# The Impact of Environmental Variability on Fishers' Harvest Decisions in Chile using a Multi-Species Approach

Felipe J. Quezada-Escalona

Departmento de Economía
Universidad de Concepción

October 03, 2025

**Abstract**

In this paper, we aim to answer how fishing decisions, aggregate catch levels, and the price of marine resources will be affected under different climatic scenarios in the multi-species small pelagic fishery (SPF) in Chile, composed by anchoveta (*Engraulis ringens*), jack mackerel (*Trachurus murphyi*), and sardine (*Strangomera bentincki*), among others. By doing this, we expect to gain a better understanding of how Chilean fishers and fishing communities will adapt to climate change. To address our research question, we will estimate a multi-species harvesting model. This model considers species' economic and biological interrelation to study the effect of climate variability on harvest decisions and substitution between species, and determine the impact of different climatic scenarios on the well-being (e.g., profits) of fishers and fishing communities in Chile. We hypothesize that when fishers have reduced access to a main target species, they will switch to the closest substitute if the expected revenue from targeting this new species exceeds the expected costs. Otherwise, the vessel would decrease fishing effort or even exit the fishery due to the lack of economically viable substitutes. Moreover, we expect that this behavior is heterogeneous depending on the geographical area of operation – as it determines the availability of other species– and the gear type used.

## 1 Introduction

The distribution and abundance of marine resources are changing in response to environmental conditions such as global ocean warming (Poloczanska et al., 2013). Climate change will shift species distribution in the future, leading to reduced species availability in some areas and increased availability in others. The literature that studies fishers' responses to either changes in fish availability or policies that restrict access to fisheries (e.g., Stafford, 2018; Vasquez Caballero et al., 2023) has identified that they can adopt the following adaptive strategies: (i) reduce or reallocate

fishing effort, either to another species or to another location (Gonzalez-Mon et al., 2021); (ii) continue following the same strategy; or (iii) exit the fishery and find alternative employment (Powell et al., 2022). Among these strategies, reallocating effort to alternative species has been identified as a potentially effective response to climate change (Young et al., 2018). Diversification of target species has also been linked to reduced income variability (e.g., Kasperski & Holland, 2013; Sethi et al., 2014) and greater resilience to both climate shocks (Cline et al., 2017; Fisher et al., 2021) and interannual oceanographic variability (Aguilera et al., 2015; Finkbeiner, 2015).

This emphasis on diversification aligns with broader evidence from food-producing sectors. As Cruz (2025) highlights, climate variability substantially affects agriculture and fisheries, where income depends heavily on environmental fluctuations (e.g., temperature, rainfall) and market forces (e.g., input costs) (Carter et al., 2018; Kasperski & Holland, 2013). With variability expected to reduce productivity, income risk is likely to rise (Carter et al., 2018; Free et al., 2019). Diversification—whether within a sector (e.g., switching crops or species) or across sectors—is often promoted as an adaptive strategy (Abbott et al., 2023). However, these strategies can be costly for resource-dependent communities with limited capital and skills (Cherdchuchai & Otsuka, 2006; Ellis, 2000), and the role of switching costs in shaping diversification remains poorly understood.

In the fisheries context, switching between species requires not only the skills but also the appropriate gear and permits (Frawley et al., 2021; Powell et al., 2022). Even if these conditions are met, diversification may still be constrained by port infrastructure, markets, and regulations (Beaudreau et al., 2019; Kasperski & Holland, 2013; Powell et al., 2022). Therefore, deciding which adaptation strategy to adopt is not straightforward and depends on multiple factors. Moreover, fishers may respond differently to similar circumstances depending on their goals, skills, and preferences (Jardine et al., 2020; Powell et al., 2022; Zhang & Smith, 2011).

In this research, we aim to answer how fishing decisions, aggregate catch levels, and the price of marine resources will be affected under different climatic scenarios in the multi-species small pelagic fishery (SPF) in Chile, composed of anchoveta (*Engraulis ringens*), jack mackerel (*Trachurus murphyi*), sardine (*Strangomera bentincki*), among others. The SPF is the most important in terms of catches in the country, accounting for almost 94% of the total Chilean catch in 2019 (SUBPESCA, 2020). Through this research, we aim to gain a deeper understanding of how Chilean fishers and fishing communities will adapt to climate change. To address our research question, we will estimate a multi-species harvesting model based on Kasperski (2015). This model considers species' economic and biological interrelations to study the effect of climate variability on harvest decisions and substitution between species, and to determine the impact of different climatic scenarios on the well-being (e.g., profits) of fishers and fishing communities in Chile. We expect to find significant effects of climate variables on species stock dynamics, the cost of fishing during a trip, and the number of trips a vessel takes. These environmental effects might influence optimal harvest levels and prices in local markets.

Under a changing climate, studying the effect of climatic variability on fishers' harvest decisions

and landings is relevant for understanding fishing communities' adaptive capacities and strategies in response to climate change, thereby enabling the design of potential mitigation measures in response to these changes by policymakers. Countries have different institutions, cultures, and norms, leading to differing responses based on the study's location. For this reason, conducting this research based on the Chilean fishing industry is necessary to develop local policies that aim to reduce climate change impacts on fisheries. While there is some literature on the effect of climate change on Chilean fisheries, I am unaware of local-level studies that consider a multiple-species framework and the interrelationship between the local market and fishing decisions seen under a variable climate context.[1]

Because predator–prey links couple these species, reductions in anchoveta or sardine availability may reflect not only environmental drivers but also changes in predation pressure from jack mackerel (Alheit & Niquen, 2004; Arancibia et al., 2019). Thus, even fishers who do not target jack mackerel can face induced changes in catch rates and revenues through ecosystem feedbacks. We hypothesize that if the availability of a main target species decreases, fishers will switch to the closest substitute when expected revenues (net of switching costs) exceed expected costs; otherwise they may reduce effort or exit the fishery. We also expect cross-fleet spillovers: in Chile, jack mackerel is predominantly harvested by the industrial purse-seine fleet, whereas anchoveta and sardine have substantial artisanal and industrial participation. Shocks in one component can propagate across fleets via both biology and markets, in addition to economic linkages (bycatch constraints, shared gear, and market spillovers). This strengthens the case for a multi-species framework that models joint dynamics and substitution rather than single-species responses. Moreover, we expect that this behavior is heterogeneous depending on the geographical area of operation—as it determines the availability of other species (Reimer et al., 2017)—and the gear type used.

## 2  SPF in Chile

The small pelagic fishery (SPF) in Chile is of critical importance to the national fisheries sector. In 2019, the SPF represented nearly 94% of total national fish landings (SUBPESCA, 2020). The fishery is primarily composed of anchoveta (*Engraulis ringens*), sardine (*Strangomera bentincki*), and jack mackerel (*Trachurus murphyi*). While in the Northern region competition mainly occurs between anchoveta and jack mackerel, in the Central-South region all three species play a major role. This makes the Central-South particularly relevant for the study of species interactions and potential substitution within a multispecies management framework, and it is therefore the focus of this research.

The jack mackerel fishery was initially concentrated in northern Chile, but since the mid-1980s the main fishing grounds have shifted to Central-South Chile, traditionally within 50 nautical miles

---

[1]For the case of Chile, as far as I know, the only article that studies fishers' behavior using discrete choice modeling is Peña-Torres et al. (2017). This article studies how the El Niño–Southern Oscillation (ENSO) affects fishers' location choices in the jack mackerel fishery.

of the coast (Peña-Torres et al., 2017). Historically, species in the SPF have been used primarily for fishmeal and fish oil production (Peña-Torres et al., 2017). In fact, about 85% of jack mackerel landings, on a yearly average between 1987 and 2004, were destined for reduction into fishmeal and fish oil (Peña-Torres et al., 2017). Today, several key ports serve as hubs for these activities, including San Antonio, Tomé, Talcahuano, San Vicente, Coronel, Lota, and Corral.

## 2.1 Status of the stocks

Historically, anchoveta in the Central-South was considered collapsed until 2018, shifted to over-exploited status in 2019, and has since 2020 been fished within maximum sustainable yield (MSY) limits. Meanwhile, sardine stocks have generally remained within MSY levels, except in 2021 and 2023 when they were classified as overexploited. Jack mackerel was overexploited until 2018 but has since been harvested within MSY limits.

## 2.2 Quota allocation

The Chilean fishing sector is managed primarily through a Total Allowable Catch (TAC; *Cuota Global*), which is divided between the industrial and artisanal sectors. A small share ( 2%) is reserved for research, with additional portions allocated to contingency and human consumption. The TAC is subdivided by region and season, and unused quotas may be reassigned during the fishing year.

Anchoveta and sardine are regulated as a mixed-species fishery: although each has its own quota, substitution between them is permitted. A share of industrial quota is also periodically reassigned to the artisanal sector.

Since 2013, the industrial sector has operated under an individual transferable quota (ITQ) system, known as Transferable Fishing Licenses (*Licencias Transables de Pesca, LTP*). Class A licenses were allocated based on historical catches, while Class B licenses—up to 15% of the industrial fraction—are auctioned, with the first auctions held in 2015. These sealed-bid, first-price auctions aimed to broaden access and limit concentration but have faced challenges such as low participation, difficulties in reflecting economies of scale, and signs of potential coordinated bidding (Peña-Torres et al., 2022).

The artisanal TAC operates under a regulated freedom-to-fish regime, allowing registered vessels to fish without individual quotas, except in areas where access is closed or suspended, in which case authorities may implement management measures. The main measure is the Régimen Artesanal de Extracción (RAE), which allocates the regional artisanal TAC by area, vessel size, landing site (caleta), organization, or individually, in agreement with artisanal fisher organizations. To date, area-based and organization-based allocations are the only observed schemes. Area-based allocations allow registered artisanal vessels in a given area to fish as in open access until the

assigned quota is exhausted, while organization-based allocations follow the historical rights of members to distribute the organization's quota.

- Sardine: RAE in V, VIII Y X regions? What about other species? Open access in anchovy and jack mackerel (only artisanal TAC matter at country level?)

## 2.3 Other regulations

### 2.3.1 Limited entry

Fishery with restricted access to new operators (just artisanal?)

### 2.3.2 Biological closures for recruitment

- Jack mackerel is open through all year.
- Sardine and anchovy: In southern-central Chile, December–April (fixed period: January to February).

### 2.3.3 Biological closures for reproduction

- Jack mackerel is open through all year.

- Sardine and anchovy: In southern-central Chile, July–October (fixed period: August-September).

- Seasonality? Include quarter dummies? Jack mackerel gather in the first 6 month of the year in shoals, great density in EEZ, then migrate outside 200nm ()

### 2.3.4 Minimum size

- Jack mackerel: 26 cm
- Sardine and anchovy?

### 2.3.5 Maximum harvest levels

- All species: Maximum catch limit per vessel owner (LMC) for industrial vessels

See Figure 1 for strategy transitions. The year 2019 is used as reference as anchoveta and jack mackerel started to recover.

Table 1 for strategy transitions.

Table 2 for industrial strategy transitions.

Table 1: Comparison of Strategies Before and After – Small-scale vessels

| Strategy | Before | | After | |
|---|---|---|---|---|
| | n | % | n | % |
| Sardine and Anchoveta | 420 | 31.9 | 376 | 63.5 |
| Only Sardine | 416 | 31.6 | 133 | 22.5 |
| Sardine and Other | 193 | 14.6 | 8 | 1.4 |
| Sardine, Anchoveta and Other | 139 | 10.5 | 21 | 3.5 |
| Sardine, JackMackerel and Anchoveta | 23 | 1.7 | 23 | 3.9 |
| Only Other | 60 | 4.6 | 2 | 0.3 |
| Only Anchoveta | 21 | 1.6 | 16 | 2.7 |
| Anchoveta and Other | 14 | 1.1 | 2 | 0.3 |
| Sardine and JackMackerel | 10 | 0.8 | 3 | 0.5 |
| Only JackMackerel | 7 | 0.5 | 3 | 0.5 |
| JackMackerel and Other | 4 | 0.3 | 2 | 0.3 |
| JackMackerel and Anchoveta | 1 | 0.1 | 3 | 0.5 |
| JackMackerel, Anchoveta and Other | 4 | 0.3 | 0 | 0.0 |
| Sardine, JackMackerel, Anchoveta, Other | 4 | 0.3 | 0 | 0.0 |
| Sardine, JackMackerel and Other | 2 | 0.2 | 0 | 0.0 |

Table 2: Comparison of Strategies Before and After – Industrial vessels

| Strategy | Before | | After | |
|---|---|---|---|---|
| | n | % | n | % |
| Only JackMackerel | 46 | 36.2 | 28 | 96.6 |
| Sardine and JackMackerel | 22 | 17.3 | 1 | 3.4 |
| Sardine and Anchoveta | 14 | 11.0 | 0 | 0.0 |
| JackMackerel and Other | 13 | 10.2 | 0 | 0.0 |
| Sardine, JackMackerel and Anchoveta | 13 | 10.2 | 0 | 0.0 |
| Only Other | 6 | 4.7 | 0 | 0.0 |
| JackMackerel and Anchoveta | 3 | 2.4 | 0 | 0.0 |
| Sardine, JackMackerel and Other | 3 | 2.4 | 0 | 0.0 |
| Only Sardine | 2 | 1.6 | 0 | 0.0 |
| Anchoveta and Other | 1 | 0.8 | 0 | 0.0 |
| Only Anchoveta | 1 | 0.8 | 0 | 0.0 |
| Sardine and Other | 1 | 0.8 | 0 | 0.0 |
| Sardine, Anchoveta and Other | 1 | 0.8 | 0 | 0.0 |
| Sardine, JackMackerel, Anchoveta, Other | 1 | 0.8 | 0 | 0.0 |
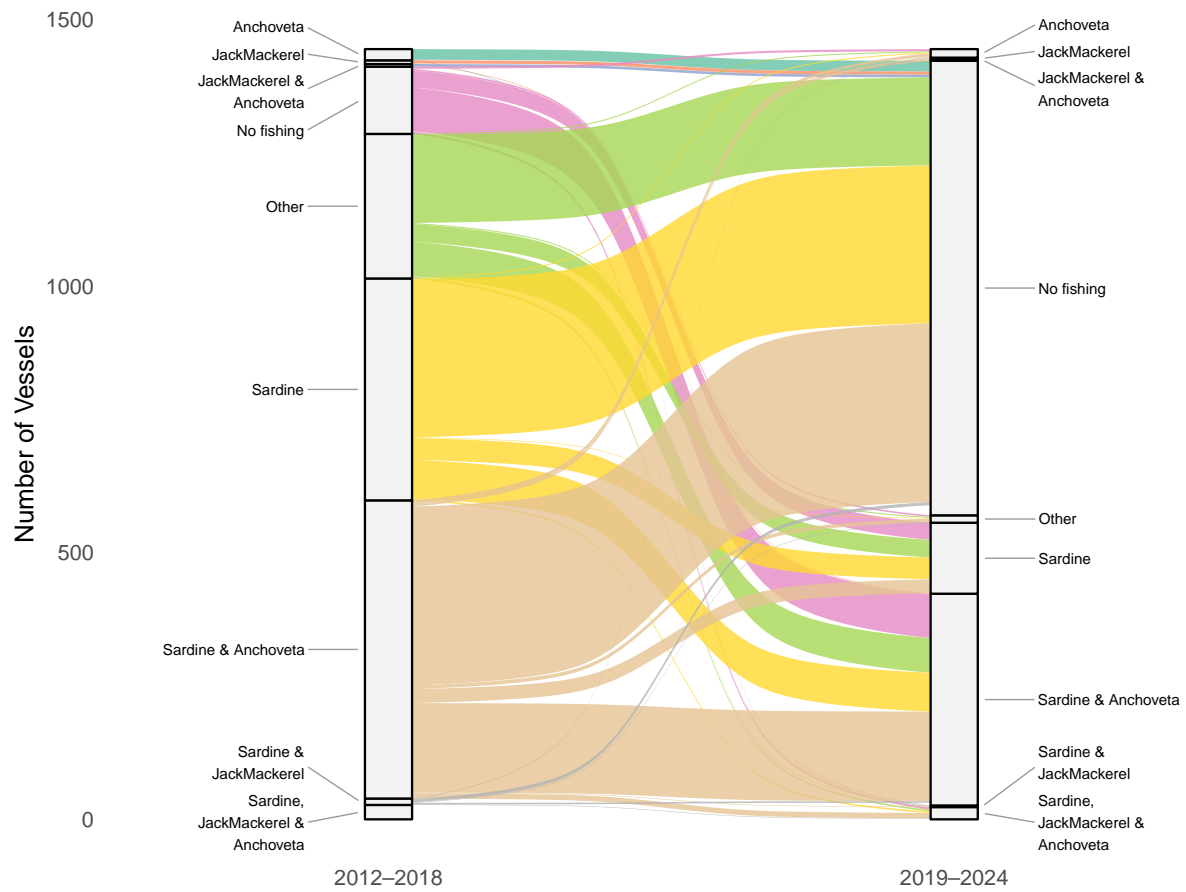
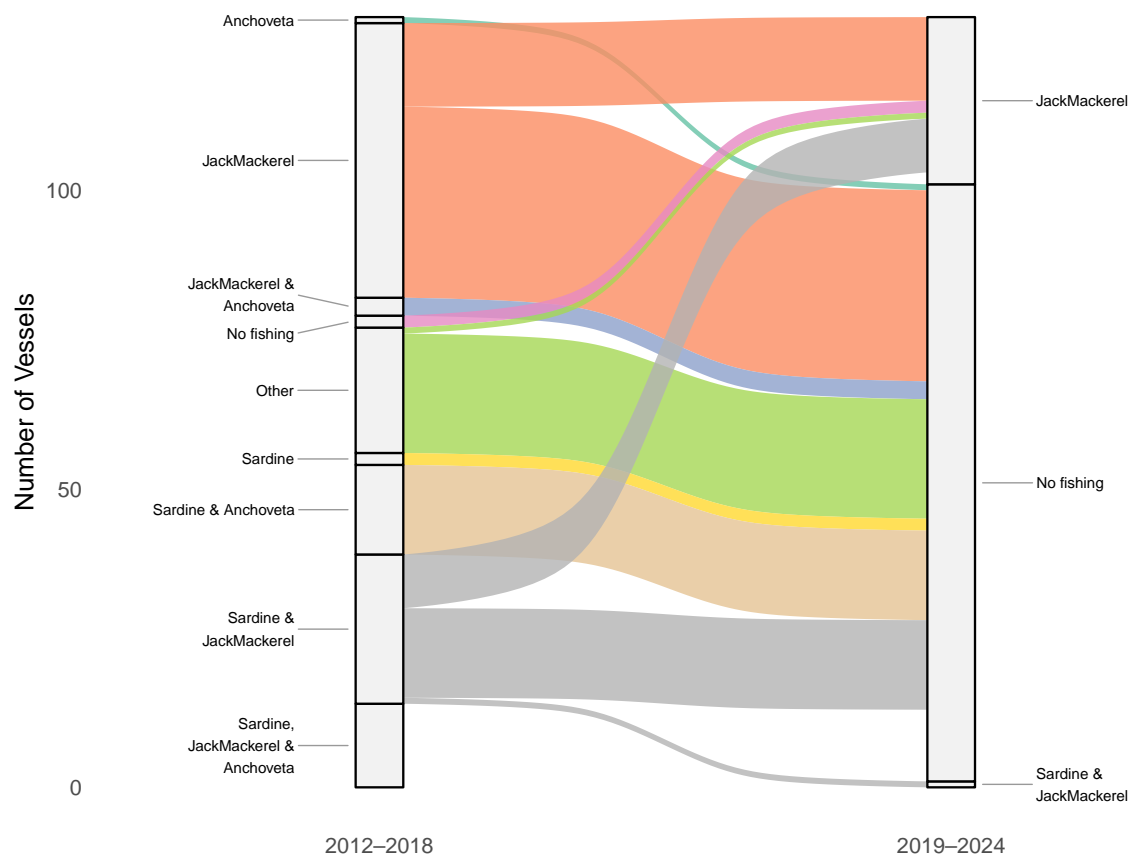Figure 1: Strategy transitions for small-scale vessels

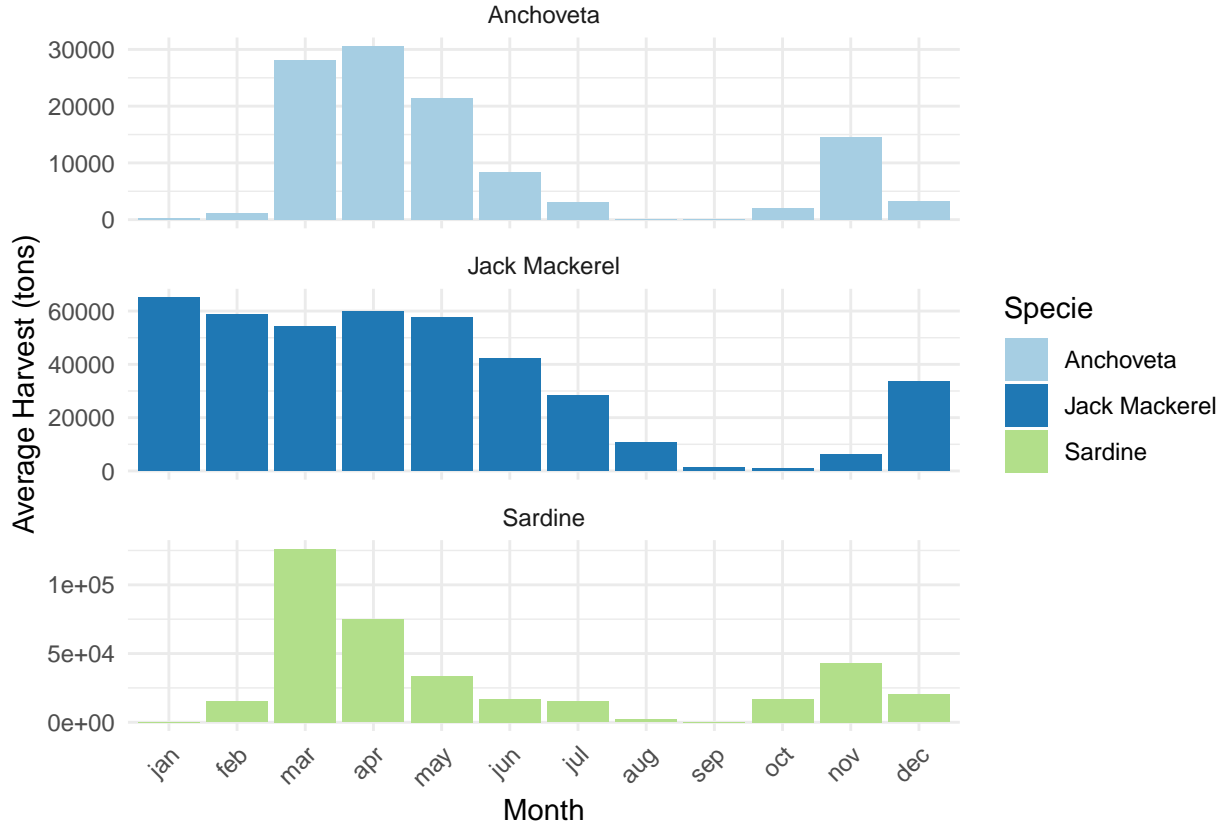Figure 2: Strategy transitions for industrial vessels

Figure 3: Average monthly landings by species (2012-2024; South-Central Chile)

# 3 Data and methodology

To fulfill the research's objectives, and following Kasperski (2015), the research entails five different stages: (i) estimating the annual stock dynamics of each species included in the model, (ii) estimating trip level cost functions, (iii) estimating total annual trips, (iv) estimate the inverse demand model for outputs (i.e., price responses to supply), and (v) conduct numerical optimization to examine how harvest and profits levels evolve over time. The numeral optimization uses estimated parameters from the previous four stages to conduct the optimization procedure.

## 3.1 Data

- **SOLICITADO A IFOP 2012-2024:**

  - Stock abundance and vessel landings (annual by port/county/region/country and species)
  - Data at the trip level (IFOP data observatory?]).
  - Ex-vessel prices (monthly or annual by port/county/region/country and species)

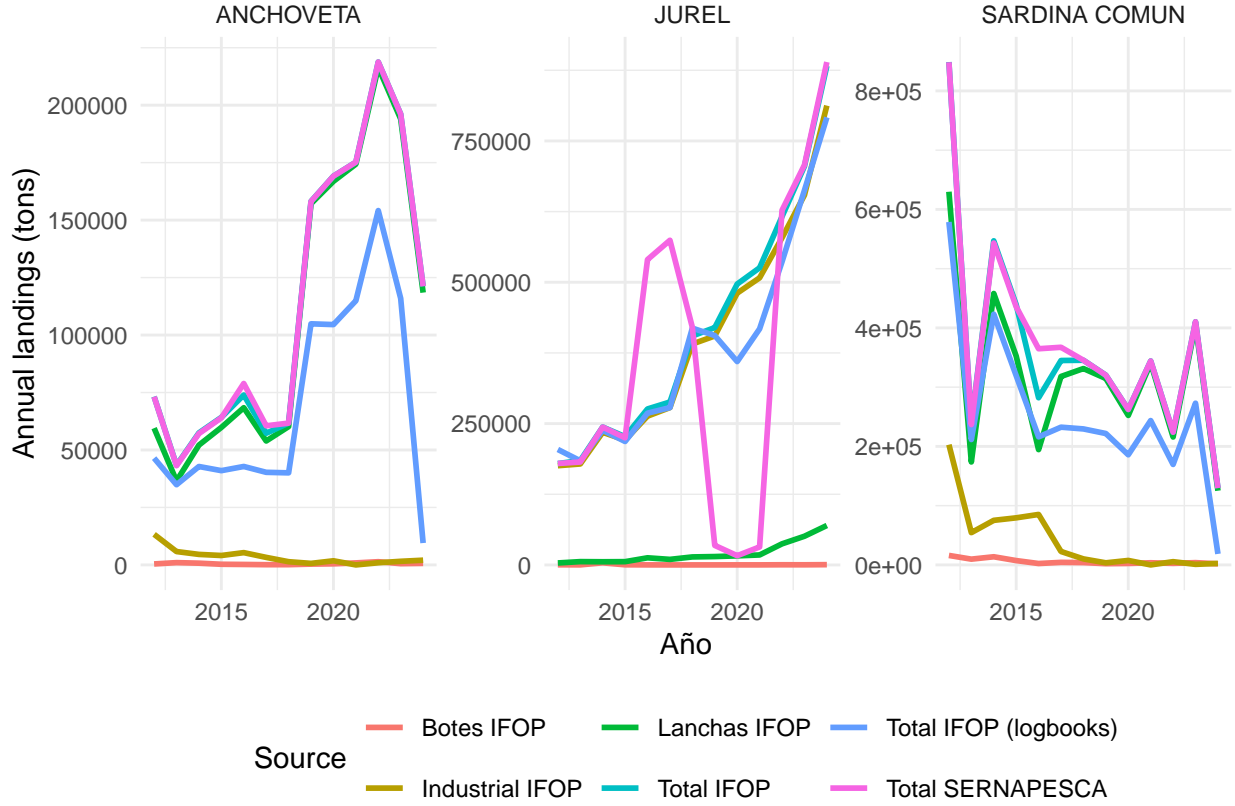How different are SERNAPESCA and IFOP harvest data? (Figura 4)



Figure 4: Desembarques anuales (IFOP vs SERNAPESCA)

For the environmental covariates, we use data from the E.U. Copernicus Marine Service Information, accessed through the Copernicus Marine Toolbox API. Salinity, sea surface temperature, and current speed and direction were obtained from the Global Ocean Physics Reanalysis (GLORYS12V1), which provides data at a 1/12° horizontal resolution with 50 vertical levels (E.U. Copernicus Marine Service Information, 2025c). Wind speed and direction at the surface were obtained from the Global Ocean Hourly Reprocessed Sea Surface Wind and Stress from Scatterometer and Model dataset, available at 0.125° horizontal spatial resolution and hourly frequency (E.U. Copernicus Marine Service Information, 2025b). Chlorophyll-a concentrations were obtained from the Global Ocean Colour dataset, which provides data at ~4 km horizontal resolution (E.U. Copernicus Marine Service Information, 2025a). All environmental data were retrieved daily (hourly in the case of winds) for the 2012–2024 period, covering the Chilean Exclusive Economic Zone (EEZ) between 32°S and 41°S.

- Future (2040–2050): - OracleBio – Unfurtunally only decadal projections for different scenarios for SST, salinity, currents and chlorophyll (4km resolution) – no winds; - CMIP6 for winds? (~100 km).

- **POR SOLICITAR:**

- Other data?

  - Average wage pay to crew member per hour
  - Diesel cost.
  - Permits by vessels
  - Quota prices?

- Birkenbach et al. (2024):

  - *Day at sea price captures elements of forward-looking behavior and information. Reimer et al. (2022) similarly argue that including a quota price captures forward looking behavior and allows one to simplify the dynamic model to a static one.*
  - *Data on wind speed and direction were collected from NOAA's National Center for Atmospheric Prediction's high-resolution North American Regional Reanalysis dataset and averaged to the daily level for each stock centroid location, defined as gear and month-specific average latitudes and longitudes where fishing occurs for each stock.*

- Also

  - Quota price? Auction market but also secondary market if available
  - Quota level, by area/fishing organization for Artisanal, and TAC for industrial with ITQ levels by vessel?
  - If no data, mybe intrapolate prices from other auctions????
  - Reallocations of quotas?

## 3.2   Econometrics models

### 3.2.1   Stock dynamics

To estimate stock dynamics, we use annual data on stock abundance and vessel landings. Following Kasperski (2015), the base model for the growth of each species follows a discrete logistic function:

$$x_{i,y+1} + h_{iy} = \underbrace{(1+r_i)x_{iy} + \eta_i x_{iy}^2}_{R_i(x_{iy})} + \underbrace{\sum_{j\neq i}^{n-1} a_{ij}x_{iy}x_{jy}}_{I_i(x_y)} \quad i = 1,...,n \tag{1}$$

where $x_{iy}$ is the fish stock by species $i = 1,...,n$ in year $y$, $n$ is the total number of species, $h_{iy}$ is the annual harvest of species $i$ on year $y$, $r_i$ is the intrinsic growth rate of the resource $i$, $\eta_i$ is a density-dependent factor related to the carrying capacity, and $\alpha_{ij}$ are the interaction parameters between species. The system of $n$ growth equations is estimated simultaneously using seemingly unrelated

regression (SUR). Following Richter et al. (2018), we augment (1) by including environmental covariates $Env_{iy}$ that affect the fish stock and an error term $\varepsilon_{iy}$ that captures random recruitment:

$$x_{i,y+1} + h_{iy} = \underbrace{(1 + r_i)x_{iy} + \eta_i x_{iy}^2}_{R_i(x_{iy})} + \underbrace{\sum_{j \neq i}^{n-1} a_{ij}x_{iy}x_{jy}}_{I_i(x_y)} + \rho_i Env_{iy} + \varepsilon_{iy} \quad i = 1, \dots, n \qquad (2)$$

where $\rho_i$ are the coefficient for the environmental covariates. Specifically, we included as environmental covariates the sea surface temperature and chlorophyll levels averages for the South-Central chile region. We include only data within the EEZ Chilean region and

As shown in Figure 5, biomass levels vary by species, and there is some interrelation between them. It is also clear that these biomass levels are affected by the harvests that occurred during those periods. For instance, in the case of jack mackerel, an abrupt decline in biomass is observed, likely due to a combination of overexploitation of the resource and unfavorable environmental conditions.

- From (Yáñez et al., 2014):
  - *"Fuenzalida et al. (2007) forecast that surface winds would strengthen in the coast of Chile, with an increase of 6 m/s in some areas of Chile during the period 2046-2065 in comparison to 2000–2005; this might increase upwelling and thus, fisheries productivity (Garreaud & Falvey, 2009)."*
    * *"Wind direction and strength will probably influence the distribution and abundance of marine species. Small and coastal pelagic species, for example, show different behaviors: while anchovy maximizes recruitment at current speeds of 5.46 m/s, showing an important decrease with lower and higher values, sardine maximizes recruitment at 5.63 m/s or more (Yáñez et al., 2001).*
  - *Anchovy dominates during cold inter-decadal periods, while sardine prevail during warm inter-decadal periods. Such interdecadal variations in SST also influence recruitment, a situation that has been documented in anchovies off the Peruvian coast (Cahuin et al., 2009)."*
    * *Longer term predictions based on two global warming scenarios of the IPCC (Intergovernmental Panel on Climate Change) done by Fuenzalida et al. (2007) shows a warming on the Chilean coast."*

Adding harvest:

### 3.2.2  Trip level cost functions

Ignoring trip subscript, the cost functions vary by vessel $v = 1, \dots, V_g$ and gear used $g = 1, \dots, G$, where $V_g$ is the number of observations using gear type $g$, and $G$ is the total number of available

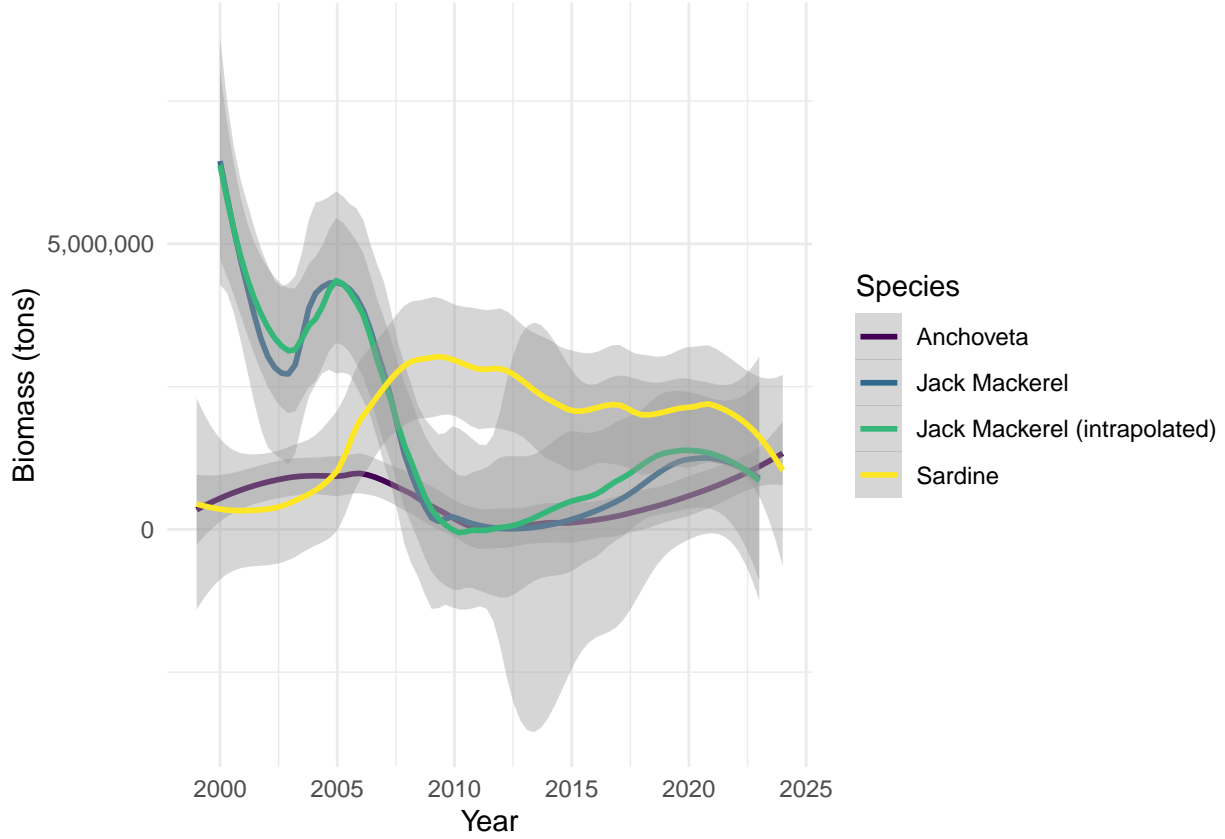Figure 5: Estimated biomass of small pelagic species in Chile (2000–2024)

(or observed) gears:

$$C_{vg} = \sum_{i=1}^{2n+M+k} \alpha_{g,\mathbf{X}_i} \mathbf{X}_{ivg} + \frac{1}{2} \sum_{i=1}^{2n+M+k} \sum_{j=1}^{2n+M+k} \alpha_{g,\mathbf{X}_i\mathbf{X}_j} \mathbf{X}_{ivg} \mathbf{X}_{jvg} \qquad (3)$$

where $C_{vg} = wz_{vg}^*$, $\mathbf{X}_{vg} = [w; h_{vg}; x; Z_v]$, $w$ is a $V_g \times M$ matrix of variable input prices, $h_{vg}$ is an $V_g \times n$ matrix of harvest quantities, $x$ is an $V_g \times n$ matrix of given stock levels of the species of interest, and $Z_v$ is an $V_g \times k$ matrix of given vessel characteristics. Therefore, $\mathbf{X}_{vg}$ is a $V_g \times (2n + M + k)$ matrix, and $\mathbf{X}_{ivg}$ represents the $i$th column of the $\mathbf{X}_{vg}$ matrix.

Together with estimating the restricted cost function, we estimate the conditional input demand equations. This addition allows an increase in the degrees of freedom by imposing cross-equation parameter constraints and allows for the testing of, for instance, jointness in inputs (Kasperski, 2015). The conditional input demand equations are derived by Shepard's Lemma:

$$\frac{\partial C_{vg}}{\partial w_m} = z_{vg,w_m}^* = \alpha_{g,w_m} + \sum_{j=1}^{2n+M+k} \alpha_{g,w_m,\mathbf{X}_j} \mathbf{X}_{jvg} \quad m = 1, ..., M. \qquad (4)$$
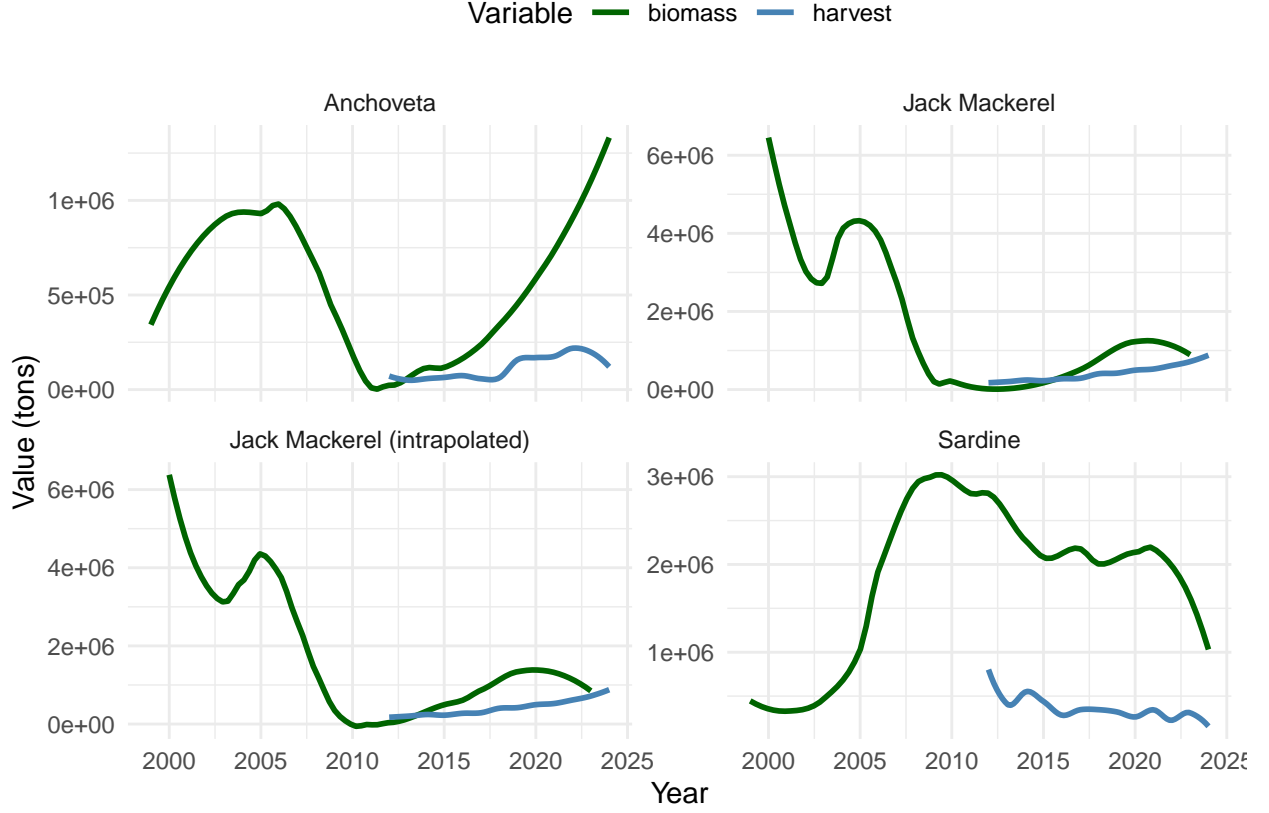
Figure 6: Estimated biomass vs harvest of small pelagic species in CentralSouth Chile (2000–2024)

Similar to stock dynamics, the system of equations formed by (3) and (4) can be estimated using SUR. To comply with economic theory, and to reduce even more the number of parameters to estimate, the following restrictions are imposed when estimating (4):

1. Symmetry of the cost function, where

$$\alpha_{g,\mathbf{X}_i\mathbf{X}_j} = \alpha_{g,\mathbf{X}_j\mathbf{X}_i} \quad \forall \quad i = 1, \dots, (2n + M + k); \ i \neq j; \ g = 1, \dots, G.$$

2. Linear homogeneity in input prices, where

$$\sum_m^M \alpha_{g,w_m} = 1 \text{ and } \sum_m^M \alpha_{g,w_m,\mathbf{X}_i} = 0 \quad i = 1, \dots, (2n + M + k); \ g = 1, \dots, G.$$

Data at the trip level is available upon request from the Chilean Fisheries Research Institute (IFOP), which registers geo-referenced catch information on the Chilean fleet's fishing operation per trip (see e.g. Peña-Torres et al., 2017 and IFOP data observatory). As inputs we can use the time spent at sea during a trip, where the price is the average wage pay to crew member per hour, and the distance traveled during a trip, where the price of distance traveled is the diesel cost.

Therefore, the total cost function $C_{vg} = wz^*_{vg}$ for vessel $v$, using gear $g$ in a trip would be sum of the total cost of distance travelled plus the total cost of the time spent at sea.

**Note:** *Depending on the type of vessel, this cost should change. Some vessels are more efficient, other one are more heavy. How to capture this? The righ hand side has vessel characteristics, so the effect of harvest would be conditional on vessel characteristics, the stock levels and input prices. As we only care in the margin how harvest increase cost, this should be fine. Kasperski (2015) mention this "...no reliable fixed cost information on these vessels exists, but these should not affect the optimization as economic decisions are made at the margin. Therefore, this study does not measure true profit, but rather a proxy based on the net operating rent accruing to vessels in the fishery."*

To link this function to climate change, we can also include additional environmental variables $Env$ to $\mathbf{X}_{vg}$ such as wind intensity and wave conditions in each trip at the harvest location, upon data availability. Therefore, the augmented $X_{vg}$ matrix becomes $\mathbf{X}'_{vg} = [w; h_{vg}; x; Z_v; Env]$.

MAYBE INCLUDE QUOTA PRICE? **Higher quota prices for depleted stocks (e.g., GOM cod) reduce incentives to target them.** and **Active leasing markets for quota (and previously for DAS) allow fishermen to treat quota as a "priced input" rather than a fixed, exhaustible resource.**

Add - liters/hours x hours trip x fuel price - crew member x harvest x price x share - certification cost per landed ton x landing

### 3.2.3 Total annual trips

The number of trips a vessel will take in a given year for each gear type used is assumed to follow a Poison distribution (Kasperski, 2015):

$$Pr\left[T^*_{vgy} = t_v\right] = \frac{exp^{-exp(U'_{vg}\beta_g)} exp(U'_{vg}\beta_g)^{t_v}}{t_v!} \tag{5}$$

where $U_{vg} = [p, w, h_{vg}, \bar{q}, Z_{vg}]$ is a $(3n + M + k + 1) \times V_g$ matrix of explanatory variables, $\beta_g$ is a $(3n + M + k + 1) \times 1$ matrix of coefficients to be estimated, $t_v$ is the number of trips taken by vessel $v$ using gear type $g$ in year $y$, and $\bar{q}$ is the annual quota level. Additionally, we can add the accumulation of "bad weather days" as an explanatory variable to incorporate weather conditions into this decision, thus $U_{vg} = [p, w, h_{vg}, \bar{q}, Z_{vg}, Env]$

### 3.2.4 Inverse demand model for outputs

The price of each species is modeled using an inverse demand model, which assumes weak separability between the species into consideration and other products (Kasperski, 2015). The price of a species $i$ in year $y$ is the following:

$$p_{iy} = \sum_{j}^{n} \gamma_j p_{j,y-1} + \gamma_{h_i} h_{iy} + \epsilon_{iy}, \quad i = 1, \ldots, n, \; j = 1, \ldots, n. \tag{6}$$

The system formed by (6) can be estimated using maximum likelihood. Note that harvest may be endogenous in this system due to simultaneity. Kasperski (2015) solves this by assuming that the TAC is exogenous, and the catch, in general, is determined by this quota. We can relax this assumption by considering that all variables in the inverse demand equations are endogenous by estimating a vector autoregressive (VAR) model (Juselius, 2006). In other words, harvest $h_{vg}$ has its own equations in the system.

## 3.3  Numerical optimization

To obtain the effect of future climate variability on stock, harvest, quota and profits, we conduct numerical optimization for different climate scenarios using the parameters estimates for the stock dynamic, cost functions, total annual trips and inverse demand equations. In each year, a vessel maximizes profits by choosing their optimal number of trips $T_g$ and harvest levels per trip $h_{g\tau}$ given a gear type:

$$\max_{h_{gt},T_g} \quad \pi_{vgt} = \sum_{\tau=t}^{T_g} \rho^\tau \left\{ P(h)h_{g\tau} - C_g(h_{g\tau}|w,x,Z,Env) \right\} \quad \tau = t, \ldots, T_g$$

$$\textbf{s.t} \quad q_{g,t+1} = \omega * \bar{q} - \sum_{t=1}^{t} h_{gt} \geq 0, \quad t = 1, \ldots, T-1, \quad g = 1, \ldots, G \tag{7}$$

where $\rho$ is the intra-annual discount factor, $\omega$ is a vector of shares of $\bar{q}$, and $h_{lt} = 0$ for all $l \neq g$. The vector of shares is obtained from historical data on harvest. The optimal profit from the maximization problem in (7) is denoted as $\pi_{vgy}^*(p,w,x,Z,\bar{q},\omega,Env)$, and $h_{vgty}^*$ and $T_{vgy}^*$ are the optimal choices harvest per trip and total number of trips in year $y$ for vessel $v$. To obtain the optimal quota level, we must solve the social-planner optimization problem to maximize the net value of the fishery by choosing the quota levels per year and by species.

Following Kasperski (2015), the optimization problem will be conducted for the next 25 years. I will use different climate scenarios and compare different optimal outcomes between them by using future projections for the environmental variables included in the model.

## 3.4  Projections

*From (Yáñez et al., 2014):*

- "To project the model, the average structure of catches and temperature (of Antofagasta and the region Niño 3 + 4) for the years 2005, 2006 and 2007 were used as starting point. We

16

consider a linear increase in temperature, taking into account four climate change scenarios based on the scenarios presented by IPCC, designed for the northern part of Chile until 2100.

1. The first scenario considers an increase in temperature of 0.034ºC per year (Fuenzalida et al., 2007), similar to that estimated by Trenberth et al. (2007).
2. A second scenario, more moderate, of 0,025ºC/year is also proposed by Fuenzalida et al. (2007).
3. The third scenario is not considered a significant effect on the area, following the work of Trenberth et al. (2007).
4. The fourth scenario is contradictory, indicating a cooling de 0.02 ºC/year (Falvey & Garreaud, 2009). It should be noted that according to the work of Fuenzalida et al. (2007) and Falvey & Garreaud (2009) the same SST increase (or decrease) were considered for both temperatures (in Antofagasta and in the Niño 3 + 4 region)."

# 4 Results

NO RESULTS YET

# 5 Discussion

If ITQ in this fishery in Chile: **The theoretical findings on multispecies harvest patterns in Birkenbach et al. (2020) give rise to nuanced hypotheses about how behavior and outcomes will change after the adoption of catch shares. For example, a secure property right to catch fish at any time in the fishing season allows firms to spread the catch of stocks with high prices and downward-sloping demand over a longer fishing season. This minimizes market gluts that steer product toward lower priced frozen markets (Homans & Wilen, 2005) and can result in higher prices for those species. Fishermen might also shift their efforts toward lower-priced species with cheaper quota or toward non-catch-share fisheries, intensifying the race to fish for those species during portions of the season (Asche et al., 2007; Cunningham et al., 2016).** – However, we do not include other species than jack mackerel, sardine and anchovy that might be caught by thise fleet. This would require to expand the model by **N** species, which would increase dimensionality of the model. WE NEED PERMITS TO CHECK IF ACTUALLY THIS HAPPEN! (Still problem with Open-Access)

## 5.1 Potential extension of the project

Several other extensions to the model can be incorporated to be improved. For instance, the geographical space where fishermen operate is relevant, as depending on the location chosen and

when to participate, the set of potential choices would vary (Reimer et al., 2017). As I mentioned above, it is possible to extend the stock dynamic model by considering different locations. The model would also require that the participation decision, which is captured by the Poisson model on the annual number of trips, should then consider the decision to participate in a determined fishing ground, connecting the multi-species model of Kasperski (2015) to the literature of location choice modeling (e.g., Dupont, 1993; Hicks et al., 2020; Smith, 2005).

## 5.2   Damage function for the fisheries sector

Link to the work made in the U.S. West Coast. Similar weather, but different development. We would need to also have estimate of the dose-response function in other latitudes, with significantly different temperatures...

# 6   Conclusions

NO CONCLUSION YET

## 6.1   Future research question

- Does higher quota allocation of jack mackerel, a predator for anchovy and sardine, helps small scale sector actually?

# 7   Repository

The source code for this project is available on GitHub

# References

Abbott, J. K., Sakai, Y., & Holland, D. S. (2023). Species, space and time: A quarter century of fishers' diversification strategies on the US west coast. *Fish Fish (Oxf.)*, *24*(1), 93–110.

Aguilera, S. E., Cole, J., Finkbeiner, E. M., Le Cornu, E., Ban, N. C., Carr, M. H., Cinner, J. E., Crowder, L. B., Gelcich, S., Hicks, C. C., Kittinger, J. N., Martone, R., Malone, D., Pomeroy, C., Starr, R. M., Seram, S., Zuercher, R., & Broad, K. (2015). Managing small-scale commercial fisheries for adaptive capacity: Insights from dynamic social-ecological drivers of change in monterey bay. *PLoS One*, *10*(3), e0118992.

Alheit, J., & Niquen, M. (2004). Regime shifts in the humboldt current ecosystem. *Progress in Oceanography*, *60*(2-4), 201–222. https://doi.org/10.1016/j.pocean.2004.02.006

Arancibia, H., Klarian, S., Alarcón, R., Barros, M., Harrod, C., Jackson, A., Schultz, E. T., Medina, M., Neira, S., & Valdés, J. (2019). *Informe final proyecto FIPA 2017-63: Conducta trófica del jurel*. Universidad de Concepción; Universidad Andrés Bello; Universidad Arturo Prat; Universidad de Antofagasta. https://www.subpesca.cl/fipa/613/articles-98303_informe_final.pdf

Asche, F., Gordon, D. V., & Jensen, C. L. (2007). Individual vessel quotas and increased fishing pressure on unregulated species. *Land Economics*, *83*(1), 41–49.

Beaudreau, A. H., Ward, E. J., Brenner, R. E., Shelton, A. O., Watson, J. T., Womack, J. C., Anderson, S. C., Haynie, A. C., Marshall, K. N., & Williams, B. C. (2019). Thirty years of change and the future of alaskan fisheries: Shifts in fishing participation and diversification in response to environmental, regulatory and economic pressures. *Fish Fish*, *20*(faf.12364), 601–619.

Birkenbach, A. M., Cojocaru, A. L., Asche, F., Guttormsen, A. G., & Smith, M. D. (2020). Seasonal harvest patterns in multispecies fisheries. *Environ. Resour. Econ.*, *75*(3), 631–655.

Birkenbach, A. M., Lee, M.-Y., & Smith, M. D. (2024). Counterfactual modeling of multispecies fisheries outcomes under market-based regulation. *Journal of the Association of Environmental and Resource Economists*, *11*(3), 755–796. https://doi.org/10.1086/727356

Cahuin, S. M., Cubillos, L. A., Niquen, M., & Escribano, R. (2009). Climatic regimes and the recruitment rate of anchoveta, engraulis ringens, off peru. *Estuarine, Coastal and Shelf Science*, *84*(4), 591–597.

Carter, C., Cui, X., Ghanem, D., & Mérel, P. (2018). Identifying the economic impacts of climate change on agriculture [Journal Article]. *Annual Review of Resource Economics*, *10*(Volume 10, 2018), 361–380. https://doi.org/https://doi.org/10.1146/annurev-resource-100517-022938

Cherdchuchai, S., & Otsuka, K. (2006). Rural income dynamics and poverty reduction in thai villages from 1987 to 2004. *Agricultural Economics*, *35*(s3), 409–423. https://doi.org/https://doi.org/10.1111/j.1574-0862.2006.00187.x

Cline, T. J., Schindler, D. E., & Hilborn, R. (2017). Fisheries portfolio diversification and turnover buffer alaskan fishing communities from abrupt resource and market changes. *Nat. Commun.*, *8*, 14042.

Cruz, S. J. (2025). *Climate variability and labor allocation: Evidence from mexican small-scale fisheries*. Working Paper. https://sjcruz.github.io/publication/jmp/

Cunningham, S., Bennear, L. S., & Smith, M. D. (2016). Spillovers in regional fisheries management: Do catch shares cause leakage? *Land Economics*, *92*(2), 344–362.

Dupont, D. P. (1993). Price uncertainty, expectations formation and fishers' location choices. *Mar. Resour. Econ.*, *8*(3), 219–247.

Ellis, F. (2000). The determinants of rural livelihood diversification in developing countries. *Journal of Agricultural Economics*, *51*(2), 289–302. https://doi.org/https://doi.org/10.1111/j.1477-9552.2000.tb01229.x

E.U. Copernicus Marine Service Information. (2025a). *Global ocean colour (copernicus-GlobColour)*

[Dataset]. Marine Data Store (MDS). https://doi.org/10.48670/moi-00185

E.U. Copernicus Marine Service Information. (2025b). *Global ocean hourly reprocessed sea surface wind and stress from scatterometer and model* [Dataset]. Marine Data Store (MDS). https://doi.org/10.48670/moi-00185

E.U. Copernicus Marine Service Information. (2025c). *Global ocean physics reanalysis* [Dataset]. Marine Data Store (MDS). https://doi.org/10.48670/moi-00021

Falvey, M., & Garreaud, R. D. (2009). Regional cooling in a warming world: Recent temperature trends in the southeast pacific and along the west coast of subtropical south america (1979–2006). *Journal of Geophysical Research: Atmospheres*, *114*(D4).

Finkbeiner, E. M. (2015). The role of diversification in dynamic small-scale fisheries: Lessons from baja california sur, mexico. *Glob. Environ. Change*, *32*, 139–152.

Fisher, M. C., Moore, S. K., Jardine, S. L., Watson, J. R., & Samhouri, J. F. (2021). Climate shock effects and mediation in fisheries. *Proc. Natl. Acad. Sci. U. S. A.*, *118*(2).

Frawley, T. H., Muhling, B. A., Brodie, S., Fisher, M. C., Tommasi, D., Le Fol, G., Hazen, E. L., Stohs, S. S., Finkbeiner, E. M., & Jacox, M. G. (2021). Changes to the structure and function of an albacore fishery reveal shifting social-ecological realities for pacific northwest fishermen. *Fish Fish*, *22*(2), 280–297.

Free, C. M., Thorson, J. T., Pinsky, M. L., Oken, K. L., Wiedenmann, J., & Jensen, O. P. (2019). Impacts of historical warming on marine fisheries production. *Science*, *363*(6430), 979–983. https://doi.org/10.1126/science.aau1758

Fuenzalida, H., Aceituno, P., Falvey, M., Garreaud, R., Rojas, M., & Sánchez, R. (2007). *Study on climate variability for chile during the 21st century* [Technical report]. National Environmental Committee.

Garreaud, R. D., & Falvey, M. (2009). The coastal winds off western subtropical south america in future climate scenarios. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *29*(4), 543–554.

Gonzalez-Mon, B., Bodin, Ö., Lindkvist, E., Frawley, T. H., Giron-Nava, A., Basurto, X., Nenadovic, M., & Schlüter, M. (2021). Spatial diversification as a mechanism to adapt to environmental changes in small-scale fisheries. *Environ. Sci. Policy*, *116*, 246–257.

Hicks, R. L., Holland, D. S., Kuriyama, P. T., & Schnier, K. E. (2020). Choice sets for spatial discrete choice models in data rich environments. *Res. Energy Econ.*, *60*, 101148.

Homans, F. R., & Wilen, J. E. (2005). Markets and rent dissipation in regulated open access fisheries. *Journal of Environmental Economics and Management*, *49*(2), 381–404.

Jardine, S. L., Fisher, M. C., Moore, S. K., & Samhouri, J. F. (2020). Inequality in the economic impacts from climate shocks in fisheries: The case of harmful algal blooms. *Ecol. Econ.*, *176*, 106691.

Juselius, K. (2006). *The cointegrated VAR model: Methodology and applications*. Oxford university press.

Kasperski, S. (2015). Optimal multi-species harvesting in ecologically and economically interde-

pendent fisheries. *Environ. Resour. Econ.*, *61*(4), 517–557.

Kasperski, S., & Holland, D. S. (2013). Income diversification and risk for fishermen. *Proc. Natl. Acad. Sci. U. S. A.*, *110*(6), 2076–2081.

Peña-Torres, J., Dresdner, J., & Vasquez, F. (2017). El niño and fishing location decisions: The chilean straddling jack mackerel fishery. *Mar. Resour. Econ.*, *32*(3), 249–275.

Peña-Torres, J., Muñoz, R., Quezada, F., & Kaufmann, C. (2022). Entry deterrence and collusion at repeated multiunit auctions of ITQs. *Marine Resource Economics*, *37*(4), 437–465. https://doi.org/10.1086/721014

Poloczanska, E. S., Brown, C. J., Sydeman, W. J., Kiessling, W., Schoeman, D. S., Moore, P. J., Brander, K., Bruno, J. F., Buckley, L. B., Burrows, M. T., Duarte, C. M., Halpern, B. S., Holding, J., Kappel, C. V., O'Connor, M. I., Pandolfi, J. M., Parmesan, C., Schwing, F., Thompson, S. A., & Richardson, A. J. (2013). Global imprint of climate change on marine life. *Nat. Clim. Chang.*, *3*(10), 919–925.

Powell, F., Levine, A., & Ordonez-Gauger, L. (2022). Climate adaptation in the market squid fishery: Fishermen responses to past variability associated with el niño southern oscillation cycles inform our understanding of adaptive capacity in the face of future climate change. *Clim. Change*, *173*(1-2), 1.

Reimer, M. N., Abbott, J. K., & Haynie, A. C. (2022). Structural behavioral models for rights-based fisheries. *Resource and Energy Economics*, *68*, 101294.

Reimer, M. N., Abbott, J. K., & Wilen, J. E. (2017). Fisheries production: Management institutions, spatial choice, and the quest for policy invariance. *Mar. Resour. Econ.*, *32*(2), 143–168.

Richter, A., Eikeset, A. M., Van Soest, D., Diekert, F. K., & Stenseth, N. C. (2018). Optimal management under institutional constraints: Determining a total allowable catch for different northeast arctic cod fishery fleet segments. *Environmental and Resource Economics*, *69*, 811–835. https://doi.org/10.1007/s10640-016-0106-3

Sethi, S. A., Reimer, M., & Knapp, G. (2014). Alaskan fishing community revenues and the stabilizing role of fishing portfolios. *Mar. Policy*, *48*, 134–141.

Smith, M. D. (2005). State dependence and heterogeneity in fishing location choice. *J. Environ. Econ. Manage.*, *50*(2), 319–340.

Stafford, T. M. (2018). Accounting for outside options in discrete choice models: An application to commercial fishing effort. *J. Environ. Econ. Manage.*, *88*, 159–179.

SUBPESCA. (2020). *Informe sectorial de pesca y acuicultura 2019*. Subsecretaría de Pesca y Acuicultura. https://www.subpesca.cl/portal/618/articles-106845_documento.pdf

Trenberth, K. E., Jones, P. D., Ambenje, P., Bojariu, R., Easterling, D., Klein, T. A., Parker, D., Rahimzadeh, F., Renwick, J. A., Rusticucci, M., Soden, B., & Zhai, P. (2007). Observations: Surface and atmospheric climate change. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & H. L. Miller (Eds.), *Climate change 2007: The physical science basis. Contribution of working group i to the fourth assessment report of the intergovernmental panel on climate change* (pp. 235–336). Cambridge University Press.

Vasquez Caballero, S., Sylvia, G., & Holland, D. S. (2023). Fishery participation and location choice model: The west coast salmon troll commercial fishery. *Can. J. Fish. Aquat. Sci.*

Yáñez, E., Barbieri, M. A., Plaza, F., & Silva, C. (2014). Climate change and fisheries in chile. In M. Behnassi, M. Syomiti Muteng'e, G. Ramachandran, & K. N. Shelat (Eds.), *Vulnerability of agriculture, water and fisheries to climate change: Toward sustainable adaptation strategies* (pp. 259–270). Springer Netherlands. https://doi.org/10.1007/978-94-017-8962-2_16

Yáñez, E., Barbieri, M., Silva, C., Nieto, K., & Espındola, F. (2001). Climate variability and pelagic fisheries in northern chile. *Progress in Oceanography*, *49*(1-4), 581–596.

Young, T., Fuller, E. C., Provost, M. M., Coleman, K. E., St. Martin, K., McCay, B. J., & Pinsky, M. L. (2018). Adaptation strategies of coastal fishing communities as species shift poleward. *ICES Journal of Marine Science*, *76*(1), 93–103.

Zhang, J., & Smith, M. D. (2011). Heterogeneous response to marine reserve formation: A sorting model approach. *Environ. Resour. Econ.*, *49*(3), 311–325.