Global Fisheries: Quantifying the Externalities from Open Access

Elliot Kang*
University of Michigan

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Abstract

The tragedy of the commons has long been studied in economics, yet estimating its economic impact 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) fishery subsidies are positively correlated with high sea fishing. Then, I build a dynamic quantitative spatial model of global fisheries. I compare two polar cases of open access with the model: the decentralized equilibrium where atomistic firms have no property rights and the optimal allocation where planner has property rights. By taking the model to the data, I find that the average global fishery stock increases by 88% and the net present value of global welfare increases by 0.11% by the planner, compared to decentralized equilibrium. The policy counterfactual suggests that fuel subsidies are welfare-reducing globally. 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, a market failure to internalize the social cost under open access, has long been studied in economics (Hardin, 1968; Ostrom, 1990), but quantifying its economic impact remains challenging. Global fisheries present a prominent example of the tragedy of commons. 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 but also play a critical role in human diets, accounting for 20% of global animal protein intake (FAO, 2024b). For some developing countries, the share of fish on animal protein intake is much higher, for example 52% in Indonesia, emphasizing its significance in food security.[1]

Recognizing the importance of fisheries stocks, policymakers have sought to manage them effectively. A landmark initiative was the establishment of Exclusive Economic Zones (EEZs) under the 1982 United Nations Convention on the Law of the Sea. 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, 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 through subsidies. While the first discussion to regulate fishery subsidies began in the 2001 Doha Round (Chang, 2003), effective global regulation has not been achieved. Consequently, fishery remains a highly subsidized industry, with subsidies accounting for 10% of global fishery output (Sala et al., 2018). Among these, fuel subsidies are one of the largest in a single category, representing a common tool to incentivize fishing and exacerbating over-exploitation (Sumaila et al., 2019).

This paper aims to quantify the externalities in global fisheries arising from open access and investigate how global fishery policies impact the spatial distribution of fishing activities and global welfare. To answer these questions, I develop a dynamic spatial model of global fisheries and compare two polar cases of property rights: a decentralized equilibrium where atomistic firms have no property rights under open access, and a social planner who owns exclusive property rights over global fisheries. To understand policy impact, I conduct

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

counterfactual analysis where I permanently eliminate fuel subsidies. From the quantitative exercises, I find that the externality from open access is substantial in magnitude and that fuel subsidies are globally welfare-reducing.

I begin by compiling a novel comprehensive geospatial dataset, consisting of fishery production, international trade, fishery stock, and other fishery statistics. The geospatial dataset on fishery production provides detailed information on production country and quantity by species at the grid-level ($0.5° \times 0.5° \approx 60km \times 60km$). I construct the international trade dataset for global fisheries by harmonizing bilateral trade flows with domestic consumption from FAO food balance sheets. By combining the geospatial production dataset ("production flows") with the international trade dataset ("trade flows"), I construct a novel dataset of global fisheries that connects production locations to final destinations, offering a valuable resource for quantitative analysis. Furthermore, I gather geospatial data on fishery stock and habitat suitability. I also collect fishery ex-vessel prices, employment, and subsidies, which I use for model calibration and estimation.

Using this novel dataset, I document three empirical findings that motivate the quantitative model to understand global fisheries. First, in the past 40 years, global fishery stocks have decreased by 35%, and the number of overfished species has more than doubled. Second, there is a positive correlation between lack of property rights and overfishing. Oceans shared by multiple countries are more likely to be overfished, underscoring the importance of property rights in global fisheries. Third, government subsidies toward the fishing industry are correlated with high seas fishing. For example, fuel subsidies incentivize firms to travel further for fishing. This finding emphasizes the role of production policies in spatial distribution of fishery and informs the key elasticity of substitution across production location at the calibration stage.

I then develop a dynamic spatial model of global fisheries that incorporates the evolution of fishery stocks and multiple production locations under a global trade system. To quantify the externalities, I compare two polar cases: the decentralized equilibrium and the social planner. In the decentralized equilibrium, firms act atomistically without property rights, thereby disregarding the social cost of depleting future stocks. However, the planner with absolute property rights over global stocks fully internalizes the social cost.

The quantitative model accounts for multiple exporters and importers, multiple production locations consisting of EEZs and high seas, and two industries with outside good sector and fishery sector. The fishery output is consumed as nested constant elasticity of substitution (CES), where fish are differentiated by the order of species, exporters, and production locations at each tier of nests.[2] The fishery stocks evolve according to a law of motion governed by nature, closely following the literature from biology on population dynamics. Firms in the fishery sector are subject to two frictions: iceberg commuting costs to reach production locations from home countries and iceberg trade costs to ship fish from home countries to final destinations.

The quantitative model features two key characteristics. First, fishing productivity is an increasing function of fishery stocks. Fishery production today results in fishery sector becoming less productive in future, implying additional cost of fishing, which I refer to as the dynamic social cost. Second, the only dynamic force in the decentralized equilibrium is the evolution of fishery stock. Without property rights, atomstic firms are aware that any firm can enter and exploit the fishery stock in future. Consequently, atomistic firms solve a static optimization problem, not accounting for the dynamic social cost of fishing. As a result, in the decentralized equilibrium, the allocation is determined where the marginal utility of fishery consumption equalizes with the static marginal cost of fishing, which is the input cost per unit of output.

Next, I characterize the planner's problem where planner directly chooses the allocation of labor and consumption. In contrast to firms in the decentralized equilibrium, the planner fully internalizes the dynamic social cost of fishery production. From the planner's first-order conditions, I show that the equilibrium allocation is determined where marginal utility of fishery equalizes with the total cost of fishing, which includes both the static marginal cost and the dynamic social cost. The dynamic social cost, the cost of fishing that the decentralized equilibrium fails to internalize, becomes the source of the externality. Since the dynamic social cost is positive and the marginal utility of fishery consumption diminishes, the planner allocates less inputs to fishery and keeps larger fishery stock than in the decentralized equilibrium.

Then, I take the quantitative model to data. I disaggregate the world into 30 countries, comprising 25 individual countries and 5 continental groups, carefully chosen based on the size of fishery industries and overall economies. Additionally, I divide the high seas into 16 regions as defined by FAO fishing regions, resulting in a total of 46 production locations. I classify fish species into 10 groups following the ISSCAAP classification. By calibrating the model to data in 2018, I calibrate the fundamentals from model inversion. Finally, I estimate the parameters governing the elasticity of substitution from instrument variable regression, where I use the exogenous variations in the geographical proximity to fishery habitat as a supply-side shock to estimate the gravity equation.

[2] An example of differentiation across production locations at the bottom tier is the Tuna from Pacific Ocean caught by China versus the Tuna from Atlantic Ocean caught by USA.

I use the calibrated model to study the baseline decentralized equilibrium, planner's allocation, and counterfactual scenario. First, I compare the baseline decentralized equilibrium with the optimal allocation by the planner. Second, I examine the effect of fuel subsidies by eliminating the fuel subsidies in the counterfactual.

In the baseline decentralized equilibrium, I find that the average fishery stock decreases by 32% at the steady state compared to the initial year. With the fishery stock becoming scarce, the fishery sector becomes less productive and the fish becomes more expensive, resulting in lower fishery consumption at the steady state. In contrast, with the optimal allocation by planner, I show that the average fishery stock increases by 27% at the steady state compared to the initial year. The net present value of global welfare increases by 0.11% compared to the decentralized equilibrium. The mechanism is that the planner allocates fewer workers toward fishery for all periods than in the decentralized equilibrium. While less fish is consumed in the first few periods, fishery consumption exceeds the level of the decentralized equilibrium as time evolves, since the accumulated stock increases fishery productivity and allows for more fishery consumption even with fewer labor. Moreover, since more labor is allocated to the outside good sector, the consumption of outside good is larger than in the decentralized equilibrium.

In the counterfactual exercise where I eliminate fuel subsidies, I 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%. While the magnitude is small, the result implies that fuel subsidies are welfare-reducing from a global perspective. By eliminating fuel subsidies, as in the case of the planner, fishery consumption decreases in the first periods but increases as the stock accumulates.

Related Literature. This paper contributes to three major strands of literature in economics. First, I extend the growing body of work at the intersection of trade, spatial economics, and the 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, Farrokhi et al. (2024) on global deforestation, and Hsiao (2024) on international cooperation in the palm oil market. This study aligns closely with Carleton et al. (2024), which examines agricultural trade and the spatial allocation of global water use. However, my focus on global fisheries presents unique context as production policies, in addition to trade policies, could affect the spatial distribution of fishery. To my knowledge, this is the first paper to apply a dynamic spatial quantitative model to global fisheries.

Second, I build upon the literature examining optimal environmental policies in 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. The contribution of this paper lies in the quantitative analysis of optimal allocation in dynamic setting.

Lastly, I contribute to the extensive literature on the extraction of natural resources and fisheries. 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). The 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 EEZ introduction. My paper distinguishes itself by linking global production data with international trade for the first time, offering a comprehensive study of global fisheries.

The rest of paper proceeds as follows. Section 2 describes the data sources used in the paper. Section 3 establishes empirical facts to motivate 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 decentralized equilibrium. Section 6 calibrates the model by taking the model to data. Section 7 shows the quantitative results from decentralized equilibrium, social planner, and the counterfactual scenario. Section 8 concludes.

2 Data

In this section, I construct a novel dataset combining geospatial dataset of global fishery production and stock with international trade flows and other fishery datasets. Detailed explanations of each data source and harmonization process can be found in Appendix A.

Fishery Production. The fishery production dataset is sourced from Sea Around Us.[3] The dataset provides the production quantity for each species by individual country at the granular grid-level of production location ($0.5° \times 0.5° \approx 60km \times 60km$). The dataset spans annually from year 1980 for approximately 200 countries, covering 1,100 species around the world. While the information on fishery production is available from FAO fishery database, their geographic units are much broader, classifying global ocean into 19 FAO major fishing area.[4] The dataset from Sea Around Us enhances FAO fishery database by estimating the production location at the grid-level.The grid-level estimation process integrates the information from several sources, including grid-level natural habitat conditions, national statistics by individual countries, FAO fishery database, and existing literature.(Zeller and Pauly, 2015). The major benefit of granular dataset is the feasibility of distinguishing between EEZ and high sea, otherwise infeasible under the broader classification of major fishing areas. Figure 1 panel (a) shows a graphical illustration of the production dataset, which is the map for the production of Big Eye Tuna in 2018.

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 the model of stock growth.

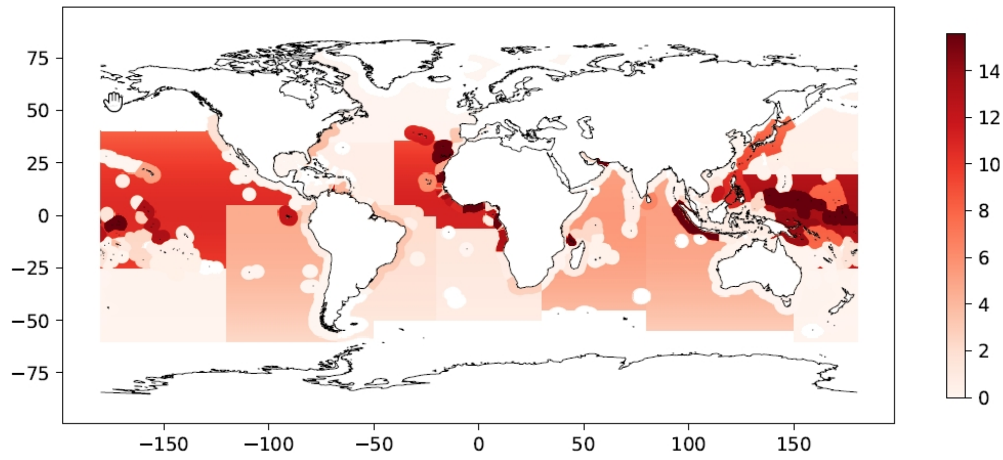
To estimate fishery stock levels, I employ the CMSY++ package provided by the Sea Around Us, which combines the indirect method with machine learning algorithms. The package takes historical catch data and biological information as inputs and estimates the time-series of fishery stock. The estimation allows to infer the carrying capacity, which is the maximum population that can be attained at the grid by species. That is, taking the inputs as given, the model infers the stock and carrying capacity that best rationalizes the

[3]Sea Around is the research initiative at the University of British Columbia, specializing at quantifying the impact of fisheries on marine environments.

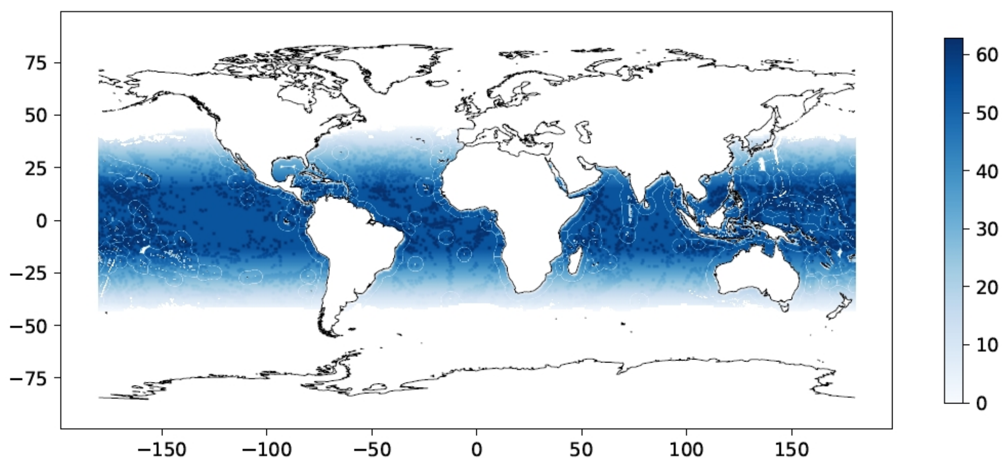
[4]FAO publishes the annual global fisheries statistics based on surveys from individual countries (FAO, 2024a).

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.

time-series of catch.[5] The machine learning algorithm, trained on direct observation data, enhances its estimation accuracy.[6] Figure 1 panel (b) shows a graphical illustration of the stock dataset, which is the map for the stock of Big Eye Tuna in 2018.

Fishery Trade. I construct fishery trade dataset combining the bilateral trade flows with the domestic consumption from food balance sheet, both from FAO. FAO dataset on bilateral trade flows 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

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

[6]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.

trade literature. I overcome the difficulty by complementing the trade dataset with FAO food balance sheet.[7] The food balance sheet dataset provides the information on food production, domestic consumption, exports, and imports by type of 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.[8] 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 available from 2002 to 2018 and collected by Sumaila et al. (2019). Lastly, fishery employment data come from OECD.

Geographic Boundaries. I 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). I 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.[9] In order to classify high seas, I use the shapefile from FAO major fishing area boundaries.[10] FAO major fishing area disaggregates the entire ocean into 19 major fishing areas. By overlaying the shapefile of EEZ with the shapefile of FAO major fishing areas, I exclude the EEZ portion from major fishing areas and define them as high seas.

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

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

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

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

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

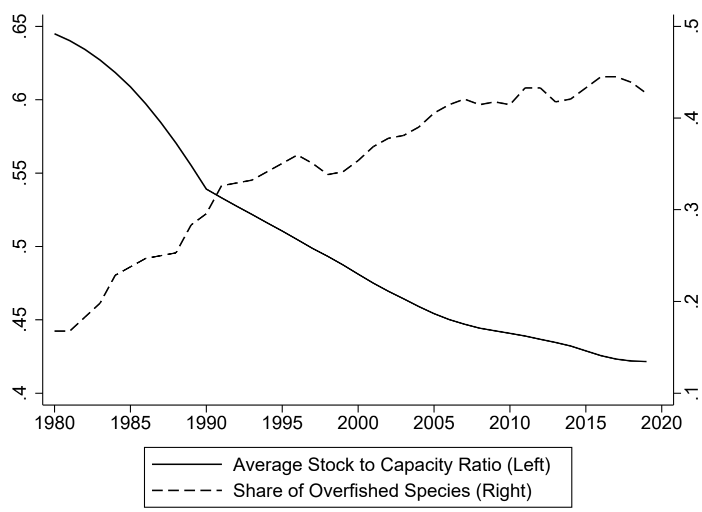
3 Empirical Patterns

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

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 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 the same carrying capacity, the stock would have decreased by 35%. I also calculate the proportion 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 proportion of overfished species increased from 17% to 43% during these period.[11]

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).

[11] These figures are in line with the statistics from FAO in 2020, from 20% to 35%, implying that 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 Rights is associated with Overfishing

Next, I examine how the lack of property rights is associated with overfishing. In the quantitative exercise, I take two polar cases of property rights: one case where atomistic firms don't have property rights and the case where a social planner has globally exclusive property rights. To motivate the relationship between property rights and overfishing, I estimate equation 1. As proxy for property rights at the grid-level, I use the following two measures: the number of fishing countries and inverse of Herfindahl–Hirschman index (HHI). Both measure capture the concentration of production across countries within a grid. For example, if the grid is located at the territorial sea, 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, the number of fishing countries or HHI could exceed one. For the measure for overfishing, I define as a species at the grid as overfishing if total harvest for the species at the grid exceeds 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 total harvest across countries, $MSY_{k,s}$ 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	Fuel	All	Fuel
	(1)	(2)	(1)	(2)
$\Delta \ln S_{i,t}$	0.237**	0.165**	0.323*	0.111**
	(0.097)	(0.061)	(0.163)	(0.042)
Other Controls	Y	Y	Y	Y
R^2	0.119	0.301	0.176	0.268
N	108	43	30	30

Notes: The regression is weighted by log output in 2002, which is the initial year for subsidy dataset. "All Countries" sample include all countries available from data, while "Model Countries" sample restricts the sample to 30 regions used in the quantitative 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

I 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, boat-construction subsidies, and infrastructure subsidies. Fuel subsidies constitute the largest subsidies type in a single category, accounting for 21% of total subsidies. The discussion to regulate the subsidies has started since the Doha round in 2001, but the effective regulation has not been enforced.[12] I consider the following equation (2) to explore the relationship between subsidies and production location:

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

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 correlation between fishery subsidies and 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 seas 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, I control for population growth and gdp growth.

[12] Following the continued concern, WTO has recenrly made another agreement to prohibit subsidies that promote fishing (WTO, 2023).

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

Since the provision of fuel subsidies has been a persistent issue among policy makers (Sala et al., 2018; WTO, 2023), I examine the impact of fuel subsidies in the quantitative exercise. Moreover, the regression is informative about the elasticity 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, I simulate the model and estimate equation (2) using the simulated results to discipline the elasticity of substitution parameter.

4 A Model of Global Fishery

In this section, I develop a dynamic spatial model of global fishery, where a home country harvests from fishing region (production location) and exports to foreign countries. I consider two polar cases of property rights. In the decentralized equilibrium, I assume atomistic firms don't have property rights and have open access to production locations. In the planner's problem, I assume a global social planner has absolute property rights over all part of the oceans. While the atomistic firms solve static problem, the global social planner solves dynamic problem fully internalizing the social cost.[13] I begin by describing the model setup and characterize the decentralized equilibrium.

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 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

[13] 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.

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, I suppress the subscript f for fishery sector.

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

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

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 toward fishery bundle, $P_{j,t}$ is the price index for fishery bundle, and $E_{j,t}$ is the aggregate 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 aggregators. 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

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

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}

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

Finally, in the lower tier, varieties 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 $b_{k,s}$

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

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

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

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

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

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

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

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

$$\begin{aligned} x_{k,st} - x_{k,st-1} &= G(x_{k,st}) - H(x_{k,st}) \\ &= \gamma_{k,s} x_{k,st-1}\left(1 - \frac{x_{k,st-1}}{M_{k,s}}\right) - \sum_{i \in I} \sum_{j \in I} d_{ij,s} \tau_{ik,s} Q_{ijk,st} \end{aligned} \tag{4}$$

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, $d_{ij,s}$

is the iceberg trade cost, $\tau_{ik,s}$ is the iceberg commuting cost, and $Q_{ijk,st}$ is the quantity of fishery exported by country i to country j 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 decreasing function of $x_{k,st}$ and the second partial derivative is negative. Thus, the fishery growth is invert U-shaped and takes its maximum at $x_{k,st}/M_{k,s} = 0.5$. The intuition is that when the stock level is too low relative to the carrying capacity, the reproduction is difficult because fish are harder to find mates. When the stock level is too high relative to carrying capacity, reproduction is also hindered due to overcrowding.[14]

Fishery Technology. For every variety of fisheries, there is an atomistic representative firm which chooses the 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

$$Q_{ijk,st} = \frac{z_i\left(x_{k,st-1}/M_{k,s}\right)^{\xi}}{d_{ij,s}\tau_{ik,s}}L_{ijk,st} \tag{5}$$

where $Q_{ijk,st}$ is the quantity of fishery exported, $d_{ij,s}$ 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.

The firm is subject to the iceberg commuting cost and iceberg trade cost. In order to sell one unit of fish, the firm needs to send $d_{ij,s}$ units of fish where the friction is iceberg. Additionally, 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 production location.

The productivity is an increasing function of fish stock to capacity ratio, reflecting the notion that it becomes easier to harvest when there are more stocks. One percent increase in stock to capacity ratio generates ξ percents increase in output.

The only dynamic factor in the decentralized equilibrium is the evolution of fishery stock. Under the open access, atomstic firms without property rights solve a static problem since they are aware that any firm can enter and exploit the fishery stock in future.

[14] 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.

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

$$Q_{i,t}^o = z_i^o L_{i,t}^o \tag{6}$$

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. The wage that applies to all workers is exogenously determined as

$$w_i^o = w_i = z_i^o \tag{7}$$

I 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

$$Y_{ijk,st} = \pi_{ijk,st}\pi_{ij,st}\pi_{j,st}X_{j,t} \tag{8}$$

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

$$X_{j,t} = b_j \tag{9}$$

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

$$\sum_{i\in I} Y_{i,t}^o = \sum_{j\in I} X_{j,t}^o \tag{10}$$

Labor market clearing requires that payments to labor equal output

$$w_{i,t}L_{ijk,st} = Y_{ijk,st}, \quad w_{i,t}^o L_{i,t}^o = Y_{i,t}^o \tag{11}$$

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

$$\sum_{j\in I}\sum_{s\in S}\sum_{k\in K} w_{i,t}L_{ijk,st} + w_{i,t}^o L_{i,t}^o = X_{i,t} + X_{i,t}^o \tag{12}$$

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 (5) and (6), stock of fish evolves according to (4), markets clear according to (8) and (10) and (11), and the balance of budget holds according to (12)

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

$$\gamma_{k,s} x_{k,st}(1 - \frac{x_{k,st}}{M_{k,s}}) = \sum_{i \in I} \sum_{j \in I} d_{ij,s} \tau_{ik,s} Q_{ijk,st} \tag{13}$$

4.4 Discussion of Equilibrium.

Rearranging the first-order conditions from households and firms, I can characterize the decentralized equilibrium as following. The details are provided in Appendix.

$$\underbrace{\frac{\partial U_{j,st}}{\partial C_{ijk,st}}}_{\text{MU of fishery consumption}} = \underbrace{\frac{\partial U_{j,st}}{\partial C^o_{i,t}} \left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}} / \frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}} \right)}_{\text{MC of fishery consumption}} \tag{14}$$

$$\Leftrightarrow p_{ijk,st} = \frac{d_{ij,s} \tau_{ik,s}}{z_i \left(x_{k,st-1} / M_{k,s} \right)^{\xi}} w_{i,t} \tag{15}$$

The equation (14) implies that the allocation is determined where the marginal utility of fishery consumption equalizes with the marginal cost of fishery consumption, which is the foregone utility from outside good that could have been achieved if the additional fishery good were not produced. The equation (15) implies that the relative price of fishery equals to the marginal cost of fishing, which is the input cost per unit of output. These expressions are useful when comparing with the planner's allocation in Section 5.

5 Planner's Problem

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

5.1 Planner's FOC

Given the GE equations (3)∼(11), 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

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

where $\lambda_{k,st}, \mu_{i,t}, \theta_{ijk,st}, \alpha_t$ denote the Lagrangian multipliers for stock constraint, labor constraint, and technology constraint for fishery and outside good, respectively.

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

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

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

where each variable inside the bracket refers to the variable with the partial derivatives.

5.2 Comparison between Planner and Decentralized Equilibrium

In this subsection, I compare the first-order conditions of social planner and decentralized equilibrium to draw an intutition for the source of externalities.

Rearranging the first-order conditions of global planner at the steady state,

$$
\underbrace{\frac{\partial W_t}{\partial C_{ijk,st}}}_{\text{MU of fishery consumption}} = \underbrace{\underbrace{\frac{\partial W_t}{\partial C^o_{i,t}}\left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}} / \frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}}\right)}_{\text{static MC}} + \underbrace{\frac{\beta\Omega_{k,st}}{1-\beta\Theta_{k,st}}\frac{\partial H_{k,st}}{\partial Q_{ijk,st}}}_{\text{dynamic MC}}}_{\text{MC of fishery consumption}} \tag{16}
$$

where $\Omega_{k,st} = \partial W_{t+1}/\partial x_{k,st}$ and $\Theta_{k,st} = \partial x_{k,st+1}/\partial x_{k,st}$

For each variety of fishery $C_{ijk,st}$, the planner consumes until the marginal utility of consumption equalizes with the marginal cost of consumption. The left-hand side of equation (16) is the marginal utility of additional fishery $C_{ijk,st}$. The right-hand side of equation (16) is the marginal cost of fishery consumption, which consists of two terms, the static marginal cost and the dynamic marginal cost. The first term on the right-hand side of equation (16) refers to the static marginal cost, which is the foregone welfare from outside good that could have been achieved if the additional fishery good were not produced.

The second term on the right-hand side of equation (16) refers to the dynamic marginal cost, which is the foregone welfare from lower productivity by decrease in fishery stock. Recall that the fishery productivity is an increasing function of fishery stock. When the fishery stock decreases due to additional consumption, the fishery stock decreases and the fishery sector becomes less productive incurring the welfare loss. $\Omega_{k,st}$ captures the dynamic productivity cost, which is the change in welfare per unit of stock via productivity channel.

The total size of welfare loss depends not only on the welfare cost per unit of stock, but also on how many units of stock were affected by additional consumption. The amount of total stock affected are determined by the static stock multiplier and dynamic stock multiplier. The static multiplier $\partial H_{k,st}/\partial Q_{ijk,st}$ captures the amount of fish need to be extracted for additional consumption today, which is the iceberg frictions for the planner. The dynamic stock multiplier $\Theta_{k,st}$ captures the change in the number of stock next period, given one unit change in fishery stock today. Since regrowth and harvest of fish depends on the stock level, the amount of change in stock at next period given one unit change of stock today is not necessarily one, but is endogeneously determined as $\Theta_{k,st}$. Given a unit decrease in fishery stock today, the number of stock at next period decreases by $\Theta_{k,st}$, and the effect is accumulated over periods through the law of motion. At the steady state, the total number of affected stock becomes $1/\left(1-\beta\Theta_{k,st}\right)$ units, in the formulation of infinite sum up to the discount rate.

Unlike the planner who takes the static stock multiplier as $\partial H_{k,st}/\partial Q_{ijk,st} = d_{ij,s}\tau_{ik,s}$, an atomistic firm in the decentralized equilibrium perceives the static stock multiplier as $\partial H_{k,st}/\partial Q_{ijk,st} = 0$. Rearranging equation (16) with $\partial H_{k,st}/\partial Q_{ijk,st} = 0$, equation (17) coincides with the first-order condition from decentralized equilibrium in equation (14).

$$
\begin{aligned}
\frac{\partial W_t}{\partial C_{ijk,st}} &= \frac{\partial W_t}{\partial C^o_{i,t}}\left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}}\Big/\frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}}\right) \\
\Leftrightarrow \frac{\partial U_{j,t}}{\partial C_{ijk,st}} &= \frac{\partial U_{j,t}}{\partial C^o_{i,t}}\left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}}\Big/\frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}}\right)
\end{aligned}
\tag{17}
$$

The key difference between planner and decentralized equilibrium is that the planner internalizes dynamic marignal cost while the decentralized equilibrium does not. Thus, the source of externality is the ignorance of dynamic marginal cost by atomistic firms in the decentralized equilibrium. Since the dynamic social cost is positive and the marginal utility of fishery consumption diminishes, the planner allocates less inputs to fishery and keeps larger fishery stock than in the decentralized equilibrium by internalizing the dynamic marginal cost. If there were no productivity gains from fishery stock ($\xi = 0$), the allocation by planner would equalize with the decentralized equilibrium.

Lastly, I point out the sufficient condition for the dynamic stock multiplier $\Theta_{k,st}$ 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 look at the Appendix C.1. □

The intuition is as following. When ξ is large, given an increase in stock, the response from harvest becomes larger, which suppresses $\Theta_{k,st}$ so that it does not explode. When ξ is small, since the harvest does not suppress $\Theta_{k,st}$ as much as in the previous case, smaller $\gamma_{k,s}$ is required so that the regrowth does not respond too rapidly against the increase in stock. As ξ approaches to zero, $\gamma_{k,s}$ needs to decrease and gets closer to $1/\beta - 1$.

5.3 Extension: Dual Approach

In this subsection, I 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

$$p_{ijk,st} = (1 + t_{ijk,st}) \frac{d_{ij,s}\tau_{ik,s}}{z_i \left(x_{k,st-1}/M_{k,s}\right)^{\xi}} w_{i,t} \tag{18}$$

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 (12) now becomes

$$\sum_{j\in I}\sum_{s\in S}\sum_{k\in K} w_{i,t}L_{ijk,st} + w^o_{i,t}L^o_{i,t} + \sum_j\sum_s\sum_k \left[1 - \frac{1}{1 + t_{ijk,st}}\right] Y_{ijk,st} = X_{i,t} + X^o_{i,t} \tag{19}$$

Under this extension, the planner can directly choose the optimal policy instruments that achieve the optimal allocations from Section 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, 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 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.

Table 3: Parameter calibration

Parameter	**Value**	**Source**
a. Preferences		
Demand shifter	$b_i, b_s, b_{ij}, b_{k,s}$	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	$\tau_{ik,s}$	Model inversion
Trade costs	$d_{ij,s}$	Gravity residuals
c. Planner-related parameter		
Growth rate	$\gamma_{k,s}$	CMSY++ Package
Discount rate	$\beta = 0.95$	
Pareto weights	$\phi_i = 1$	

6 Taking the Model to Data

This section provides the calibration of the quantitative model. For the quantitative exercises, I aggregate the world into 25 individual countries, where countries are carefully picked based 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 countries. Furthermore, I 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, I have 46 production locations. Appendix Table A.2 provides the list of production locations. For the species, I classify the fishery species into 10 species, according to the ISSCAAP classification. Appendix Table A.3 provides the list of species in the model.

6.1 Calibration of Fundamentals

This subsection calibrates the fundamentals using model inversion. Taking the dataset constructed in Section 2, I use the standard model inversion methods to recover the demand shifters. For b_i, leveraging the property of quasi-linear preference, I directly match the fishery expenditure by each country i. For b_s, I match the expenditure share of species s among all fishery. For b_{ij}, I match the expenditure share of exporter i among all exports to importer i. Lastly, for $b_{k,s}$, I match the expenditure share of production location k among all production locations for species s.

I then calibrate the productivity shifters. For z_i^o, I match the GDP per capita for each country i. I calibrate z_i by matching the fishery output of country i. Lastly, I 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 parameters ν, η, κ, and one supply-side paramters ξ that need to be calibrated. For the supply-side parameter ξ, I calibrate the stock elasticity to output $\xi = 1$, as in the canonical case of Brander and Taylor (1998). Next, I 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) and Carleton et al. (2024), I use the supply-side instrument for productivity to identify the demand relationship in gravity equation. I start from the estimation of the elasticity of substitution across countries η, then estimate the elasticity of substitution across species ν. Lastly, I estimate the elasticity of substitution across production locations κ using the indirect inference disciplined by equation (2).

6.2.1 Elasticity of Substitution across Exporters (η)

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

$$\begin{aligned}
\log\left(\frac{X_{ij,s}}{X_{j,s}}\right) &= \log b_{ij} + (1-\eta)\log P_{ij,s} - (1-\eta)\log P_{j,s} \\
&= (1-\eta)\log P_{i,s} - (1-\eta)\log P_{j,s} + \log b_{ij} + (1-\eta)\log d_{ij,s} \\
&= (1-\eta)\log P_{i,s} + \phi_{j,s} + \phi_{ij} + \varepsilon_{ij,s}
\end{aligned}$$

where $P_{i,s}$ is the border price for species s by country i.

Due to the endogenity issue arising from that the price can be correlated with unobserved demand shifter, I introduce the supply-side instrument which is correlated with prices but uncorrelated with unobserved demand shifter. Specifically, I instrument prices with proximity to habitat suitability $Z_{i,s}$ by each country i for species s. From the data, the habitat suitability $Z_{g,s}$ is measured at grid-species level, using the geography variation including ocean depth, temperature, and climate. I construct the measure for proximity to habitat suitability $Z_{i,s}$ by country-species, by taking the distance-weighted average of the habitat suitability where the weights are the log of linear distance to each grid g from the closest port at country i such that

$$Z_{i,s} = \sum_{g\in G}\frac{Z_{g,s}}{\log dist_{ig}}$$

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 concentration of exporters across species, such that $HHI_s = \sum_{i \in I} EXP_{i,s}^2$ where $EXP_{i,s}$ is the output share of country i from total output for species s. "HHI Top 50" sample includes species whose Herfindahl–Hirschman index is over median, while "HHI Bottom 50" sample includes species whose Herfindahl–Hirschman index is below median.

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 with with unobserved demand shifter. Table 4 shows the estimates of η, where I 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 coefficient might have an upward bias, since the preference shifter would be positively correlated with the proximity. To deal with such concern, I estimate the parameter restricting the sample to the species that are produced by multiple countries. I do not find a statistical significance that the coefficients are different across samples.

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 concentration of importers across species, such that $HHI_s = \sum_{i\in I} IMP_{i,s}^2$ where $IMP_{i,s}$ is the consumption share of country i from total consumption for species s. "HHI Top 50" sample includes species whose Herfindahl–Hirschman index is over median, while "HHI Bottom 50" sample includes species whose Herfindahl–Hirschman index is below median.

6.2.2 Elasticity of Substitution across Species (ν)

Next, I estimate the elasticity of substitution across species ν from the gravity equation, in the similar 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, I 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 previous section. Similarly, the potential endogeneity is that consumer price index is correlated with unobserved demand residuals across species. Thus, I instrument $\log P_{js}$ with the consumer's proximity to suitable habitat Z_{js}. The relevance condition requires that the consumer price index for species is cheaper if consumer is closer to the suitable habitat of the species. The exclusion 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, I obtain $\nu = 7.562$. In response to the potential concern that geography shapes the preference across species, I again restrict the sample to the species that are consumed in a geographically concentrated region. I again don't find evidence that the coefficients are statistically different across samples.

6.2.3 Elasticity of Substitution across Locations (κ)

Lastly, I estimate the elasticity of substitution across locations κ from indirect inference. The idea is that 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 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, I compare the results from decentralized equilibrium with the results from social planner using the calibrated model. I also study the impact of eliminating the fuel subsidies.

7.1 Comparison between Decentralized Equilibrium and Planner

I begin by presenting the dynamic path of average stock to capacity ratio for both the decentralized equilibrium (Business As Usual) and planner. 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 decentralized equilibrium. In contrast, under the planner, the average stock to capacity ratio increases to 53.8% at the steady state.

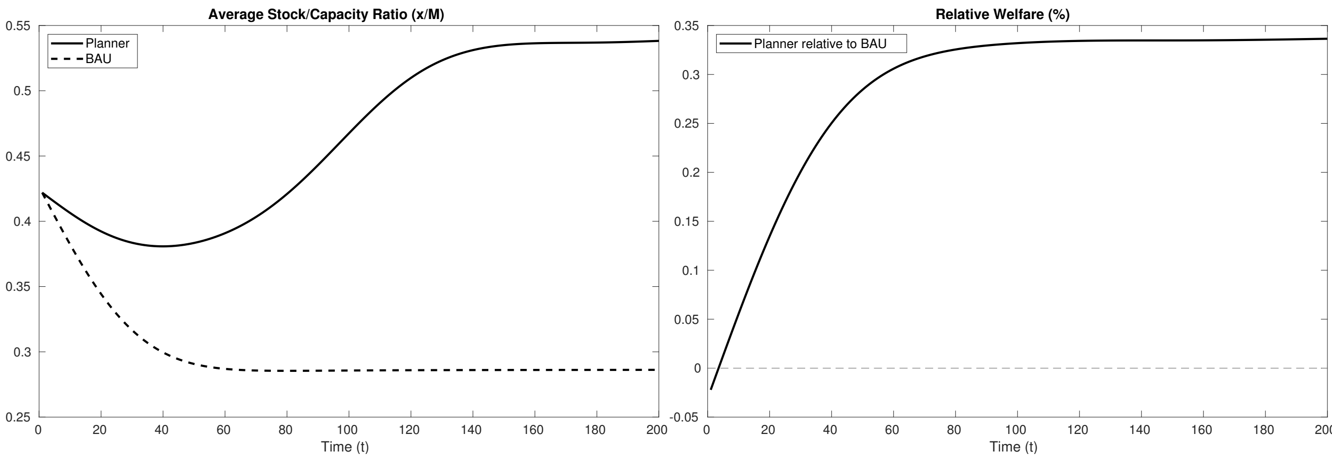
Table 6 summarizes the steady state results between the decentralized equilibrium and planner. The underlying mechanism is the relocation of labor from fishery to outside good. Under the planner, 35% of fishery labor is relocated to outside good sector at the initial year. Since labor has been reallocated to fishery, the fishery output decreases and the outside good output increases at the initial year. Since the quasi-linear utility is additive, I can disentangle the global welfare into two parts, which are the welfare portion of fishery and the welfare portion of outside good. In particular, under the planner relative to the decentralized equilibrium, the welfare from fishery decreases by 7.8% at the initial year, while the welfare from outside good increases by 0.13% in the initial year.

With less fishery produced at the initial year, the fishery stock gets to accumulate over time. At the steady state, the average stock to capacity ratio becomes 88% larger under the planner, compared to the steady state of decentralized equilibrium. As stock gets to accumulate, the fishery sector becomes productive, allowing the planner to produce more

Figure 3: Decentralized Equilibrium (BAU) vs 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.

output even with fewer labor inputs. Figure 3 shows the global welfare under the planner relative to the decentralized equilibrium. While the relative welfare slightly decreases at the initial periods with lower fishery consumption, the larger productivity from accumulated stock allows the relative global welfare to increase by 0.39% at the steady state. Taking the discounted sum of the path of global welfare, Table 6 shows that the net present value of global welfare increases by 0.11% under planner relative to the decentralized equilibrium.

7.2 Counterfactual: Eliminating Fuel Subsidies

Next, I simulate the counterfactual scenario where I permanently eliminate the fuel subsidies. In particular, I impose the production tax particularly to high sea, in order to undo the fuel subsidies present in the BAU scenario. From the extended model presented in Section 5.3, I calibrate the tax rate by country so that the amount of tax revenue matches the amount of fuel subsidies from data.

I present the dynamic path of average stock to capacity ratio in Figure 3. By eliminating the fuel subsidies, the average stock to capacity ratio increases from 28.6% to 29.5% at the steady state. Table 7 summarizes the counterfactual result. Without the fuel subsidies, the relative price of fishery to outside good rises. As the demand for fishery goes down, labor is reallocated from fishery to outside good, similarly with the planner allocation. The welfare from fishery consumption decreases at the initial period, while the welfare from outside good increases. With less harvest, fishery stock gets to accumulate over time, increasing the fishery productivity in the long-run. At the steady state, even with fewer labor, the welfare from fishery increases compared to BAU. Finally, the net present of welfare increases by 0.004%,

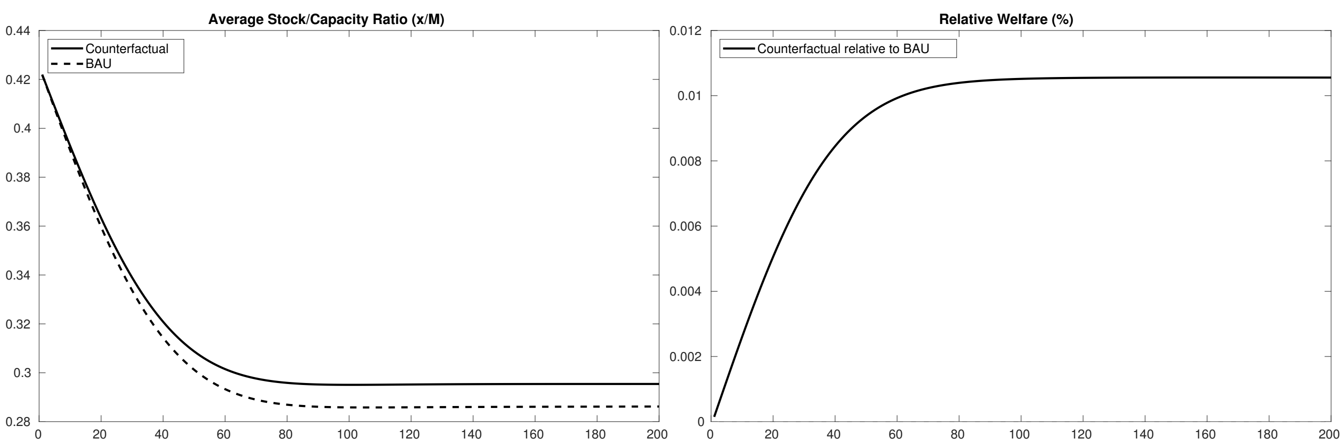
Table 6: Decentralized Equilibrium (BAU) vs. Planner

	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 4: Counterfactual vs. BAU

(a) Average Stock to Capacity Ratio (b) Relative Welfare (Counterfactual 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.

implying that the fuel subsidies were not welfare-improving.

Table 7 suggests that, while the production taxes are particularly targeted to high sea, the fishery stock increases not only at the high sea, but also at the territorial sea. The 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. Such spillover effect underscores the significance of well-targeted policy.

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, I calibrate the model and estimate key elasticities, providing a comprehensive framework for understanding global fishery.

The 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, the 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.

The 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, the 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.

The 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 the gap between current stock and optimal stock. For example, tariffs could be imposed when stocks fall below optimal levels, while subsidies could be offered when stocks exceed optimal levels. This 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 aggregated 30 regions in the quantitative 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 30 regions (column region) in the 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 the 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 the 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.

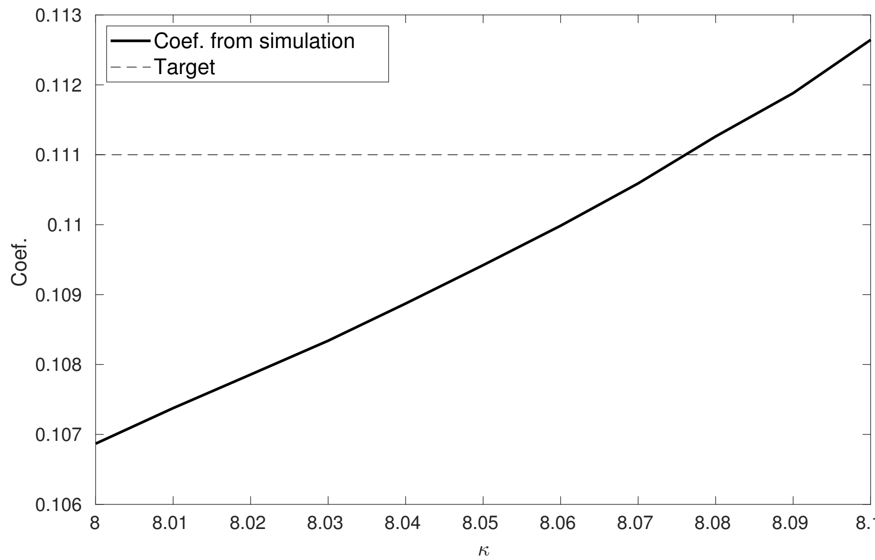
Table A.3: List of Fishery Species

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 the 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



Notes: The figure shows the relationship between the parameter value of κ and the regression coefficient β_1 from equation (2).

C Proofs

C.1 Proof for Lemma

I 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 (4) with respect to $x_{k,st}$,

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

From equation (13), at the steady state,

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

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

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

1) $\xi \geq 1$

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

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

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, $\Delta_{0\to 16} S_{i,t}^{model} = \Delta_{2002\to 2018} S_{i,t}^{Data}$

3. Run regression using simulated data and obtain κ that matches β_1 from 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 $L_{ijk,st}^{new} = \frac{Y_{ijk,st}}{w_{i,t}}$

5. Update $L_{ijk,st} = \alpha L_{ijk,st}^{new} + (1-\alpha) L_{ijk,st}$ 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

Given 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, I assume that 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