Global Fisheries: Quantifying the Externalities from Open Access

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Abstract

This paper uses a novel geospatial dataset of global fishery catch and develops a quantitative dynamic spatial model to quantify the externalities from open access in global fishing. 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 lower fishery stock, and (iii) fuel subsidies to vessels are positively correlated with high sea fishing. Then, I build a dynamic spatial model of global fisheries and compare two polar cases of open access: the decentralized equilibrium, where atomistic firms have open access to the fishery, and the socially optimal allocation, where the social planner has exclusive property rights. By taking the model to the data, I find that in the socially optimal allocation, the average global fishery stock at the steady state increases by 88%, and the net present value of global welfare increases by 0.11%, compared to the decentralized equilibrium. Through the policy counterfactual, I find that fuel subsidies are globally welfare-reducing and decrease the average global fishery stock at the steady state by 3.2%.

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 total animal protein intake globally (FAO, 2024b). For some developing countries, the share of fish in total animal protein intake is much higher, for example 52% in Indonesia, emphasizing its significance in food security.[1] Recognizing the importance of fisheries, multilateral global initiatives have sought to preserve fishery stocks by assigning property rights or designating protected areas (UN, 1982, 2023).[2] Despite these efforts, individual countries unilaterally continue to subsidize fishing activities (Sala et al., 2018).

This paper quantifies the externalities in global fisheries arising from open access and investigates how global fishery policies impact the spatial distribution of fishery activities and global welfare. I compile a novel geospatial dataset on fishery catch, fishery stock, and international trade. Guided by the stylized facts about the patterns of global fisheries with open access and subsidies, I develop a dynamic spatial model of global fisheries featuring multiple fishing locations, exporters, and importers, along with the evolution of fish stocks. To quantify the externalities from open access, I compare the outcomes from two polar cases: a decentralized equilibrium, where atomistic firms have open access to the fishery, and the optimal allocation, where a social planner has exclusive property rights. I analytically characterize the difference in outcomes between the two, where the social planner fully internalizes the externalities of fishery production while the atomistic firms do not. The quantitative results show that in the social planner allocation, the average global fishery stock at the steady state increases by 88%, and the net present value of global welfare increases by 0.11% compared to the decentralized equilibrium. To understand policy impacts, I conduct a coun-

[1] The 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).

[2] 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 (UN, 1982). More recently, attention has shifted to protecting fish stocks in areas beyond national jurisdiction, called 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).

terfactual analysis of permanently eliminating fuel subsidies and find that fuel subsidies are globally welfare-reducing and decrease the average global fishery stock at the steady state by 3.2%.

I begin by compiling a novel comprehensive geospatial dataset, consisting of global fishery catch, global fishery stocks, international trade, and other complementary statistics. First, the geospatial dataset on global fishery catch from Sea Around Us provides detailed information on catch weights by countries and species at the grid-level ($0.5° \times 0.5° \approx 60km \times 60km$). Second, the fishery stocks are estimated at the grid level using the estimation package from natural science literature, taking the fishery catch data as one of the inputs. Third, I construct a fishery trade dataset with domestic consumption by harmonizing bilateral fishery trade flows with FAO food balance sheets. Fourth, I collect other complementary statistics on fishery such as fishery habitat suitability, ex-vessel prices, employment, and subsidies, which I use for model calibration and estimation. By combining the geospatial catch dataset ("production flows") with the international trade dataset ("trade flows"), I track the flow of fisheries from fishing locations to final destinations, offering a valuable resource for quantitative analysis.

Using this dataset, I present three empirical findings that motivate my quantitative model of 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, the lack of property rights is associated with lower fishery stock. Taking the declaration of EEZ in 1994 as a natural experiment, I show that the fishery stock decreased relatively more in the high sea compared to EEZ. Third, government subsidies to the fishing industry, such as fuel subsidies toward vessels, are correlated with high seas fishing. This finding suggests that understanding the spatial dimension of the global fishery is crucial to examining the impact of fishery policies and informs the key elasticity of substitution across fishing locations at the calibration.

I then develop a dynamic spatial model of global fisheries that incorporates the evolution of fishery stocks under a global trade system. The quantitative model accounts for multiple exporters and importers, multiple fishing locations, and two industries with outside good and fishery sectors. The fishery output is consumed as nested constant elasticity of substitution (CES), where fish are differentiated by the order of species, exporters, and fishing locations at each tier of the nests.[3] The fishery stocks evolve according to a law of motion governed by nature, closely following the literature from natural science on population dynamics. Firms in the fishery sector are subject to two frictions: iceberg commuting costs to reach fishing locations from home countries and iceberg trade costs to ship fish from home countries to

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

final destinations.

The quantitative model features two key characteristics. First, fishing productivity is an increasing function of fishery stocks. Fishery production today results in the fishery sector becoming less productive in the future, implying an 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. The atomistic firms ignore the impact of harvesting on future stock and solve a static optimization problem, not accounting for the dynamic social cost of fishing. As a result, the decentralized equilibrium allocation equalizes the marginal utility of fishery consumption with the static marginal cost of fishing, which is the input cost per unit of output.

To quantify the externalities, I compare the decentralized equilibrium with the optimal allocation by the social planner. I begin with characterizing the planner's problem that directly chooses the allocation of labor and consumption. In contrast to atomistic 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 planner allocation equalizes the marginal utility of fishery with the total cost of fishing, which includes both the static marginal cost and the dynamic social cost. The dynamic social 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 fewer inputs to the fishery and keeps a 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, 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 fishing locations. I group fish species into 10 broader species following the ISSCAAP classification. By calibrating the model to data in 2018, I estimate the elasticities of substitution from IV regression that uses the exogenous variations in the geographical proximity to fishery habitat as a supply-side shock. Finally, I recover the fundamentals from model inversion.

I use the calibrated model to quantitatively address the two questions of this paper. First, I compare the baseline decentralized equilibrium with the optimal allocation by the social planner. This comparison allows me to measure the inefficiencies associated with the externalities in global fisheries. Second, I examine a counterfactual scenario where I permanently eliminate all fuel subsidies. This exercise allows me to quantify the effect of fishery policy on the spatial distribution of fishing activities and global welfare.

In the baseline decentralized equilibrium, I find that the average global fishery stock decreases by 32% at the steady state compared to the initial year of 2018. 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, in the socially optimal allocation, the average global fishery stock increases by 27% at the steady state compared to the initial year of 2018. Comparing steady states, the average global fishery stock in the socially optimal allocation is 88% larger than the average global fishery stock in the decentralized equilibrium. In the socially optimal allocation, the net present value of global welfare increases by 0.11% compared to the decentralized equilibrium. The reason is that the planner internalizes the effect that fishing today has on the productivity of fishing tomorrow, and consequently allocates fewer workers toward fishery than in the decentralized equilibrium. While less fish is consumed in the earlier periods, fishery consumption exceeds the level of the decentralized equilibrium over time since the accumulated stock increases fishery productivity and allows for more fishery consumption even with less labor. Moreover, since more labor is allocated to the outside good sector, the consumption of outside good is larger than in the decentralized equilibrium.

Lastly, I turn to examine the impact of fuel subsidies. In a scenario where all such subsidies are permanently eliminated, I find the average global 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 earlier periods but increases as the stock accumulates.

Related Literature. This paper contributes to three major strands of literature. First, this study contributes to 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 advances, as noted by Desmet and Rossi-Hansberg (2024), have incorporated spatial dimensions into quantitative models. Several recent 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). Recent work has also started studying the quantitative relationship between trade and natural resources. These papers 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, Hsiao (2024) on international cooperation in the palm oil market and Carleton et al. (2024) on the agricultural trade and the spatial allocation of global water use. My paper is unique in characterizing the optimal allocation by the planner and quantifying the externalities from open access to natural resources in the context of global fisheries. 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 work includes 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. Elliott et al. (2010) and Shapiro (2021) develop quantitative analyses of environmental policies. More recently, Farrokhi and Lashkaripour (2024) characterize optimal climate and trade policies in a multi-country general equilibrium model and quantitatively assess the performance of these policies. The contribution of my paper lies in the quantitative analysis of optimal allocation in dynamic settings.

Lastly, I contribute to the extensive literature on the extraction of natural resources and fisheries. Building on the seminal 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; Noack and Costello, 2024). 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). I complement these studies by linking the global fishery catch data with international trade and offering a global general equilibrium quantification of externalities from open access to fishery.

The rest of the 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 4.3 describes the planner's problem and discusses the comparison with the decentralized equilibrium. Section 5 calibrates the model by taking the model to data. Section 6 shows the quantitative results from the decentralized equilibrium, the social planner, and the counterfactual scenario. Section 7 concludes.

2 Data

This section describes a novel dataset that combines geospatial datasets of global fishery catch and stock with international trade flows and other fishery datasets.

Fishery Catch. The fishery catch dataset is sourced from Sea Around Us.[4] The dataset spans annually since 1980 for approximately 200 countries, covering 1,100 species worldwide. This dataset provides the catch quantity in tonnes for each species by individual country at the grid level of fishing location ($0.5° \times 0.5° \approx 60km \times 60km$). The grid level estimation process integrates information from several sources, including grid-level natural habitat conditions, national statistics by individual countries, and the Food and Agriculture Organization fishery database (Zeller and Pauly, 2015).[5] To give a graphical illustration of the catch dataset, Figure 1 panel (a) displays a map of the catch of Big Eye Tuna in 2018.

Fishery Stock. I employ the CMSY++ package provided by the Sea Around Us to estimate fishery stock levels. The package takes historical catch data and biological information of species as inputs and estimates the time series of fishery stock.[6] The estimation also allows me to infer the carrying capacity, which is the maximum population that can be attained at the grid by species. Taking the inputs as given, the model infers the stock and carrying capacity that best rationalizes the time series of observed catch.[7] The machine learning algorithm, trained on direct observation data, enhances the estimation accuracy.[8] Inputting the fishery catch dataset to the CMSY++ package, I obtain the time series of fishery stock since 1980 and the carrying capacity for 1,100 species at the grid-level. To give a graphical illustration of the stock dataset, Figure 1 panel (b) displays a map of the stock of Big Eye Tuna in 2018.

Fishery Trade. I construct a fishery trade dataset by combining bilateral trade flows with domestic consumption from the food balance sheet, both sourced from FAO. The FAO dataset on bilateral trade flows includes the quantity and value of trade between 240 countries for over 1,000 products since 2019. Dealing with domestic consumption has often been

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

[5]The FAO publishes the annual global fisheries statistics with fishing location information based on individual country surveys (FAO, 2024a). However, the FAO dataset's geographic units are much broader than the Sea Around Us dataset, classifying the global ocean into 19 FAO major fishing areas. The primary benefit of the granular dataset from Sea Around Us is that it allows me to distinguish between EEZ and high sea.

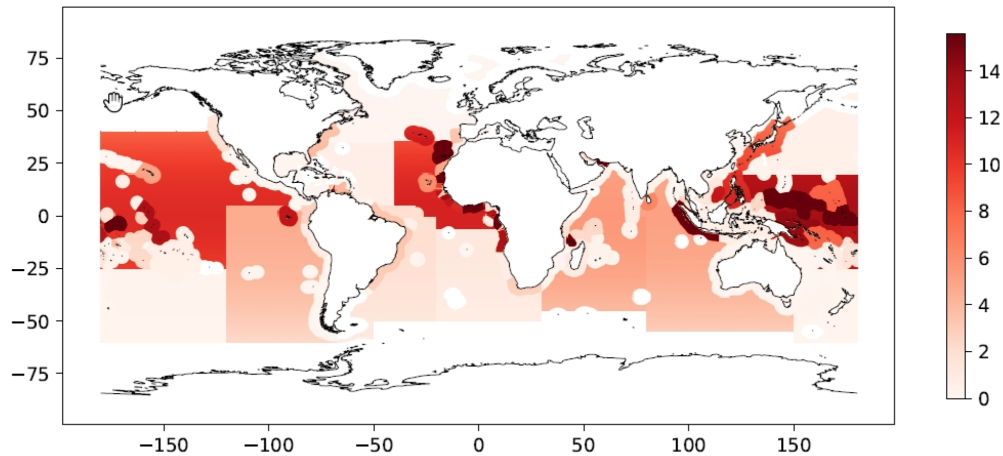
[6]Estimating fishery stock is inherently more complicated than estimating fishery catch. Broadly, there are two methods of measuring fishery stock in the literature: direct estimation via research vessels, which is limited in scope and commonly conducted by developed countries, and indirect estimation from historical catch and biological data. The indirect method, while broader and longitudinal, relies on assumptions about the model of stock growth. CMSY++ package combines the indirect method with a machine learning algorithm.

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

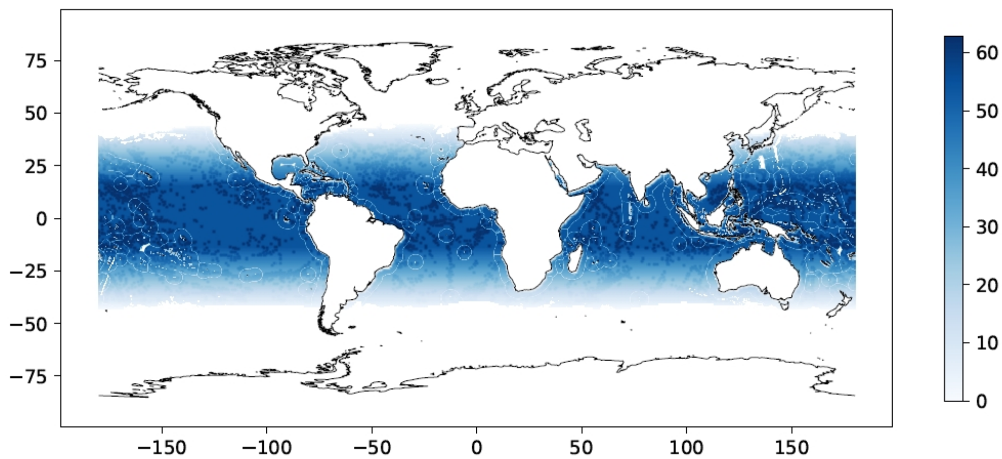
[8]Froese et al. (2023) validate this methodology, demonstrating that stock levels for 91% of species in the training set fall within the model's 95% confidence interval in cross-validation.

Figure 1: Global Catch and Stock of Big Eye Tuna (2018, in tonnes)

(a) Global Catch of Big Eye Tuna (2018, in tonnes)



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



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

problematic in international trade literature. I overcome this difficulty by complementing the trade dataset with the FAO food balance sheet.[9] The food balance sheet dataset provides information on food production, domestic consumption, exports, and imports by type of commodities after 2010. I merge 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 the two datasets.

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

Other Fishery Datasets. Other fishery datasets used in the paper include fishery habitat suitability, fishery ex-vessel prices, fishery subsidies, and fishery employment. The fishery habitat suitability, provided by Sea Around Us, measures the time-invariant suitability of overall geographic conditions at the grid level for over 1,000 species.[10] The fishery ex-vessel prices, also published by Sea Around Us, measure the landed value of fishery at the port, expressed in nominal USD per tonne since 1980.[11] While the fishery ex-vessel price data does not vary across fishing locations, it provides a consistent comparison of landed value across countries and species (Sumaila et al., 2015). The country-level fishery subsidies data, sourced from Sumaila et al. (2019), are available from 2002 to 2018. Lastly, fishery employment data are from the OECD since 2010.

Geographic Boundaries. I use the geographic boundary shapefiles to assign $0.5° \times 0.5°$ grids into EEZs and high seas. To assign the grids into EEZs, I use the shapefile of EEZ boundaries from version 12 of Flanders Marine Institute, one of the most commonly accepted boundaries in the literature.[12] To assign the grids into high seas, I use the shapefile from FAO major fishing area boundaries.[13]

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

Harmonization of Datasets. For the rest of the paper, I harmonize the dataset in the following way. First, I classify countries into 30 countries, consisting of 25 individual countries and 5 regional aggregates. 25 individual countries are picked based on the national GDP and fishery output, covering 78% of global GDP and 84% of global fishery output. The remaining countries are regrouped into 5 regional aggregates based on their continents. Appendix Table A.1 provides the mapping of countries. Second, I classify $0.5° \times 0.5°$ grids of the global ocean into 46 fishing locations, consisting of 30 EEZs and 16 high seas. Each EEZ maps to the EEZ of each country, picked earlier based on the size of the overall economy and fishery industry. Each high sea corresponds to each of FAO major fishing areas that are exclusive of EEZs. By overlaying the shapefile of EEZs with the shapefile of FAO major fishing areas, I define each high sea as the grids belonging to each of FAO major fishing areas but not to any of EEZs.

[10] The geographic conditions include but are not limited to depth, distance from the coast, and the existence of coral reefs (Zeller and Pauly, 2015).

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

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

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

Appendix Table A.2 provides the list of 46 fishing locations. Lastly, I aggregate individual species into 10 species. While the fishery catch dataset covers more than 1,100 species and the fishery trade dataset covers about 1,000 products, I harmonize the dataset by mapping them into 10 species from the International Standard Statistical Classification of Aquatic Animals and Plants (ISSCAAP). Appendix Table A.3 provides the list of 10 species. As a result, the harmonized dataset consists of 30 countries, 46 fishing locations, and 10 species.

3 Empirical Patterns

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

Pattern 1. Decreasing Global Fishery Stock

Figure 2 shows the trend in global fishery stock between 1980 and 2018. The solid line refers to the average stock to capacity ratio across all units globally, 10 species by 46 fishing locations. During this period, the average stock to capacity ratio decreased from 65% to 42%, implying a 35% decrease. The dotted line refers to the proportion of overfished species. Following the criteria from FAO, which defines the species as overfished if the stock level falls below 40% of carrying capacity, I find that the proportion of overfished species increased from 17% to 43% during this period. Appendix Table B.4 provides detailed descriptive statistics of fishery stock changes by species.[14]

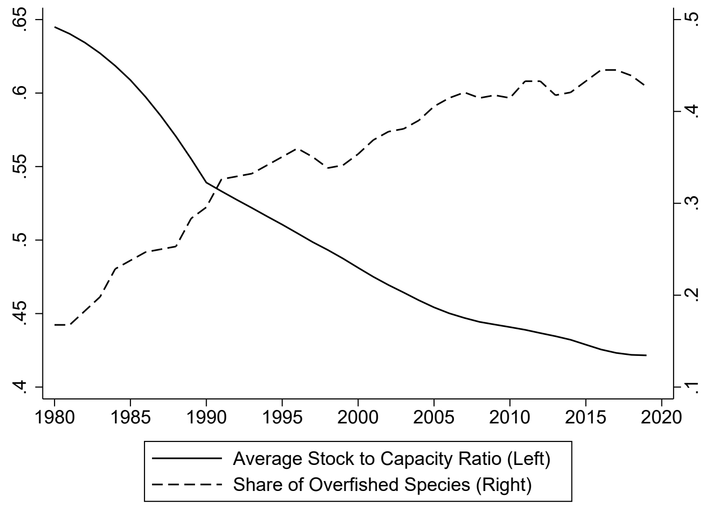
Pattern 2. Lack of Property Rights is Associated with Lower Fishery Stock

Next, I examine the relationship between property rights and fishery stock. To do so, I employ the following difference-in-difference framework, taking the declaration of EEZs as a quasi-experiment. In 1994, the declaration of EEZs provided coastal nations with property rights over marine resources within 200 nautical miles of their shores.[15]I argue that the declaration of EEZs was exogenous to the fishery stock, as the focus of the introduction

[14]Appendix Table B.4 suggests the heterogeneity in stock changes across species. Some stocks, such as squids, experienced more than 40% decrease in stock, while some stocks, such as codes, only decreased by 6%.

[15]While EEZs were first defined in the 1982 United Nations Convention on the Law of the Sea, they were formally declared and became effective in 1994.

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



Notes: Species and fishing locations are aggregated into 10 species and 46 fishing locations. A species by region is defined to be overfished if the stock is below 40% of carrying capacity, following the criteria from FAO (FAO, 2022).

of EEZs was primarily on energy and mineral resources due to the relative size of sectors (Osherenko, 2006).

Taking the declaration of EEZ in 1994 as a quasi-experiment, I estimate equation (1) to study the effect of property rights on fishery stock

$$\frac{x_{k,st}}{M_{k,s}} = \beta_0 + \beta_1 HS_k \times Post_t + \delta_{k,s} + \delta_t + \varepsilon_{k,st} \tag{1}$$

where $x_{k,st}/M_{k,s}$ is the stock to capacity ratio in fishing location k for species s at year t, HS_k is the indicator variable for whether fishing location k belongs to the high sea, $Post_t$ is the indicator variable for whether year t is after the EEZ declaration, $\delta_{k,s}$ is the fishing location-species fixed effect, δ_t is the year fixed effect, and $\varepsilon_{k,st}$ is the error term. The coefficient β_1 measures the average differences in the outcome variable across stocks in the high sea relative to EEZ after the EEZ declaration.

Table 1 shows the estimation result of equation (1). I find that the average stock to capacity ratio decreased by around 5.3 percentage points in the high sea relative to EEZ after 1994. This pattern motivates a model in which lack of property rights lead to exploiting fishery stock. Thus, I compare two polar cases of property rights in the model: the decentralized equilibrium where firms are atomistic and the socially optimal allocation where the planner has globally exclusive property rights.

Table 1: Lack of Property Rights and Fishery Stock (1980-2018)

	(1)
$HS_k \times Post_t$	-0.053***
	(0.007)
Location-Species FE	Y
Year FE	Y
N	15,480
R^2	0.618

Notes: The fishing locations and species are aggregated into 46 fishing locations and 10 species. HS_k is the indicator variable for whether fishing location k belongs to the high sea and $Post_t$ is the indicator variable for whether year t is after the EEZ declaration.

Pattern 3. Subsidies are Correlated with High Sea Production

Finally, I investigate the impact of fishery subsidies on the location of fishing. Despite global efforts to preserve fishery stocks (UN, 1982, 2023), individual countries continue to promote fishing activities, mainly 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, the fishery remains highly subsidized, with subsidies accounting for 10% of global fishery output (Sala et al., 2018).[16]

Among the major types of fishery subsidies, fuel subsidies are important for the following reasons.[17] First, they constitute the largest single category of subsidies, representing 21% of total subsidies in the fishing industry in 2018. Second, they have become the primary target for global regulation due to their role in facilitating the exploitation of resources in the high sea by extending the operational range of fishing fleets (Sumaila et al., 2019). Appendix Table B.5 shows the summary statistics of fuel subsidies between 2002 and 2018.[18]

I consider equation (2) to explore the relationship between subsidies and the location of fishing:

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

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

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

[17] The major types of subsidies include fuel, infrastructure, and management subsidies (Sumaila et al., 2019).

[18] China has more than doubled its fuel subsidies during this period, accounting for more than 40% of total fuel subsidies in 2018.

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

	All (1)	Fuel (2)
$\Delta \ln S_{i,t}$	0.323*	0.111**
	(0.163)	(0.042)
Other Controls	Y	Y
R^2	0.176	0.268
N	30	30

Notes: The regression is weighted by log output in the initial year 2002. Each column refers to the type of subsidies. Other controls include log differences of population and GDP per capita.

There could be a concern about the confounding factors that affect the incentives to provide subsidies and the fishing locations. For example, if EEZs were fully exploited due to higher demand for fishery, governments could have larger incentives to provide subsidies, affecting the amount of subsidies and the relative production at the high sea. To address the endogeneity issue, I control for population growth and GDP growth.

Table 2 shows the regression results where each column refers to different types of subsidies. Column (1) suggests that a 10 percent increase in fishery subsidies is associated with a 3 percent increase in the output from high sea relative to EEZ. Column (2) implies that the effect is particularly larger for fuel subsidies. I find that a 10 percent increase in fuel subsidies is correlated with an 11 percent increase in the output from high sea relative to EEZ.

Motivated by this empirical fact, I examine the impact of fuel subsidies on the spatial distribution of fishing activities in the quantitative exercise. Moreover, the regression is informative about the elasticity of substitution across fishing locations. 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 5, I simulate the model and estimate equation (2) using the simulated results to discipline the elasticity of the substitution parameter.

4 A Model of Global Fishery

In this section, I develop a dynamic spatial model of global fishery, where each country produces from fishing locations and exports to another country. I compare two polar cases: a decentralized equilibrium, where atomistic firms have open access to the fishery, and the socially optimal allocation, where a social planner has exclusive property rights. While the atomistic firms solve a static problem, the global social planner solves a dynamic problem, fully internalizing the social cost.[19] I describe the environment and characterize the decentralized equilibrium and the planner's problem.

4.1 Environment

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 country. Since I and H are disjoint, there are in total $K = I + H$ fishing locations, indexed by k. Time is discrete and indexed by t. The economy has two sectors: fishery, f, and outside good, o. The fishery sector is disaggregated into $s \in S$ species. Outside good is freely traded and serves as numeraire. The frictions in the economy are iceberg commuting costs and iceberg trade costs. The iceberg commuting costs are frictions that the exporter i faces when it harvests at fishing location k and brings back the output to its port. The iceberg trade costs are frictions that the exporter i faces to ship fishery to the importer j. The economy is endowed with the initial fishery stock $x_{k,s0}$, distinguished by fishing location and species, and total labor force $\tilde{L}_i$ by each country. For expositional purposes, I suppress the subscript f for the fishery sector.

4.1.1 Preferences.

The aggregate household in country j has quasi-linear preferences between outside good and fishery bundle:

$$U_{j,t} = C^o_{j,t} + b_j \ln C_{j,t} \tag{3}$$

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, and b_j is the demand shifter of the fishery bundle.

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

[19] The real world can be interpreted as in-between two polar cases, where individual countries internalize some dynamic costs within their EEZs.

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

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

4.1.2 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

$$\begin{aligned} x_{k,st+1} - x_{k,st} &= G(x_{k,st}) - H(x_{k,st}) \\ &= \gamma_{k,s} x_{k,st} (1 - \frac{x_{k,st}}{M_{k,s}}) - \sum_{i \in I} \sum_{j \in I} d_{ij,s} \tau_{ik,s} Q_{ijk,st} \end{aligned} \tag{7}$$

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 fishery growth is an inverted U-shape and takes its maximum at $x_{k,st}/M_{k,s} = 0.5$.[20] The intuition is that when the stock level is too low relative to the carrying capacity, reproduction is difficult because fish are harder to find mates. When the stock level is too high relative to carrying capacity, overcrowding hinders reproduction.[21]

[20] The first partial derivative of fishery growth is a decreasing function of $x_{k,st}$ and the second partial derivative is negative.

[21] This is closely related to 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.

4.1.3 Technology.

In the fishery sector, given the stock to capacity ratio $x_{k,st-1}/M_{k,s}$, each variety of fish is produced under the constant to returns to scale technology:

$$Q_{ijk,st} = \frac{z_i \left(x_{k,st-1}/M_{k,s}\right)^{\xi}}{d_{ij,s}\tau_{ik,s}} L_{ijk,st} \tag{8}$$

where $Q_{ijk,st}$ is the output quantity of fishery, $d_{ij,s}$ is the iceberg trade cost, $\tau_{ik,s}$ is the iceberg commuting cost, z_i is the country-specific productivity shifter, ξ is the stock elasticity of output, and $L_{ijk,st}$ is the labor input.

Since the output $Q_{ijk,st}$ is specific to the exporter, the importer, and the fishing location, the fishery technology is subject to the iceberg trade and commuting costs. For the importer to consume one unit of fish, the exporter sends $d_{ij,s}$ units of fish under the iceberg trade cost. Additionally, for the exporter to send $d_{ij,s}$ units of fish, the exporter needs to catch $d_{ij,s}\tau_{ik,s}$ units of fish from the fishing location under the iceberg commuting cost.

Moreover, the fishery productivity is an increasing function of the stock to capacity ratio, reflecting that harvesting becomes easier when there are more stocks. One percent increase in stock to capacity ratio generates ξ percent increase in output.

In the outside good sector, outside good is produced under the constant to returns to scale technology:

$$Q^o_{i,t} = z^o_i L^o_{i,t} \tag{9}$$

where z^o_i is the productivity shifter, and $L^o_{i,t}$ is the labor input. I assume that the outside sector is large enough to be produced at every country.

4.2 Decentralized Equilibrium

In this subsection, I characterize the decentralized equilibrium where fishery firms are atomistic under open access to the fishery. All markets are perfectly competitive. The outside good is freely traded and serves as numeraire. Each atomistic firm solves a static problem, ignoring the impact of its harvest on future stock. The only dynamic factor is the evolution of fishery stock in the decentralized equilibrium. The details are provided in Appendix The details are provided in Appendix C.1.

4.2.1 Utility Maximization

Given equations 3, 4, 5, and 6, the aggregate household in country j maximizing its utility allocates a fixed amount of its expenditure b_j on fishery bundle and the rest to the outside good such that

$$X_{j,t} = b_j, \quad X^o_{j,t} = E_{j,t} - b_j$$

where $X_{j,t}$ is the fishery expenditure and E_{jt} is the household income.

The expenditure share of species s in all fishery expenditure by country j, $\pi_{j,st}$, and the consumer price index in country j 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 of country i in all expenditure by country j for species s, $\pi_{ij,st}$, and the consumer price index in country j for 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 of fishing location k in all expenditure by country j for species s from country i, $\pi_{ijk,st}$, and the consumer price index in country j for species s from country i, $P_{ij,st}$, are given by

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

where $p_{ijk,st}$ equals to the marginal cost of production for species s from exporter i to importer j at fishing location k.

4.2.2 Profit Maximization

Given equation 8, for each variety of fish, a representative firm in the fishery sector chooses its labor inputs, thus its output, to maximize the profit. I assume that each firm is atomistic under open access. The atomistic firm ignores the impact of its harvest on future stock. Instead of solving a dynamic problem, each firm solves a static problem, taking the stock to capacity ratio as given. The price of fishery equals the marginal cost of production such that

$$p_{ijk,st} = \frac{d_{ij,s}\tau_{ik,s}}{(x_{k,st-1}/M_{k,s})^{\xi}} \frac{w_{i,t}}{z_i} \tag{10}$$

Given equation 9, a representative firm in the outside good sector chooses its labor inputs, thus its output, to maximize the profit. I assume that the outside good is freely traded and serves as numeraire. I further assume that the outside good sector is large enough and the fishery sector is relatively small such that the outside good is produced in all countries.

4.2.3 Labor Mobility

I assume a perfect mobility of workers across sectors. Since the outside good serves as numeraire, the wage that applies to all workers is exogenously determined as the productivity shifter of outside good such that

$$w_i^o = w_i = z_i^o \tag{11}$$

4.2.4 Market Clearing.

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

$$Y_{ijk,st} = \pi_{ijk,st}\pi_{ij,st}\pi_{j,st}X_{j,t} \tag{12}$$

where $Y_{ijk,st}$ is the fishery output and $X_{j,t}$ is the total expenditure on fishery in destination j

$$X_{j,t} = b_j \tag{13}$$

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

$$\sum_{i\in I} Y_{i,t}^o = \sum_{j\in I} X_{j,t}^o \tag{14}$$

where $Y_{i,t}^o$ is the outside good output and $X_{j,t}^o$ is the outside good expenditure

Labor market clearing requires that payments to labor equal output

$$w_{i,t}L_{ijk,st} = Y_{ijk,st}, \quad w_{i,t}^o L_{i,t}^o = Y_{i,t}^o \tag{15}$$

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

$$\sum_{j\in I}\sum_{s\in S}\sum_{k\in K} w_{i,t}L_{ijk,st} + w_{i,t}^o L_{i,t}^o = X_{i,t} + X_{i,t}^o \tag{16}$$

4.2.5 Definition of 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 $\{C_{ijk,st}, C^o_{i,t}\}$, output $\{Q_{ijk,st}, Q^o_{i,t}\}$, labor allocation $\{L_{ijk,st}, L^o_{i,t}\}$, prices $\{p_{ijk,st}\}$, wages $\{w_{i,t}, w^o_{i,t}\}$, and fish stock $\{x_{k,st}\}$, such that household maximizes its utility according to (3), firms maximize their profits according to (8) and (9), stock of fish evolves according to (7), markets clear according to (12) and (14) and (15), and the balance of budget holds according to (16)

Definition. **[Steady-state equilibrium]** A **steady state equilibrium** is the allocation that satisfies the conditions of competitive equilibrium in addition to the condition where the regrowth of fishery equals with total harvest such that

$$\gamma_{k,s} x_{k,st}(1 - \frac{x_{k,st}}{M_{k,s}}) = \sum_{i \in I} \sum_{j \in I} d_{ij,s} \tau_{ik,s} Q_{ijk,st} \quad \forall k, s \tag{17}$$

4.2.6 Fishery Consumption in the Decentralized Equilibrium.

Rearranging the first-order conditions from households and firms, I can characterize the fishery consumption in the decentralized equilibrium as:

$$\underbrace{\frac{\partial U_{j,t}}{\partial C_{ijk,st}}}_{\text{MU of fishery consumption}} = \underbrace{\frac{\partial U_{j,t}}{\partial C^o_{j,t}} \left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}} \Big/ \frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}} \right)}_{\text{MC of fishery consumption}} \tag{18}$$

Equation (18) implies that the fishery consumption for each variety is determined where the marginal utility of fishery consumption equals the marginal cost of fishery consumption. Since each atomistic firm ignores the impact of its harvest on stock and future productivity, the marginal cost is static, and it is the foregone utility from outside goods that could have been achieved if the additional fishery were not consumed. As in equation (10), the price of fishery equals the static marginal cost of fishing, which is the input cost per unit of output. These expressions will be useful when comparing with the planner allocation in Section 4.3.

4.3 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 socially optimal allocation with the decentralized equilibrium.

4.3.1 Planner's FOC

Given the GE equations (3)∼(9), define the global welfare W_t as

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

where $\phi_i \geq 0$ is the Pareto weights.

The planner allocates the labor, consumption, and fishery stock to maximize the discounted present value of global welfare such that

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

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.

4.3.2 Fishery Consumption in the Planner Allocation.

In this subsection, I compare the first-order conditions of the planner allocation and the decentralized equilibrium. The key difference between the planner allocation and the decentralized equilibrium is that the planner fully internalizes the social cost of fishing.

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

$$\underbrace{\frac{\partial W_t}{\partial C_{ijk,st}}}_{\text{MU of fishery consumption}} = \underbrace{\underbrace{\frac{\partial W_t}{\partial C^o_{j,t}} \left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}} \Big/ \frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}} \right)}_{\text{static MC}} + \underbrace{\frac{\beta \Omega_{k,st}}{1 - \beta \Theta_{k,st}} \frac{\partial H_{k,st}}{\partial Q_{ijk,st}}}_{\text{dynamic MC}}}_{\text{MC of fishery consumption}} \tag{19}$$

where $\Omega_{k,st} = \partial W_{t+1} / \partial x_{k,st}$ and $\Theta_{k,st} = \partial x_{k,st+1} / \partial x_{k,st}$. The derivation details are provided in Appendix C.2.

For each variety of fishery $C_{ijk,st}$, the planner allocates consumption until the marginal utility of consumption equalizes with the social cost of consumption. The left-hand side of equation (19) is the marginal utility of additional fishery $C_{ijk,st}$. The right-hand side of equation (19) 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 (19) 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 (19) refers to the dynamic marginal cost, which is the foregone welfare from lower future productivity due to decreased fishery stock. Recall that 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 the 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 static and dynamic stock multiplier determine the amount of total stock affected. The static multiplier $\partial H_{k,st}/\partial Q_{ijk,st}$ captures the amount of fish that needs to be extracted for additional consumption today, which is the iceberg friction. The dynamic stock multiplier $\Theta_{k,st}$ captures the change in the number of stocks next period, given one unit change in fishery stock today. Since regrowth and harvest of fish depend on the stock level, the change in stock at the next period, given one unit change of stock today, is not necessarily one. However, it is endogenously determined by $\Theta_{k,st}$. Given a unit decrease in fishery stock today, the number of stock in the 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, each atomistic firm in the decentralized equilibrium ignores the impact of its own harvest on the future stock and perceives the static stock multiplier as $\partial H_{k,st}/\partial Q_{ijk,st} = 0$. Rearranging equation (19) with $\partial H_{k,st}/\partial Q_{ijk,st} = 0$, equation (20) coincides with the first-order condition from decentralized equilibrium in equation (18).

$$\begin{aligned} \frac{\partial W_t}{\partial C_{ijk,st}} &= \frac{\partial W_t}{\partial C^o_{i,t}}\left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}}/\frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}}\right) \\ \Leftrightarrow \frac{\partial U_{j,t}}{\partial C_{ijk,st}} &= \frac{\partial U_{j,t}}{\partial C^o_{i,t}}\left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}}/\frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}}\right) \end{aligned} \tag{20}$$

The key difference between the planner allocation and the decentralized equilibrium is that the planner internalizes the dynamic marginal 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 marginal cost is positive and the marginal utility of fishery consumption diminishes, the planner allocates fewer inputs to the fishery and keeps larger fishery stocks than in the decentralized equilibrium. If there were no productivity gains from fishery stock ($\xi = 0$), there would be no externalities, implying that the planner allocation 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. See Appendix C.4. □

The intuition is as follows. When ξ is large enough, given a unit increase in stock, the harvest increases enough to suppress $\Theta_{k,st}$. 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 given a unit increase in stock. As ξ approaches zero, the required $\gamma_{k,s}$ decreases and gets closer to $1/\beta - 1$.

4.4 Policy Instruments

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

The policy instrument $t_{ijk,st}$ additively increases the marginal cost of production, so that the price after the policy instrument $\tilde{p}_{ijk,st}$ becomes

$$\tilde{p}_{ijk,st} = p_{ijk,st} + t_{ijk,st} \tag{21}$$

where $p_{ijk,st}$ is the price without policy tools as described in equation (10).

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 (16) now becomes

$$\sum_{j\in I}\sum_{s\in S}\sum_{k\in K} w_{i,t}L_{ijk,st} + w^o_{i,t}L^o_{i,t} + \sum_{j}\sum_{s}\sum_{k} t_{ijk,st}Q_{ijk,st} = X_{i,t} + X^o_{i,t} \tag{22}$$

From the the dual approach, the planner can directly choose the optimal policy instruments $t^*_{ijk,st}$ that achieve the socially optimal allocation from Section 4.3.1 (Ljungqvist and Sargent, 2018).

Respecting the first-order conditions from the decentralized equilibrium, the optimal policy instruments $t^*_{ijk,st}$ equals the dynamic marginal cost from equation (19).

$$t^*_{ijk,st} = \frac{\beta\Omega_{k,st}}{1-\beta\Theta_{k,st}}\frac{\partial H_{k,st}}{\partial Q_{ijk,st}}$$

where the details are explained in Appendix C.3.

The first and second Welfare Theorem guarantee that the allocation from the primal approach, where the planner directly chooses optimal allocation, coincide with the dual approach, up to the lump-sum transfers across countries. However, the lump-sum transfers are not relevant to the allocation of fishery since there is no income effect in the fishery consumption under the quasi-linear preferences. The lump-sum transfers are Any lump-sum transfer is consistent with the optimal allocation as the outside good market clears globally all of the remaining income to the outside good. 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.

5 Taking the Model to Data

This section provides the calibration of the quantitative model. As described in Section 2, I aggregate the world into 30 countries, the ocean grids into 46 fishing locations, and the fishery species into 10 species. I take the model to data in 2018 to calibrate the model. I begin by describing the calibration of elasticities of substitutions, and proceed to the calibration of remaining parameters.

5.1 Calibration of Elasticities of Substitutions

In this subsection, I calibrate the parameters governing the elasticities of substitutions. In the spirit of Costinot et al. (2016), I use a supply-side instrument for productivity to identify the demand relationship in the gravity equation. I start by estimating the elasticity of substitution across countries η, then estimate the elasticity of substitution across species ν. Lastly, I estimate the elasticity of substitution across fishing locations κ using the indirect inference disciplined by equation (2) about the relationship between the subsidies and the location of fishing.

5.1.1 Elasticity of Substitution across Exporters (η)

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

$$\log\left(\frac{X_{ij,s}}{X_{j,s}}\right) = (1-\eta)\log p_{i,s} + \phi_{j,s} + \phi_{ij} + \varepsilon_{ij,s}$$

where $X_{ij,s}/X_{j,s}$ is the expenditure share for exporter i in all expenditure by importer j for species s, $p_{i,s}$ is the producer prices at the border of exporter i for species s, $\phi_{j,s}$ is the importer-species fixed effect, ϕ_{ij} is the exporter-importer fixed effect, and $\varepsilon_{ij,s}$ is the residual term. I observe the expenditure share $X_{ij,s}/X_{j,s}$ from the trade dataset, and the producer prices at the border $p_{i,s}$ from the ex-vessel prices dataset, which is invariant cross fishing locations. In particular, the producer prices at the border $p_{i,s}$ is:

$$p_{i,s} = \left[\sum_{k\in K} b_{k,s}\left(p_{ik,s}\right)^{1-\kappa}\right]^{\frac{1}{1-\kappa}}$$

where $p_{ik,s}$ equals to the marginal cost of production by exporter i at fishing location k for species s. From the exporter-importer fixed effect $\phi_{j,s}$ and the residual term $\varepsilon_{ij,s}$, I recover the exporter-importer specific preference shifter b_{ij} and the trade cost $d_{ij,s}$ such that $b_{ij} = \exp\left(\phi_{ij}\right)$ and $d_{ij,s} = \exp\left(\frac{1}{1-\eta}\varepsilon_{ij,s}\right)$.

A concern about endogeneity arises because prices can be correlated with unobserved demand shifters. To mitigate this concern, I adopt a supply-side IV, which is correlated with the producer prices at the border but uncorrelated with an unobserved demand shifter. Specifically, I instrument the producer prices at the border $p_{i,s}$ with the proximity to suitable habitats $Z_{i,s}$ by exporter i for species s.

I construct the instrument, the proximity to suitable habitats $Z_{i,s}$, using the grid level data on habitat suitability and the linear distance between each grid and the closest port of countries. The grid level data on habitat suitability $Z_{g,s}$ measures how suitable habitat a grid g is for the species s, using the geographic conditions including ocean depth, temperature, and climate. I construct the country level measure for proximity to habitat suitability, $Z_{i,s}$ by taking the weighted average of the habitat suitability $Z_{g,s}$ across grids, where the inverse of weights is the log of linear distance to each grid g from the closest port at country i:

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

The argument for the valid instrument is as follows. The relevance condition requires that the producer prices at the border for species s in exporter i are lower than that in the

Table 3: 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: The 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" restricts the sample to the species of which the Herfindahl–Hirschman Index is aobve the median, while "HHI Bottom 50" restricts the sample to the species of which the Herfindahl–Hirschman Index is below the median.

other countries if exporter i is located closer to the suitable habitat for species s than other countries are. The exclusion restriction holds as long as the distance to the suitable habitat is not correlated with the unobserved demand shifter.

Table 3 shows the estimates of η. Columns (1) and (2) show the estimation results from PPML and OLS, respectively. Column (3) shows the result from IV regression, where I obtain the elasticity of substitution across exporters $\eta = 5.025$. The first stage is negative, confirming the relevance condition that the proximity to suitable habit is associated with lower fishery prices. The large difference in the coefficient between OLS and IV indicates that the endogeneity concern from OLS could be severe.

A concern for exclusion restriction is that tastes toward the importer could reflect the proximity to suitable habitats. For example, consumers 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 suitable habitats. To investigate the validity of the concern, I estimate the parameter restricting the sample by whether the species are produced by multiple countries. In particular, I construct the relevant Herfindahl–Hirschman

Index 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 in total output of species s.

Column (4) restricts the sample to the species of which the production is concentrated in particular countries such that the HHI is above the median across all species. While the point estimate of column (4) is larger than that of column (3), I do not find a statistical significance that the coefficients are different across samples. Column (5) restricts the sample to the species of which the production is dispersed across countries such that the HHI is below the median across all species. While the point estimate of column (5) is smaller than that of column (3), I again do not find a statistical significance that the coefficients are different across samples.

5.1.2 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 the previous subsection.

$$\log\left(\frac{X_{j,s}}{X_j}\right) = (1-\nu)\log P_{j,s} + \phi_j + \varepsilon_{j,s}$$

where $X_{j,s}/X_j$ is the expenditure share for species s in all expenditure by importer j, $P_{j,s}$ is the consumer prices for fishery bundle of importer j for species s, ϕ_j is the importer fixed effect, and $\varepsilon_{j,s}$ is the residual term.

To construct the consumer prices for fishery bundle $P_{j,s}$, I use the observed producer prices at the border $p_{i,s}$ and the estimates of the preference shifter b_{ij}, the trade cost $d_{ij,s}$, and the elasticity of substitution across exporters η from the previous subsection such that

$$P_{j,s} = \left(\sum_i b_{ij} d_{ij,s}^{1-\eta} p_{i,s}^{1-\eta}\right)^{\frac{1}{1-\eta}}$$

Similarly, a concern about endogeneity arises because prices can be correlated with unobserved demand shifters. To alleviate this concern, I instrument the consumer prices $P_{j,s}$ with the proximity to suitable habitats $Z_{j,s}$ by importer j for species s. The relevance condition requires that the consumer prices in importer j for species s are lower than that for the other species if importer j is located closer to the suitable habitat of species s than to the other species. The exclusion restriction assumes that geography is uncorrelated with unobserved

Table 4: 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: The Herfindahl–Hirschman Index is constructed to measure the concentration of importers across species, such that $HHI_s = \sum_{j \in I} IMP_{j,s}^2$ where $IMP_{j,s}$ is the expenditure share of country j from total expenditure of species s. "HHI Top 50" restricts the sample to the species of which the Herfindahl–Hirschman Index is aobve the median, while "HHI Bottom 50" restricts the sample to the species of which the Herfindahl–Hirschman Index is below the median.

demand shifters across species.

Table 4 shows the estimates for ν . Columns (1) and (2) show the estimation results from PPML and OLS. Column (3) shows the result from IV regression, where I obtain $\nu = 7.562$. The first stage is negative, as expected, confirming that the relevance condition holds. The large difference in the coefficient between OLS and IV justifies the need for the instrument.

Again, a concern for exclusion restriction is that tastes toward the species could reflect the proximity to suitable habitats. For instance, Norwegian consumers might have built up a particular taste for salmon if they were disproportinately exposed to salmon and lacked exposure to other species whose habitat is distant from Norway. The coefficient would be upward-biased if such concern is valid since the preference shifter is positively associated with the proximity to suitable habitats. To study the validity of the concern, I again estimate the parameter restricting the sample by whether the species are consumed by multiple countries. I construct the relevant Herfindahl–Hirschman Index to measure the concentration of importers across species such that:

$$HHI_s = \sum_{j \in I} IMP_{j,s}^2$$

where $IMP_{j,s}$ is the expenditure share of country j in total expenditure of species s.

Column (4) restricts the sample to the species of which the consumption is concentrated in particular countries such that the HHI is above the median across all species. Column (5) restricts the sample to the species of which the consumption is dispersed across countries such that the HHI is below the median across all species. I do not find a statistical significance that the coefficients are different across samples.

5.1.3 Elasticity of Substitution across Locations (κ)

Lastly, I estimate the elasticity of substitution across locations κ from the indirect inference. The idea is that equation (2) about the relationship between the fuel subsidies and the location of fishing is informative about the elasticity of substitution across locations κ. The impact of fuel subsidies on the outputs at high sea relative to EEZ depends on how substitutable the varieties across regions are.

To estimate the elasticity of substitution across locations κ, I start by simulating the extended version of the model in Section 4.4 with the policy instruments. For a given κ, I shock the model with exogenous changes in the fuel subsidies over time that are calibrated to match the changes in fuel subsidies from actual data, where the fuel subsidies are modeled to target the high sea to generate a disproportionate effect on fishing location. Then, for each κ, I run equation (2) using the simulated data. Finally, I pick κ that generates the coefficient β_1, which best matches the coefficient from Table 2 using the actual data. The detailed step is described in the Appendix D.1.

The Appendix Figure B.2 shows the relationship between the elasticity of substitution parameter across locations κ and the estimated coefficient β_1, confirming that the effect of fuel subsidies on the outputs at high sea relative to EEZ is larger when the elasticity of substitution across locations is larger. From the indirect inference, I obtain the elasticity of substitution $\kappa = 8.075$.

5.2 Calibration of Remaining Parameters

This subsection calibrates the remaining parameters along with fundamentals. I calibrate the stock elasticity of output $\xi = 1$ as in the canonical case of Brander and Taylor (1998). The discount rate is set to $\beta = 0.97$ following Nordhaus (2007). The Pareto weights are calibrated to have equal weights across households such that $\phi_i = 1$.

Taking the model to data in 2018, I use the standard model inversion methods to recover the fundamentals. For the demand shifter toward the fishery bundle b_i, I directly match the fishery expenditure for each country i by leveraging the property of quasi-linear preference. For the demand shifter toward the species b_s, I match the expenditure share of species s in total fishery expenditure. For the demand shifter toward the exporter b_{ij}, I match the expenditure share of exporter i in total expenditure by importer j. Lastly, for the demand

Table 5: 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	$\beta = 0.97$	Nordhaus (2007)
Pareto weights	$\phi_i = 1$	

shifter toward the fishing location $b_{k,s}$, I match the expenditure share of fishing location k in all fishing locations for species s.

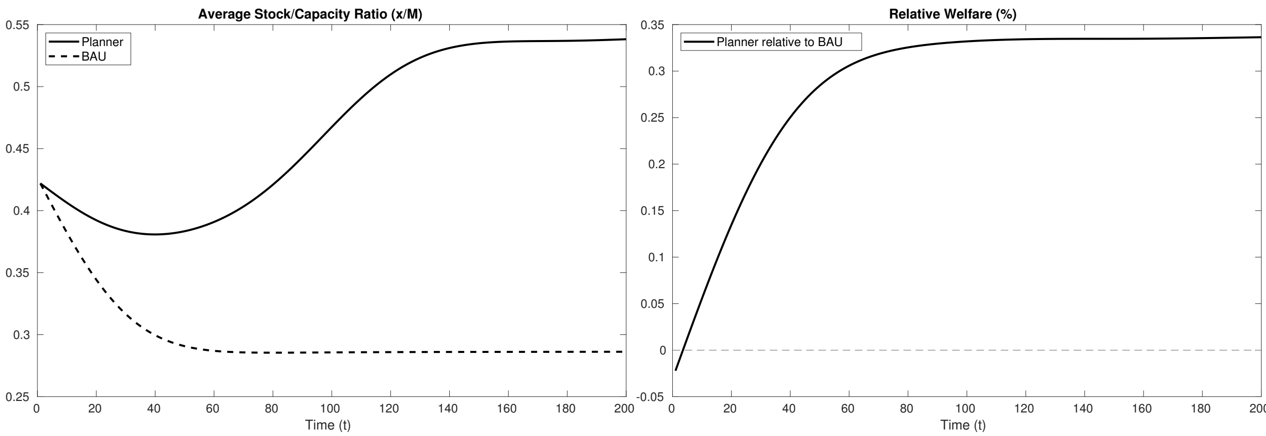
I then proceed to calibrate the productivity shifters. For the outside good productivity shifter z_i^o, I match the GDP per capita for each country i. For the fishery productivity shifter z_i, I match the levels of fishery output of country i. I recover the commuting costs $\tau_{ik,s}$ by matching the output share of fishing location k in all fishing locations by country i for species s. I use the gravity equation to recover the trade costs $d_{ij,s}$. Table 5 provides the summary of parameter calibration.

6 Quantitative Results

In this section, I examine the quantitative results from three scenarios: the decentralized equilibrium, the planner allocation, and a policy counterfactual. Using the model calibrated to data in 2018, I first project the economy forward under a Business As Usual (BAU) scenario to assess the trajectory of the decentralized equilibrium. I then contrast the BAU outcomes from the decentralized equilibrium with those from the planner allocation to quantitatively illustrate the externalities the decentralized equilibrium fails to internalize. Finally, I simulate a policy counterfactual that permanently eliminates fuel subsidies across all countries. The difference in outcomes between the BAU and the counterfactual demonstrate the impact of fuel subsidies.

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 the average stock to capacity ratio for both scenarios, the BAU and the planner allocation. Panel (b) represents the welfare from the planner allocation relative to the BAU, in percentage change.

6.1 Decentralized Equilibrium (Business As Usual) and Planner

Panel (a) in Figure 3 presents the dynamic path of the average stock to capacity ratio for both the BAU and the planner allocation. In the BAU, the average stock to capacity ratio decreases from 42.2% in the initial year to 28.6% at the steady state. In contrast, under the planner allocation, 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 that the planner internalizes the externalities of fishery production and relocates the labor from the fishery to the outside good. Under the planner allocation, 35% of fishery labor is relocated to the outside good in the initial year. Since labor has been reallocated to the fishery, the fishery output decreases, and the output from outside good increases in the initial year. Due to the additive feature in the quasi-linear utility, I can disentangle global welfare into two parts: the portion of global welfare from fishery consumption and the portion of global welfare from outside good consumption. In particular, under the planner allocation relative to the BAU, the welfare from fishery consumption decreases by 7.8% in the initial year, while the welfare from outside good consumption increases by 0.13%. With less fishery produced in the initial year, the fishery stock accumulates over time. At the steady state, the average stock to capacity ratio becomes 88% larger under the planner allocation than at the BAU steady state. As stocks accumulate, the fishery sector becomes productive, allowing for larger outputs even with fewer labor inputs. Figure 3 shows the global welfare under the planner allocation relative to

Table 6: Decentralized Equilibrium (BAU) vs. Planner

	BAU		Planner		% Difference	
	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 outcomes from the BAU and the planner allocation for the initial period and the steady state. "% Difference" refers to the percentage difference between the BAU to the planner allocation 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.

the BAU. While the relative welfare slightly decreases during the initial periods with lower fishery consumption, the larger productivity from accumulated stocks 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 the planner allocation relative to the BAU.

Appendix Figure B.3 shows the change in the average stock to capacity ratio under the BAU. Panel (b) presents the average stock to capacity ratio at the BAU steady state. Panel (c) displays the change in the average stock to capacity ratio between the initial year and the BAU steady state, indicating that most regions experience a large decline in fishery stock at the steady state under the BAU, with high seas particularly approaching complete depletion.

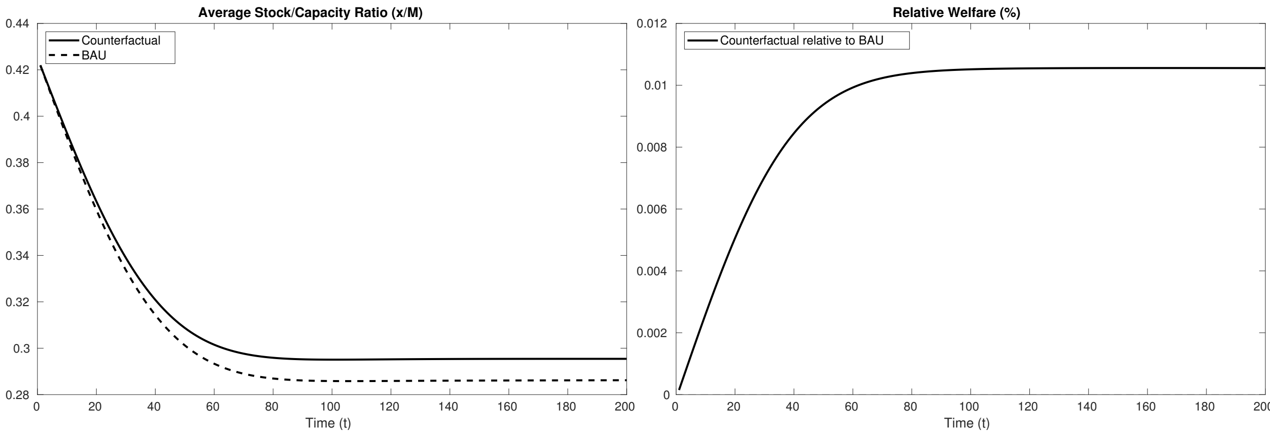
Appendix Figure B.4 displays the change in the average stock to capacity ratio under the planner allocation. Panel (b) shows the change in the average stock to capacity ratio between the initial year and the steady state. Unlike in the BAU scenario, some regions gain stock at the steady state compared to the initial year. Panel (c) reports the change in the average stock to capacity ratio between the steady states under the BAU and the planner allocation. After the planner internalizes the externalities, most regions show increase in the stock to capacity ratio, with the high seas in the Pacific Ocean showing the largest increase.

6.2 Policy Counterfactual: Eliminating Fuel Subsidies

Next, I turn to simulate the counterfactual scenario where I permanently eliminate the fuel subsidies across all countries. In particular, I impose the production tax particularly to high sea to undo the fuel subsidies present in the BAU. From the extended model with policy

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 the average stock to capacity ratio for both scenarios, the BAU and the counterfactual. Panel (b) represents the welfare from the counterfactual relative to the BAU, in percentage change.

Table 7: Counterfactual vs. BAU

	BAU		Counterfactual		% Difference	
	t=0	steady state	t=0	steady state	t=0	steady state
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%
EEZ	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 outcomes from the BAU and the counterfactual for the initial period and the steady state. "% Difference" refers to the percentage difference between the BAU to the counterfactual 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.

instruments presented in Section 4.4, I calibrate the tax rate by country so that the tax revenue matches the fuel subsidies from data.

Figure 4 presents the dynamic path of the average stock to capacity ratio under the counterfactual. 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 the fishery to outside good rises. As the demand for fishery decreases, labor is reallocated from the fishery to the outside good, similarly to the planner allocation. The welfare from fishery consumption decreases in the initial year, while the welfare from outside good consumption increases. With less harvest, fishery stocks accumulate over time, increasing the fishery productivity in the long run. At the steady state, even with less labor inputs, the welfare from fishery consumption increases compared to BAU. Finally, the net present of welfare increases by 0.004%, implying that the fuel subsidies are not welfare-improving.

Table 7 suggests that, while the production taxes are modeled to target the high sea, the fishery stock increases both at the high sea and the EEZs. The result comes from the CES structure of fishery consumption and asymmetric subsidies changing the relative price of fishery bundles across countries. Then, the production tax not only increases the price of the fishery from the high sea but also increases the price of the fishery from the EEZ since these varieties are substitutable. Such spillover effect underscores the significance of well-targeted policy.

Appendix Figure B.5 shows the change in the average stock to capacity ratio between the counterfactual steady state and the BAU steady state. The results show significant heterogeneity in the impact such that some high seas, particularly in the Atlantic Ocean, benefit the most by eliminating the fuel subsidies.

7 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. I calibrate the model and estimate key elasticities by leveraging novel geospatial data on fishery catch and stocks, providing a comprehensive framework for understanding global fishery.

The results reveal substantial inefficiencies under the Business As Usual scenario of the decentralized equilibrium. Under open access to the fishery, the atomistic firms fail to account for the dynamic social costs of fishery production, leading to the overexploitation of fishery stocks. In contrast, the social planner fully internalizes the social costs and reallocates the labor from the fishery sector to the outside good sector. While reducing the short-term fishery output, this reallocation leads to long-term gains through larger stock and increased productivity. The stark difference between the BAU and the planner allocation 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 the socially optimal allocation. To implement the socially optimal allocation, the corresponding optimal policy should vary across exporters, importers, fishing 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 fishing locations.

The contingent trade policies described in Harstad (2024) could offer a feasible approach. Such policies could mandate the specification of fishery fishing locations in trade agreements, with tariff rates contingent on the gap between current 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 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 Fishing Location. Appendix Table A.2 provides the list of 46 fishing locations in the quantitative model.

Table A.2: List of Fishing 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 fishing 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

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

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

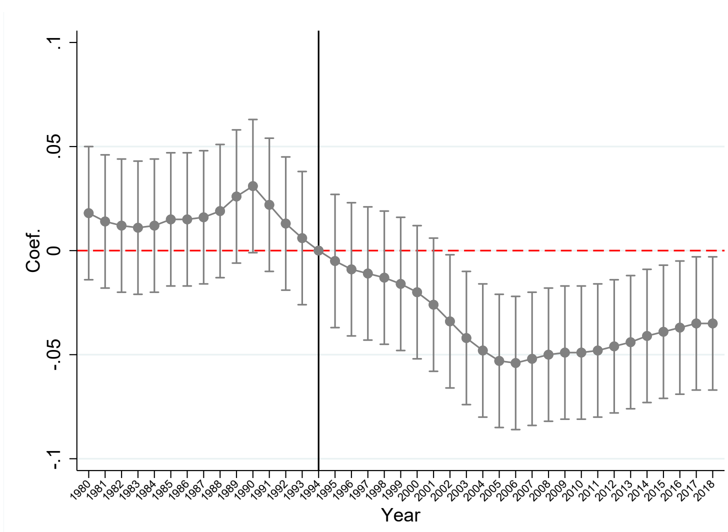
B Additional Tables and Figures

Table B.4: Summary Statistics of Fishery Stock

Species	Carrying Cap. (mil. tonnes)	Stock (mil. tonnes)		Stock/Cap. (%)		Stock (% chg.)	Stock/Cap. (p.p chg.)
		1980	2018	1980	2018		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Cods, hakes, haddocks	220.6	111.9	98.0	50.7	44.4	-6.3	-12.4
Crustaceans and mollusks	38.3	28.4	17.8	74.2	46.5	-27.6	-37.3
Herrings, sardines, anchovies	454.3	289.6	179.2	63.8	39.4	-24.3	-38.1
Salmons, trouts, smelts	80.7	59.9	40.1	74.3	49.7	-24.6	-33.1
Shrimps, prawns	18.7	14.3	9.5	76.1	50.5	-25.7	-33.7
Squids, cuttlefishes, octopuses	27.6	22.9	11.1	83.0	40.1	-43.0	-51.7
Tunas, bonitos, billfishes	112.3	83.1	57.7	74.0	51.3	-22.6	-30.6
Other Demersal and Pelagic fish	551.0	301.3	272.0	54.7	49.4	-5.3	-9.7
Other Diadromous fish	91.7	38.4	37.8	41.9	41.2	-0.7	-1.6
Other fish not identified	218.4	118.8	115.9	54.4	53.0	-1.3	-2.5

Notes: This table reports summary statistics of changes in global stock between 1980 and 2018 by fishery species used in quantitative model. Column 1 shows the global carrying capacity of species, where the global carrying capacity is calculated by summing the carrying capacity over all regions. Column 2 and 3 report the global stock of species in 1980 and 2018, where the global stock is calculated by summing the stock over all regions. Column 4 and 5 show the stock to capacity ratio in 1980 and 2018. Column 6 and 7 display the percentage change in stock and the percentage points change in stock to capacity ratio, respectively.

Figure B.1: Event Study Regression



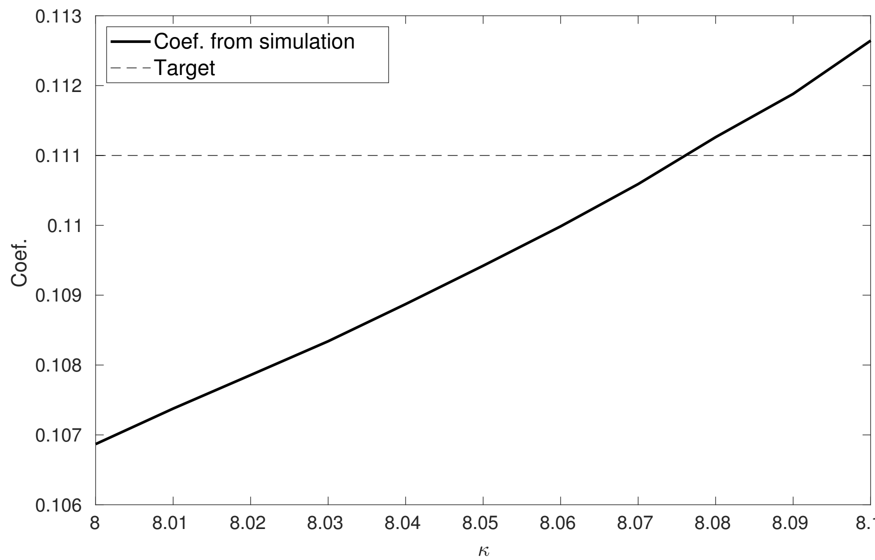
Notes: The figure shows the coefficients for the event study regression of equation (1).

Table B.5: Summary Statistics of Fuel Subsidies

ISO	Fuel Subsidies in 2003 (MM) (1)	Fuel Subsidies in 2018 (MM) (2)	Country Share in 2003 (%) (3)	Country Share in 2018 (%) (4)
CHN	1,814	3,433	28.85	44.44
JPN	1,115	632	17.73	8.18
KOR	331	604	5.26	7.82
TWN	120	593	1.91	7.67
XEU	147	479	2.34	6.21
THA	241	251	3.83	3.25
XAF	129	246	2.06	3.19
USA	243	201	3.86	2.60
IDN	171	141	2.72	1.83
XAS	116	121	1.84	1.56
XAM	129	113	2.05	1.47
ITA	0	104	0.00	1.35
IND	222	90	3.53	1.17
FRA	85	87	1.36	1.13
PHL	166	87	2.63	1.12
ESP	120	86	1.91	1.11
MYS	116	75	1.84	0.97
CAN	93	69	1.48	0.89
GBR	0	64	0.00	0.83
NOR	110	58	1.75	0.75
XOC	69	53	1.10	0.69
TUR	17	53	0.27	0.68
BGD	8	35	0.13	0.45
MEX	175	24	2.78	0.31
DEU	0	18	0.00	0.23
BRA	60	6	0.96	0.08
RUS	491	2	7.81	0.02
CHL	0	0	0.00	0.00
PER	0	0	0.00	0.00
VNM	0	0	0.00	0.00
World	6,288	7,727	100.00	100.00

Notes: This table shows the summary statistics of fuel subsidies for our model regions. Column 1 and 2 report the fuel subsidies measured in million USD for 2003 and 2018, respectively. Column 3 and 4 report the country share of fuel subsides among all regions in 2003 and 2018, respectively. 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".

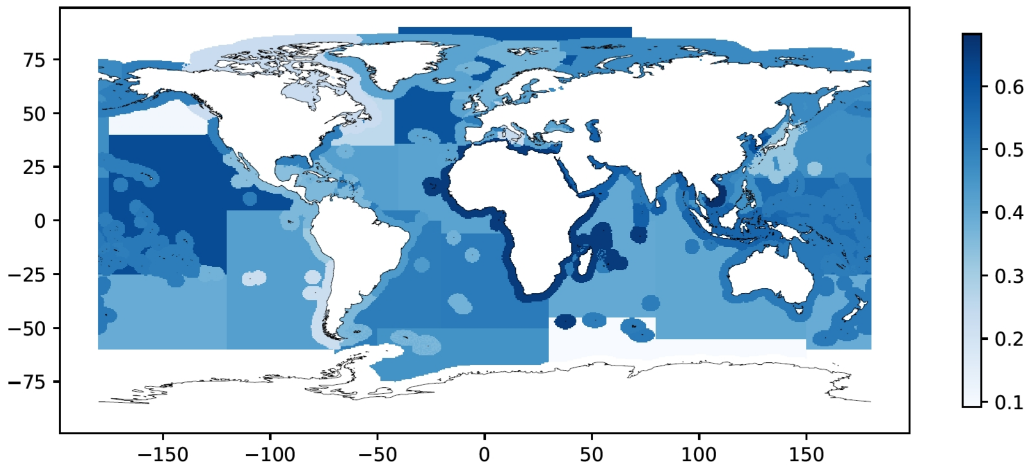
Figure B.2: Relationship between κ and β_1



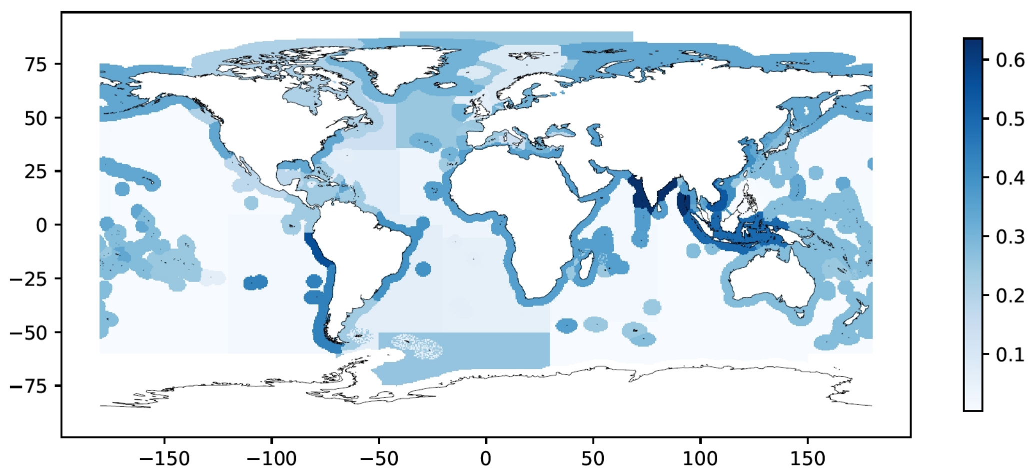
Notes: The figure shows the relationship between the parameter value of κ and the regression coefficient β_1 from equation (2).

Figure B.3: Average Stock to Capacity Ratio (Business As Usual)

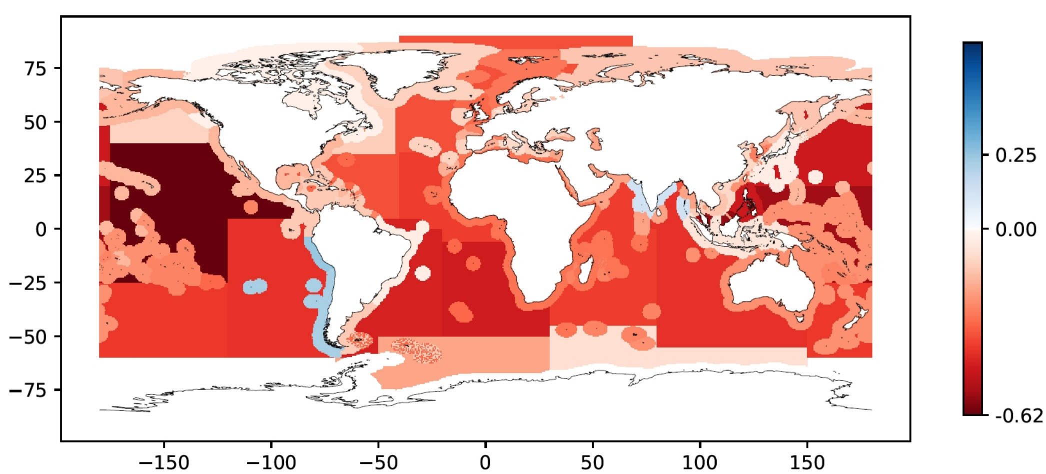
(a) Initial Year



(b) BAU Steady State



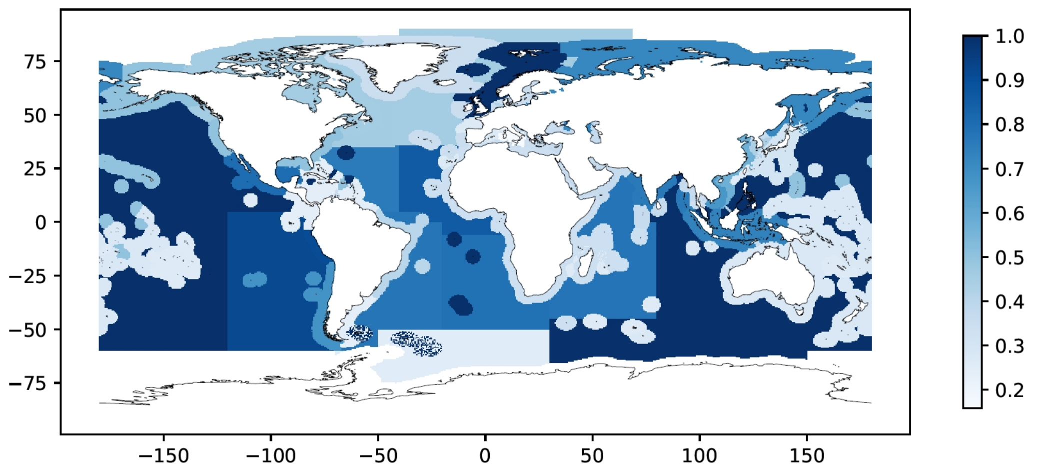
(c) BAU Steady State relative to Initial Year



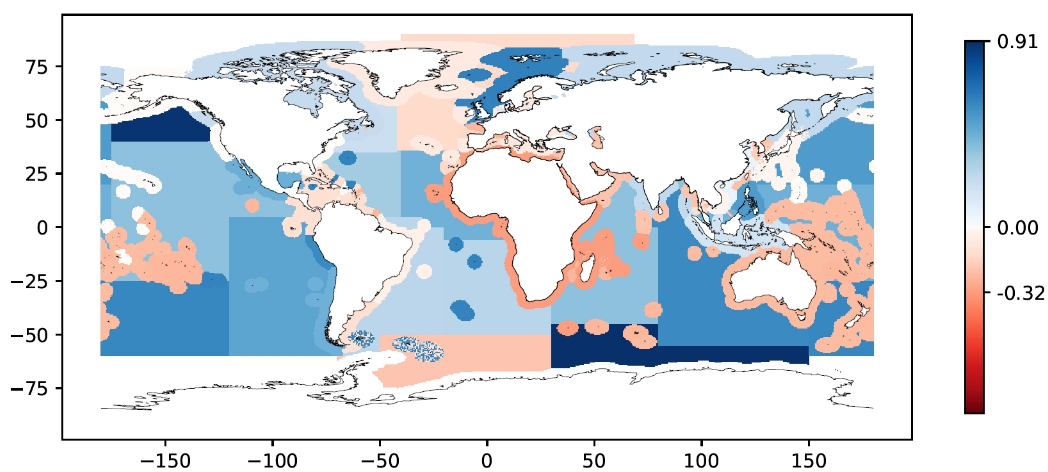
Notes: The map shows average stock to capacity ratio across species in each fishing location from the quantitative model, where the average was weighted by the carrying capacity of species within the fishing location. Panel (a) and (b) show the average stock to capacity ratio in the initial year and in the BAU steady state, respectively. Panel (c) shows the change in average stock to capacity ratio between initial year and BAU steady state.

Figure B.4: Average Stock to Capacity Ratio (Planner)

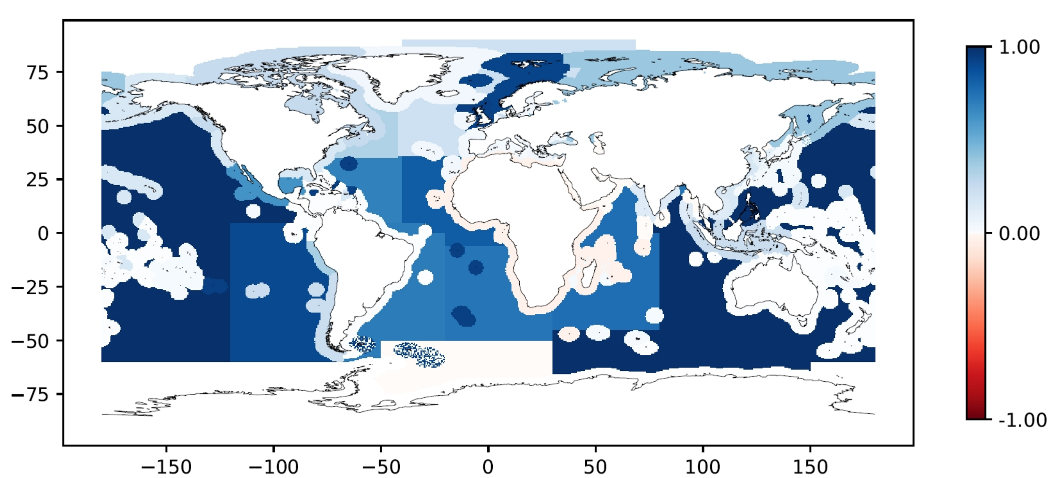
(a) Steady State



(b) Planner Steady State relative to Initial Year



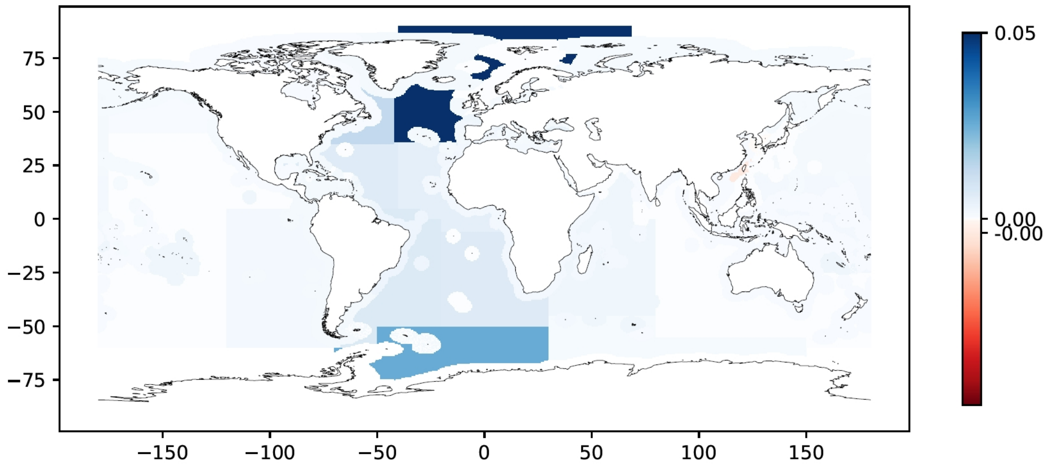
(c) Planner Steady State relative to BAU Steady State



Notes: The map shows average stock to capacity ratio across species in each fishing location from the quantitative model, where the average was weighted by the carrying capacity of species within the fishing location. Panel (a) shows the average stock to capacity ratio in the initial year and in the Planner steady state. Panel (b) displays the change in average stock to capacity ratio between initial year and Planner steady state. Panel (c) reports the change in average stock to capacity ratio between BAU steady state and Planner steady state.

Figure B.5: Average Stock to Capacity Ratio (Counterfactual)

(a) Counterfactual Steady State relative to BAU Steady State



Notes: The map shows average stock to capacity ratio across species in each fishing location from the quantitative model, where the average was weighted by the carrying capacity of species within the fishing location. Panel (a) reports the change in average stock to capacity ratio between BAU steady state and counterfactual steady state.

C Derivations

C.1 Decentralized Equilibrium

- FOC of households

$$\max_{C_{ijk,st}, C^o_{j,t}} U_{j,t} \quad \text{s.t.} \quad \sum_{i \in I} \sum_{k \in K} \sum_{s \in S} p_{ijk,st} C_{ijk,st} + p^o_{j,t} C^o_{j,t} = E_{j,t} \quad \forall t$$

$$\begin{aligned} \mathcal{L} &= U_{j,t} + \lambda_{j,t} \left(E_{j,t} - p^o_{j,t} C^o_{j,t} - \sum p_{ijk,st} C_{ijk,st} \right) \\ [C^o_{j,t}] &: \qquad \frac{\partial U_{j,t}}{\partial C^o_{j,t}} = \lambda_{j,t} p^o_{j,t} \\ [C_{ijk,st}] &: \qquad \frac{\partial U_{j,t}}{\partial C_{ijk,st}} = \lambda_{j,t} p_{ijk,st} \end{aligned}$$

- Rearranging,

$$\frac{\partial U_{j,t}}{\partial C_{ijk,st}} = \frac{\partial U_{j,t}}{\partial C^o_{j,t}} \frac{p_{ijk,st}}{p^o_{j,t}} \tag{C.1}$$

- FOC of atomistic fishery firms

$$\max_{L_{ijk,st}} \sum_t \left(p_{ijk,st} Q_{ijk,st} - w_{i,t} L_{ijk,st}\right) \quad \text{where} \quad Q_{ijk,st} = \frac{z_i \left(x_{k,st-1}/M_{k,s}\right)^{\xi}}{d_{ij,s}\tau_{ik,s}} L_{ijk,st}$$

$$\begin{aligned} \mathcal{L} &= p_{ijk,st} Q_{ijk,st} - w_{i,t} L_{ijk,st} \\ [L_{ijk,st}] : \qquad p_{ijk,st} \frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}} &= w_{i,t} \end{aligned} \tag{C.2}$$

- Price

$$p_{ijk,st} = \frac{d_{ij,s}\tau_{ik,s}}{\left(x_{k,st-1}/M_{k,s}\right)^{\xi}} \frac{w_{i,t}}{z_i} \tag{C.3}$$

- FOC of outside good firms

$$\begin{aligned} \mathcal{L} &= p^o_{i,t} Q^o_{i,t} - w^o_{i,t} L^o_{i,t} \\ \left[L^o_{i,t}\right] : \qquad p^o_{i,t} \frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}} &= w^o_{i,t} \end{aligned} \tag{C.4}$$

- Note that outside good is freely traded $p^o_{i,t} = p^o_{j,t}$ and labor is perfectly mobile $w_{i,t} = w^o_{i,t}$
- Putting (C.2) and (C.4) into (C.1), we get (18)

$$\frac{\partial U_{j,t}}{\partial C_{ijk,st}} = \frac{\partial U_{j,t}}{\partial C^o_{j,t}} \left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}} \Big/ \frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}} \right)$$

- From (C.2), we get (10)

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

C.2 Planner

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

- FOCs

$$[C_{ijk,st}]: \qquad \theta_{ijk,st} = \frac{\partial W_t}{\partial C_{ijk,st}} \tag{C.5}$$

$$[C^o_{j,t}]: \qquad \alpha_t = \frac{\partial W_t}{\partial C^o_{j,t}} \tag{C.6}$$

$$[L_{ijk,st}]: \qquad \theta_{ijk,st} = \left(\mu_{i,t} + \lambda_{k,st}\frac{\partial H_{k,st}}{\partial L_{ijk,st}}\right) / \left(\frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}}\right) \tag{C.7}$$

$$[L^o_{i,t}]: \qquad \alpha_t = \mu_{i,t} / \left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}}\right) \tag{C.8}$$

$$[x_{k,st}]: \qquad \lambda_{k,st} = \beta\left[\lambda_{k,st+1}\left(1 + \frac{\partial G_{k,st+1}}{\partial x_{k,st}} - \frac{\partial H_{k,st+1}}{\partial x_{k,st}}\right) + \sum_{i\in I}\sum_{j\in J}\theta_{ijk,st+1}\frac{\partial Q_{ijk,st+1}}{\partial x_{k,st}}\right] \tag{C.9}$$

$$[\mu_{i,t}]: \qquad \bar{L}_i = \sum_{s\in S}\sum_{k\in K}\sum_{j\in I} L_{ijk,st} + L^o_{i,t} \tag{C.10}$$

$$[\theta_{i,st}]: \qquad Q_{ijk,st} = C_{ijk,st} \tag{C.11}$$

$$[\alpha_t]: \qquad \sum_{i\in I} Q^o_{i,t} = \sum_{j\in I} C^o_{j,t} \tag{C.12}$$

$$[\lambda_{k,st}]: \qquad x_{k,st-1} + G_{k,st} = H_{k,st} + x_{k,st} \tag{C.13}$$

- From (C.6) and (C.8),

$$\mu_{i,t} = \frac{\partial W_t}{\partial C^o_{j,t}}\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}} \tag{C.14}$$

- Putting (C.5) and (C.14) into (C.7),

$$\frac{\partial W_t}{\partial C_{ijk,st}}\frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}} = \frac{\partial W_t}{\partial C^o_{j,t}}\frac{\partial Q^o_{ij,t}}{\partial L^o_{i,t}} + \lambda_{k,st}\frac{\partial H_{k,st}}{\partial Q_{ijk,st}} \tag{C.15}$$

- From (C.9) and (C.13),

$$\lambda_{k,st} = \beta\left[\lambda_{k,st+1}\left(1 + \frac{\partial G_{k,st+1}}{\partial x_{k,st}} - \frac{\partial H_{k,st+1}}{\partial x_{k,st}}\right) + \frac{\partial W_{t+1}}{\partial C_{ijk,st+1}}\frac{\partial Q_{ijk,st+1}}{\partial x_{k,st}}\right] \tag{C.16}$$

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

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

- At the steady state, $\lambda_{k,st} = \lambda_{k,st+1} = ...$

$$\lambda_{k,st} = \frac{\beta\Omega_{k,st}}{1 - \beta\Theta_{k,st}} \tag{C.17}$$

- Putting (C.17) into (C.15), and rearranging, we get (19)

$$\frac{\partial W_t}{\partial C_{ijk,st}} = \frac{\partial W_t}{\partial C^o_{j,t}} \left(\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}} / \frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}} \right) + \frac{\beta\Omega_{k,st}}{1 - \beta\Theta_{k,st}} \frac{\partial H_{k,st}}{\partial Q_{ijk,st}} \tag{C.18}$$

C.3 Dual Approach

- Now the government imposes per unit tax $t_{ijk,st}$ where $\tilde{p}_{ijk,st} = p_{ijk,st} + t_{ijk,st}$
- FOC of households

$$\begin{aligned}
\mathcal{L} = U_{j,t} + \lambda_{j,t} \left(E_{j,t} - p^o_{j,t} C^o_{j,t} - \sum \tilde{p}_{ijk,st} C_{ijk,st} \right) \\
[C^o_{j,t}] : \qquad \frac{\partial U_{j,t}}{\partial C^o_{j,t}} = \lambda_{j,t} p^o_{j,t} \\
[C_{ijk,st}] : \qquad \frac{\partial U_{j,t}}{\partial C_{ijk,st}} = \lambda_{j,t} \tilde{p}_{ijk,st}
\end{aligned}$$

- Rearranging,

$$\frac{\partial U_{j,t}}{\partial C_{ijk,st}} = \frac{\partial U_{j,t}}{\partial C^o_{j,t}} \frac{\tilde{p}_{ijk,st}}{p^o_{j,t}} \tag{C.19}$$

- FOC of fishery firms

$$\begin{aligned}
\mathcal{L} = (\tilde{p}_{ijk,st} - t_{ijk,st}) Q_{ijk,st} - w_{i,t} L_{ijk,st} \\
[L_{ijk,st}] : \qquad (\tilde{p}_{ijk,st} - t_{ijk,st}) \frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}} = w_{i,t} \\
\tilde{p}_{ijk,st} = w_{i,t} \left(\frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}} \right)^{-1} + t_{ijk,st} \qquad \text{(C.20)} \\
= p_{ijk,st} + t_{ijk,st}
\end{aligned}$$

- FOC of outside good firms

$$\begin{aligned}
\mathcal{L} = p^o_{i,t} Q^o_{i,t} - w^o_{i,t} L^o_{i,t} \\
[L^o_{i,t}] : \qquad p^o_{i,t} \frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}} = w^o_{i,t}
\end{aligned} \tag{C.21}$$

- Balance of Budget

$$w_{i,t}^o L_{i,t}^o + w_{i,t} L_{i,t} + t_{ijk,st} Q_{ijk,st} = X_{i,t}^o + X_{i,t}$$

- Claim: the following optimal policy $t_{ijk,st}^*$ realizes the optimal allocation from equation (C.18)

$$t_{ijk,st}^* = \frac{\beta\Omega_{k,st}}{1-\beta\Theta_{k,st}} \frac{\partial H_{k,st}}{\partial Q_{ijk,st}}$$

- With $\phi_j = 1$, note that

$$\frac{\partial W_t}{\partial C_{ijk,st}} = \frac{\partial U_{j,t}}{\partial C_{ijk,st}}, \quad \frac{\partial W_t}{\partial C_{j,t}^o} = \frac{\partial W_t}{\partial C_{j,t}^o}$$

- Then, (C.18) becomes

$$\frac{\partial U_{j,t}}{\partial C_{ijk,st}} = \frac{\partial U_{j,t}}{\partial C_{j,t}^o} \left(\frac{\partial Q_{i,t}^o}{\partial L_{i,t}^o} / \frac{\partial Q_{ijk,st}}{\partial L_{ijk,st}} \right) + \frac{\beta\Omega_{k,st}}{1-\beta\Theta_{k,st}} \frac{\partial H_{k,st}}{\partial Q_{ijk,st}}$$

- Plugging in (C.19), (C.20), and (C.21) into (C.18)

$$\frac{\partial U_{j,t}}{\partial C_{j,t}^o} \frac{\tilde{p}_{ijk,st}}{p_{j,t}^o} = \frac{\partial U_{j,t}}{\partial C_{j,t}^o} \frac{\left(\tilde{p}_{ijk,st} - t_{ijk,st}^*\right)}{w_{i,t}} + \frac{\beta\Omega_{k,st}}{1-\beta\Theta_{k,st}} \frac{\partial H_{k,st}}{\partial Q_{ijk,st}}$$

- With the quasi-linear preferences, free labor mobility, and choice of numeraire where $\partial U_{j,t}/\partial C_{j,t}^o = 1$, $w_{i,t} = z_i^o$, and $p_{j,t}^o = 1$, the optimal policy $t_{ijk,st}^*$ is indeed

$$\begin{aligned} \tilde{p}_{ijk,st} &= \left(\tilde{p}_{ijk,st} - t_{ijk,st}^*\right) + \frac{\beta\Omega_{k,st}}{1-\beta\Theta_{k,st}} \frac{\partial H_{k,st}}{\partial Q_{ijk,st}} \\ \Leftrightarrow t_{ijk,st}^* &= \frac{\beta\Omega_{k,st}}{1-\beta\Theta_{k,st}} \frac{\partial H_{k,st}}{\partial Q_{ijk,st}} \end{aligned}$$

C.4 Proof for Lemma

WTS: 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 (7) with respect to $x_{k,st}$,

$$\theta_{k,st} = \frac{\partial x_{k,st+1}}{\partial x_{k,st}} = \frac{\partial G_{k,st+1}}{\partial x_{k,st}} - \frac{\partial H_{k,st+1}}{\partial x_{k,st}} = (1+\gamma_{k,s}) - 2\gamma_{k,s}\frac{x_{k,st}}{M_{k,s}} - \frac{\xi}{x_{k,s}} \sum_i \sum_j d_{ij,s}\tau_{ik,s} Q_{ijk,st} \tag{C.22}$$

From equation (17), at the steady state,

$$\gamma_{k,s} x_{k,st} (1 - \frac{x_{k,st}}{M_{k,s}}) = \sum_{i \in I} \sum_{j \in I} d_{ij,s} \tau_{ik,s} Q_{ijk,st} \tag{C.23}$$

Combining (C.22) and (C.23), 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 $\gamma_{k,s} < \frac{1}{1-\xi} \left(\frac{1}{\beta} - 1 \right)$

$$\begin{aligned} &\gamma_{k,s} < \frac{1}{1-\xi} \left(\frac{1}{\beta} - 1 \right) \\ \Leftrightarrow &\left(1 - \frac{1}{2-\xi} \right) - \frac{1}{(2-\xi)\,\gamma_{k,s}} \left(\frac{1}{\beta} - 1 \right) < 0 \end{aligned} \tag{C.24}$$

At the steady state,

$$\begin{aligned} \Theta_{k,st} =& 1 + \gamma_{k,s} \left(1 - 2\frac{x_{k,st}}{M_{k,s}} - \xi (1 - \frac{x_{k,st}}{M_{k,s}}) \right) < 1/\beta \\ \Leftrightarrow & \frac{x_{k,st}}{M_{k,s}} > \left(1 - \frac{1}{2-\xi} \right) - \frac{1}{(2-\xi)\,\gamma_{k,s}} \left(\frac{1}{\beta} - 1 \right) \end{aligned} \tag{C.25}$$

Combining (C.24) and (C.25),

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

D Calibration Details

D.1 Steps for Calibration of κ

1. Under the environment described in 4.4, the government imposes the policy instruments $t_{ijk,st} = s_{i,t}$

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

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 $L^{new}_{ijk,st} = \frac{Y_{ijk,st}}{w_{i,t}}$

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

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

E.3 Partial Derivatives

$$
\begin{aligned}
\frac{\partial W_t}{\partial C_{ijk,st}} &= b_j b_s b_{ij} b_{k,s} C_{j,t}^{-1+\frac{1}{\nu}} C_{j,st}^{\frac{1}{\eta}-\frac{1}{\nu}} C_{ij,st}^{\frac{1}{\kappa}-\frac{1}{\eta}} C_{ijk,st}^{-\frac{1}{\kappa}} \\
\frac{\partial W_t}{\partial C^o_{j,t}} &= 1 \\
\frac{\partial Q_{ijk,kt}}{\partial L_{ijk,st}} &= \frac{z_i}{d_{ij,s}\tau_{ik,s}} \left(\frac{x_{k,st-1}}{M_{k,s}}\right)^{\xi} \\
\frac{\partial Q^o_{i,t}}{\partial L^o_{i,t}} &= z^o_i \\
\frac{\partial Q_{ijk,st}}{\partial x_{k,st-1}} &= \frac{\xi}{x_{k,st-1}} z_i \left(\frac{x_{k,st-1}}{M_{k,s}}\right)^{\xi} L_{ijk,st} \\
\frac{\partial G_{k,st}}{\partial x_{k.st-1}} &= (1+\gamma_{k,s}) - 2\gamma_{k,s}\frac{x_{k,st-1}}{M_{k,s}} \\
\frac{\partial H_{k,st}}{\partial x_{k,st-1}} &= \sum_i \sum_j d_{ij,s}\tau_{ik,s} \frac{\partial Q_{ijk,st}}{\partial x_{k,st-1}} = \sum_i \sum_j \frac{\xi}{x_{k,st-1}} z_i \left(\frac{x_{k,st-1}}{M_{k,s}}\right)^{\xi} L_{ijk,st} = \frac{\xi}{x_{k,st-1}} \sum_i \sum_j Q_{ijk,st} \\
\frac{\partial H_{k,st}}{\partial L_{ijk,st}} &= d_{ij,s}\tau_{ik,s} \frac{\partial Q_{ijk,kt}}{\partial L_{ijk,st}}
\end{aligned}
$$