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

REALLY EARLY DRAFT – PLEASE DO NOT CITE

Felipe J. Quezada-Escalona

Departmento de Economía
Universidad de Concepción

diciembre 12, 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 (Sumaila et al., 2011). 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. According to Cheung et al. (2010), the Chilean Exclusive Economic Zone (EEZ) is projected to experience one of the largest losses in maximum catch potential due to climate change. However, the Southeast Pacific remains one of the least studied regions regarding the impacts of climate change on fisheries (Sumaila et al., 2011).

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.

Take into consideration the economic interaction between species is relevant to include how firms adjust to changes in policies, as relative prices between species might change. Also, cost complementarities between trageiting multispcies should be consideredn as it might be cheaper to harvest two species instead of one... In this paper we allow for economic interaction between species by allowing vessel to have multiple-output production and the output price to be dependent on other species, similar to Kasperski (2015).

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.

– ADD the fact that the government define the TAC using sa single species model. This modelling

[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.

effort allow to move further to a better management of the SPF fishery by using a multispecies approach to obtain optimal TAC

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 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.

"La pesquería de sardina común (Strangomera bentincki) y anchoveta (Engraulis ringens) de la zona centro sur de Chile se caracteriza por ser una pesquería mixta. A pesar de contener especies distintas, éstas conviven y se reproducen en un mismo hábitat. Las artes de pesca utilizadas para capturar estas especies no permiten diferenciarlas." (Dresdner et al., 2013)

"La pesquería de sardina común y anchoveta ha sido por largos años una de las pesquerías más importante de Chile. La disminución paulatina de los desembarques de jurel (Trachurus murphyi) ha llevado a la sardina común a posicionarse como el principal recurso pelágico extraído, seguido por la anchoveta" (Dresdner et al., 2013)

2.1 Status of the stocks

Historically, anchoveta in the Central-South was considered collapsed until 2018, shifted to overexploited 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?)

2.2.1 Chile regionalized fisheries governance framework

Chile has a regionalize fisheres governance framework, where boat register in one region can not fish in another one. For instance, a recent conflict between the Biobío and Ñuble regions has reignited the debate over the spatial governance of the small pelagic fishery (SPF) in south–central Chile. In late August 2025, the Chilean Chamber of Deputies approved a resolution urging the Government to repeal the authorization that allows vessels from Biobío to operate in the coastal waters of Ñuble. The measure, promoted by local authorities and artisanal organizations from Ñuble, aims to protect local fishing grounds and reduce pressure on nearshore ecosystems.

However, representatives from Biobío have warned that such restrictions could have severe economic consequences for the region, given its strong dependence on small pelagic landings. This episode highlights the institutional tensions arising from Chile's regionalized fisheries governance framework, where jurisdictional boundaries often conflict with the biological and economic interdependencies of fish stocks.

2.3 Other regulations

2.3.1 Limited entry

Fishery with restricted access to new operators

2.3.2 Biological closures for recruitment

- Jack mackerel is open through all year.
- Sardine and anchovy: In southern-central Chile, December–March (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, based on the industrial share of the TAC.

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

	Before		After	
Strategy	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

2.4 Switching patterns

ARE THIS SPF TRIPS?????

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.

2.5 Fishing seasons

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.

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

	Before		After	
Strategy	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

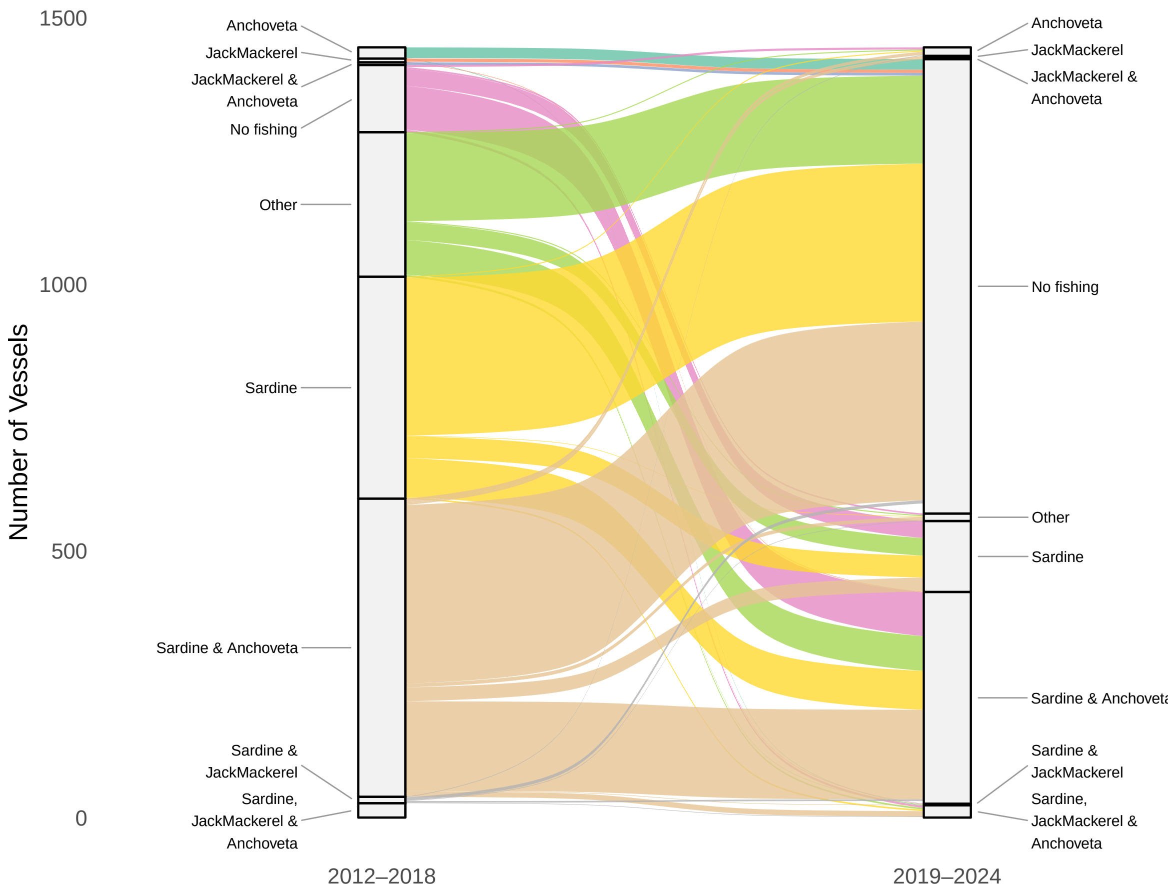

Figure 1: Strategy transitions for small-scale vessels

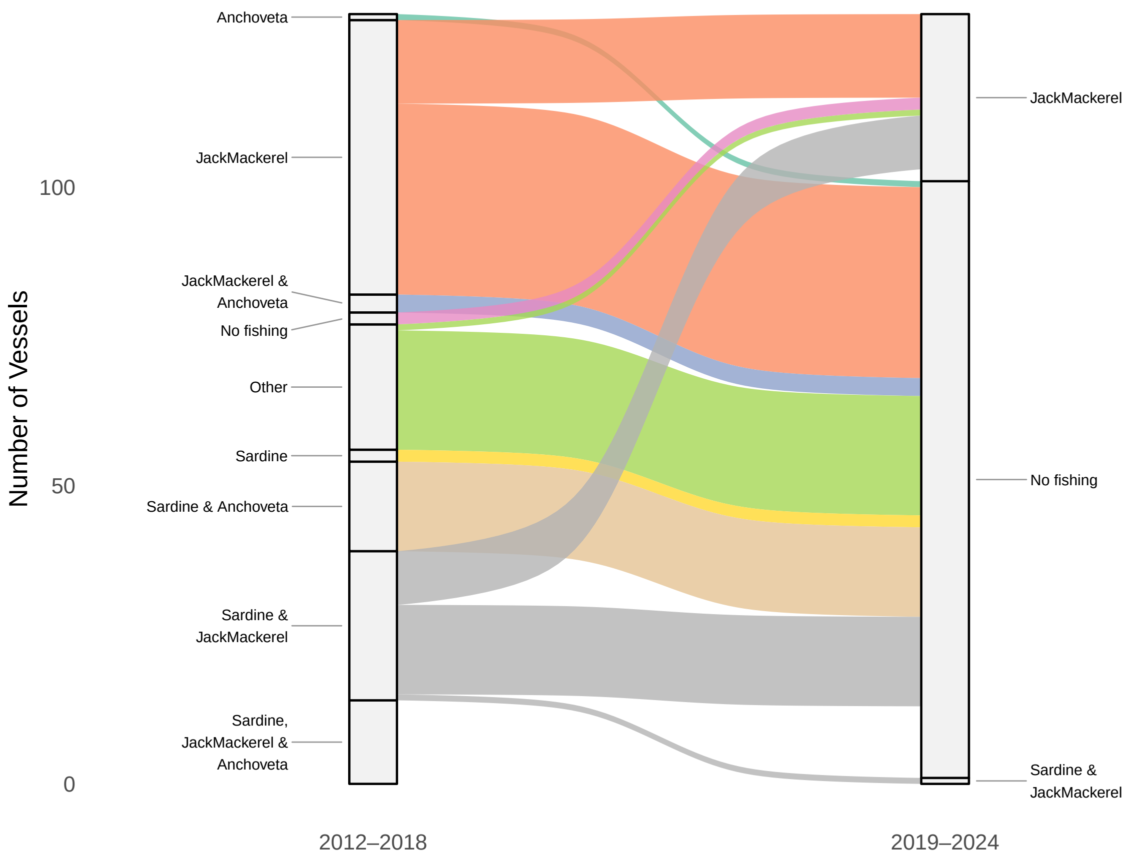

Figure 2: Strategy transitions for industrial vessels

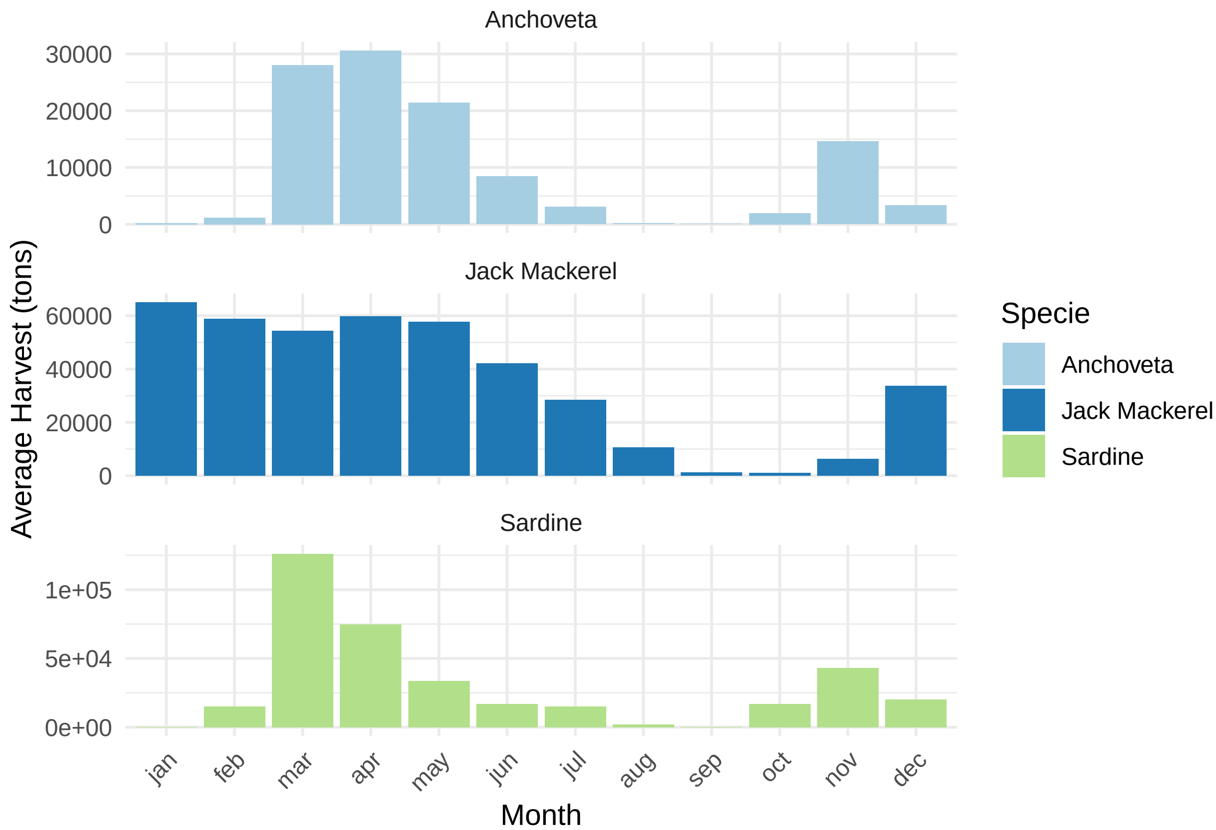

Figure 3: Average monthly landings by species (2012-2024; South-Central Chile)

3.1 Historical data

We use data requested from the Chilean Fisheries Development Institute (Instituto de Fomento Pesquero, IFOP) covering the 2012–2024 period. The dataset includes trip-level microdata, which contain detailed records on vessel identifiers, departure and arrival times, vessel capacity, fleet and gear type, ports of departure and landing, fishery codes, haul timing and location, species composition, retained catch, and trip activity. In addition, we requested annual information on stock abundance and vessel landings by port, county, region, country, and species. Finally, we use ex-vessel prices, reported monthly or annually by port, county, region, country, and species. These prices reflect those paid by processing plants to fishers at the point of first sale and are obtained through IFOP's landing surveys, which do not necessarily cover all market transactions.

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 (Figure 4)

To address the years in which no acoustic survey was conducted in south-central Chile—or in which insufficient information was available to produce a stock assessment—we imputed missing jack mackerel biomass values using an auxiliary generalized linear model (GLM) with a Gamma distribution and a log link. The model specifies the log of expected biomass in the south-central region as a nonlinear function of (i) northern jack mackerel biomass, (ii) its squared term, (iii) the squared biomass index estimated by the South Pacific Regional Fisheries Management Organisation (OROP-PS) within the exclusive economic zones of Chile, Ecuador, and Peru, and (iv) an interaction between northern biomass and the SPRFMO biomass index. We estimated five alternative specifications and selected the preferred one based on the Akaike Information Criterion and the squared correlation between observed and fitted values—used here as a pseudo-R^2 measure. The selected model provides an excellent fit (pseudo-$R^2 \approx 0.97$). In two years, however, the model produced extreme and biologically implausible predictions; in those cases, we replaced the estimated values with NA to avoid propagating outliers in subsequent analyses.

3.1.1 To be requested

- Diesel cost.
- Permits by vessels
- Quota prices?
  - Auction market but also secondary market if available
    - If no data, maybe intrapolate prices from other auctions?
  - Captures elements of forward-looking behavior and information (Birkenbach et al., 2024). 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.
- Quota by area/fishing organization for Artisanal, and TAC for industrial with ITQ (by vessel?)

3.2 Future data for projections

- OracleBio
  - Unfurtunally, only decadal (e.g., 2040–2050) projections for different scenarios for SST, salinity, currents and chlorophyll (4km resolution)

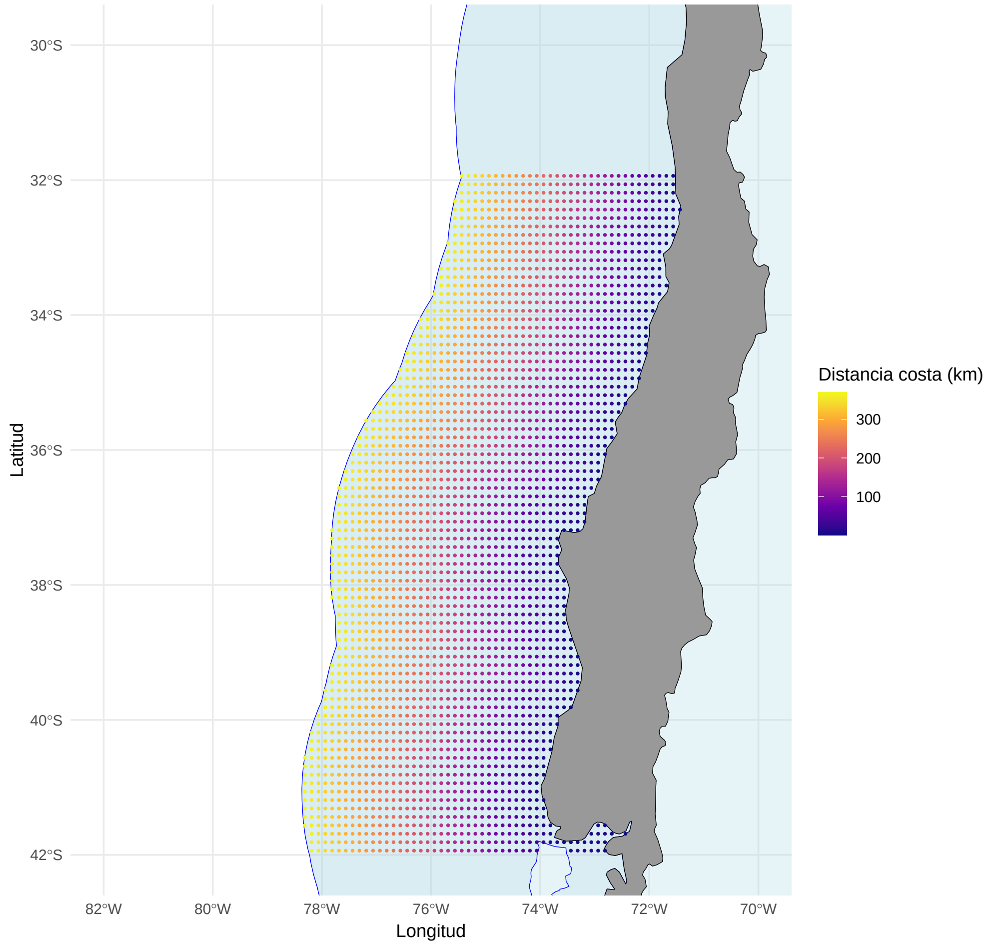

Figure 4: Geographical extent of the study area used for environmental covariates limited to the Chilean Exclusive Economic Zone

  - No winds; CMIP6 for winds? (~100 km).

3.3 Econometrics models

3.3.1 Stock dynamics

To estimate stock dynamics, we use annual data on species-specific biomass (stock abundance) and vessel landings within Chile's Exclusive Economic Zone (EEZ). Following Kasperski (2015), the baseline model for the interannual growth of each species i is represented by a discrete logistic function that accounts for intra- and inter-species interactions:

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

where x_{iy} is the biomass of species i in year y, n is the total number of species, h_{iy} is the annual harvest, r_i is the intrinsic growth rate, η_i is the density-dependent parameter, and α_{ij} captures pairwise species interactions. 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 stock dynamics, along with an error term ε_{iy} representing stochastic recruitment:

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

where ρ_i denotes the environmental response parameters. Importantly, each species has its own equation, allowing for species-specific growth, density dependence, and environmental sensitivities.

Environmental conditions were summarized annually using sea surface temperature (SST) and chlorophyll-a concentration (CHL), both averaged over the South-Central Chile region within the EEZ. These variables were selected due to their recognized influence on small pelagic productivity and spatial distribution (Axbard, 2016). To capture nonlinear responses, we include both linear and quadratic terms for SST and CHL. Early specifications also tested wind effects, but excluding them did not reduce explanatory power ($F_{6,21} = 0.919$, p-value $= 0.509$).

SST serves as a proxy for large-scale oceanographic regimes (warm vs. cold phases) that shape recruitment success along the Humboldt Current System. Anchoveta typically dominates during cold, nutrient-rich phases, whereas sardine tends to increase under warmer regimes (Cahuin et al., 2009; Yáñez et al., 2014). CHL reflects interannual variation in primary productivity, which forms the energetic base sustaining small pelagics. As emphasized by Sumaila et al. (2011), "Changes in primary productivity and planktonic community structure affect the amount of energy transferred to higher trophic levels and, eventually, the productivity of trophic groups that contribute to fisheries catches" (see also Cheung et al., 2008; Jennings et al., 2008).

Figure 5 shows that anchoveta, sardine, and jack mackerel exhibit distinct biomass trajectories over time, with no evidence of strong interannual co-movement across species. Biomass levels differ markedly between them, and the figure suggests only limited interrelation alongside clear divergences in year-to-year dynamics. Harvest pressure is also visibly associated with these fluctuations; for instance, jack mackerel experienced an abrupt decline during the late 2000s, consistent with the combined effects of intense fishing pressure and unfavorable environmental conditions.

The SUR framework is particularly suited to this multi-species setting, as it allows for contemporaneous correlation among residuals that naturally arise from shared non-observed environmental shocks, trophic linkages, and imperfectly observed ecological processes. Cross-species interaction terms are specified between predator (jack mackerel) and prey (anchoveta, sardine) pairs, enabling the model to capture both direct biological coupling and environmental spillovers transmitted

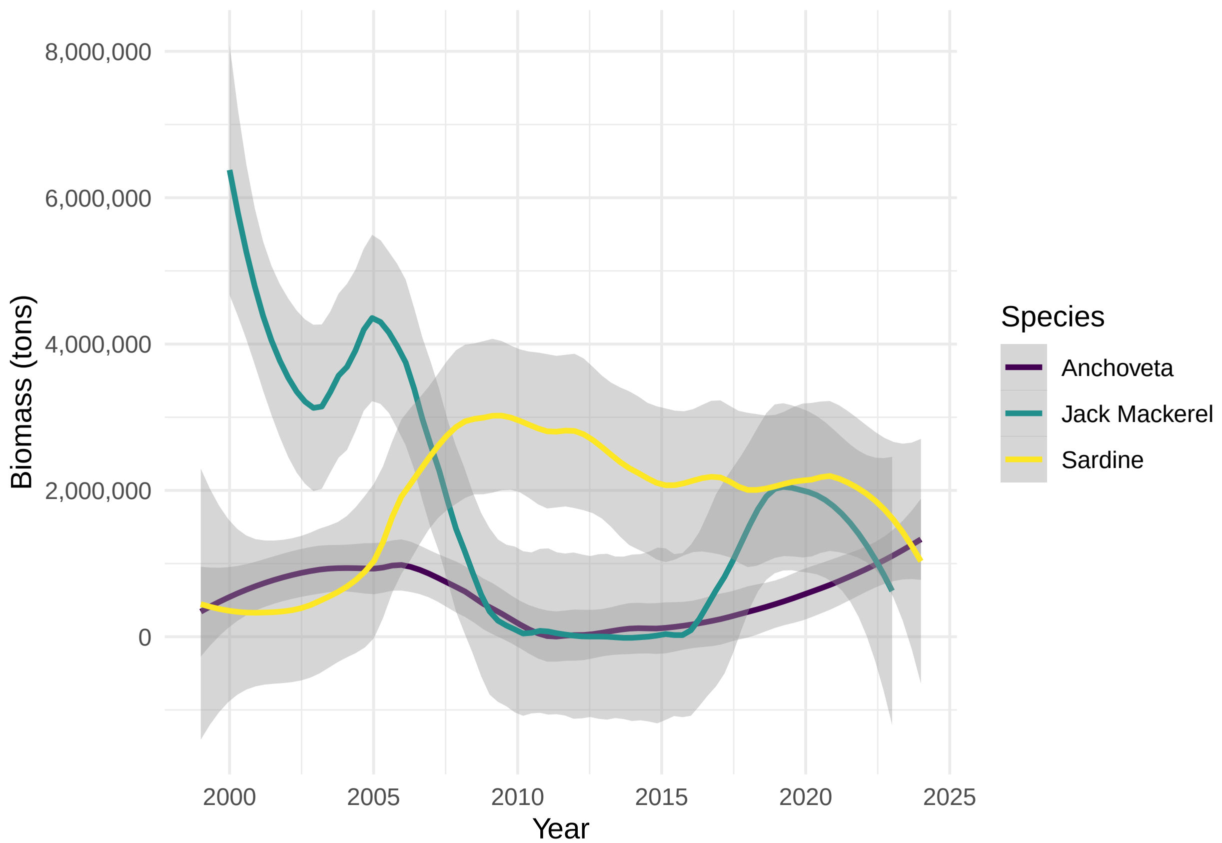

Figure 5: Estimated biomass of small pelagic species in Chile (2000–2024)

across species. We estimate a three-equation SUR system using the SEM framework implemented in lavaan, freely allowing the error terms across biomass equations to be correlated. The model is estimated via robust maximum likelihood (MLR), yielding SUR coefficients with Huber–White robust standard errors.

3.3.2 Trip level cost functions

Two different estimations (one for industrial, 1 for small scale- both use purse seine…)

Just usea real SPF trips (consider 95% of total revenue…) DO I HAVE DATA IN CREW SIZE???? Opportunity cost… (paid by time at sea x hourly wage) – MAYBE USE TIPO EMBARCACION TO LINK CREW SIZE!??? USE BODEGA SIZE TO LINK CREW SIZE??? Fixed cost excluded. Should not affect as econ decision made at the margins (optimization behavior) hard to use share of revenue, as how they implement this depend on each operator

- Sumaila et al. (2011): "Capital costs, that is, the cost of vessels, fishing gear, processing plants and so on, would be affected by climate change if additional capital for fishing and processing operations is required to adapt to climate change impacts on the quantity, composition and

> distribution of fisheries resources65. Changes in migratory routes and fish distribution would affect travel time, which can lead to increases or decreases in fuel and ice cost depending on catch levels and patterns, and the management regime in place."

We estimate restricted cost function for both small-scale and industrial vessel. The inputs that we assume fixed are vessel characteristics and the population of each species.

Ignoring trip subscript, the quadratic approximation of 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 by fleet g, and G is the total number of fleets:

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

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 ith 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:

$$\frac{\partial C_{vg}}{\partial w_m} = z^*_{vg,w_m} = \alpha_{g,w_m} + \sum_{j=1}^{2n+M+k} \alpha_{g,w_m,\mathbf{X}_j} \mathbf{X}_{jvg} \quad m = 1, \dots, M. \tag{4}$$

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 ensure that the estimated cost function is consistent with microeconomic theory, we impose the standard regularity conditions of symmetry and linear homogeneity in input prices.

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

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

These restrictions reduce even more the number of parameters to estimate in (4). Symmetry guarantees that the function is twice differentiable with consistent mixed partial derivatives, allowing it to be interpreted as a valid dual cost function. Linear homogeneity (adding-up) ensures that the cost function is homogeneous of degree one in input prices, so that proportional changes in all prices translate into proportional changes in total cost. These restrictions ensure theoretical coherence and prevent the model from being a purely statistical approximation.

A potential concern is the endogeneity between harvest and costs. However, following Kasperski (2015), we assume that vessel optimization occurs in two stages. In the first stage, vessels choose the cost-minimizing combination of inputs for any given vector of outputs. In the second stage, they choose their optimal output mix to maximize profits. Under this sequential decision process, outputs are treated as exogenous when estimating the restricted cost function, because they are taken as given in the underlying cost-minimization problem.

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

3.3.3 Total annual trips

We model the annual number of fishing trips taken by vessel v in year y as a Poisson count process following Kasperski (2015). Since our logbooks only include purse-seine trips, the unit of observation is a vessel–year. Separate models are estimated by fleet segment (industrial versus artisanal), allowing effort responses to differ across sectors.

$$T_{vy} \sim \text{Poisson}(\lambda_{vy}), \qquad \lambda_{vy} = \exp\bigl(U'_{vy}\beta\bigr)\,, \tag{5}$$

where T_{vy} denotes the total number of purse-seine trips recorded for vessel v in year y. The vector of explanatory variables U_{vy} includes output prices by species, input prices, vessel-level allocated harvest, aggregate total allowable catches (TACs), fixed vessel characteristics, and operating conditions:

$$U_{vy} = [p_{sy},\, w_y,\, H^{alloc}_{vy},\, \bar{Q}_y,\, Z_v,\, Env_y]. \tag{6}$$

Output prices p_{sy} correspond to species-specific processed fish prices, while w_y captures key variable input costs, including diesel prices. Consistent with Dresdner et al. (2013), prices are measured as annual averages over peak fishing months to reflect economically relevant conditions faced by vessels when planning annual effort.

Because the objective of the model is to characterize vessels' effort responses to changes in prices, quotas, and environmental conditions within the small pelagic fishery, we restrict attention to SPF trips recorded in logbooks. These trips account for approximately 95% of observed fishing revenue and therefore capture the primary economic margin through which vessels adjust annual fishing effort.

Quota shares do not enter Eq.~(5) directly. Instead, shares are used to translate annual TACs into vessel-level allocated harvests, which then enter the trip equation. Let ω_{vs} denote vessel v's historical share of landings of species s within the purse-seine fleet. Given a candidate TAC $\bar{Q}_{sy}$ for species s in year y, vessel-level allocated harvest is defined as:

$$H^{alloc}_{vy,s} = \omega_{vs}\,\bar{Q}_{sy}, \qquad H^{alloc}_{vy} = \sum_s H^{alloc}_{vy,s}. \tag{7}$$

This construction is essential for the forward-looking simulation framework. When the social planner chooses aggregate TAC paths $\{\bar{Q}_{sy}\}$, Eq. (7) generates internally consistent vessel-level harvest allocations that can be combined with predicted trips and trip-level cost functions to compute total harvesting costs.

The vector Env_y captures operating and regulatory constraints, including the number of days closed to fishing due to seasonal bans (vedas), as well as environmental conditions that affect the feasibility of fishing operations, such as the number of bad weather days.

Quota prices are not included explicitly in the trip equation. Instead, the economic scarcity of quota is captured implicitly through aggregate TAC levels and vessel-level allocated harvest. In the simulation stage, quota scarcity generates shadow values that affect optimal harvest and effort decisions through profits rather than through an explicit quota price term.

Trips, harvest, and prices may be jointly determined within the year, implying potential endogeneity in reduced-form trip regressions. However, the purpose of Eq. (5) is not causal identification but rather to provide an empirically grounded behavioral relationship that maps changes in prices, quotas, and environmental conditions into expected fishing effort for use in the bioeconomic simulation.

3.3.4 Inverse demand model

The price of each species is modeled using an Inverse Almost Ideal Demand System (IADS). The price of a species i in year y is the following:

$$\ln p_{iy} = \sum_{j}^{n} \gamma_j \ln h_{j,y} + \gamma_H \ln H + \gamma_{FM} \ln P^{\text{FishMeal}} + \epsilon_{iy}, \quad i = 1, \ldots, n, \; j = 1, \ldots, n. \tag{8}$$

Note that harvest may be endogenous in this system due to simultaneity. For this reason, the system formed by (8) will be estimated using a Three Stage Least Squares (3SLS) procedure, where h_j{j,y} would be instrumented by variables that affect the fishers' supply function such as SST, Chl, and fuel prices.

- DIFERENCIAR ENTRE CONSUMO HUMANO DIRECTO e INDIRECTO? Ricardo y Arnol usan solo información de procesamiento. Darle una vuelta a esto
- NECESITO MODELO ANUAL??? SIMPLE CON REZAGOS DE CANTIDAD??? O MAS SIMPLE SIGUIENDO A KASPERSKI PERO INSTRUMENTANDO LA CANTIDAD???

3.4 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 and optimal portfolio of harvest on each trip h_τ:

$$
\begin{aligned}
&\max_{h_{gt},T_g} \quad \pi_{vgt} = \sum_{\tau=t}^{T_g} \rho^\tau \left\{ P(h)h_{g\tau} - C_g(h_{g\tau}|w,x,Z,Env) \right\} \quad \tau = t, \dots, T_g \\
&\textbf{s.t} \quad q_{g,t+1} = \omega * \bar{q} - \sum_{t=1}^{t} h_{gt} \geq 0, \quad t = 1, \dots, T-1, \quad g = 1, \dots, G
\end{aligned} \tag{9}
$$

where ρ is the intra-annual discount factor, ω 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 (9) 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.

- Note that the optimal quota would that we would find using historical data might differ from the actual quota set by the regulator as they model is for single species.
- We assume that quota is not tradable, but allocated individually to each vessel. This avoid to consider other vessle participation decision on vessel yeraly maximization process (Kasperski, 2015).

3.5 Projections

According Kasperski (2015), the model presented in this project is more suitable for long-term projections of fish population and profits than intra-anuial impacts of short-term management action. Therefore, is suitable to studyn long term effect of climate variability. However, based on Aufhammer, because we are using short-term variability instead of decadal vsariability, then our model is onlpy able to capture the impact of climate without adaptation.

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 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

1.
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 1.
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

4.1 Stock biomass model

ADD: Classic logistic growth curves

Figure 6 show biomass adding harvest

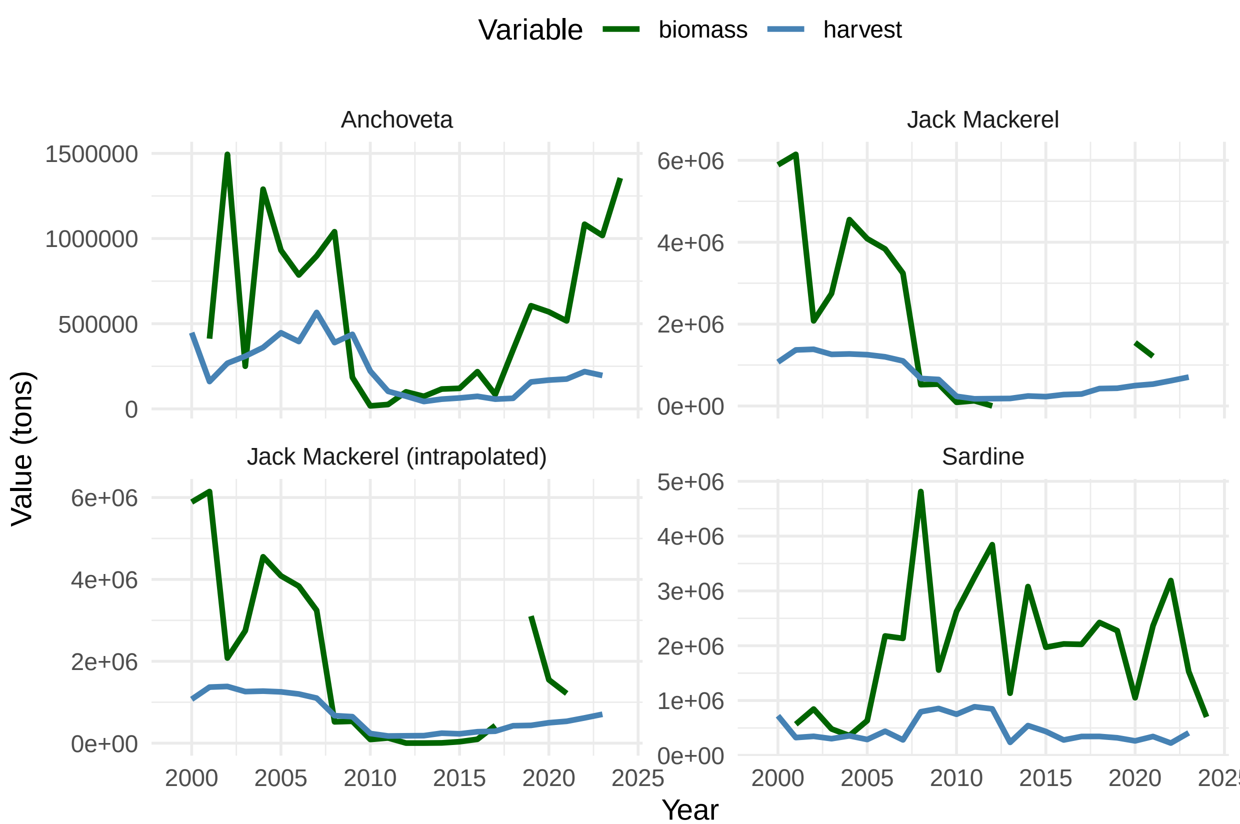

Figure 6: Estimated biomass vs harvest of small pelagic species in CentralSouth Chile (2000–2024)

Estimar modelo

Table 3 reports the SUR estimates of annual biomass dynamics for sardine, anchoveta, and jack mackerel using robust standard errors. Including sea surface temperature (SST) and chlorophyll-a (CHL) significantly improves model performance, leading us to reject the joint exclusion of environmental covariates at the 10% significance level ($F_{12,27} = 1.874$, p-value $= 0.07$).

The three species exhibit strong interannual persistence and significant density dependence, consistent with discrete logistic growth. Sardine biomass responds positively to chlorophyll-a concentration and negatively to SST, indicating that productivity-rich and cooler conditions enhance its growth. This SST response contrasts with evidence from the California Current, where sardine abundance tends to increase under warm regimes (Herrick et al., 2009). **IS THIS TRUE FOR CHILE?** Anchoveta shows a similar negative response to temperature, together with pronounced density dependence, reflecting its high environmental sensitivity. In contrast, jack mackerel displays weaker environmental dependence, but its SST quadratic term is significant, suggesting a thermal optimum and reduced biomass under extreme temperatures.

Cross-species effects reveal one notable ecological interaction: anchoveta biomass declines in years with high sardine biomass. **IS THIS PATTERN CONSISTEN WITH LITERATURE?**. No significant interaction effects are detected for jack mackerel, consistent with its broader spatial range and weaker coupling to coastal pelagic dynamics.

Overall, the model captures distinct species-specific responses to environmental variability. Sardine biomass is strongly driven by ocean productivity, anchoveta by density dependence and thermal conditions, and jack mackerel by a combination of persistence and nonlinear temperature responses.

The R^2 seems to be good, considering the high variability that small pelagic species exhibits in their stock.

4.2 Trip level costo function

EMPEZAR A ESTIMAR ESTO!!!! USANDO LOGBOOKS

« NO RESULTS YET »

4.3 Total Annual trips

« NO RESULTS YET »

4.4 Inverse demand model

« NO RESULTS YET »

Two undergrad students working on this module for their thesis... Results by July 2026

Table 3: Seemingly Unrelated Regression (SUR) estimates of biomass dynamics

	Sardine	Anchovy	Jack mackerel
	(1)	(2)	(3)
Sardine biomass (t)	0.366** (0.152)		
Sardine biomass $(t)^2$	−0.008 (0.011)		
Anchovy biomass (t)		1.212*** (0.205)	
Anchovy biomass $(t)^2$		−0.233*** (0.041)	
Jack mackerel biomass (t)			0.903*** (0.140)
Jack mackerel biomass $(t)^2$			−0.023*** (0.006)
SST	−20.122*** (4.171)	−6.062*** (2.162)	13.033** (5.801)
SST^2	42.107* (22.300)	−8.483 (9.298)	−49.589** (23.583)
Chlorophyll-a	87.856*** (19.053)	1.030 (14.722)	6.583 (32.068)
Chlorophyll-a^2	−240.056 (200.636)	−115.129 (171.700)	380.375 (295.463)
Sardine × Anchovy	−0.010 (0.027)	−0.028** (0.012)	
Sardine × Jack mackerel	0.008 (0.010)		−0.006 (0.008)
Anchovy × Jack mackerel		−0.009 (0.020)	0.030 (0.033)
Constant	25.350*** (4.090)	13.079*** (2.515)	28.717*** (5.613)
Observations	18	18	18
R^2	0.772	0.621	0.858
Adjusted R^2	0.570	0.285	0.731
Residual Std. Error (df = 9)	8.329	4.774	10.543

Note: $^*p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$. Robust standard errors in parenthesis.

4.5 Numerical optimization

« NO RESULTS YET »

Once I have results for the four models, then I can run optimizations

5 Discussion

- From Sumaila et al. (2011): "A shift in species' geographic range will thus affect the distribution and composition of fisheries resources. This may affect fishing operations, the allocation of catch shares and the effectiveness of fisheries management measures"
- For the ITQ fisheries (i.e., industrial jack mackerel?:
  - 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 too 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 fisheries that do not require permits)

- Although the present model captures the historical relationships between biomass, temperature, and productivity, future strengthening of coastal winds and warming of the Chilean coast (Fuenzalida et al. 2007; Garreaud et al. 2009) could shift these dynamics, altering species overlap and fishery composition.
- About using CHL for future predictions.
  - From Sumaila et al. (2011): "However, our understanding of the magnitude and direction of climate change effects on primary productivity is uncertain. For example, projections of primary production based on an empirical relationship estimate increases of 0.7–8.1% by 2050 relative to 2000 (ref. 39), whereas outputs from four Earth-system models suggest a possible decrease of 2–20% by 2100 relative to pre-industrial conditions12. The opposite trends and the large regional differences of the estimates highlight the uncertainty in the projection of large-scale changes in primary productivity".
- About prices (Sumaila et al., 2011):
  - "Everything being equal, when climate change reduces fish supply, fish price should increase, which could be large enough to balance out the loss in gross revenues due to reduced catches. However, consumers may seek substitutes as prices increase, thereby dampening the demand for fish and reducing the potential for price increases."
  - "Ex-vessel revenues can be affected by climate change through effects first on the quantity, quality and distribution of catches, and then, on ex-vessel prices of fish."
- Adaptation (Sumaila et al., 2011):
  - "When climate change affects the composition and productivity of exploited species in a region, some fishers can adapt by switching target species or gear type81 or by moving to marginally productive areas. Grafton, R. Q. Adaptation to climate change in marine capture fisheries. Mar. Policy 34, 606–615 (2010)."
    * "For example, new fisheries have already developed for several southern species in the UK (for example, red mullet) as these species have started to migrate to the North Sea because of an increase in sea temperature. Beare, D. J. et al. Long-term increase in prevalence of North Sea fishes having southern biogeographic affinities. Mar. Ecol. Prog. Ser. 284, 269–278 (2004)."

        * “The ability of fishers and fishing enterprises to adapt depends on a number of factors, including the mobility of the fishing fleet. -”At present, the dominant hypothesis is that more technologically advanced fleets, usually located in rich northern countries, are more likely to be better prepared to adapt to climate change by moving to other fishing grounds and by shifting gears. MacNeil, M. A. et al. Transitional states in marine fisheries: adapting to predicted global change. Phil. Trans. R. Soc. B 365, 3753–3763 (2011).”

- we did not added production risk…. risk preferences? maybe using random coefficients? Discusse!!!

__ Julio Peña: Mejorar transferibilidad multispecie de las cuotas, y entre sectores artesanales e industrial

6 Conclusions

NO YET!

6.1 Future research question

- 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 multispecies model of Kasperski (2015) to the literature of location choice modeling (e.g., Dupont, 1993; Hicks et al., 2020; Smith, 2005).
    - About the DCM?
        * Including other economic activity would be relevant, as aquaculture is become more relevant in the country, where some fishermen have swith to small-scale aquaculture practice.
        * Outside option…
- 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.

Axbard, S. (2016). Income opportunities and sea piracy in indonesia: Evidence from satellite data. *American Economic Journal: Applied Economics*, *8*(2), 154–194. https://doi.org/10.1257/app.20140404

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

Cheung, W. W., Close, C., Lam, V., Watson, R., & Pauly, D. (2008). Application of macroecological theory to predict effects of climate change on global fisheries potential. *Marine Ecology Progress Series*, *365*, 187–197.

Cheung, W. W., Lam, V. W., Sarmiento, J. L., Kearney, K., Watson, R., Zeller, D., & Pauly, D. (2010). Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, *16*(1), 24–35.

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.

Dresdner, J., Chávez, C., Dresdner, D., Estay, M., Neira, S., Quiroga, M., & Salgado, H. (2013). Evaluación socio-económica de la aplicación de medidas de administración sobre la pesquería mixta de pequeños pelágicos de la zona centro sur. *Informe Final Revisado Del Proyecto*, 539.

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)*. Marine Data Store (MDS). https://doi.org/10.48670/moi-00281

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

E.U. Copernicus Marine Service Information. (2025c). *Global ocean physics reanalysis*. 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.

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.

Herrick, S. F. Jr. et al. (2009). Lobal production and economics. In D. M. Checkley, C. Roy, J. Alheit, & Y. Oozeki (Eds.), *Climate change and small pelagic fish* (pp. 256–274). Cambridge University Press.

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.

Jennings, S., Mélin, F., Blanchard, J. L., Forster, R. M., Dulvy, N. K., & Wilson, R. W. (2008). Global-scale predictions of community and ecosystem properties from simple ecological theory. *Proceedings of the Royal Society B: Biological Sciences*, *275*(1641), 1375–1383.

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

Sumaila, U. R., Cheung, W. W., Lam, V. W., Pauly, D., & Herrick, S. (2011). Climate change impacts on the biophysics and economics of world fisheries. *Nature Climate Change*, *1*(9), 449–456.

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

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.