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

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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), sardine (either Sardinops sagax or Strangomera bentincki), among others. By doing this, we expect to understand better 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 if the availability of a main target species is reduced, fishers will switch to the closest substitute if the expected revenue obtained from targeting this new species is high enough to cover the expected cost. Otherwise, the vessel would decrease fishing efforts 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). Due to climate change, species distribution is expected to change in the future, reducing species availability in some areas but increasing in others. The literature that studies fishermen' 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 fishers can adopt the following adaptive strategies: (i) fishermen can reduce or reallocate fishing effort, either to another species or to another location (Gonzalez-Mon et al., 2021), (ii) keep following the same strategy, or, (iii) in the worst-case scenario, stop fishing entirely and find alternative employment elsewhere (Powell et al., 2022). Among all those strategies, reallocating fishing efforts to other alternative species might be an effective adaptation strategy to climate change (Young et al., 2018). Diversification of target species has been associated with reducing income variability (e.g., Kasperski & Holland, 2013; Sethi et al., 2014) and increasing resilience to both climate shock (Cline et al., 2017; Fisher et al., 2021) and interannual oceanographic variability (Aguilera et al., 2015; Finkbeiner, 2015).

Climate variability affects income risk... From Cruz paper:

- *"Climate variability has a substantial impact on key food-producing sectors, particularly agriculture and fisheries, where income is closely tied to environmental fluctuations (e.g., temperature and rainfall) and market forces (e.g., input costs) (Carter et al., 2018; Kasperski & Holland, 2013)."*
- *"With climate variability expected to reduce productivity in these sectors, the associated income risk is likely to increase (Carter et al., 2018; Free et al., 2019)."*
- *"Adaptive strategies like diversification, both within (e.g. switching crop or species) and across sectors, are widely advocated to mitigate risks associated with climate variability (Abbott et al., 2022; Markowitz, 1952), but these strategies can be costly, particularly for rural, resource-dependent communities with limited capital and skills (Cherdchuchai & Otsuka, 2006; Ellis, 2000)."*
- *"The role of these switching costs, and how they might hinder or aid diversification within and across sectors remain largely unexplored in this context".*

However, switching between species requires fishers to have the skills, the gear, and the permits to do so (Frawley et al., 2021; Powell et al., 2022). Moreover, even though a fisher may satisfy these requirements, diversification might not be possible (Beaudreau et al., 2019) as it might be constrained depending on port infrastructure, markets, and regulations (Kasperski & Holland, 2013; Powell et al., 2022). Therefore, deciding which adaptation strategy to take is not straightforward and would depend on many factors. Additionally, fishers might respond differently to an analogous situation as they have different goals, skills, and preferences (Jardine et al., 2020; Powell et al., 2022; Zhang & Smith, 2011).

In this project, 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*), sardine (either *Sardinops sagax* or *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). By doing this research, we expect to understand better 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 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 if the availability of a main target species is reduced, fishers will switch to the closest substitute if the expected revenue obtained from targeting this new species is high enough to cover the expected cost. Otherwise, the vessel would decrease fishing efforts 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 (Reimer et al., 2017) – and the gear type used.

At the end of the project, I 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 would take. The combinations of these environmental effects would be reflected in the optimal harvest level and the prices seen on the local market. I also expect to find significant interrelations between species stock and harvest, and that the composition of the catch will vary depending on the climate scenario we use for future predictions.

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, so responses might differ depending on where the study is conducted. 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]

2 SPF in Chile

The small pelagic fishery (SPF) in Chile is primarily composed of anchoveta (*Engraulis ringens*) and sardine (*Strangomera bentincki*), with jack mackerel (*Trachurus murphyi*) also playing a significant role, particularly for small-scale fishers engaged in a "race for fish" dynamic. The Central-South region of Chile is especially important for sardine harvests and will therefore be the focus of this research, as it provides a relevant setting to study potential species substitution within a multispecies management framework. In 2019, the SPF represented nearly 94% of total

[1] For the case of Chile, as far as I know, the only article that study fishers' behavior using discrete choice modelling is Peña-Torres et al. (2017). This article study how El Niño Southern Oscillation (ENSO) affect fishermen location choices that participate in the Jack Mackerel fishery.

national fish landings, highlighting its critical importance to the Chilean fisheries sector (SUBPESCA, 2020). Historically, anchoveta in the Central-South was considered collapsed until 2018, shifted to overexploited status in 2019, and has since been fished within maximum sustainable yield (MSY) limits. Sardine stocks have generally remained within MSY levels, except in 2021 and 2023 when they were classified as overexploited. Similarly, jack mackerel was overexploited until 2018 but has since been harvested sustainably. Anchoveta and sardine are regulated as a mixed-species fishery: they have separate quotas, but if one species is unavailable, the quota for the other can be used as a substitute. Additionally, some quota originally allocated to industrial fleets is transferred to the artisanal sector, with these transactions potentially traceable through SERNAPESCA data.

Strategy	Industrial	Small-Scale	Total	Percent (%)
Only JackMackerel	26	1154	1180	37.0
Only Sardine	3	762	765	24.0
Sardine and Anchoveta	1	700	701	22.0
Sardine , JackMackerel and Anchoveta	0	202	202	6.3
Sardine and JackMackerel	28	138	166	5.2
Only AustralSardine	0	78	78	2.4
Sardine and AustralSardine	0	25	25	0.8
Only SpanishSardine	0	19	19	0.6
Only Anchoveta	0	16	16	0.5
Anchoveta and AustralSardine	0	13	13	0.4
JackMackerel and SpanishSardine	0	11	11	0.3
JackMackerel and Anchoveta	0	6	6	0.2
Sardine , Anchoveta and AustralSardine	0	5	5	0.2
Sardine , JackMackerel and SpanishSardine	0	2	2	0.1
Sardine , JackMackerel , Anchoveta and AustralSardine	0	1	1	0.0
Sardine , JackMackerel , Anchoveta and SpanishSardine	0	1	1	0.0
Sardine , JackMackerel and AustralSardine	0	1	1	0.0
Sardine and SpanishSardine	0	1	1	0.0

3 Data and methodology

To fulfill the project's objectives, and following Kasperski (2015), the research entails five different stages: (i) estimating the 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

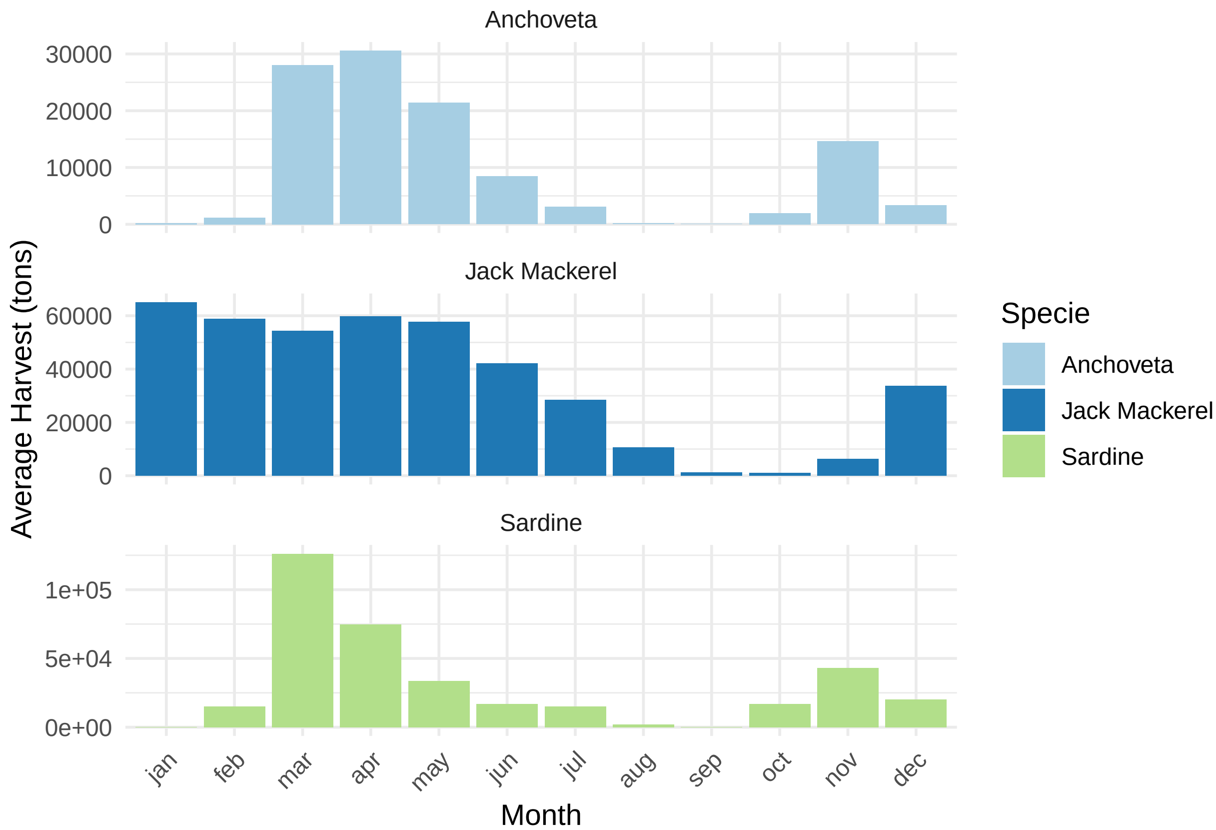

Figure 1: Average monthly landings by species (2012-2024; South-Central Chile)

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 2)

- **POR SOLICITAR:**
  - Environmental covariates – Ask Fabian Tapia, UdeC

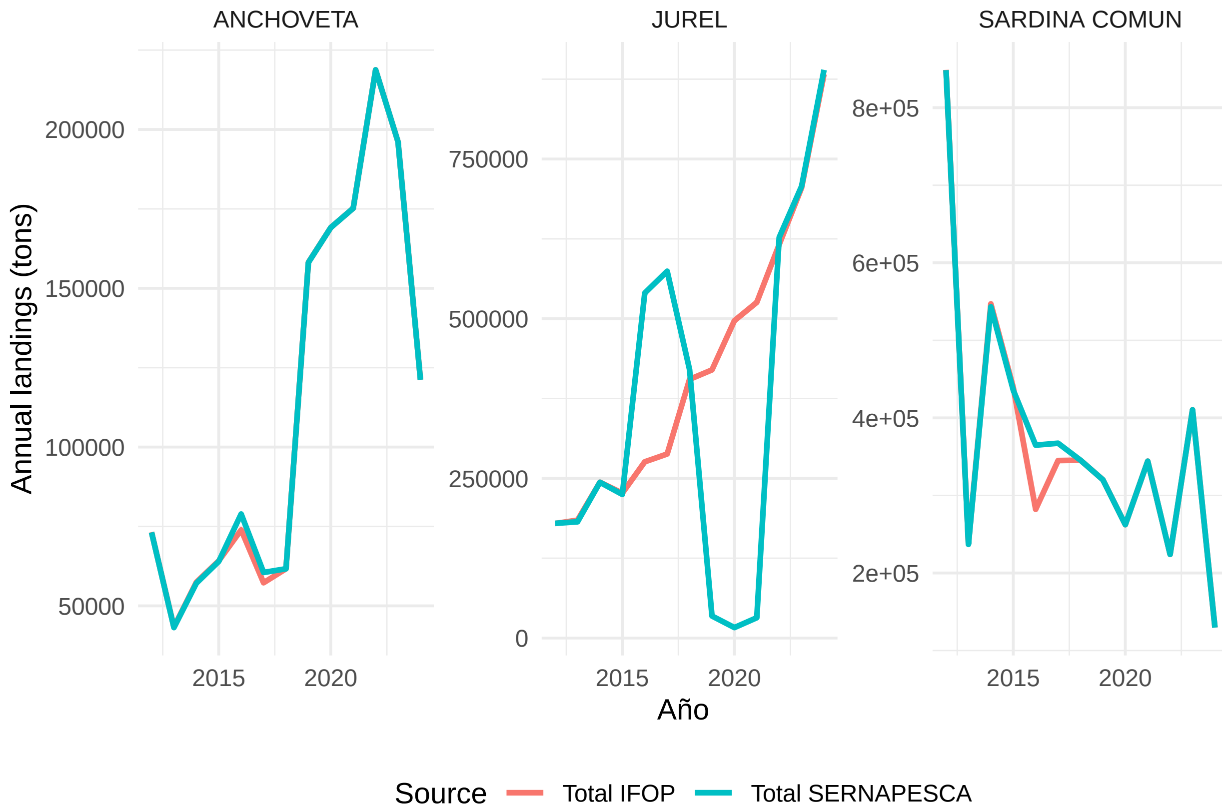

Figure 2: Desembarques anuales (IFOP vs SERNAPESCA)

    * Sea surface temperature
    * Chlorophyll levels
    * Wind intensity and wave conditions in each trip at the harvest location
    * Bad weather days?

- Other data?
    * Average wage pay to crew member per hour
    * Diesel cost.

3.2 Econometrics models

3.2.1 Stock dynamics

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

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

where x_{iy} is the fish stock by species $i = 1, \dots, n$ 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, η_i is a density-dependent factor related to the carrying capacity, and α_{ij} are the interaction parameters between species. The system of n growth equations can be estimated simultaneously using seemingly unrelated regression (SUR) or other similar approaches.

Following Richter et al. (2018), we can augment (1) by including environmental covariates Env_{iy} that affect the fish stock, such as sea surface temperature and chlorophyll levels, and an error term ε_{iy} that captures random recruitment:

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

where ρ_i are the coefficient for the environmental covariates. The model could also be expanded to different spatial locations conditional on data availability.

As shown in Figure 3, 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.

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

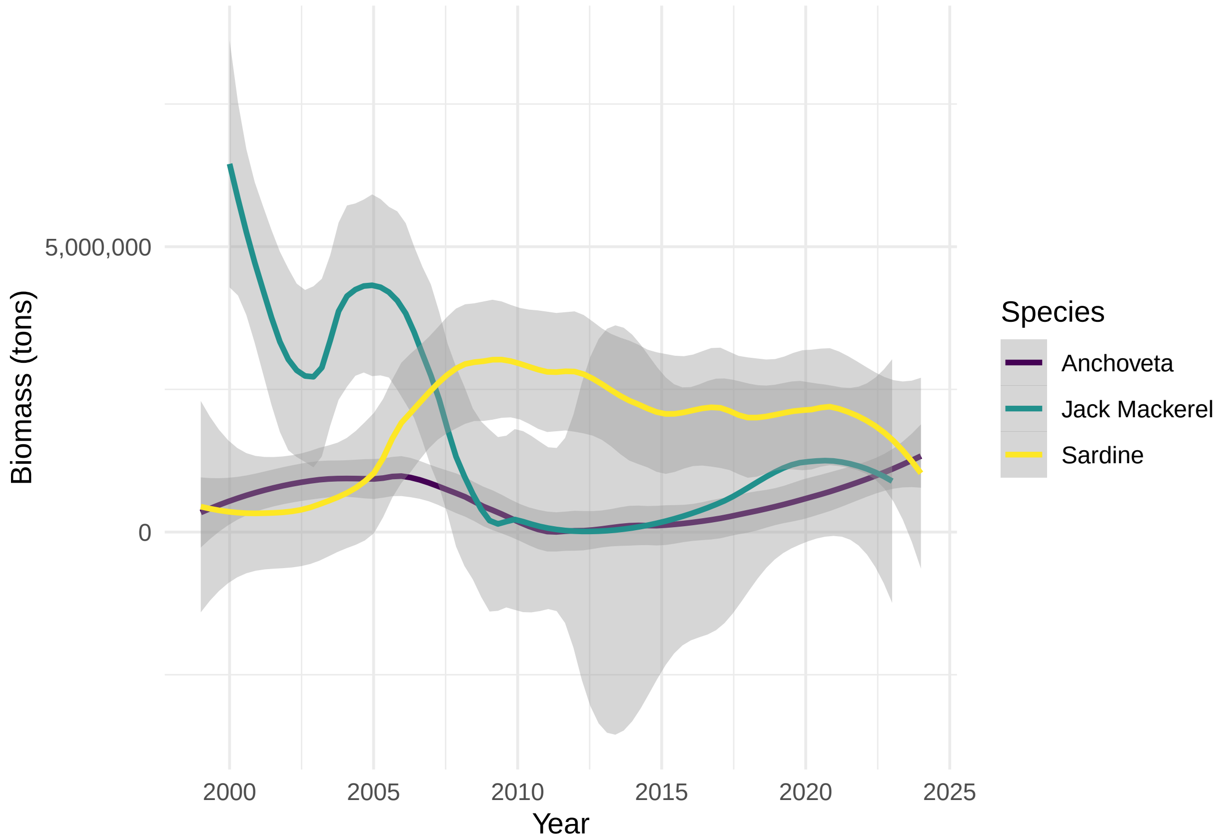

Figure 3: Estimated biomass of small pelagic species in Chile (2000–2024)

(or observed) gears:

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

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:

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

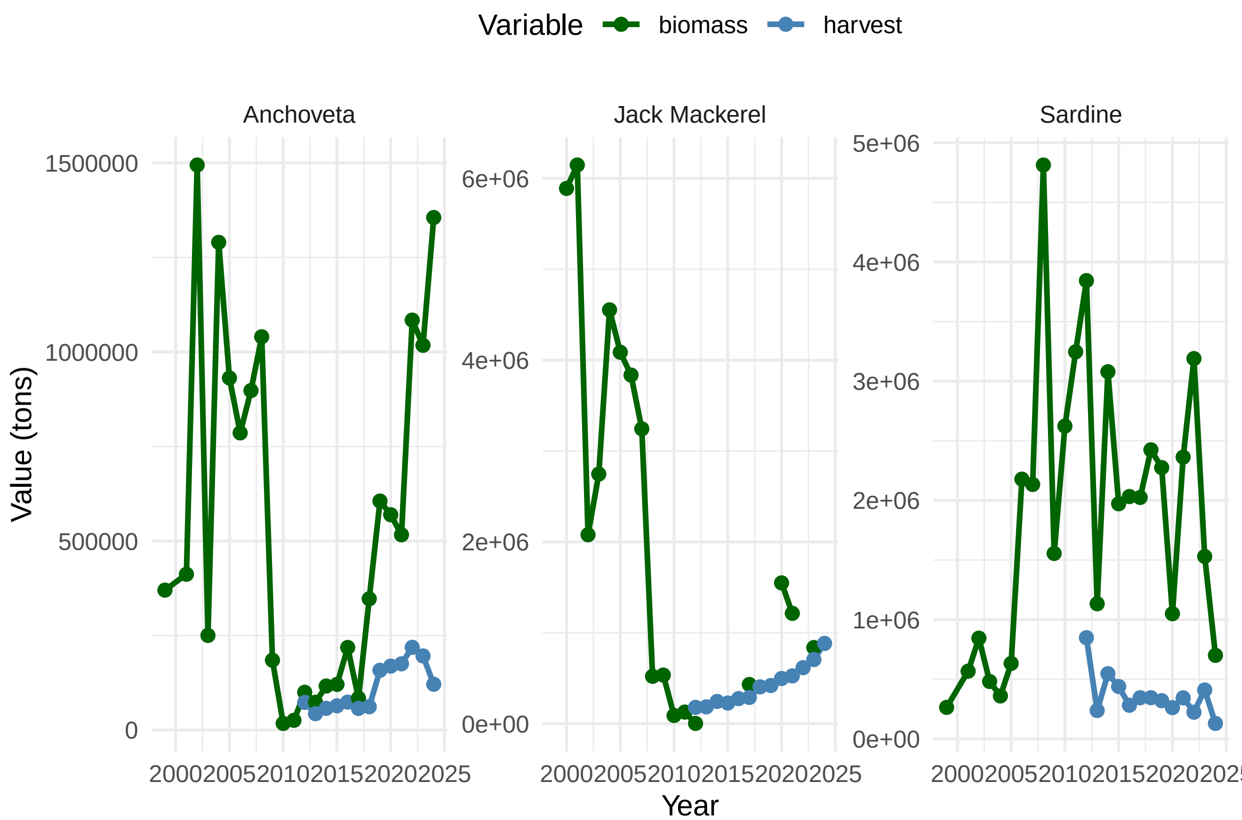

Figure 4: Estimated biomass vs harvest of small pelagic species in CentralSouth Chile (2000–2024)

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 $\mathbf{X}'_{vg} = [w; h_{vg}; x; Z_v; Env]$.

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, β_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:

$$\begin{aligned} \max_{h_{gt}, T_g} \quad & \pi_{vgt} = \sum_{\tau=t}^{T_g} \rho^{\tau} \left\{ P(h) h_{g\tau} - C_g(h_{g\tau}|w, x, Z, Env) \right\} \quad \tau = t, \dots, T_g \\ \textbf{s.t} \quad & q_{g,t+1} = \omega * \bar{q} - \sum_{t=1}^{t} h_{gt} \geq 0, \quad t = 1, \dots, T-1, \quad g = 1, \dots, G \end{aligned} \tag{7}$$

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 (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.

4 Results

NO RESULTS YET

5 Discussion

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

7 Repository

The source code for this project is available on GitHub

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