Global Fisheries: Quantifying the Externalities from Open Access

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Abstract

Tragedy of the Commons has been extensively studied in economics, yet estimating its economic cost remains challenging. I address this gap by leveraging a novel spatial dataset on global fisheries. In this paper, I quantify the externalities from open access to fishery and show how far the real-world policy is from the optimal policy. I first show that i) the average global fishery stock decreased by 35% between 1980 and 2018, ii) lack of property rights is associated with overfishing, and iii) fuel subsidies are positively correlated with high sea fishing. Then, I build a dynamic quantitative spatial model of global fisheries where firms act as atomistic with open access. After characterizing the planner's problem, I take the model to the data. I find that addressing the externalities increase the average stock by 88% and increases the net present value of global welfare by 0.11%. On the other hand, my policy counterfactual suggests that fuel subsidies decrease the global welfare. While fuel subsidies are targeted to high sea, the average stock increases at both high sea and territorial sea by 10.3% and 2.8%. These findings underscore the significance of well-targeted production and trade policies.

Keywords: International trade, natural resources, global fishery, tragedy of commons
JEL Codes: F13, F18, H23, Q22

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1 Introduction

The tragedy of the commons, arising from the failure to fully internalize the social costs in the market with open access, remains a persistent issue in economics. This issue, while long stuied, is still not fully understood, particularly in relation to combining data and theoretical frameworks. A prominent example is the global fisheries. Since 1980, the proportion of over-fished species has risen from 20% to 35%, underscoring the increasing pressure on marine resources (FAO, 2022). Fish are not only essential for marine biodiversity—contributing to half of the world's oxygen production (Breitburg et al., 2018)—but they also serve a critical role in human diets, accounting for 20% of the global animal protein intake. (FAO, 2024b).[1]

Recognizing the importance of fisheries stocks, policymakers have long sought to manage fish stocks effectively. One landmark initiative was the establishment of Exclusive Economic Zones (EEZs) under the 1982 United Nations Convention on the Law of the Sea (UNCLOS). By providing coastal nations with property rights over marine resources within 200 nautical miles of their shores, the EEZ framework aimed to foster responsible fisheries management. More recently, attention has shifted to protecting fish stocks in areas beyond national jurisdiction, commonly referred to as the high seas. The 2023 High Seas Treaty aims to protect 30% of the global ocean through the designation of marine protected areas (UN, 2023).

Despite global efforts to preserve fishery stocks, individual countries continue to promote fishing activities, particularly in the high seas, through subsidies. Fuel subsidies, for example, remain a common tool to incentivize high-seas fishing, exacerbating over-exploitation and threatening long-term sustainability (Sala et al., 2018; Sumaila et al., 2019).

This paper aims to quantify the externalities from the open acess to fishery and investigate how global fishery policies impact not only the spatial distribution of fishing activities but also the global welfare. To answer the question, we develop a dynamic spatial model of global fisheries. Then we compare two polar cases of open access, one case where atomistic firms have no property rights and the other case where social planner owns property rights over global fisheries. Moreover, we conduct counterfactual analysis where we eliminate fuel subsidies by individual countries.

Our dynamic spatial model is particularly helpful for understanding global fisheries. The standard international literature focuses on the trade flows, the flows from exporter to importer. However, the fisheries industry is distinct that there is another layer of production flows, the flows from production location to exporter. The fish stock is heterogeneous over space, and the production location is spatially differentiated. For example, tuna exported

[1] The degree of reliance on fish as a protein source varies substantially across countries, from Indonesia's 52% to Japan's 34%, China's 25%, and the USA's 7% (FAO, 2024b).

from China to USA could be produced from different location such as Pacific ocean or Atlantic ocean. Moreover, countries share common-pool resources, particularly in the high seas. For instance, any country can produce fish at Western Pacific High Sea, a key high seas area for tuna fishing, and export to global market. The global and spatial approach is particularly important since the policy instruments of affecting fishery can have effects elsewhere. A dynamic approach is necessary since, as natural resources, current exploitation affects future growth of fishery stock. As far as we know, our paper is the first attempt to study the global fishery, and broadly the tragedy of the commons problem, using the dynamic quantiative spatial model.

We begin by constructing a comprehensive dataset on global fisheries. This dataset links novel geospatial information on global fishery production and stocks with international fishery trade data. The geospatial dataset on fishery production provides detailed information on production flows, including information on which country catches specific species and at which location at the grid level. The dataset on global fishery stocks offers estimates by fishery species. Then, we combine these novel dataset with standard international trade dataset. By integrating these geospatial datasets with standard international trade data, we create what we believe to be the first comprehensive dataset in global fisheries that connects production locations to final destinations, offering a valuable resource for quantitative analysis of global fisheries.

Using this dataset, we document three empirical findings that motivate the use of a quantitative model to understand the global fisheries. First, in the past 40 years, the global fishery stocks have decreased by 35% and the number of overfished species has more than doubled, which is in line with the FAO reports. Second, there is a positive correlation between open access and overfishing. Oceans shared by multiple countries are more likely to be overfished, underscoring the importance of property rights in addressing the common-pool problem in global fisheries. Lastly, we find that the government subsidies toward fishing industry are correlated with the high seas fishing. Fuel subsidies, for example, incentivize firms to travel further for fishing, while environmental subsidies may reduce fishing in EEZ, indirectly encouraging high-seas fishing. This finding emphasizes the role of production subsidies and is informative of the substiution across production location.

Then, we develop a dynamic spatial model of global fishery to mesaure the externalities and evaluate the policy tools. Our quantitative model account for multiple exporters and importers, multiple production locations consisting of EEZ and high sea, and two industries consisting of outside good sector and fishery sector. The fishery output is consumed as nested constant elasticity of substitution (CES). At the top tier, fish are differentiated by species (eg., tuna vs. squid); at the middle tier, they are further distinguished by exporters (eg., tuna from China vs. tuna from USA); and at the bottom tier, they are further differentiated across production locations (eg., tuna from China caught in the Pacific vs. tuna from China caught in the Atlantic). Fishery stocks are modeled to evolve according to the law of motion governed by nature. The firms in the fishery sector are subject to two frictions: i) iceberg commuting costs to reach the production location ii) iceberg trade costs to ship their fish to final destination.

Notably, our model incorporates two key characteristics. First, fishing productivity is modeled as an increasing function of fishery stocks, meaning that larger stocks in the ocean lead to higher productivity in fishing activities. Second, we assume open access at all production locations. This implies that each firm acts atomistically, with individual production efforts not impacting the overall stock level, thereby disregarding the social cost of depleting future stocks. Consequently, firms solve a static optimization problem rather than a dynamic one. In turn, the only dynamic force in the model comes from the evolution of fishery stock. Since our paper does not focus on the strategic behavior of individual countries, thus no distinction is made in terms of open access between territorial seas and the high seas.

Next, we characterize the planner's problem. In contrast to firms in decentralized equilibrium, the planner fully internalizes the dynamic social costs of fishery production. The planner directly chooses the labor and consumption, and, from the first order conditions, we provide an expression that captures the dynamic social costs. There are three terms that constitute the dynamic social costs: i) the dynamic productivity cost, ii) the dynamic stock multiplier, and iii) the static stock multiplier. The dynamic productivity cost is a welfare loss from foregone productivity per unit of stock. Since the fishing productivity is an increasing function of stock, lower stock diminishes the future productivity, resulting in a dynamic productivity cost. The stock multipliers capture how many stocks are reduced in the future given a change in fishery consumption today. The static stock multiplier is the iceberg friction. In order to increase the fishery consumption by one unit today, the planner needs to catch the fishery by the amount of iceberg friction. Thus, the stock decreases by the static stock multiplier. The dynamic multiper is the change in stock next period given an unit change in stock today. From the law of motion, the dynamic multiplier is governed by the relative size of regrowth and harvest from one unit change in stock today. Then, the change in stock is multiplied by dynamic stock multipler every period. As long as fishing productivity increases in fishery stock, the dynamic social costs are positive, thus the planner allocates less labor to fishery and keeps more fishery stock than the decentralized equilibrium.[2]

[2]The first and second welfare theorem imply that the planner allocation coincide with the decentralized allocation, up to the lump-sum transfer.

We then calibrate our quantitative model by bringing the model to data. We disaggregate the world into 30 countries —comprising 25 individual countries and 5 continental groups— seleted based on the size of fishery industries and overall economies. Additionally, we divide the high seas into 16 regions as defined by FAO fishing regions, resulting in a total of 46 production locations including 30 countries and 16 highs sea regions. We classify fish species into 10 groups following the ISSCAAP classification. By bringing the model to data in 2018, we calibrate the demand shifters and productivity shifters from model inversion . We calibrate the trade costs and commuting costs by residuals from gravity regressions. Finally, we estimate the parameters governing the elasticity of substitutions from the instrument variable regression, where we use the exogeneous variations in the geographical proximity to fishery habitat to estimate the gravity equation.

We then use our calibrated model to study the baseline decentralized equilibrium and counterfactual scenarios. First, we compare the baseline decentralized equilibrium with the optimal allocation by planner. Then, we examine the effect of fuel subsidies provided by individual countries.

In the baseline decentralized scenario, the average fishery stock decreases by 32% at the steady state compared to the intial year 2018. With the fishery stock becoming scarce, the fishery productivity goes down and the fishery becomes more expensive, resulting in the decreased fishery consumption at the steady state. In contrast, with the optimal allocation by planner, the global stock increases by 27% at the steady state compared to the initial year 2018. The net present value of global welfare increases by 0.11% compared to the decenteralized equilibrium. The mechanism is that the planner allocates less workers toward fishery through the whole period than the decenteralized equilibrium. While less fish is consumed at the first few periods, the fishery consumption surpasses the level of the decenteralized equilibrium as time goes by, since the accumulated stock increases the fishery productivity and allows to consume more fishery even with less labor. Moreover, since more labor is allocated to outside good sector, the consumption outside good is larger than the decenteralized equilibrium.

In the counterfactual exercise where we eliminate the fuel subsidies, we find that the average fishery stock at the steady state increases by 3.22% compared to the steady state of the baseline. The net present value of global welfare increases by 0.004%. That is, the fuel subsidy is welfare-reducing in the global perspective. Without the fuel subsidies, as in the case of planner, the fishery consumption decreases at the first periods but increases as the stock accumlates.

Related Literature. Our research contributes to three major strands of literature in economics. First, we extend the growing body of work at the intersection of trade, spatial economics, and environment. Copeland and Taylor (2004) and Copeland et al. (2022) provide comprehensive overviews. Recent advancements, as noted by Desmet and Rossi-Hansberg (2024), have incorporated spatial dimensions into quantitative models. Numerous studies have focused on climate change and air pollution (Desmet and Rossi-Hansberg, 2015; Costinot et al., 2016; Shapiro, 2016; Gouel and Laborde, 2021; Conte et al., 2021). More recently, attention has been made to the quantitative relationship between trade and natural resources. Notable works include Farrokhi (2020) on global oil markets, Dominguez-Iino (2023) on environmental policies in South American supply chains, and Hsiao (2024) on international cooperation in the palm oil market. Our research aligns closely with Carleton et al. (2024), which examines agricultural trade and the spatial allocation of global water use. However, our focus on global fisheries presents unique context as production policies, in addition to trade policies, could affect the location of fishery. To our knowledge, we are the first paper to apply a dynamic spatial quantitative model to global fisheries, which allow us to study resource extraction problems with spatially heterogeneous costs.

Second, we build upon the literature examining optimal environmental policies in the open economies. Early theoretical works include Markusen (1975), Copeland (1996), and Hoel (1996). Recent studies by Kortum and Weisbach (2021) and Weisbach et al. (2023) analyze unilaterally-optimal carbon tax policies in two-country models. Quantitative examinations of environmental policies have been studied by Elliott et al. (2010) and Shapiro (2021). At the frontier in the literature, Farrokhi and Lashkaripour (2024) characterize optimal policy in a multi-country general equilibrium model and quantitatively assess trade and climate policy outcomes. Our contribution lies in the quantitative analysis of resource allocation dynamics.

Lastly, we contribute to the extensive literature on fisheries, natural resources, and property rights. Building on the seminar work by Hotelling (1931), natural resource extraction has been widely studied (Chichilnisky, 1994; Brander and Taylor, 1997, 1998; Copeland and Taylor, 2009; Anderson et al., 2018; Arkolakis and Walsh, 2023). Our focus on global fisheries allows for an unique opportunity to quantitatively examine the open-access externalities. While early works on fisheries were primarily theoretical (Gordon, 1954; Smith, 1969), recent empirical studies have focused on specific regions or species (Costello and Polasky, 2008; Huang and Smith, 2014; Kroodsma et al., 2018; Fenichel et al., 2020). Noack and Costello (2024) stand out for their global perspective, examining how property rights assignment affects exploitation using the historical example of Exclusive Economic Zone (EEZ) introduction. Our research distinguishes itself by linking global production data with international trade, offering a comprehensive study of global fisheries through a quantitative spatial model.

The rest of paper proceeds as follows. Section 2 describes the data sources used in the paper. Section 3 establishes empirical facts to movitate the main framework in the paper. Section 4 builds the dynamic spatial model of global fishery. Section 5 describes the planner's problem and discusses the comparison with the Laissez-faire. Section 6 calibrates the model by taking the model to data. Section 7 shows the quantitative results from baseline and counterfactual scenarios. Section 8 concludes.

2 Data

We combine geospatial global fishery data with international trade flows and other country-level standard datasets. This section summarizes our dataset. Detailed explanations of each data source and our harmonization process can be found in Appendix A.

Fishery Production. Our fishery production dataset is sourced from the research initiative at the University of British Columbia, Sea Around Us. Since 1950, the FAO has compiled annual global fisheries statistics based on surveys from individual countries.(FAO, 2024a) This FAO production dataset spans approximately 240 countries, covering 1,100 species across 26 major fishing areas. While FAO dataset is valuable, the Sea Around Us dataset enhances it by estimating production locations at a granular resolution ($0.5° \times 0.5° \approx 60km \times 60km$), intergreating FAO datasets with other national statistics, existing literature, and natural habitat conditions.(Zeller and Pauly, 2015) The major benefit of this granular dataset is that we can distinguish between EEZ and high sea, which were not possible under the broad definition of major fishing areas. Thus, we utilize granular dataset by Sea Around Us for the purpose of this paper.

Fishery Stock. Estimating fishery stock is inherently more complicated than estimating fishery production. Broadly, there are two methods of measuring fishery stock in the literature: direct estimation via research vessels, which is limited in scope and commonly conducted by developed countries, and indirect estimation from historical catch and biological data. The indirect method, while broader and longitudinal, relies on assumptions about stock growth models.

To estimate fishery stock levels, we employ the CMSY++ package provided by the Sea Around Us, which combines the indirect method with machine learning algorithms. The package takes historical catch data and biological information as inputs and estimates the time-series of fishery stock and carrying capacity. Taking the inputs as given, the model infers the stock and carrying capacity that best rationalizes the time-series of catch.[3] The machine learning algorithm, trained on direct observation data, enhances estimation accuracy. Froese et al. (2023) validate this methodology, demonstrating that stock levels for 91% of species in the training set fall within the model's 95% confidence interval in cross-validation.

Fishery Trade. Since 2019, FAO has offered a new dataset on bilateral trade flows. This dataset includes both the quantity and value of trade between 240 countries for over 1,000 species. Dealing with the domestic consumption has often been problematic in international trade literature. I overcome the difficulty by complementing the trade dataset with FAO food balance sheet dataset.[4] The food balance sheet dataset provides the information on food production, domestic consumption, exports, and imports by commodities. I harmonize the food balance sheet data with bilateral trade flows and infer the domestic consumption by each country, so that the trade patterns are consistent in two dataset.

Other Fishery Datasets. Other fishery datasets used in the paper include the fishery habitat suitability, fishery landed price, fishery subsidies, and fishery employment. The fishery habitat suitability, provided by Sea Around Us, measures the suitability of geographic conditions at the grid-level for over 1,000 species. The geographic conditions include but not limited to depth, distance from coast, and existence of coral reefs.(Zeller and Pauly, 2015) The fishery ex-vessel price, also published by Sea Around Us, measures the landed value of fishery species at the port.[5] The data is known to provide the consistent comparison of fishery ex-vessel price across countries and species over time (Sumaila et al., 2015). The country-level fishery subsidies data are collected by Sumaila et al. (2019) and available from 2002 to 2018. Lastly, fishery employment data come from OECD.

Geographic Boundaries. We classify geographic grids into EEZs (within 200 miles from the coastline) and high seas using the shapefiles of geographic boundaries. While most EEZs were declared post-1982 following the adoption of United Nations Convention on the Law of the Sea (UNCLOS), some regions remain disputed (e.g., South China Sea).[6] We use the shapefile of EEZ boundaries from the version 12 of Flanders Marine Institute (VLIZ), which is one of the most commonly accepted boundaries in the literature.[7] In order to classify high

[3]The Scaffer growth model from CMSY++ is consistent with the growth model used in this paper.

[4]FAO food balance sheet dataset was surveyed to understand the current status of food consumption and security.

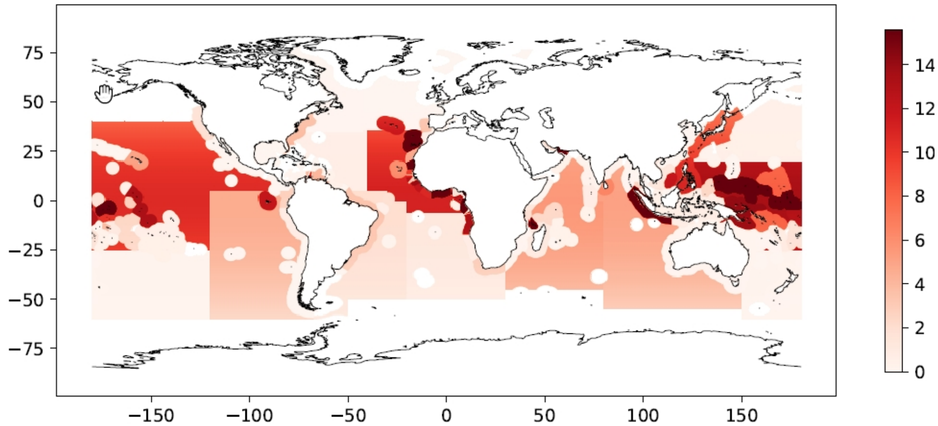
[5]The dataset is constructed by compiling various data sources including FAO, OECD, the European Commission, etc.

[6]One example of a disputed zone is the South China Sea.

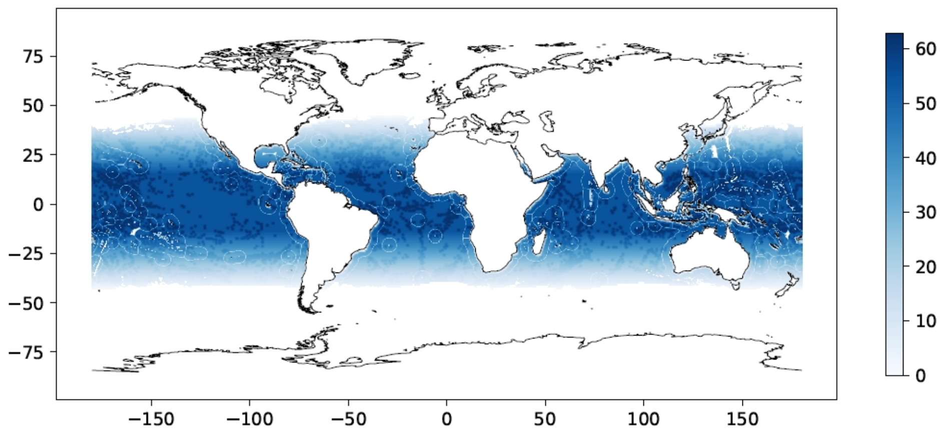
[7]The shapefile of EEZ boundaries can be downloaded at https://www.vliz.be/en/imis?dasid=8394&doiid=911

Figure 1: Global Production and Stock of Big Eye Tuna (2018)

(a) Production of Big Eye Tuna (2018, in tonnes)



(b) Stock of Big Eye Tuna (2018, in tonnes)



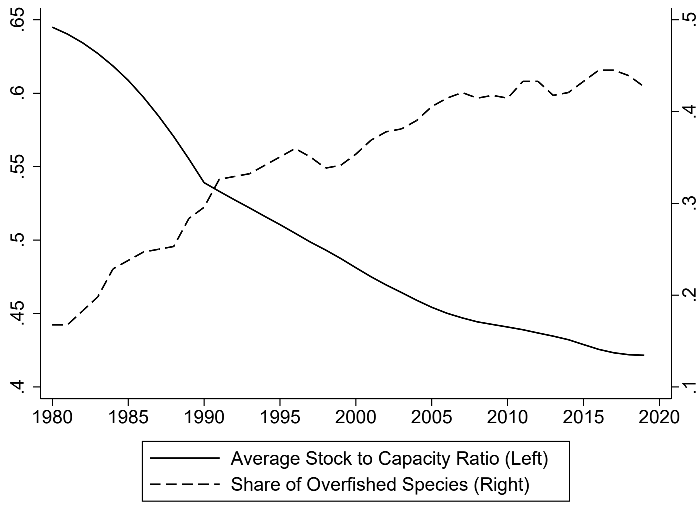
Notes: Panel (a) shows the spatial distribution for global production of Big Eye Tuna in 2018. Panel (b) shows the spatial distribution for global stock of Big Eye Tuna in 2018.

seas, we use the shapefile from FAO major fishing area boundaries.[8] FAO major fishing area disaggregates the entire ocean into 26 major fishing areas. By overlaying the shapefile of EEZ with the shapefile of FAO major fishing areas, we exclude the EEZ portion from major fishing areas and define them as high seas.

Other Country-level Datasets. We use data on GDP and total employment from World Economic Outlook and UN-ILO.

[8]The shapefile of FAO major fishing area boundaries can be downloaded at https://www.fao.org/fishery/en/area/search

Figure 2: Global Fishery Stock over Time (1980-2018)



Notes: Species and grids are classified into 10 species and 46 regions, which are the units for the quantitative exercise. A species by region is defined to be overfished if the stock is below 40% of carrying capacity, following the criteria from FAO(2020).

3 Empirical Patterns

In this section, I document three empirical patterns about global fishery that motivates the use of our quantitative model. We first show the decline in fishery stock between 1980 and 2020. Second, we find that the lack of property rights is associated with overfishing. Third, we document that the fishery subsidies are correlated with the fishing at high seas, which is informative about the substitution across production locations.

Pattern 1. Global Fishery Stock Decreases

Figure 2 shows the trend in global fishery stock between 1980 and 2020. I first classify the species and the regions into 10 species and 46 regions used in the quantitative analysis. The list of species and regions are described in the Appendix Section A. Then, I compute the average stock to capacity ratio across all units (10 species and 46 regions). During these periods, the average stock to capacity ratio has decreased from 65% to 42%, implying that if all units had same carrying capacity, the stock would have decreased by 35%. I also calculate the share of overfished species following the metric from FAO. FAO defines the species as overfished if the stock level falls below the 40% of carrying capacity. I show that the share of overfished species increased from 17% to 43% during these period. These figures are in line with the statistics from FAO in 2020, from 20% to 35%, implying that our data or analysis units are comparable to what FAO used for their calculation.

Table 1: Open Access and Overfishing (2018)

	$\mathbb{1}\{Y_{k,s} > MSY_{k,s}\}$		$\mathbb{1}\{Y_{k,s} > MSY_{k,s}\}$	
	(1)	(2)	(3)	(4)
$\log N_{k,s}$	0.050***	0.125***		
	(0.000)	(0.000)		
inv $\text{HHI}_{k,s}$			0.011***	0.026***
			(0.000)	(0.000)
Species FE	Y	Y	Y	Y
Grid FE	N	Y	N	Y
N	4,268,885	4,265,317	4,268,885	4,265,317
R^2	0.131	0.300	0.124	0.281

Notes: The regression uses the full granular sample in 2018, which includes over 2,000 species and 140,000 grids. $N_{k,s}$ is the number of fishing countries at grid k for species s. inv $\text{HHI}_{k,s}$ is the inverse of Herfindahl-Hirschman Index, which is computed by adding the square of the output share for each country at grid k for species s and taking its inverse. Both measures capture the concentration of output across countries at grid k for species s.

Pattern 2. Lack of Property Right is associated with Overfishing

We next examine how the lack of property right is associated with overfishing. In the quantitative exercise, we will take two polar cases where a) atomistic firms don't have property rights and solve static problem and b) social planner has globally exclusive property rights and solve dynamic problem internalizing the dynamic social cost. To motivate the relationship between property rights and overfishing, we estimate the equation 1. As proxy for property rights at the grid-level, we use the following two measures, which are the number of fishing countries and inverse of Herfindahl–Hirschman index (HHI) to measure the concentration of production across countries. For example, if the grid is located at the territorial sea, then the number of fishing countries and its inverse of HHI would not exceed one. However, if the grid is located at the high sea or at the EEZ where multiple countries can fish, then the number of fishing countries or HHI could exceed one. For the measure for overfishing, we define as overfishing if total harvest by all countries in the region for species exceed the maximum regrowth at the grid (MSY). Table 1 shows that, regardless of the measure, lack of property rights is are positively correlated with overfishing.

$$\mathbb{1}\{Y_{k,s} > MSY_{k,s}\} = \beta_0 + \beta_1 \log N_{k,s} + \delta_s + \delta_k + \varepsilon_{k,s} \tag{1}$$

where $Y_{k,s}$ is production, $MSY_{k,s}$ is Maximum Sustainable Yield (maximum regrowth at given geography), and $N_{k,s}$ is number of fishing countries

Table 2: Subsidy and High Sea Production (2002-2018)

	All Countries			Model Regions		
	All (1)	Fuel (2)	Management (3)	All (1)	Fuel (2)	Management (3)
$\Delta \ln S_{i,t}$	0.237**	0.165**	0.239**	0.323*	0.111**	0.252**
	(0.097)	(0.061)	(0.060)	(0.163)	(0.042)	(0.101)
Other Controls	Y	Y	Y	Y	Y	Y
R^2	0.119	0.301	0.189	0.176	0.268	0.247
N	108	43	108	30	30	30

Notes: The regression is weighted by log output in 2002, which is the initial year with available data. "All Countries" sample include all countries available from data, while "Model Countries" sample restricts the sample to 30 regions used in the quantiative model. Each column refers to the type of subsidies. Other controls include log differences of population and gdp per capita.

Pattern 3. Subsidies are associated with High Sea Production

We investigate the impact of fishery subsidies on the production location. Fishery is a highly subsidized industry and the subsidy accounts for 10% of global fishery output (Sala et al., 2018). According to Sumaila et al. (2019), major types of subsidies include fuel subsidies and management subsidies. We explore the relationship between subsidies and production location. Recently, WTO has made an agreement to prohibit subsidies that promote fishing, such as fuel subsidies (WTO, 2023). We consider the following equation (2):

$$\Delta \ln(Y_{i,t}^{HS}/Y_{i,t}^{nonHS}) = \beta_0 + \beta_1 \Delta \ln S_{i,t} + \Delta X_{i,t} + \varepsilon_{i,t} \tag{2}$$

where $Y_{i,t}^{HS}$ and $Y_{i,t}^{nonHS}$ are the high sea and non-high sea production, $S_{i,t}$ is the fishery subsidy, $X_{i,t}$ is other controls, and $\varepsilon_{i,t}$ denotes the error term for country i at time t. The operator Δ refers to the change between year 2002 and year 2018. The coefficient β_1 captures the effect of fishery subsidies on the relative production at the high sea.

There could be confounding factors which affect the incentives to provide subsidies and also the production locations. For example, if territorial sea were fully exploited due to higher demand for fishery, governments could have larger incentives to provide subsidies which both affect the amount of subsidies and the relative production at the high sea. To deal with the endogeneity issue, we control for population growth and gdp growth.

Table 2 shows the regression results for both all countries sample and our 30 countries sample used in the quantitative model. Each column refers to different types of subsidies. We find that fishery subsidies are positively correlated with high sea production across all subsidies or sub-types of subsidies such as fuel subsidies and management subsidies. The results are robust across the samples.

While fuel subsidies and management subsidies are positively correlated with high-sea production, the underlying mechanism could be different. Since the input share is disproportionately larger in the long-haul travel, fuel subsidies disproportionately lower the fishery prices at the high sea. On the other hand, the management subsidies, which are provided to manage the fishery stock at the territorial sea, disproportionately increase the fishery prices at the territorial sea. While the underlying mechanism is different, both subsidies direct toward disproportionately larger high sea production relative to non-high sea production.

Since the provision of fuel subsidies has been a persistent issue among policy makers (Sala et al., 2018; WTO, 2023), we will examine the impact of fuel subsidies in the quantitative exercise. Moreover, the regression is informative about the Relasticity of substitution across production location. The idea is that, if the fishery goods are more substitutable across locations, the effect of subsidies on relative production would be larger. In Section 6, we will simulate the model and estimate the equation (2) using the simulated to discipline the elasticity of substitution parameter.

4 A Model of Global Fishery

In this section, we develop a dynamic spatial model of global fishery, where a home country harvests from fishing region (production location) and exports to foreign countries. We will compare two polar cases of open access. In the decentralized equilibrium, we assume atomistic firms don't have property rights and have open access to sea. In the planner's problem, we assume a global social planner has absolute property rights over all part of the sea. While the atomistic firms solve static problem, the social planner solves dynamic problem fully internalizing the social cost.[9] The model enables us to quantify the changes in fishery stock and welfare resulting from the change in frictions (commuting costs and trade costs) over periods of time.

4.1 Environment

Geography, Time, and Markets The economy consists of I countries indexed by i or j. There are H high sea locations, which are the sea locations that are beyond the jurisdiction of any countries. Since I and H are disjoint by definition, there are total $K = I + H$ production locations, indexed by k. Time is discrete and indexed by t. There are two sectors

[9] The real-world can be imagined as in-between of two polar cases, where individual countries internalize some dynamic costs within their territorial sea or EEZ.

in the economy: fishery, f, and outside good, o. Outside good is freely traded and serves as numeraire. Within fishery, there exist S species, which are indexed by s. The frictions in the economy are iceberg commuting costs and iceberg trade costs. The iceberg commuting costs are frictions that the exporter i face when it produces fishery at the production location k and bring back to its port. The iceberg trade costs are frictions that the exporter i face to ship fishery to importer j. The economy is endowed with the initial fishery stock $x_{k,s0}$, distinguished by species and production location, and total labor force $\tilde{L}_i$ by each country. All markets are perfectly competitive. For the expositional purpose, we suppress the subscript f for fishery sector.

Preferences. Consumers in country j have quasi-linear preferences between outside good and fishery bundle. The aggregate welfare of consumers in country j follows

$$\max_{C^o_{j,t}, C_{j,t}} \quad U_{j,t} = C^o_{j,t} + b_j \ln C_{j,t} \quad \text{s.t.} \quad C^o_{j,t} + P_{j,t} C_{j,t} = E_{j,t} \tag{3}$$

where $U_{j,t}$ is the aggregate household welfare, $C^o_{j,t}$ is the consumption of outside good, $C_{j,t}$ is the consumption of fishery bundle, b_j is the demand shifter towad fishery bundle, $P_{j,t}$ is the price index for fishery bundle, and $E_{j,t}$ is the household income. Note that the price of outside good is normalized to one, since outside good serves as numeraire.

The fishery bundle is comprised of three tiers of CES aggreators. In the upper tier, varieties of fishery goods are differentiated by species s. Consumers in country j combine varieties of every species s according to CES preferences, for example tuna vs. squid, with elasticity of substitution ν and demand shifters b_s

$$C_{j,t} = \left(\sum_{s \in S} b_s C_{j,st}^{\frac{\nu-1}{\nu}} \right)^{\frac{\nu}{\nu-1}} \tag{4}$$

In the middle tier, varieties of species s are differentiated by origin country i. Consumers in country j consuming species s combine varieties of every origin country i according to CES preferences, for example tuna exported by China vs. tuna exported by Chile, with elasticity of substitution η and demand shifters b_{ij}

$$C_{j,st} = \left(\sum_{i \in I} b_{ij} C_{ij,st}^{\frac{\eta-1}{\eta}} \right)^{\frac{\eta}{\eta-1}} \tag{5}$$

Finally, in the lower tier, varieites of species s from origin country i are differentiated by production location k. Consumers in country j consuming species s exported by i combine varieties of every production location k according to CES preferences, for example tuna exported by China caught from Pacific ocean vs. tuna exported by China caught from Atlantic ocean, with elasticity of substitution κ and demand shifters b_{sk}

$$C_{ij,st} = \left(\sum_{k \in K} b_{k,s} C_{ijk,st}^{\frac{\kappa-1}{\kappa}} \right)^{\frac{\kappa}{\kappa-1}} \tag{6}$$

Due to the property of the quasi-linear demand, from (3), the aggregate household allocates fixed amount of their expenditure

$$X_{j,t} = P_{j,t} C_{j,t} = b_{j,t}$$

The expenditure share for upper tier CES, $\pi_{j,st}$, and the consumer price index for aggregate fishery bundle, $P_{j,t}$, are given by

$$\pi_{j,st} = \frac{b_s P_{j,st}^{1-\nu}}{P_{j,t}^{1-\nu}}, \quad P_{j,t} = \left[\sum_{s \in S} b_s P_{j,st}^{1-\nu} \right]^{\frac{1}{1-\nu}} \tag{7}$$

The expenditure share for middle tier CES, $\pi_{ij,st}$, and the consumer price index for fishery species s, $P_{j,st}$, are given by

$$\pi_{ij,st} = \frac{b_{ij} P_{ij,st}^{1-\eta}}{P_{j,st}^{1-\eta}}, \quad P_{j,st} = \left[\sum_{i \in I} b_{ij} P_{ij,st}^{1-\eta} \right]^{\frac{1}{1-\eta}} \tag{8}$$

The expenditure share for lower tier CES, $\pi_{ijk,st}$, and the consumer price index for fishery species s exported by i, $P_{ij,st}$, are given by

$$\pi_{ijk,st} = \frac{b_{k,s} P_{ijk,st}^{1-\kappa}}{P_{ij,st}^{1-\kappa}}, \quad P_{ij,st} = \left[\sum_{k \in K} b_{k,s} P_{ijk,st}^{1-\kappa} \right]^{\frac{1}{1-\kappa}} \tag{9}$$

Nature. The law of motion for fishery stock closely follows the biology literature on population dynamics. Following Schaefer (1954), the growth function of fish follows a logistics function. The fishery stock $x_{k,st}$ at location k for species s at time t evolves according to

$$\begin{aligned} x_{k,st} - x_{k,st-1} &= G(x_{k,st}) - H(x_{k,st}) \\ &= \gamma_{k,s} x_{k,st-1} \left(1 - \frac{x_{k,st-1}}{M_{k,s}}\right) - \sum_{i \in I} \sum_{j \in I} d_{ij,s} \tau_{ik,s} Q_{ijk,st} \end{aligned} \tag{10}$$

where $G(x_{k,st})$ is a logistic growth function of fishery stock and $H(x_{k,st})$ is a total harvest at location k for species s, $\gamma_{k,s}$ is the intrinsic growth rate, $M_{k,s}$ is the carrying capacity, and $Q_{ijk,st}$ is the export quantity by country i to country j caught at location k for species s at time t.

The first and second partial derivatives of logistic growth function are

$$G'(x_{k,st}) = \gamma_{k,s}\left(1 - 2\frac{x_{k,st-1}}{M_{k,s}}\right), \quad G''(x_{k,st}) < 0$$

The first partial derivative of fishery growth is a function of $x_{k,st}$ and positive when $\frac{x_{k,st}}{M_{k,s}} < \frac{1}{2}$ and negative $\frac{x_{k,st}}{M_{k,s}} > \frac{1}{2}$. The second partial derivative is negative. Thus, the fishery growth is invert U-shaped and takes its maximum at $\frac{x_{k,st}}{M_{k,s}} = \frac{1}{2}$. The intuition is that when the stock level is too low relative to the carrying capacity, reproduction becomes difficult because it's harder for fish to find mates. On the other hand, when the stock level is too high relative to carrying capacity, reproduction is also hindered due to overcrowding.[10]

Fishery Technology. For every varieties of fishery, there is an atomstic representative firm which chooses its quantity. Given fish stock to capacity ratio $x_{k,st-1}/M_{k,s}$, the firm chooses its labor input $L_{ijk,st}$ to maximize its profit according to

$$Q_{ijk,st} = \frac{z_i\left(x_{k,st-1}/M_{k,s}\right)^{\xi}}{d_{ij,s}\tau_{ik,s}} L_{ijk,st} \tag{11}$$

where $Q_{ijk,st}$ is the quantity fishery produced, $d_{ij,s}$ is the iceberg trade cost, $\tau_{ik,s}$ is the iceberg commuting cost, z_i is the country-specific productivity shifter, $x_{k,st-1}/M_{k,s}$ is the fish stock to capacity ratio, and ξ is the stock elasticity of output.

There are a few things to mention regarding the fishery technology. First, the firm is subject to the iceberg trade cost and iceberg commuting cost. In order to sell one unit of fish, the firm is subject to the iceberg trade cost $d_{ij,s}$, implying that it needs to send $d_{ij,s}$ units of fish. In order to send $d_{ij,s}$ units of fish, the firm needs to catch $d_{ij,s}\tau_{ik,s}$ units of fish from the production location. Second, the output is an increasing function of fish stock to capacity ratio, reflecting the notion that it is easier to harvest when there are more stocks. One percent increase in stock to capacity ratio generates ξ percents increase in output.

It is important to highlight the assumption that the firms are atomistic. Under open access, since any firm can enter the market and begin production in the next period, an

[10]This is closely related with the notion from biology literature that $\frac{x_{k,st}}{M_{k,s}} = \frac{1}{2}$ is called "Maximum Sustainability Yield (MSY)", which is the maximum yield could be achieved at the steady state where harvest equals growth.

individual firm does not account for the impact of its production on the total stock in the following period. Thus, the firm solves a static problem rather than a dynamic one. As a result, an externality emerges, where the cost of dynamic stock loss, resulting in lower fishery productivity in future, is overlooked in the decentralized equilibrium. The only dynamic factor in this equilibrium is the evolution of fishery stock.

Outside Good Technology and Labor Mobility. There exists a representative firm producing outside good, who chooses the employment to outside good L_i^o to maximize its profits according to

$$Q_{i,t}^o = z_i^o L_{i,t}^o \tag{12}$$

where z_i^o is the productivity shifter, w_i^o is the wage for outside good worker. Note that the price of outside good is normalized to one.

I also assume a perfect mobility across sectors for workers. From the first order condition, we get that the wage that applies to all workers is exogenously determined as

$$w_i^o = w_i = z_i^o \tag{13}$$

We further assume that the outside sector is large enough that it is produced at every country.

4.2 Market Clearing.

For the fishery good, the origin country $i's$ exports to destination j for species s produced at location k equals

$$Y_{ijk,st} = \pi_{ijk,st}\pi_{ij,st}\pi_{j,st}X_{j,t} \tag{14}$$

where $X_{j,t}$ is the total expenditure on fishery in destination j

$$X_{j,t} = b_j \tag{15}$$

For the outside good, since it is homogeneous and freely traded, the market clears globally such that

$$\sum_{i \in I} Y_{i,t}^o = \sum_{j \in I} X_{j,t}^o \tag{16}$$

Labor market clearing requires that payments to labor equal output:

$$w_{i,t}L_{ijk,st} = Y_{ijk,st}, \quad w_{i,t}^o L_{i,t}^o = Y_{i,t}^o \tag{17}$$

Lastly, the sum of factor rewards are identical to the sum of expenditures

$$\sum_{j\in I}\sum_{s\in S}\sum_{k\in K} w_{i,t}L_{ijk,st} + w^o_{i,t}L^o_{i,t} = X_{i,t} + X^o_{i,t} \tag{18}$$

4.3 Competitive Equilibrium.

Definition. [Competitive equilibrium] Given taste and geography, initial vector of fish stock $\{x_{k,s0}\}$ and labor endowment $\{\bar{L}_i\}$, a **competitive equilibrium** is a path of consumption $\left\{C_{ijk,st}, C^o_{i,t}\right\}$, output $\left\{Q_{ijk,st}, Q^o_{i,t}\right\}$, labor allocation $\left\{L_{ijk,st}, L^o_{i,t}\right\}$, prices $\{p_{ijk,st}\}$, wages $\left\{w_{i,t}, w^o_{i,t}\right\}$, and fish stock $\{x_{k,st}\}$, such that household maximizes its utility according to (3), firms maximize their profits according to (11) and (12), stock of fish evolves acccording to (10), markets clear according to (14) and (16) and (17), and the balance of budget holds according to (18)

Definition. [Steady-state equilibrium] A **steady state equilibrium** is the allocation that satisfies the conditions of competitive equilibrium in addition to

$$\gamma_{k,s}x_{k,st}(1-\frac{x_{k,st}}{M_{k,s}}) = \sum_{i\in I}\sum_{j\in I} d_{ij,s}\tau_{ik,s}Q_{ijk,st} \tag{19}$$

4.4 Discussion.

Rearranging FOCs from households and firms, we can characterize the decentralized equilibrium as following.

$$\underbrace{\frac{\partial U_{j,st}}{\partial C_{ijk,st}}}_{\text{MU of fishery consumption}} = \underbrace{\frac{\partial U_{j,st}}{\partial C^o_{i,t}}\left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}}/\frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}}\right)}_{\text{MC of fishery consumption}} \tag{20}$$

From households FOC, the LHS is $\frac{\partial U_{j,st}}{\partial C_{ijk,st}} = p_{ijk,st}$. The RHS is $\frac{\partial W_t}{\partial C^o_{i,t}}\left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}}/\frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}}\right) = z^o_i/\left(w_i/z_i\right) = z_i$. The last inequality holds given the free labor mobility (13).

Thus, in the decentralized equilibrium, the relative price between fishery and outside good adjusts to equalize the marginal utility from fishery consumption to the marginal cost of fishery consumption. We come back to (20) in the next section.

5 Planner's Problem

This section characterizes the planner's problem, where the planner has exclusive property rights over global fishery stock. We provide the expression comparing the planner's problem with the decentralized equilibrium.

5.1 Planner's FOC

Given the GE equations (3) $\sim$ (17), define the global welfare W_t as

$$W_t = \sum_{i \in I} \phi_i U_{i,t}$$

where ϕ_i is the Pareto weights.

The social planner chooses the labor allocation and consumption to maximize the discounted present value of global welfare, such that

$$\begin{aligned}
\max_{C_{ijk,st}, C^o_{ij,t}, L_{ijk,st}, L^o_{ij,t}, x_{k,st}} \sum_t \beta^t W_t \quad \text{s.t.} \quad & [\lambda_{k,st}] \quad x_{k,st-1} + G_{k,st} = H_{k,st} + x_{k,st} \\
& [\mu_{i,t}] \quad \bar{L}_i = \sum_{j \in I} \sum_{s \in S} \sum_{k \in K} L_{ijk,st} + L^o_{i,t} \\
& [\theta_{ijk,st}] \quad Q_{ijk,st} = C_{ijk,st} \\
& [\alpha_t] \quad \sum_i Q^o_{i,t} = \sum_i C^o_{i,t}
\end{aligned}$$

Provided that the interior solution exists, the planner sets up the following Lagrangian and obtains the following first order conditions.

$$\begin{aligned}
\mathcal{L} = \sum_t \beta^t \Bigg[& W_t + \sum_{k \in K} \sum_{s \in S} \lambda_{k,st} \left(G_{k,st} - H_{k,st} - x_{k,st+1} \right) + \sum_{i \in I} \mu_{i,t} \left(\bar{L}_i - \sum_{s \in S} \sum_{k \in K} \sum_{j \in I} L_{ijk,st} - \sum_{j \in I} L^o_{ij,t} \right) \\
& + \sum_{i \in I} \sum_{s \in S} \sum_{k \in K} \sum_{j \in I} \theta_{ijk,st} \left(Q_{ijk,st} - C_{ijk,st} \right) + \sum_{i \in I} \sum_{j \in I} \alpha_{ij,t} \left(Q^o_{ij,t} - C^o_{ij,t} \right) \Bigg]
\end{aligned}$$

$$[C_{ijk,st}]: \qquad \theta_{ijk,st} = \frac{\partial W_t}{\partial C_{ijk,st}} \tag{21}$$

$$[C^o_{ij,t}]: \qquad \alpha_{ij,t} = \frac{\partial W_t}{\partial C^o_{ij,t}} \tag{22}$$

$$[L_{ijk,st}]: \qquad \theta_{ijk,st} = \left(\mu_{it} + \lambda_{k,st}\frac{\partial H_{k,st}}{\partial L_{ijk,st}}\right) / \left(\frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}}\right) \tag{23}$$

$$[L^o_{ij,t}]: \qquad \alpha_{ij,t} = \mu_{it} / \left(\frac{\partial Q^o_{ij,t}}{\partial L^o_{ij,t}}\right) \tag{24}$$

$$[x_{k,st+1}]: \qquad \lambda_{k,st} = \beta\left[\lambda_{k,st+1}\left(\frac{\partial G_{k,st+1}}{\partial x_{k,st+1}} - \frac{\partial H_{k,st+1}}{\partial x_{k,st+1}}\right) + \sum_{i\in I}\sum_{j\in J}\theta_{ijk,st+1}\frac{\partial Q_{ijk,st+1}}{\partial x_{k,st+1}}\right] \tag{25}$$

$$[\mu_{i,t}]: \qquad \bar{L}_i = \sum_{s\in S}\sum_{k\in K}\sum_{j\in I} L_{ijk,st} + \sum_{j\in I} L^o_{ij,t} \tag{26}$$

$$[\theta_{i,st}]: \qquad Q_{ijk,st} = C_{ijk,st} \tag{27}$$

$$[\alpha_t]: \qquad Q^o_{ij,t} = C^o_{ij,t} \tag{28}$$

$$[\lambda_{k,st}]: \qquad G_{k,st} = H_{k,st} + x_{k,st+1} \tag{29}$$

5.2 Comparison between Planner and Decentralized Equilibrium

Rearranging Planner's FOCs at the steady state,

$$\underbrace{\frac{\partial W_t}{\partial C_{ijk,st}}}_{\text{MU of fishery consumption}} = \underbrace{\underbrace{\frac{\partial W_t}{\partial C^o_{i,t}}\left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}} / \frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}}\right)}_{\text{static MC}} + \underbrace{\frac{\beta\Omega_{k,st}}{1-\beta\Theta_{k,st}}\frac{\partial H_{k,st}}{\partial Q_{ijk,st}}}_{\text{dynamic MC}}}_{\text{MC of fishery consumption}} \tag{30}$$

For each variety of fishery $C_{ijk,st}$, the planner chooses how much to produce considering its marginal utility and marginal cost. The left-hand side of (30) is the marginal utility of additional fishery $C_{ijk,st}$. The right-hand side of (30) is the marginal cost of fishery consumption, which consists of two terms, the static marginal cost and the dynamic marginal cost. The static marginal cost, the first term, refers to the foregone welfare from outside good at period t that could have been achieved if the additional fishery good were not produced.

The dynamic marginal cost, the second term, is the foregone welfare from decrease in fishery stock. The fishery stock affects the welfare through the fishery productivity, since the fishery productivity is an increasing function of fishery stock. $\Omega_{k,st} := \frac{\partial W_{t+1}}{\partial x_{k,st}}$ is the dynamic productivity cost per stock, which is the change in welfare per unit of stock, via productivity channel. The amount of fishery stock decrease depends on static stock multiplier $\left(\frac{\partial H_{k,st}}{\partial Q_{ijk,st}}\right)$ and dynamic stock multiplier $\left(\Theta_{k,st} := \frac{\partial x_{k,st+1}}{\partial x_{k,st}} = 1 + \frac{\partial G_{k,st+1}}{\partial x_{k,st}} - \frac{\partial H_{k,st+1}}{\partial x_{k,st}}\right)$. For the planner, the static stock multiplier is the iceberg frictions. One unit of $C_{ijk,st}$ requires harvesting additional $\frac{\partial H_{k,st}}{\partial Q_{ijk,st}} = d_{ij,s}\tau_{ik,s}$ units of fishery from the ocean, due to the iceberg frictions.

The dynamic stock multiplier $\Theta_{k,st}$ captures the change in the number of stock next period, given a decrease in fishery stock. Since regrowth and harvest of fish is a function of stock, the number of stock next period decreases by $\Theta_{k,st}$ units, given a unit decrease in fishery stock today. Again, through the law of motion, it affects the stock by $\Theta^2_{k,st}$ units in the period after. Up to the discount factor, after taking the infinite sum of changes in stock over time, the stock is affected by $\frac{1}{1-\beta\Theta_{k,st}}$ units at the steady state.

The output elasticity of stock parameter ξ governs the responsiveness of output with respect to stock change. On the dynamic marginal cost, it has two effects. First, it increases $\Omega_{k,st}$. Second, it decreases $\Theta_{k,st}$ since $\frac{\partial H_{k,st+1}}{\partial x_{k,st}}$ gets larger. The aggregate effect on dynamic marginal cost depends on the relative size of two effects. On the other hand, the growth rate parameter $\gamma_{k,s}$ affects $\frac{\partial G_{k,st+1}}{\partial x_{k,st}}$. Note that the partial derivative $\frac{\partial G_{k,st+1}}{\partial x_{k,st}} = \gamma_{k,s}\left(1 - 2\frac{x_{k,st-1}}{M_{k,s}}\right)$. Its sign depends on the stock to capacity ratio. If the stock to capacity ratio is greater than 1/2, then $\frac{\partial G_{k,st+1}}{\partial x_{k,st}} < 0$, meaning that larger $\gamma_{k,s}$ decreases $\Theta_{k,st}$ and decreases dynamic marginal cost. If the stock to capacity ratio is smaller than 1/2, then $\frac{\partial G_{k,st+1}}{\partial x_{k,st}} > 0$, meaning that larger $\gamma_{k,s}$ increases $\Theta_{k,st}$ and increases dynamic marginal cost.

Unlike the planner who considers the static stock multipler as $\frac{\partial H_{k,st}}{\partial Q_{ijk,st}} = d_{ij,s}\tau_{ik,s}$, a firm in the decentralized equilibrium perceives the static stock multiplier as $\frac{\partial H_{k,st}}{\partial Q_{ijk,st}} = 0$. This is because each firm is considered as atomistic under open access without the property rights.

$$
\begin{aligned}
\frac{\partial W_t}{\partial C_{ijk,st}} &= \frac{\partial W_t}{\partial C^o_{i,t}}\left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}} / \frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}}\right) \\
\Leftrightarrow \frac{\partial U_{j,t}}{\partial C_{ijk,st}} &= \frac{\partial U_{j,t}}{\partial C^o_{i,t}}\left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}} / \frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}}\right)
\end{aligned} \tag{31}
$$

Rearranging (30) with $\frac{\partial H_{k,st}}{\partial Q_{ijk,st}} = 0$, we have (31) which coincides with (20) from decentralized equilibrium. That is, atomistic firms only consider static marginal cost, while planner considers both static and dynamic marginal cost. Since the marginal utility of fishery consumption is decreasing in the level of consumption, the fishery consumption by the planner is no larger than the fishery consumption in the decentralized equlibrium. One case where the fishery consumption equalizes in two cases is when $\xi = 0$, meaning that there is no productivity gain from larger stock. If we eliminate the productivity channel, we don't have dynamic cost, meaning that the loss of productivity is the source of externality.

Lastly, I point out the sufficient condition for the dynamic stock multiplier to converge.

Lemma. *At the steady state, sufficient conditions for $\theta_{k,st}$ to converge are i) $\xi \geq 1$ or ii) $0 < \xi < 1$ and $\gamma_{k,s} < \frac{1}{1-\xi}\left(\frac{1}{\beta} - 1\right)$*

Proof. Please take a look at the Appendix C.1.

The intuition is as following. When $\xi \geq 1$, given an increase in stock, the harvest gets larger, which suppresses $\Theta_{k,st}$ so that it does not explode. When $0 < \xi < 1$, since the harvest does not suppress $\Theta_{k,st}$ as much as in the previous case, we need smaller $\gamma_{k,s}$ so that the regrowth does not respond too rapidly against the increase in stock, which is the condition $\gamma_{k,s} < \frac{1}{1-\xi}\left(\frac{1}{\beta} - 1\right)$. The right-hand side is an increasing function of ξ and gets closer to zero as ξ approaches to zero. $\square$

5.3 Extension: Dual Approach

In this subsection, we extend the decentralized equilibrium, where policy instruments, either subsidies or taxes, are implemented by government.

The policy instruments $t_{ijk,st}$ changes the marginal cost of production by $1 + t_{ijk,st}$, so that the price becomes

$$p_{ijk,st} = (1 + t_{ijk,st}) \frac{d_{ij,s}\tau_{ik,s}}{z_i \left(x_{k,st-1}/M_{k,s}\right)^{\xi}} w_{i,t} \tag{32}$$

The collected taxes (or subsidies) are redistributed to (or funded by) households as a lump-sum transfer. In turn, the balance of budget condition for households in equation (18) now becomes

$$\sum_{j\in I}\sum_{s\in S}\sum_{k\in K} w_{it}L_{ijskt} + w^o_{it}L^o_{it} + \sum_{j}\sum_{s}\sum_{k}\left[1 - \frac{1}{1+t_{ijskt}}\right] Y_{ijskt} = X_{it} + X^o_{it} \tag{33}$$

Under this extension, the planner can directly choose the optimal policy instruments that achieve the optimal allocations from 5.1, which is referred as dual approach. The first and second Welfare Theorem guarantee that the allocation from primal approach and dual approach coincide, up to the lump-sum transfer across countries. However, in our case, since the consumer preference is modelled as quasi-linear, households allocate the fixed amount b_i of income to the fishery and all of the remaining income is spent to outside good. That is, any change in income through lump-sum transfer does not affect the fishery sector. As we assume that the outside good market clears globally, the bilateral flow of outside good is undetermined. Therefore, any lump-sum transfer across countries is consistent with the optimal allocation.

6 Taking the Model to Data

This section provides the calibration of our model. For the quantitative exercises, we aggregate the world into 25 individual countries, where countries are carefully picked based

Table 3: Parameter calibration

Parameter	Value	Source
a. Preferences		
Demand shifter	b_i, b_s, b_{ij}, b_{sk}	Model inversion
Elasticity of substitution	$\nu = 7.56$, $\eta = 5.03$	IV regression
	$\kappa = 8.08$	Subsidy regression
b. Technology and geography		
Productivity shifter	z_i^o, z_i	Model inversion
Stock elasticity	$\xi = 1$	Brander and Taylor 1998
Commuting costs	τ_{isk}	Model inversion
Trade costs	d_{ijs}	Gravity residuals
c. Planner-related parameter		
Growth rate	γ_{sk}	CMSY++ Package
Discount rate	$\beta = 0.95$	
Pareto weights	$\phi_i = 1$	

on the national GDP and fishery output, and 5 regional groups based on the continents. This results in the total of 30 countries. Appendix Table A.1 provides the mapping of our countries. Furthermore, we disaggregate the high seas into 16 high sea regions based on FAO major fishing area, on top of 30 locations from the EEZ of each regions. Therefore, we have 46 production locations. Appendix Table A.2 provides the list of our production locations. For the species, we classify the fishery species into 10 species, according to the ISSCAAP classification. Appendix Table A.3 provides the list of our species in the model.

6.1 Calibration of Fundamentals

We start with the calibration of demand shifters. Taking our dataset constructed in Section 2, we use the standard model inversion methods to recover the demand shifters. For b_i, leveraging the property of quasi-linear preference, we directly match the fishery expenditure by each country i. For b_s, we match the expenditure share of species s among all fishery. For b_{ij}, we match the expenditure share of exporter i among all exports to importer i. Lastly, for b_{sk}, we match the expenditure share of production location k among all production locations for species s.

We then calibrate the productivity shifters. Similarly, we use the standard model inversion method. For z_i^o, we match the GDP per capita for each country i. We calibrate z_i by matching the fishery output share of country i among all countries. Lastly, we use the gravity equations to recover the trade cost and commuting cost.

Table 3 provides the summary of parameter calibration.

6.2 Calibration of Demand-side Elasticities

There are three demand-side parmeters (ν, η, κ) and one supply-side paramters (ξ) that need to be calibrated. For the supply-side parameter ξ, a stock elasticity to output, we calibrate $\xi = 1$, as in the canonical case of Brander and Taylor (1998). in this section, we estimate the demand-side parameters, which govern the elasticities of substitution in each tier of CES preferences. In the spirit of Costinot et al. (2016), we use the supply-side instrument to identify the demand relationship in gravity equation. We start from the estimation of middle tier parameter, and estimate the upper tier parameter, then finally estimate the bottom tier parameter.

6.2.1 Elasticity of Substitution across Exporters (η)

We estimate the elasticity of substitution across exporter η from the following gravity equation.

$$\begin{aligned}
\log\left(\frac{X_{ijs}}{X_{js}}\right) &= \log b_{ij} + (1-\eta)\log P_{ijs} - (1-\eta)\log P_{js} \\
&= (1-\eta)\log P_{is} - (1-\eta)\log P_{js} + \log b_{ij} + (1-\eta)\log d_{ijs} \\
&= (1-\eta)\log P_{is} + \phi_{js} + \phi_{ij} + \varepsilon_{ijs}
\end{aligned}$$

where P_{is} is the border price for species s by country i. The data is obtained from Sea Around Us.

Due to the endogenity issue arsing from that the price can be correlated with unobserved demand shifter, we introduce the supply-side instrument which is correlated with prices but uncorrelated with unobseved demand shifter. Specifically, we instrument prices with proximity to habitat suitability Z_{is}. The habitat suitability, obtained from Sea Around Us, is measured at species-grid level, using the geography variation including ocean depth, temperature, and climate. We then construct the measure for the proximity to habitat suitability by

$$Z_{is} = \sum_{g \in G} \frac{Z_{sg}}{\log dist_{ig}}$$

The idea for the valid instrument is as following. The relevance condition holds if the closer a country is located to the suitable habitat for species s, the cheaper the price would be. The exclusion restriction holds as long as distance to suitable habitat is not correlated

Table 4: Estimation of η

	(1) PPML	(2) OLS	(3) IV	(4) IV	(5) IV
$\log P_{is}$	-0.386***	-0.808***	-4.025***	-3.905***	-5.917***
	(0.057)	(0.078)	(0.461)	(0.628)	(1.309)
Implied η	1.386	1.808	5.025	4.905	6.917
Importer-species FE	Y	Y	Y	Y	Y
Exporter-importer FE	Y	Y	Y	Y	Y
Sample	Full	Full	Full	HHI Top 50	HHI Bottom 50
N	8,760	6,223	6,223	2,988	3,153
First stage			-1.903***	-1.771***	-1.262***
			(0.129)	(0.182)	(0.205)
CD-F			220.22	94.22	35.21

Notes: Herfindahl–Hirschman index is constructed to measure the contentration of exporters across species.

with with unobseved demand shifter. Table 4 shows the estimates of η, where we obtain $\eta = 5.025$ A possible concern for exclusion restriction could that the unobserved demand shifter could be correlated with the proximity to natural habitat. For example, one might argue that the consumer might have built up a particular taste for Norwegian Salmon since Norway is known to have a better habitat for salmon. If such concern is valid, the coffeicient might have an upward bias, since the preference shifter would be positively correlated with the proximity. To deal with such concern, we estimate the parameter restricting the sample to the species that are produced by multiple countries. We do not find a statistical significance that the coefficients are different across samples.

6.2.2 Elasticity of Substitution across Species (ν)

Next, we estimate the elasticity of substitution across species ν from the gravity equation, in the simlar step from previous subsection.

$$\begin{aligned}\log\left(\frac{X_{js}}{X_j}\right) &= \log b_{js} + (1-\nu)\log P_{js} - (1-\nu)\log P_j \\ &= (1-\nu)\log P_{js} + \phi_j + \varepsilon_{js}\end{aligned}$$

Instead of observing the prices from data, we construct $P_{js} = \left(\sum_i b_{ij} P_{ijs}^{1-\eta}\right)^{\frac{1}{1-\eta}} = \left(\sum_i b_{ij} d_{ijs}^{1-\eta} P_{is}^{1-\eta}\right)^{\frac{1}{1-\eta}}$ using the estimates from the previous section. Similarly, the potential endogeneity is that consumer price index is correlated with unobserved demand residuals across species. Thus, we instrument $\log P_{js}$ with the consumer's proximity to suitable habitat Z_{js}. The relevance

Table 5: Estimation of ν

	(1) PPML	(2) OLS	(3) IV	(4) IV	(5) IV
$\log P_{js}$	-0.695***	-0.938***	-6.562***	-7.889***	-6.872***
	(0.268)	(0.277)	(2.507)	(3.429)	(3.095)
Implied ν	1.695	1.938	7.562	8.889	7.872
Importer FE	Y	Y	Y	Y	Y
Sample	Full	Full	Full	HHI Top 50	HHI Bottom 50
N	300	300	300	150	150
First stage			-1.155***	-1.289***	-0.798***
			(0.394)	(0.543)	(0.215)
CD-F			11.14	4.49	11.30

Notes: Herfindahl–Hirschman index is constructed to measure the contentration of importers across species.

condition requires that the consumer price index for species is cheaper if consumer is closer to the suitable habitat of the species. The exlcusion restriction assumes that geography is uncorrelated with unobserved demand residuals across species. Table 5 shows the estimates for ν using the IV regression. While the first stage is negative as expected, we obtain $\nu = 7.562$. In response to the potential concern that geography shapes the preference across species, we again restrict the sample to the species that are produced in a geographically concentrated region. We again don't find evidence that the coefficients are statistically different across samples.

6.2.3 Elasticity of Substitution across Locations (κ)

Lastly, we estimate the elasticity of substitution across locations (κ) from indirect inference. The idea is that the equation (2) is informative about the parameter κ since, given the change in fuel subsidy that particularly targets high sea, the change in relative output between high sea and non-high sea is positively correlated with how substitutable the varieties across regions is. Thus, in this subsection, I estimate the equation (2) using the simulated results from the model and find κ that matches β_1 from Table 2. The detailed step is described in the Appendix D.1. The Appendix Figure B.1 shows the relationship between the parameter κ and the estimated coefficient β_1.

7 Quantitative Results

In this section, we compare the results from decentralized equilibrium with the results from social planner using the calibrated model. We also study the impact of eliminating the fuel subsidies.

7.1 Comparison between Decentralized Equilibrium and Planner

We begin by presenting the dynamic path of average stock to capacity ratio for both Business As Usual and planner scenario. As shown in Figure 3, the average stock to capacity ratio decreases from 42.2% in the initial year to 28.6% at the steady state in the BAU. In contrast, in the planner scenario, the average stock to capacity ratio increases to 53.8% at the steady state. The underlying mechanism is the relocation of labor from fishery to outside good. Table 6 summarizes the steady state results between Business As Usual and planner. Under the planner, 35% of fishery labor is relocated to outside good sector at the initial year. Since labor has been reallocated to fishery, the fishery output decreases and the outside good output increases.

Since the quasi-linear utility is additive, we can disentangle the global welfare into two parts, which are the welfare portion of fishery and the welfare portion of outside good. In particular, the welfare from fishery decreases by 7.8% in the initial year, while the welfare from outside good increases by 0.13% in the initial year. With less fishery output produced, the fishery stock gets to accumulate over time and the average stock to capacity ratio becomes 88% larger at the steady state. As stock gets to accumulate, the productivity increases, so even with the smaller labor, the planner can produce more output than in the BAU, which becomes the source of externality that the planner is taking care of. While the global welfare slightly decreases at the initial year, the global welfare increases by 0.39% at the steady state, as shown in Figure 3. Finally, we show that the net present value of global welfare increases by 0.11%.

7.2 Counterfactual: Eliminating Fuel Subsidies

Next, we simulate the counterfactual scenario where we eliminate the fuel subsidies. In particular, we impose the production tax to high sea, in order to undo the fuel subsidies present in the BAU scenario. From the extended model presented in section 5.3, we calibrate the subsidy rate to match the amount of fuel subsidies by each country. In particular, we impose the calibrated subsidy rate for all periods.

Table 7 summarizes the counterfactual result. By eliminating the fuel subsidy, the average

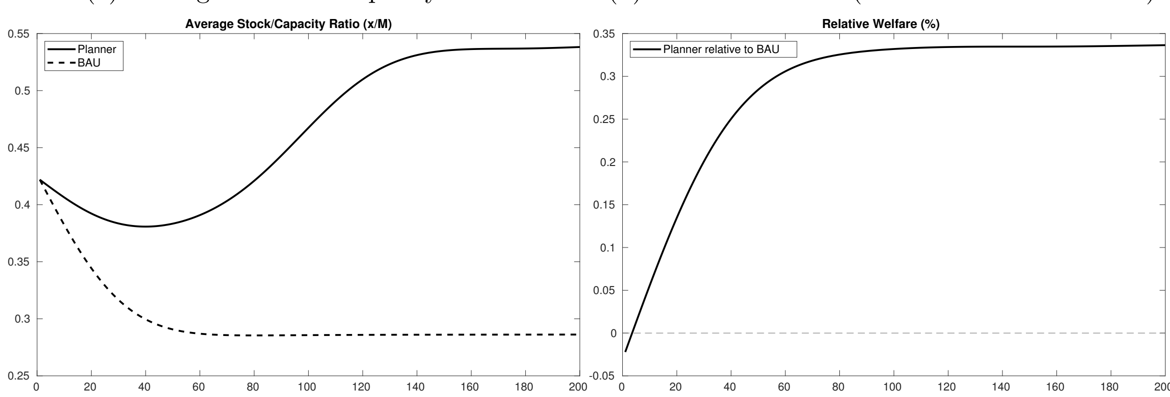
Table 6: Decentralized Equilibrium vs. Planner

	BAU		Planner		% Change	
	t=0	t=ss	t=0	t=ss	t=0	t=ss
Average stock to capacity ratio	0.422	0.286	0.422	0.538	-	88.1%
Share of fishery labor					-35.1%	-39.0%
Share of outside good labor					0.28%	0.35%
Welfare from fishery					-7.8%	15.3%
Welfare from outside good					0.13%	0.12%
Welfare					-0.02%	0.39%
Net present value of welfare					0.11%	

Notes: This table compares the Business As Usual results (BAU) with planner results. "% change" refers to the percentage change from BAU to planner for the corresponding period. Welfare from fishery refers to the fishery portion of quasi-linear utility, while welfare from outside good refers to the outside good portion of quasi-linear utility.

Figure 3: Decentralized Equilibrium vs Social Planner

(a) Average Stock to Capacity Ratio (b) Relative Welfare (Planner relative to BAU)



Notes: Panel (a) shows the dynamic path of average stock to capacity ratio for both scenario, BAU and Planner. Panel (b) represents the welfare from planner scenario relative to BAU, in percentage change.

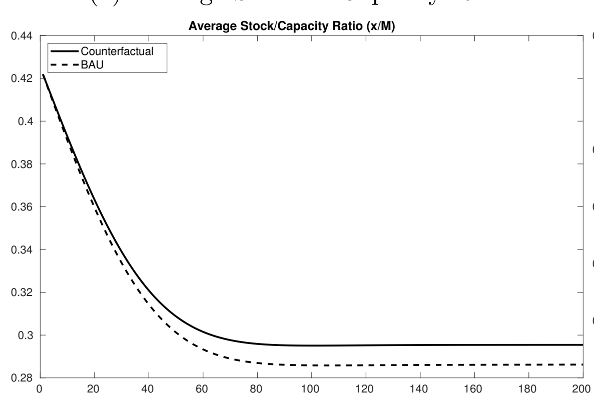
Table 7: Counterfactual vs. BAU

	BAU		Counterfactual		% Change	
	t=0	t=ss	t=0	t=ss	t=0	t=ss
Average stock to capacity ratio	0.422	0.286	0.422	0.295	-	3.22%
high sea	0.379	0.090	0.379	0.099	-	10.3%
territorial sea	0.431	0.326	0.431	0.335	-	2.76%
Welfare from fishery					-0.17%	1.42%
Welfare from outside good					0.001%	0.001%
Welfare					0.000%	0.01%
Net present value of welfare					0.004%	

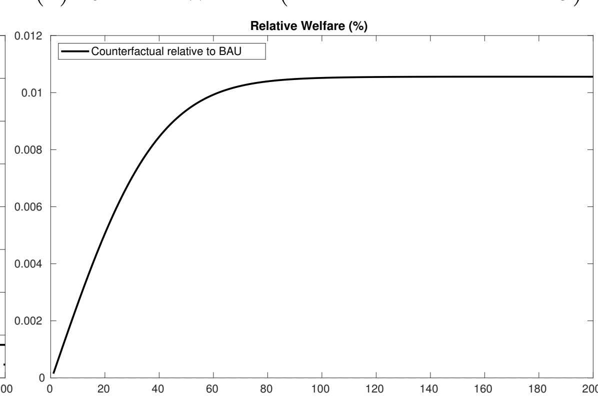
Notes: This table compares the Business As Usual results (BAU) with planner results. "% change" refers to the percentage change from BAU to planner for the corresponding period. Welfare from fishery refers to the fishery portion of quasi-linear utility, while welfare from outside good refers to the outside good portion of quasi-linear utility.

Figure 4: Counterfactual vs. BAU

(a) Average Stock to Capacity Ratio



(b) Relative Welfare (Planner relative to BAU)



Notes: Panel (a) shows the dynamic path of average stock to capacity ratio for both scenario, BAU and Planner. Panel (b) represents the welfare from planner scenario relative to BAU, in percentage change.

stock to capacity ratio increases from 28.6% to 29.5% at the steady state. This is because, as the relative price of fishery to outside good rises, the demand for fishery goes down and labor is reallocated from fishery to outside good. By doing so, the welfare from consumption goes down, while the welfare from outside good increases at the initial period. With less harvest, fishery stock gets to accumulate over time, resulting in increase in productivity. At the steady state, even with less labor, the welfare from fishery increases compared to BAU. Finally, the net present of welfare increases by 0.004%, implying that the fuel subsidies were not welfare-improving.

One interesting result is that the fishery stock increases not only at the high sea, but also at the territorial sea. This result comes from the CES structure of fishery bundle and the fact that subsidies change the relative price of fishery bundle across countries. When the production tax is imposed, it does not only increase the price of fishery from high sea, but it also increases the price of fishery from territorial sea since these varieties are substitutable.

8 Conclusions

This paper develops a dynamic spatial model of global fisheries to quantify the externalities arising from open access and evaluate the impact of fishery policies on global welfare. By leveraging novel geospatial data on fishery production and stocks, we calibrate the model and estimate key elasticities, providing a comprehensive framework for understanding global fishery.

Our results reveal substantial inefficiencies under the Business As Usual (BAU) scenario. The atomistic firms, driven by open access, fail to account for the dynamic social costs of fishery production, leading to overexploitation of fishery stocks. In contrast, our model demonstrates that a social planner, by internalizing the full dynamic social costs, would implement a reallocation of labor from the fishery sector to the outside good sector. This reallocation, while potentially reducing short-term fishery output, leads to long-term gains through larger stock and increased productivity. The stark difference between the BAU and planner scenarios underscores the magnitude of externalities in global fisheries and the potential gains from policy interventions.

Our counterfactual analysis of eliminating fuel subsidies yields important policy insights. The results suggest that current fuel subsidy practices are not welfare-enhancing from a global perspective. Eliminating these subsidies could lead to improved stock levels and increased global welfare, challenging the rationale behind such policies.

It is crucial to acknowledge the feasibility of implementing optimal policies. The planner's optimal policy varies across exporters, importers, production locations, species, and time. In practice, our policy tools are more constrained. For instance, production policies often lack the dimension of importers, while trade policies may not account for the dimension of production locations. Given these constraints, we propose that contingent trade policies, as described in Harstad (2024), could offer a feasible approach. Such policies could mandate the specification of fishery production locations in trade agreements, with tariff rates contingent on current stock levels. For example, tariffs could be imposed when stocks fall below optimal levels, while subsidies could be offered when stocks exceed optimal levels. Our paper provides both theoretical foundations and quantitative evidence to support the design and implementation of such policies.

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A Data Details

List of Country. Appendix Table A.1 provides the mapping of individual country ISO to our aggregated 30 regions in our quntiative model.

Table A.1: List of Countries

Name	Region	Name	Region	Name	Region
Bangladesh	BGD	Algeria	XAF	Kuwait	XAS
Brazil	BRA	Liberia	XAF	Cambodia	XAS
Canada	CAN	Mali	XAF	Iraq	XAS
Chile	CHL	Mauritius	XAF	Kyrgyz Republic	XAS
China	CHN	Zimbabwe	XAF	United Arab Emirates	XAS
Germany	DEU	Senegal	XAF	Jordan	XAS
Spain	ESP	Mauritania	XAF	Saudi Arabia	XAS
France	FRA	Guinea	XAF	Singapore	XAS
United Kingdom	GBR	South Africa	XAF	Afghanistan	XAS
Indonesia	IDN	Burkina Faso	XAF	Sri Lanka	XAS
India	IND	Guyana	XAM	Armenia	XAS
Italy	ITA	Virgin Islands	XAM	Kazakhstan	XAS
Japan	JPN	Suriname	XAM	Timor-Leste	XAS
Korea, Rep.	KOR	Aruba	XAM	Bhutan	XAS
Mexico	MEX	Sint Maarten	XAM	Brunei Darussalam	XAS
Malaysia	MYS	St. Vincent and the Grenadines	XAM	Belarus	XEU
Norway	NOR	Barbados	XAM	Bosnia and Herzegovina	XEU
Peru	PER	Dominican Republic	XAM	Sweden	XEU
Philippines	PHL	Honduras	XAM	Estonia	XEU
Russian Federation	RUS	Bermuda	XAM	Slovenia	XEU
Thailand	THA	Trinidad and Tobago	XAM	Croatia	XEU
Turkey	TUR	Haiti	XAM	Faroe Islands	XEU
Taiwan	TWN	Bolivia	XAM	Greece	XEU
United States	USA	Paraguay	XAM	Iceland	XEU
Vietnam	VNM	Argentina	XAM	Montenegro	XEU
Mozambique	XAF	Antigua and Barbuda	XAM	San Marino	XEU
Tunisia	XAF	Cayman Islands	XAM	Romania	XEU
Cabo Verde	XAF	Panama	XAM	Netherlands	XEU
Chad	XAF	Dominica	XAM	Luxembourg	XEU
Burundi	XAF	Grenada	XAM	Slovak Republic	XEU
Congo, Dem. Rep.	XAF	Curacao	XAM	Andorra	XEU
Zambia	XAF	Colombia	XAM	Austria	XEU
Somalia	XAF	Belize	XAM	Switzerland	XEU
Sao Tome and Principe	XAF	St. Lucia	XAM	Ireland	XEU
Egypt, Arab Rep.	XAF	El Salvador	XAM	Isle of Man	XEU
Kenya	XAF	St. Kitts and Nevis	XAM	Ukraine	XEU
Rwanda	XAF	Puerto Rico	XAM	Monaco	XEU
Ghana	XAF	Jamaica	XAM	Malta	XEU
Nigeria	XAF	Nicaragua	XAM	Lithuania	XEU
Gambia	XAF	Greenland	XAM	Czech Republic	XEU
Morocco	XAF	Guatemala	XAM	Poland	XEU
Cameroon	XAF	Venezuela	XAM	Finland	XEU
Libya	XAF	Uruguay	XAM	Albania	XEU
Niger	XAF	Bahamas, The	XAM	North Macedonia	XEU
Guinea-Bissau	XAF	Ecuador	XAM	Serbia	XEU
Equatorial Guinea	XAF	Cuba	XAM	Bulgaria	XEU
Central African Republic	XAF	Costa Rica	XAM	Hungary	XEU
South Sudan	XAF	Turks and Caicos Islands	XAM	Belgium	XEU
Congo, Rep.	XAF	Yemen, Rep.	XAS	Liechtenstein	XEU
Cote d'Ivoire	XAF	West Bank and Gaza	XAS	Portugal	XEU
Uganda	XAF	Qatar	XAS	Denmark	XEU
Eswatini	XAF	Hong Kong	XAS	Latvia	XEU
Malawi	XAF	Iran, Islamic Rep.	XAS	Moldova	XEU
Comoros	XAF	Cyprus	XAS	Marshall Islands	XOC
Lesotho	XAF	Macao	XAS	American Samoa	XOC
Tanzania	XAF	Lebanon	XAS	Fiji	XOC
Sudan	XAF	Georgia	XAS	Vanuatu	XOC
Namibia	XAF	Mongolia	XAS	Nauru	XOC
Madagascar	XAF	Maldives	XAS	Northern Mariana Islands	XOC
Sudan	XAF	Turkmenistan	XAS	Micronesia, Fed. Sts.	XOC
Gabon	XAF	Nepal	XAS	Palau	XOC
Botswana	XAF	Pakistan	XAS	Kiribati	XOC
Benin	XAF	Oman	XAS	Papua New Guinea	XOC
Seychelles	XAF	Tajikistan	XAS	Tuvalu	XOC
Angola	XAF	Lao PDR	XAS	Samoa	XOC
Sierra Leone	XAF	Myanmar	XAS	New Zealand	XOC
Ethiopia	XAF	Bahrain	XAS	Guam	XOC
Togo	XAF	Israel	XAS	Solomon Islands	XOC
Djibouti	XAF	Uzbekistan	XAS	Australia	XOC
		Azerbaijan	XAS	Tonga	XOC

Notes: This table provides the mapping of individual country ISO (column ISO) to our 30 regions (column region) in our quantitative model, which are 25 individual countries and 5 continental aggregates. The regions beginning with "X" refer to the continental aggregates. "XAF" stands for "Rest of Africa", "XAM" stands for "Rest of America", "XAS" stands for "Rest of Asia", "XEU" stands for "Rest of Europe", and "XOC" stands for "Rest of Oceania".

List of Production Location. Appendix Table A.2 provides the list of 46 production locations in our quantitative model.

Table A.2: List of Production Location

EEZ				High Sea	
BGD	FRA	MEX	TWN	Atlantic, Northwest	Indian, Eastern
BRA	GBR	MYS	USA	Atlantic, Northeast	Indian, Antarctic
CAN	IDN	NOR	VNM	Atlantic, Western Central	Pacific, Northwest
CHL	IND	PER	XAF	Atlantic, Eastern Central	Pacific, Northeast
CHN	ITA	PHL	XAM	Atlantic, Southwest	Pacific, Western Central
DEU	JPN	RUS	XAS	Atlantic, Southeast	Pacific, Eastern Central
ESP	KOR	THA	XEU	Atlantic, Antarctic	Pacific, Southwest
		TUR	XOC	Indian, Western	Pacific, Southeast

Notes: This table provides the list of 46 production locations in our quantitative model, which consist of 30 EEZs and 16 high seas. 30 EEZs come from the 30 regions from Table 6, and 16 high seas are from FAO major fishing regions.

List of Species. Appendix Table A.3 provides the list of 10 species, based on ISSCAAP classification.

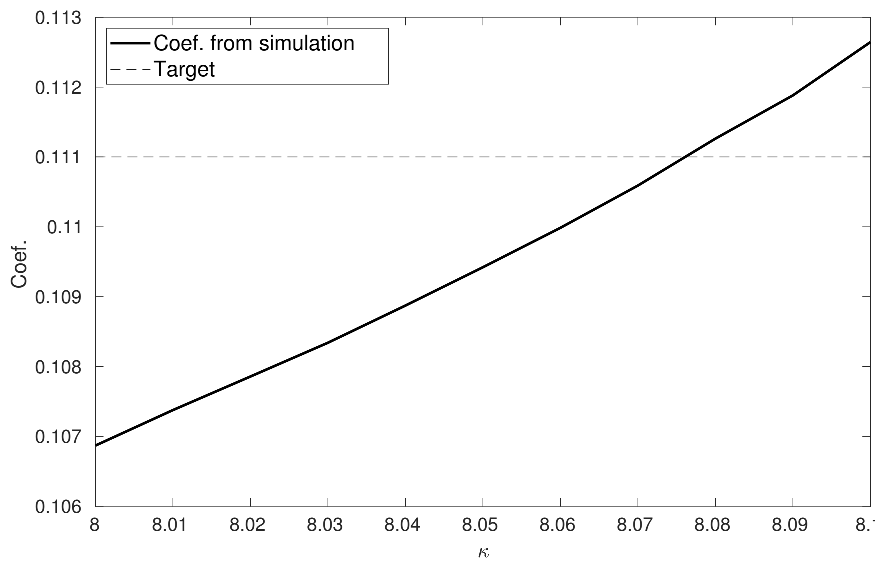
Table A.3: List of Fishery Species

Diadromous fish	Cods, hakes, haddocks	Crustaceans and mollusks
Salmons, trouts, smelts	Herrings, sardines, anchovies	Shrimps, prawns
Demersal and Pelagic fish	Tunas, bonitos, billfishes	Squids, cuttlefishes, octopuses
		Marine fish not identified

Notes: This table provides the list of 10 fishery species in our quantitative model, based on ISSCAAP classification. The original ISSCAAP classifies the fishery into 51 species, but I aggregate them into 10 larger categories to harmonize with the fishery trade dataset.

B Additional Tables and Figures

Figure B.1: Relationship between κ and β_1



C Proofs

C.1 Proof for Lemma

We want to show the following: The sufficient conditions i) $\xi \geq 1$ or ii) $0 < \xi < 1$ and $\gamma_{k,s} < \frac{1}{1-\xi}\left(\frac{1}{\beta} - 1\right)$ guarantee $\theta_{k,st} < 1/\beta$ for all ranges of $\frac{x_{k,st}}{M_{k,s}} \in [0,1]$ at the steady state.

Taking partial derivative of equation (10) with respect to $x_{k,st}$, we have

$$\theta_{k,st} = \frac{\partial x_{k,st+1}}{\partial x_{k,st}} = \frac{\partial G_{k,st+1}}{\partial x_{k,st}} - \frac{\partial H_{k,st+1}}{\partial x_{k,st}} = (1+\gamma_{k,s}) - 2\gamma_{k,s}\frac{x_{k,st}}{M_{k,s}} - \frac{\xi}{x_{k,s}}\sum_i\sum_j d_{ij,s}\tau_{ik,s}Q_{ijk,st} \tag{C.1}$$

From equation (19), at the steady state, we have

$$\gamma_{k,s}x_{k,st}(1-\frac{x_{k,st}}{M_{k,s}}) = \sum_{i\in I}\sum_{j\in I} d_{ij,s}\tau_{ik,s}Q_{ijk,st} \tag{C.2}$$

Combining (C.1) and (C.2), at the steady state, we have

$$\begin{aligned}\theta_{k,st} &= (1+\gamma_{k,s}) - 2\gamma_{k,s}\frac{x_{k,st}}{M_{k,s}} - \xi\gamma_{k,s}(1-\frac{x_{k,st}}{M_{k,s}}) \\ &= 1+\gamma_{k,s}\left(1 - 2\frac{x_{k,st}}{M_{k,s}} - \xi(1-\frac{x_{k,st}}{M_{k,s}})\right)\end{aligned}$$

1) $\xi \geq 1$
For all ranges of $\frac{x_{k,st}}{M_{k,s}} \in [0,1]$, we have

$$1 - 2\frac{x_{k,st}}{M_{k,s}} - \xi(1 - \frac{x_{k,st}}{M_{k,s}}) < 1$$

Thus,

$$\Theta_{k,st} < 1 < 1/\beta$$

2) $0 < \xi < 1$ and $\gamma_{k,s} < \frac{1}{1-\xi}\left(\frac{1}{\beta} - 1\right)$

$$\begin{aligned} \gamma_{k,s} &< \frac{1}{1-\xi}\left(\frac{1}{\beta} - 1\right) \\ \Leftrightarrow \left(1 - \frac{1}{2-\xi}\right) &- \frac{1}{(2-\xi)\,\gamma_{k,s}}\left(\frac{1}{\beta} - 1\right) < 0 \end{aligned} \tag{C.3}$$

At the steady state,

$$\begin{aligned} \Theta_{k,st} =& 1 + \gamma_{k,s}\left(1 - 2\frac{x_{k,st}}{M_{k,s}} - \xi(1 - \frac{x_{k,st}}{M_{k,s}})\right) < 1/\beta \\ \Leftrightarrow & \frac{x_{k,st}}{M_{k,s}} > \left(1 - \frac{1}{2-\xi}\right) - \frac{1}{(2-\xi)\,\gamma_{k,s}}\left(\frac{1}{\beta} - 1\right) \end{aligned} \tag{C.4}$$

Combining (C.3) and (C.4), we have

$$\Theta_{k,st} < 1/\beta \quad \text{for all ranges of } \frac{x_{k,st}}{M_{k,s}} \in [0,1]$$

D Calibration Details

D.1 Steps for Calibration of κ

1. Under the environment described in 5.3, the government imposes the ad-valorem policy instruments $s_{ijk,st} = s_{i,t}$
2. For each κ, calibrate subsidy rate $s_{i,16}$ to match the change in amount of fuel subsidy assuming $s_{i,0} = 0$. That is, $\Delta_{0\to16} S^{model}_{i,t} = \Delta_{2002\to2018} S^{Data}_{i,t}$
3. Run regression using simulated data and obtain κ that matches β_1 from the equation (2)

E Numerical Algorithm

E.1 Business As Usual

E.1.1 Static Equilibrium

For every period, given the geography, fundamentals, and endowment including fishery stock $x_{k,st}$, solve for the allocation of labor $L_{ijk,st}$

1. Initial guess for the allocation of labor $L_{ijk,st}$
2. Compute quantity and output
3. Compute prices and wages and expenditure
4. Compute $L^{new}_{ijk,st} = \frac{Y_{ijk,st}}{w_{i,t}}$
5. Update $L_{ijk,st} = \alpha L^{new}_{ijk,st} + (1-\alpha) L_{ijk,st}$ and go back to Step 1, where α is the dampening parameter
6. Iterate until convergence

E.1.2 Steady State Equilibrium

1. Initial guess for steady state stock $x_{k,st}$
2. Given the guess of stock $x_{k,st}$, solve for static equilibrium as described in E.1.1
3. Compute the growth $G(x_{k,st})$ and harvest $H(x_{k,st})$ as
   $G(x_{k,st}) = \gamma_{k,s} x_{k,st}(1 - \frac{x_{k,st}}{M_{k,s}})$ and $H(x_{k,st}) = \sum_{i \in I} \sum_{j \in I} d_{ij,s} \tau_{ik,s} Q_{ijk,st}$
4. Update $x_{k,st} = x_{k,st} \times \left(\frac{G(x_{k,st})}{H(x_{k,st})}\right)^{\alpha}$ and go back to Step 1, where α is the dampening parameter
5. Iterate until convergence

E.1.3 Dynamic Equilibrium

1. Given the stock endowment at the initial period, $x_{k,s0}$, solve for static equilibrium as described in E.1.1
2. Obtain $x_{k,s1}$ using the law of motion for fish

$$x_{k,st} - x_{k,st-1} = \gamma_{k,s} x_{k,st-1}(1 - \frac{x_{k,st-1}}{M_{k,s}}) - \sum_{i \in I} \sum_{j \in I} d_{ij,s} \tau_{ik,s} Q_{ijk,st}$$

3. Solve for static equilibrium as described in E.1.1

4. Solve for $t = 2, ..., T$

E.2 Planner's Problem

E.2.1 Steady State Equilibrium

1. Initial guess for steady state stock $x_{k,st}$

2. Given $x_{k,st}$, solve for $L_{ijk,st}$ that satisfies

$$\frac{\partial W_t}{\partial C_{ijk,st}} = \frac{\partial W_t}{\partial C^o_{i,t}} \left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}} / \frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}} \right) + \frac{\beta \Omega_{k,st}}{1 - \beta \Theta_{k,st}} \frac{\partial H_{k,st}}{\partial Q_{ijk,st}}$$

where $\Omega_{k,st} = \frac{\partial W_t}{\partial x_{k,st}}$ and $\Theta_{k,st} = \frac{\partial x_{k,st+1}}{\partial x_{k,st}}$

3. Compute the growth $G(x_{k,st})$ and harvest $H(x_{k,st})$

   where $G(x_{k,st}) = \gamma_{k,s} x_{k,st} (1 - \frac{x_{k,st}}{M_{k,s}})$ and $H(x_{k,st}) = \sum_{i \in I} \sum_{j \in I} d_{ij,s} \tau_{ik,s} Q_{ijk,st}$

4. Update $x_{k,st} = x_{k,st} \times \left(\frac{G(x_{k,st})}{H(x_{k,st})} \right)^\alpha$ and go back to step 1, where α is the dampening parameter

5. Iterate until convergence

6. Obtain the steady state $x_{k,st}, L_{ijk,st}, \lambda_{k,st}, \Omega_{k,st}, \Theta_{k,st}$ where $\lambda_{k,st} = \frac{\beta \Omega_{k,st}}{1 - \beta \Theta_{k,st}}$

E.2.2 Dynamic Equilibrium

We know the initial stock $x_{k,s0}$ and steady state $x_{k,st}, L_{ijk,st}, \lambda_{k,st}, \Omega_{k,st}, \Theta_{k,st}$ from E.2.1. Assume the last period converges to steady state such that $x_{k,sT} = x_{k,st}$, $L_{ijk,sT} = L_{ijk,st}$, and $\lambda_{k,sT} = \lambda_{k,st}$.

1. Initial guess for $\{x_{k,st}\}_{t=1}^{T-1}$ by interpolating $x_{k,st} = \frac{(T-t) x_{k,s0} + (t) x_{k,sT}}{T}$

2. Given $\{x_{k,st}\}_{t=0}^{T}$, roll backward from $t = T$

   (a) solve backward for $\lambda_{k,st-1}$ using

$$\lambda_{k,st-1} = \beta \left[\lambda_{k,st} \Theta_{k,st} + \Omega_{k,st} \right]$$

(b) solve for $L_{ijsk,t-1}$, $\Theta_{k,st-1}$, $\Omega_{k,st-1}$ using

$$\frac{\partial W_{t-1}}{\partial C_{ijk,st-1}} = \frac{\partial W_{t-1}}{\partial C^o_{i,t-1}} \left(\frac{\partial Q^o_{i,t-1}}{\partial L^o_{i,t-1}} / \frac{\partial Q_{ijk,st-1}}{\partial L_{ijk,st-1}} \right) + \frac{\beta \Omega_{k,st-1}}{1 - \beta \Theta_{k,st-1}} \frac{\partial H_{k,st}}{\partial Q_{ijk,st}}$$

(c) solve for $t = T-2, T-3, ..., 1$ and obtain $\{L_{ijk,st}, \lambda_{k,st}, \Omega_{k,st}, \Theta_{k,st}\}_{t=1}^{T}$

3. Given $x_{k,s0}$ and $\{L_{ijk,st}, \lambda_{k,st}, \Omega_{k,st}, \Theta_{k,st}\}_{t=1}^{T}$, roll forward from $t = 1$

   (a) solve for $x^{new}_{k,st}$ using the law of motion for fish

$$x_{k,st} - x_{k,st-1} = \gamma_{k,s} x_{k,st-1} (1 - \frac{x_{k,st-1}}{M_{k,s}}) - \sum_{i \in I} \sum_{j \in I} d_{ij,s} \tau_{ik,s} Q_{ijk,st}$$

4. Update $x_{k,st} = \alpha x^{new}_{k,st} + (1-\alpha)\, x_{k,st}$ and go back to Step 1, where α is the dampening parameter

5. Iterate until convergence