing (CPS workshop). Nevertheless, there is uncertainty about this assumption as it would depend on the speed that ports can anticipate and adjust their landings capacity and infrastructure in the future. In this section, we analyze our dataset to understand better how gears and ports are related to switching between species and whether individual vessels switch gears and ports during the historical data.

4.3.1 Switching by gear used

In our sample data, a vessel belonging to the CPS fleet uses 2.194 gears on average to harvest CPS species, with a standard deviation of 1.01. Seine and other net gears (e.g., round-haul nets) allow for the highest substitution level between all CPS species harvested by the CPS fleet. A vessel using seine harvest has an average of 3.55 CPS species, while a vessel using other net gear harvests 2.95 CPS species. Regarding to species, seine is the most used gear to harvest Pacific sardine, Northern anchovy, market squid, and Pacific mackerel by their corresponding fleet. 60% of vessels have used seine to harvest Pacific mackerel since 2000, 94% to harvest market squid, 90% to harvest Pacific sardine, and 94% to harvest Northern anchovy.

The ability to switch between CPS species using seine as gear is confirmed when we analyze the most important gears used by different clusters in terms of landings (see Table 2). Total landings of a cluster where substitution between CPS species is observable (Cluster 2 to 5) comes mainly from catches using seine, and in some cases, from other net gears. In the case of Cluster 6 and 7, where substitution is between a CPS species and a Non-CPS species, seine or Other Net Gear are not important, and other gears like Dip Net or Troll became relevant.

Table 2: Percentage of cluster total langings by gear used.

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
Dip Net	0.04	0.06	0.00	0.00	0.00	0.19	0.60
Other Net Gear	0.00	0.02	0.44	0.08	0.00	0.00	0.00
Pole	0.00	0.00	0.00	0.00	0.00	0.06	0.05
Seine	0.95	0.91	0.54	0.92	1.00	0.11	0.07
Troll	0.00	0.00	0.00	0.00	0.00	0.27	0.01

4.3.2 Switching by port landed

On average, vessels participating in the CPS fishery land their CPS catch in 5.36 ports, with a standard deviation of 3.65. When we disaggregate this information by species, vessels that participate in the corresponding fishery land on average market squid in 5.37 ports, Pacific sardine in 3.96 ports, Northern anchovy in 3.17 ports, and Pacific mackerel in 2.24 ports.

Using the results from the cluster analysis, we can identify how many ports, on average, a vessel that belongs to a cluster lands their CPS catch. On average, vessels belonging to Cluster 1 land CPS in 4.81 ports, Cluster 2 land CPS in 5.29 ports, Cluster 3 land CPS in 5.06 ports, Cluster 4 land CPS in 7.71 ports, Cluster 5 land in 3.5 ports, Cluster 6 land in CPS 2.88, and Cluster 7 land in CPS 2.22. Finally, Table 3 show the percentage of a cluster´s total CPS landing that is landed in a port.

4.3.3 Other determinants switching of behavior

Switching behavior might depend on whether a vessel is owner-operated or company-owned (CPS Workshop). Owner-operated vessels can freely choose what to harvest (and when and where), while company-owned vessels are restricted by what the company dictates. However, regardless of vessel ownership, most fishing behavior would be determined by market order (CPS workshop). Vessels will already have contracts with processors before fishing (CPS workshop), deciding on the target species and landing port ex-ante. Nevertheless, if favorable conditions arise, the skipper has some freedom to switch species. Therefore, we expect more flexibility in species substitution but more rigidity on port landings unless a processor owns different landing facilities, allowing vessels to increase their flexibility regarding port landing.

Within the restrictions imposed by contracts, revenues and harvest costs will affect the target decision. Price, in general, varies by port of landing and harvest cost by the distance traveled to fishing grounds. It is an empirical question whether prices and distances directly affect the decision to target a species, or fishers consider the relative prices and distance to decide with species to harvest.

5 Methods

We focus on vessels that **actively participate in at least one CPS fishery**. We only include ports areas where substitution could happen. In practical terms, we drop ports that have never landed either Pacific sardine or market squid during our analysis period.[4] We assume that this criterion would allow us to identify ports with the infrastructure to land the two species. We finally ended with ten port areas: San Diego Area, Los Angeles Area, Santa Barbara Area, Morro Bay Area, Monterrey Area, San Francisco Area, Bodega Bay Area, Coos Bay Area, Columbia River Area at Oregon, and North Puget Sound Area. Our data set contains variables measured at the port and vessel levels for the CPS fishery in the U.S. West Coast. Our outcome variable is the vessel's landings in a quarter of Pacific sardine or market squid. We expect that using quarterly data allows us to observe seasonality in fishers' behavior and reduce the risk of losing general behavior when we disaggregate data on a finer scale. We obtained daily vessel level panel data on landing by port areas from 1981 to 2020 upon request from PacFIN.

Our main treatment variables are the probabilities of presence and closures, either seasonal or total, by species. We obtained the probabilities of presence from Species Distribution Models (SDM). The future forecast of these variables allows us to simulate the CPS fishery in the future. The species distribution has changed relative to ports in the last decades [Selden et al., 2020], which could explain the variability observed in fish landings [Selden et al., 2020, Smith et al. [2021]]. For instance, Smith et al. [2021] found a positive effect of the probability of Pacific sardine presence on Pacific sardine landings. We follow the same procedure as Smith et al. [2021] to associate SDM's outputs with ports. We compute the average probability of presence within the same radius of 60 kilometers around the port for Pacific sardine. This radius also coincides with the average distance with two standard deviations traveled by vessels based on logbooks available for these fisheries.[5] We set this radius to 90 for market squid based on logbooks' average distance to the fishing ground.[6] We use the quarterly average probability of presence first within a port code defined by PacFIN and second within a port area excluding ports with no information to fill the missing values. We compute two different versions of SDM outputs for market squid: with and without spawning aggregation. We compare their capacity to explain the model empirically. From communication with squid fishers, fishers seem to aggregate in spawning aggregation of squid during its harvest. Therefore, we expect that the SDM computed using spawning aggregation works better.

We use a Hierarchical Bayesian Hurdle model to estimate the effect of species distribution on fish landings. We estimate a separate model for the two species in consideration. We use a Bayesian framework for several reasons. First, it allows

[4] We converted missing values to zero.

[5] Selden et al. [2020] use the 75th quantile of the travel distances made by vessels to define the availability of a species associated to a port for multiple species and weight these distances by the catch of those species.

[6] To see an animation of how far vessels travel, please visit this link.

us to consider uncertainty from modeling the process and its imperfect observation, assuming that all parameters are random variables. Second, Bayesian modeling allows multilevel effects (i.e., hierarchical effects) for each parameter, estimating random coefficients at different levels, such as at the port and cluster levels. Finally, we can incorporate previous knowledge as a prior. For instance, we can include a prior for the effect of SDM's on Pacific sardine landings using the results obtained in Smith et al. [2021].

Our Bayesian framework incorporates a hurdle model to model the zeros included in our landing data. **We observe a zero when no landings occur in a quarter for a particular vessel in a port where his actively harvesting another species (we transformed landings observations with "N/A" to zero)**. Therefore, the hurdle part of the model is our participation model. The hurdle model has similar variables that Richerson and Holland [2017] uses to estimate a discrete choice model for the probability of participating in a fishery. However, our analysis differs as we only consider vessels actively harvesting other CPS species in a particular port instead of not participating at all, and we use quarterly data instead of yearly. Considering vessels harvesting other CPS species during the observed period allows us not to confound the decision of what fishery to participate with the decision of whether to fish or not.

Moreover, we expand their approach, merging this model with the landing model developed by **?** in a single model. According to Richerson and Holland [2017], fisher's participation decision should depend, in general terms, on profitability, species distribution, and regulations. Our model allows us to estimate the total effect of, for example, a closure on landings, considering any effect that the explanatory variables have on participation before fishers considering their optimal level of landings.

In general, our Bayesian hurdle models have the following structure:

$$[\theta_{c,p}|q_{i,t}] \propto f\left(q_{i,t}|\theta_{c,p}\right) \times [\theta_{c,p}]$$

where q_{it} is the observed landings of the corresponding species by vessel $i \in (1,\ldots,L)$ at year t, L is the total number of vessels, and θ_i are the parameters (i.e., random-coefficients) to be estimated by ports $p \in (1,\ldots,P)$, where P is the total number of ports, and by clusters $c \in (1,\ldots,C)$, where C is the total number of clusters. The latter gives the name of hierarchical to our model.[7] The distribution $f\left(q_{i,t}|\theta_{c,p}\right)$ can be rewritten as:

$$f\left(q_{i,t}|\theta_{c,p}\right) = \begin{cases} p_{i,t} & \text{if} \quad q_{i,t} = 0 \\ [1-p_{i,t}]\ \text{gamma}\left(q_{i,t}|\frac{\mu_{i,t}^2}{\sigma^2}, \frac{\mu_{i,t}}{\sigma^2}\right) & \text{if} \quad q_{i,t} > 0. \end{cases}$$

where $\mu_{i,t} = \mathbf{X}\beta_{\mathbf{c},\mathbf{p}}$ and $\text{logit}(p_{i,t}) = \mathbf{X}\gamma_{\mathbf{c},\mathbf{p}}$. Therefore, when $q_{i,t} = 0$, we estimate a discrete choice model for the decision to partipate in a fishery using a logit model.

Besides the biological stock, landings are affected by economic conditions. Some of them are harvest cost, prices received by species and their substitutes, and regulations imposed by the authorities. Our dataset includes the average species' price that a vessel receives in a port during a quarter, obtained from the PacFIN landings dataset, and they enter

[7] For more details about Hierarchical models, see Hobbs and Hooten [2015].

the model as both absolute and relative values. When prices were missing, we replaced this value with the average species' price in the port for all vessels in the corresponding year. If we still have missing values, we use the average price during the month at the port code, then at the port area, then at the state, and then considering the whole U.S. west coast (excluding Alaska). We include the Annual Catch Limit (ACL) for the Pacific sardine model as an additional explanatory variable in the landing equation, μ_i. ACL variable is the total quota allocated each year for this fishery. We obtained this information from the CPS Fisheries Management Plan [PFMC, 2021] and the Stock Assessment and Fishery Evaluation for 2019 document [PFMC, 2020]. Our database comprises the period between 2000 and 2018. We do not include ACL as an explanatory variable as this variable has no variation between years. To capture any change in fishers' behavior when the Pacific sardine fishery is closed, we include a binary variable called **Closure** that takes the value "1" when the Pacific sardine fishery is closed and takes the value "0" when the Pacific sardine fishery is open. Concerning the Pacific sardine probability of presence, this variable takes the value of zero when the fishery is closed. Thus, the effect of this variable is only relevant to capture potential substitution between targets when the Pacific sardine fishery is open. We show a summary statistics of our data set in Table 4. Specifically μ_{it} is defined as the following:

$$
\begin{aligned}
\mu_{i,p,t} = \beta^0_{p,c} &+ \beta^1_{p,c} P(Precense.PSDN)_{p,t} + \beta^2_{p,c} P\left(Precense.PSDN\right)_{p,t} * P\left(Precense.MSQD\right)_{p,t} \\
&+ \beta^3_{p,c} Price.PSDN_{p,t} + \beta^4_{p,c} ACL_t.
\end{aligned}
$$

In the case of logit$(p_{ijt}) = \mathbf{X}\gamma_\mathbf{p}$ we can model the probability p_{ijm} that vessel i participate in a particular fishery at port p in quarter t specifically as:

$$
\begin{aligned}
\text{logit}(p_{i,t}) = \gamma^0_{c,p} &+ \gamma^1_{c,p} P(Precense.PSDN)_{i,t} + \gamma^2_{c,p} P\left(Precense.PSDN\right)_{i,t} * P\left(Precense.MSQD\right)_{i,t} \\
&+ \gamma^3_{c,p} Closure_t.
\end{aligned}
$$

where $ExpectedCatch_{p,t} = \frac{\sum_{k=0}^{K} P(Precense.PSDN)_{i,t-k}}{K}$. Note that the outside option is interpreted as "No fishing in the particular fishery," which means that the vessel is participating in another fishery or is no fishing.

6 Results

6.1 Landing model

6.1.1 Graphical posterior predictive

Before presenting the results for the three species in consideration, we check graphically whether the posterior distribution is able to predict the actual distribution. We exclude zero in our graph to avoid plotting different data generation processes. In Figure **??** we show a posterior sample compare with the true sample distribution for the three species in analysis. Some deviation from the true sample distribution is observed in the three models, but still the posterior sample follow a similar shape than the actual curve. Moreover, our pacific sardine sample do well in predicting probabilities at lower landing levels.

In addition to a posterior predictive check, we also check divergence and treedepth.[8] In all three models, we did not have any divergent step in our estimation. The maximum treedepth was 11 for the Pacific sardine model, while in the others it was 10.

6.1.2 Own species distribution effect

The inclusion of hierarchical effects by port allows us to analyze the effects of the probability of presence on landings disaggregated by ports. We only focus our analysis in owns probability of presence effects, as other probability are analyzed as interaction (see next subsection). We can observe in Figure **??** that the effects of the own probability of presence on landings are not strong (maybe I should use logs. . .). However, it is clear that it have a positive effect on landings, specially on port areas such as Columbia River at Oregon for Pacific sardine, and Monterrey for Northern anchovy, while a more moderate effect is observed at Santa Barbara Area for Northern anchovy.

6.1.3 Interaction effects

To study the effect of other species distribution on landings, we compute the conditional effects of the interaction between probabilities of presence. Let denote species A the species which we are analysing its landings, and species B and C the other species included in the model for species A landings. For each species, we compute the effect on landing of the interaction between the probability of presences of: + Species A and species B, + Species A versus species C, + Species B versus species C. For example, for the Pacific sardine equation, we compute these results for the probability of presence effect between Pacific sardine and market squid, Pacific sardine and Northern anchovy, and market squid and Northern anchovy.

Let first analyze the interaction effect of the probability of presences on Pacific sardine landings, presented in Figure **??**. We only shows results for the main three port where Pacific sardine is landed (Columbia River at Oregon, Los Angeles Area and Monterrey Area). As we already commented in Figure **??**, the effects the Pacific sardine's own probability of presence is positive, changing color from left to right in panels (a) and (b). Market squid seems to be an stronger substitute for Pacific sardine than Northern anchovy. This is suggested by the different slopes between panel (a) and panel (b). For instane, in Columbia River, an increase in the probability of presence for anchovy does decrease Pacific sardine landings as much as an increase in the probability of presece of market squid.

We found some similar findings for market squid in Figure **??**. Pacific sardine it is a strong substitute of market squid. In regard to Norther anchovy, there is some complementarity with market squid. We observe that when Northern anchovy presence increase, there is also an increase in market squid landings.

[8] Explain what are these concepts. . .

However, this complementary is not observed for Northern anchovy landings. When market squid presence increase, we observe a decrease in Northern anchovy landings. An interesting case is observed for Pacific sardine and Northern anchovy, in particular at Monterrey area. For small levels of Pacific sardine presence, Pacific sardine is a complement with Northern anchovy. However, after certain threshold, Pacific sardine is no longer complement and Pacific sardine become a substitute, reducing Northern anchovy landings when the probability of presence for Pacific sardine increase.

6.1.4 Pacific sardine closure

Finally, lets analyze the effect of the Pacific sardine closure on market squid and Northern anchovy landings. We do not find significant results in the case of Northern anchovy. In the case of market squid, we found a decrease in the level of landing after the closure was implemented. It seems that some fisher exit the CPS fishery after the closure of Pacific sardine, reducing their participation in the market squid fishery. Our participation model results give us more details about what happen after the Pacific sardine closure.

7 Conclusions

A possible extension of our research is to consider spatial autocorrelations between ports.[9] Ports landing maybe correlated as vessel have the incentives to choose the port of landing, conditional on whether the port have the infrastructure for this. It is likely that they just land wherever is closer to the area they are fishing. Nevertheless, differential in prices could encourage them to travel a little further for higher prices.

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Table 3: Percentage of cluster total landings by port.

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
ALM	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ANA	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AST	0.00	0.02	0.44	0.08	0.00	0.00	0.00
AVL	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BDG	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BKL	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BLL	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BRG	0.00	0.00	0.00	0.00	0.00	0.00	0.00
COS	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CRS	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CRZ	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ERK	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GRH	0.00	0.00	0.00	0.00	0.01	0.00	0.00
HNM	0.24	0.18	0.04	0.13	0.43	0.11	0.00
LAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LGB	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LWC	0.01	0.00	0.06	0.01	0.03	0.00	0.00
MNT	0.09	0.10	0.01	0.05	0.00	0.00	0.00
MOS	0.04	0.07	0.02	0.21	0.00	0.04	0.00
MRO	0.01	0.01	0.00	0.00	0.00	0.00	0.00
NEA	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NEW	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NWB	0.00	0.00	0.00	0.00	0.00	0.00	0.03
OBV	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OCM	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OCN	0.00	0.00	0.00	0.00	0.17	0.00	0.00
OHB	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OLA	0.00	0.00	0.00	0.00	0.00	0.01	0.85
OSD	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OSF	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OWA	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OXN	0.00	0.00	0.00	0.00	0.05	0.00	0.00
PRN	0.05	0.10	0.00	0.01	0.00	0.00	0.00
SB	0.01	0.01	0.00	0.00	0.00	0.00	0.00
SD	0.00	0.00	0.00	0.00	0.00	0.01	0.00
SF	0.00	0.01	0.00	0.00	0.00	0.00	0.00
SIM	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SP	0.19	0.32	0.11	0.22	0.00	0.53	0.03
TLL	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TML	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TRM	0.05	0.06	0.07	0.20	0.00	0.14	0.09
VEN	0.30	0.13	0.05	0.08	0.03	0.01	0.00
WIN	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WLB	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WLM	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WPT	0.00	0.00	0.19	0.00	0.27	0.14	0.00

Table 4: Summary Statistics

Variable	N	Mean	Std. Dev.	Min	Pctl. 25	Pctl. 75	Max
Prob(presence): PSDN	8242	0.287	0.13	0.016	0.187	0.369	0.741
Prob(presence): MSQD	8242	0.122	0.097	0.011	0.051	0.167	0.609
Prob(presence): MSQD (Spawn)	8316	0.036	0.029	0	0.015	0.052	0.195
Landings: PSDN	8627	108.266	360.351	0	0	5.266	6104.961
Landings: MSQD	8627	151.22	300.645	0	0	158.72	4235.044
Price: PSDN	8594	0.239	0.348	0.002	0.121	0.244	7.91
Price: MSQD	8534	0.764	0.323	0.022	0.638	0.906	11.629