Can Demand-Side Interventions Rebuild Global Fisheries?*

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6th May 2024

Abstract

Despite recent improvements in the ecological status of wild-capture fisheries, a significant share (33%) of global marine stocks remains overexploited. While top-down management has been shown to work in many settings, there is growing interest in demand-side interventions, which work through consumer-originated price signals to incentivize reduced fishing pressure. The effectiveness of demand-side interventions would rely, in part, on a large enough supply elasticity of fisheries, though this crucial statistic is notoriously difficult to estimate and remains elusive in the literature. Using plausibly exogenous variation in fish prices and extensive data on the world's fisheries, we derive an empirical approach to estimate this elasticity using an instrumental variables estimator. We find it is very low – similar to that observed in comparable sectors. This suggests that even if prices did respond to demand-side interventions, the supply response would be small. To determine whether the ensuing supply response would have meaningful ecological consequences, we combine a bioeconomic model of fisheries with a global model of supply and demand for seafood calibrated with our estimates. We find that even interventions that lead to dramatic demand shifts are unlikely to achieve more than marginal improvements to fisheries status. In contrast, we find that supply-side policies (such as well-enforced fishing quotas), even imperfectly designed or implemented, can result in substantial recovery.

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*Acknowledgments: We thank and seminar and conference participants at Oxford University, the Toulouse School of Economics, the SMART seminar in Rennes, and the AEA Economics and Marine Resource Management Session for their comments and suggestions. We are grateful to Halley Froehlich for helpful discussion and comments. We thank Micaela Davalos for excellent research assistance. Errors are ours.

Introduction

Wild capture fisheries produce about 96 million tonnes of harvested fish valued at 151 billion USD, providing employment for 39 million fishers around the world (FAO, 2020b). The sustainability status of these harvested fish populations has fundamental implications for economic well-being, food security, and ecosystem health, and consequently has attracted significant academic attention over the past half-century. The main conclusion of that literature is that fishery sustainability varies considerably around the world: many stocks have been overfished for decades and continue to decline, while others are healthy or have recovered (Worm et al., 2009; Costello et al., 2016). While this broad conclusion, and even the status of individual fisheries, is widely agreed upon, there is little consensus on the specific causal drivers of the observed diverging fates of fisheries.

Several explanations have been proposed for the observed good or poor health of fisheries. Early seminal contributions by Beverton and Holt (1957) and Ricker (1954) in the fisheries literature and Gordon (1954) and Smith (1969) in the economics literature point to the crucial role that supply-side management plays in fishery sustainability. When fisheries are unmanaged, or regulations not enforced, there are strong incentives to overfish, which can ultimately deplete the stock. Conversely, strong institutions and scientifically-guided fishery management have been shown to improve the health of fisheries (Costello et al., 2008; Heal and Schlenker, 2008; Costello and Ovando, 2019; Hilborn et al., 2020). In countries with strong institutions, fishery management is often seen as the sole driver of fishery status, echoing the conclusion of decades of theoretical and empirical evidence on the role of institutions in natural resource outcomes (Bohn and Deacon, 2000; Copeland and Taylor, 2009; Arnason, 2006). And while it is increasingly acknowledged that ecosystem dynamics also influence fishery production, even this is being subsumed under the management umbrella, where recent contributions focus precisely on how to adapt management in response to fluctuating environmental conditions (Kritzer et al., 2019; Collie et al., 2021).

The efficacy of such "supply-side" fishery management is often taken for granted by academics and practitioners. But there is growing concern that poor governance, government inertia, corruption, poorly defined or nonexistent property rights, and other realities may limit the relevance of fishery management in some settings. The recent push for sustainability improvement through "demand-side" channels stems from the acknowledgement of these possible deficiencies: with demand-side interventions such as information campaigns, seafood guides, formal certifications and supply chain commitments, NGOs, seafood buyers, and even individual consumers are increasingly making purchase decisions based on the sustainability of the associated source fisheries. The idea is that by shifting consumption from fisheries harvested unsustainably to those harvested sustainably, consumers can foster the good actors, and penalize the bad actors. This theory of change relies on the premise that reducing demand for unsustainable fisheries will translate into reduced fishing pressure where needed, thus improving fishery status overall.

If management can be regarded as a "quantity" based intervention, then demand-side policies may be regarded as a "price" based intervention, following the dichotomy of the seminal papers of Weitzman (1974, 2002). The first acts through restrictions on the quantity of fish that can be removed from the ocean, while the second acts through economic channels to lower demand for specific classes of fish, thereby aiming to reduce the economic incentives that drive fishing behavior. A sizable literature has documented causal and ecologically important benefits of quantity-based interventions (Costello et al., 2008; Isaksen and Richter, 2019; Hilborn et al., 2020; Birkenbach et al., 2017). However, no prior study has empirically examined the impact of price-based interventions on the sustainability of global fisheries. Demand-side policies are not restricted to fisheries, however, and the present work is part of a broader literature exploring its benefits and limitations; for example, in the case of deforestation caused by palm oil plantations in Southeast Asia, Hsiao (2022) finds that a globally-enforced tax on palm oil imports could stave off deforestation as much as a (politically-unfeasible) domestic policy, but its benefits are undermined by leakage if enforced unilaterally or with incomplete commitment.

In this paper we present the first global-scale analysis of the impact of demand-side, or price-based, interventions on fisheries sustainability. This requires three important research contributions. First, we develop a novel framework representing the equilibrium in the market for fish where supply is segmented between a regulated ("managed") sector and an unregulated ("unmanaged") sector. The model includes correlated shocks between the regulated and unregulated sectors, a feature that influences the empirical strategy detailed below. A key observation from this framework is that the potential impact of any demand-side intervention on sustainability critically depends on the degree of price-responsiveness in the global supply curve, i.e., on the price elasticity of supply. If harvest only weakly responds to prices, then even an aggressive demand-side intervention leading to a large shift in demand will have only modest effects on fishery sustainability.

Second, we empirically derive the global supply curve for fish by estimating the causal effect of fish prices on quantity harvested at the stock level. Establishing causality is challenging because prices are endogenous to quantities. For this empirical part of the paper, we compiled an unprecedented stock-level panel data set on harvest, biomass, and ex-vessel prices (henceforth *prices*) for 3,187 stocks (both managed and unmanaged) over the period 1990-2012. We address the identification challenge using an instrumental variables strategy that makes use of the segmented nature of the seafood market. It relies on a close substitute to wild-caught seafood, aquaculture (farmed seafood), which we have strong theoretical and empirical reasons to believe is insulated from the price variations in the wild sector. Specifically, we leverage the inter-annual variation of aquaculture production. Variation across years in the amount of farmed seafood produced primarily reflects the ramping up in capacity in farming operations under regulatory and biological constraints, and production accidents such as disease; the variation it generates in fish supply can, under certain conditions, be treated as independent of wild fish prices. Since global markets for specific fish species are formed by the combination of wild fisheries and aquaculture, variation in aquaculture influences the global prices of fish, as we demonstrate below. This allows us to construct instruments for price at the fish class-year level in (unmanaged) fisheries, and to estimate parameters of the supply function in unmanaged fisheries while addressing the standard concerns about endogeneity. We also present an alternative identification strategy relying on inter-annual variation in total allowable catch (TAC): they are decided by fishery managers and chiefly reflect biological conditions in managed stocks, therefore the variation they generate in fish supply can be treated as an exogenous price shifter for the unmanaged supply segment.

The empirical analysis shows that inter-annual variation in aquaculture production leads to strong and statistically significant effects on global fish prices within the same fish class (known as ISSCAAP group).[1] Our alternative instrument using variation in TAC-constrained stocks is likewise validated. In particular, we find that a 1% increase in aquaculture production leads to a 0.045% decrease in *global* fish prices, and a one-unit increase in harvest in TAC-constrained managed stocks (in 10^6 tonnes) leads to a 46% decline in *global* fish prices, across all managed and unmanaged stocks. Thus aquaculture production (alternatively: TAC-constrained managed stocks) can serve as instruments for price in the supply equation of unmanaged fisheries (being both relevant and exogenous), and we derive the corresponding TSLS estimates of the intercept and slope of the supply function. We find a statistically significant relationship between harvest and price with

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[1] The International Standard Statistical Classification of Aquatic Animals and Plants (ISSCAAP) is a nomenclature developed by the UN Food and Agriculture Organization (FAO). In what follows, we will simply use "species group" to mean ISSCAAP group.

both instruments, positive but relatively weak. The implied supply elasticity derived from our estimates indicates that a 1% increase in price leads to a 0.11% increase in harvest in unmanaged fisheries. This reveals a relatively weak connection between prices and fishing pressure; our empirical estimate is consistent with the lower end of the distribution of price elasticities of supply for other commodities (see Fally and Sayre (2018) for a survey).

Third, we use our estimated unmanaged sector supply curve to parametrize a global model of supply and demand for fish. Coupled with the classic model of fish population dynamics of Pella and Tomlinson (1969), the supply and demand model allows us to conduct simulation experiments comparing the sustainability effects of management vs. price-based regulation of stocks that are currently unmanaged. To do so, we evaluate four scenarios, including a baseline, two policies relying on controlling quantity (Q), one on altering price (P), namely: (1) "No-intervention," where unmanaged stocks remain unmanaged, (2) "Q-optimal," where unmanaged stocks are managed for maximum sustainable yield, (3) "Q-average," where unmanaged stocks are managed with the same historical efficacy as managed stocks, (4) "P-unit," where stocks are unmanaged but a large (2 \$/kg) unit tax is levied on ex-vessel fish sales. The Pella-Tomlinson population dynamics equation allows us to estimate the next period's biomass (which is also a key indicator of sustainability) from the current period biomass and the computed equilibrium harvest. We implement this modelling approach with a global data set of 2,287 unmanaged stocks from 1990 through 2012, where the observed values of harvest and previously-predicted values of biomass (Costello et al., 2016) in 1990 are used as initial values in the simulations. This produces four sets of projections with predicted biomass, harvest, and ex-vessel price, and where the equilibrium price and harvest endogenously determine biomass, separately for each species group and year.

These experiments produce several results of note. First, under the No-intervention conditions, the health of unmanaged fisheries significantly declines over the simulation period (1990-2012). In particular, median biomass relative to sustainability benchmarks declines by 60%, corresponding to a reduction of total biomass of 190 million tonnes. Second, and most remarkably, the aggressive demand-side scenario where demand for fish drops drastically due to a 2 \$/kg unit tax leads only to marginal improvements in biomass compared to the No-intervention case. Even as economic incentives to fish are strongly reduced by the unit-tax demand-side scenario, median relative biomass *drops* from 1.03 to 0.45 by 2012, corresponding to a decline of 56% between 1990 and 2012. Biomass declines in these two scenarios (No-intervention, P-unit) are substantially greater than those predicted under supply side interventions with regulated fishing pressure. This indicates that the prospects for demand-side intervention to produce significant sustainability benefits in unmanaged fisheries are relatively small, primarily stemming from the weak price-responsiveness of supply. Naturally this assumes that the demand-side intervention is used as stand-alone policy rather than in combination with other, e.g., supply-side interventions.

More broadly, these results shed light on the path to global fishery sustainability in two important ways. First, the empirical estimates of fish supply elasticity inform the interaction between economic conditions and sustainability, and improve our understanding of fishery dynamics. Further, the belief that fishers strongly respond to prices in their harvest decisions is an important assumption for many certification, labeling, and supply chain commitment interventions. This research shows that they do not. In practice nonetheless, interventions like certifications are often a combination of demand-side components that affect price and supply-side components that give incentives for the fishery to move towards more sustainable management through certain requirements for participation. While our analysis does not examine specific combined policies, our global-scale causal evidence on the link between price interventions and fishery sustainability largely rejects the belief that these interventions can rely solely on shifts in demand to achieve sustainability. Instead, our results suggest that effective fishery interventions must rely, at least to some extent, on direct control of catch. This could be achieved by conditioning demand-side certification with supply-side management changes, or it could be achieved through direct management interventions.

Finally, our approach combining causal identification of supply elasticities and simulations to assess the relative impact of demand-side interventions could be applied to other settings. In particular, our approach can be extended to impure public good markets where the consumer has a choice between a "conventional" good versus a "green" good (that confers larger sustainability or social benefits than the conventional good), and where the aim of demand-side interventions is to guide the consumer towards the green good (see Kotchen (2006)). Examples that could be considered in future research include shade-grown coffee, sustainable palm oil, and renewable electricity.

1 Background and data sources

1.1 Seafood as a segmented market

The empirical analysis largely exploits the segmented nature of the seafood market. Specifically, its supply is segmented: nowadays, about half of total seafood production comes from capture fisheries (also termed wild-caught seafood), the rest from farmed sources[2] (also called aquaculture, pisciculture, or mariculture); the equivalent to that distinction on land would be hunted and farmed animals, gathered and cropped plants. While both segments face different constraints and require different inputs (labor, land, permits, capital), they all face the same demand, as their products are highly substitutable (for a given species or species group).

We first describe the wild segment and related data sources, and then turn to the farmed segment. We finish with details on the price data.

1.2 Fishery outcomes

To implement the empirical analysis, we have compiled a comprehensive global database of stock-level fishing pressure, harvest, and biomass, and combined it with global annual quantities of seafood production and global annual fish prices at the species level (or more aggregated taxonomic groups) for a panel that spans the years 1990 to 2012.

Fishery outcomes - assessed stocks. We use data from the RAM Legacy Stock Assessment Database (RAMLDB, v4.494 'model-fits') to obtain stock-year level data on harvest for 900 stocks for the period 1990-2012. The fisheries included in RAMLDB tend to have a long history of stock assessments and the vast majority have some form of regulations that limit quantities that can be harvested. We supplement the RAMLDB data with information on the size of the total allowable catch (TAC) and the share of the TAC that was caught by year for each fishery (Hilborn et al., 2020; Melnychuk et al., 2021). This allows us to identify fisheries where the limit on catch was binding in a particular year. As we explain in more detail below, the

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[2] In 2020, 51% of total seafood produced (90 of 178 million tonnes) came from capture fisheries, 49% from aquaculture. Source: Food and Agriculture Organization of the United Nations (FAO), "The State of World Fisheries and Aquaculture 2022."

quantity regulations present in most fisheries contained in RAMLDB suggest that fishing behavior for these stocks is constrained and therefore may not be largely influenced by fish price. We use this feature below to form instrumental variables for global fish prices.

Fishery outcomes - unassessed stocks. The data on presumed unmanaged fisheries are taken from the 'Upsides' database for unassessed fisheries (Costello et al., 2016). Similar to the measures of stock biomass and fishing pressure for assessed stocks contained in RAMLDB (which are extracted from government stock assessments), the Upsides data also contain estimates of stock biomass and fishing pressure for the many stocks around the world that are not formally assessed. These Upsides estimates are based on a combination of raw catch data and biological model outputs for the period 1990-2012; they were obtained using a panel regression approach, drawing on stock status data from RAMLDB, catch history data from the global landings database of the UN Food and Agriculture Organization (FAO), and data from an authoritative fish biology database (www.fishbase.org). An advantage of the Upsides database is its far richer geographic coverage compared to RAMLDB, as stock status estimates are not limited to stocks formally assessed with quantitative stock assessments. Our sample includes data on 2,287 stocks from Upsides.

1.3 Fishery management

Fish stocks that are scientifically assessed, i.e., those contained in RAMLDB, tend to have a variety of fishery management measures in place. Conversely, fish stocks that are *not* formally assessed by quantitative stock assessments tend to have weaker management measures in place, or none at all (Costello et al., 2016). Exceptions exist - for example some fish stocks may be managed with a variety of tools like gear restrictions or spatial closures even though quantitative stock assessments are not carried out, or other stocks on the high seas may be scientifically assessed but have limited management in some or most of their areas of distribution. For the most part, however, the prevalence of stock assessments and management measures are correlated (Melnychuk et al., 2017b). Accordingly, for the remainder of this paper, we refer to "managed" stocks as being synonymous with scientifically-assessed stocks (those contained in RAMLDB), and "unmanaged" stocks as synonymous with unassessed stocks (those in the Upsides database that are not contained in RAMLDB). Later, we explore simulated scenarios in which management measures are applied to these unmanaged stocks.

The main estimation sample is obtained by merging the species-level price data with the stock-level biological fishery data for unmanaged stocks (a stock is a population of a given species in a given place; hence a species can be in several stocks). We use harvest data for managed stocks to construct our instrumental variable. To maximize data coverage we only consider the period 1990-2012. Further, in order to focus the analysis on the main species of fish that are commercially exploited, we restrict the sample to species that are included in the following ISSCAAP divisions:[3] crustaceans (e.g., blue crab), diadramous fishes (e.g., sockeye salmon), marine fishes (e.g., snapper), and molluscs (e.g., clam).

Altogether, this produces a sample with 2,287 unmanaged stocks across 52,601 stock-years, comprising 464 unique species or aggregated taxonomic groups. To the best of our knowledge, this constitutes the most comprehensive data set on fishery outcomes and prices compiled in the literature to date. Using these data we can define the four key variables for our analysis. The price, p_{st}, is the ex-vessel price per kilogram for species s in year t. Harvest, H_{it}, is the quantity harvested for stock i in year t in tonnes, biomass, B_{it},

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[3] A division contains several groups. A group contains several (similar) species (e.g., the Atlantic halibut (*Hippoglossus hippoglossus*) and the European plaice (*Pleuronectes platessa*) are both part of the *Flounders, halibuts, soles* group). A species can be comprised of several populations or stocks.

is the estimated size of stock i in year t in tonnes, and fishing mortality, F_{it} is the fraction of biomass of stock i that is harvested at time t. Harvest and biomass are then normalized relative to their maximum sustainable yield (MSY) or equilibrium biomass at MSY (B_{MSY}), respectively, so that quantities are more comparable across stocks. For simplicity, we will refer to relative biomass ($b_{it} = B_{it}/B_{MSY}$) and relative harvest ($h_{it} = H_{it}/MSY$) as "biomass" and "harvest" unless noted otherwise.

Fishery management - Total Allowable Catch. To refine on the notion of management, we also collect data on the maximum quantity of fish it is possible to harvest overall in a given stock (species-location combination) and a given year, i.e., total allowable catch (TAC) limits – wherever and whenever imposed. Data were collected through surveys of fishery managers (see Melnychuk et al. (2013, 2016); Ben-Hasan et al. (2021) for more information).

1.4 Aquaculture

Depleting stocks and rising demand has led to a gradual shift towards aquaculture – as opposed to capture fishery – that took of in the 1990s and currently makes up half the annual seafood tonnage supplied globally (Asche et al., 2022). Farmed seafood is an almost perfect substitute to its wild equivalent, but for our purposes, it differs from wild-caught seafood in three important ways. These differences stem from the fact that it is not subject to the same regulatory and ecological constraints as in the wild. First, aquaculture is obviously not subject to TAC and other fishery management regulations; instead, aquaculture operations require permits to be allowed to operate. Second, wild stocks are subject to population dynamics: population, hence harvest, at t is given by population in $t-1$, some set biological parameters (carrying capacity, etc.), and random fluctuations. Not so with aquaculture: population at maturity at time t, and therefore quantity produced, is determined by species-specific grow-out time, and how much was "seeded" some years ago, which itself was determined on the basis of economic and regulatory conditions over the preceding years. Third, while density dependence does not affect aquaculture through resource availability, density affects farmed populations, as they are more prone to disease, and with more drastic consequences, than their wild counterparts.

Aquaculture quantities. We obtained quantities of farmed seafood at the country-year-species group level from the Global Aquaculture Production database[4] (FAO, v2020.1.0), that we aggregated up from the species-country-year level. Note that only certain species have been developed for aquaculture for both technical and economic reasons (e.g., economies of scale), and similarly to managed stocks, we assume subsitutability across species within a species group (further discussion below). Figure 1 shows these data aggregated at the species group-year level, and from the time series it is obvious that the industry invested more in developing certain species than others, and that growth for species with the largest annual quantities has been close to exponential over the last 2-3 decades.

1.5 Prices

We obtain reconstructed global species-level annual prices from Melnychuk et al. (2017a), which contains ex-vessel prices from 1976 to 2012. The database has 187 unique price time series that are linked to a list of 1,850 species, where a single price time series is usually linked to multiple species. Ex-vessel prices, which

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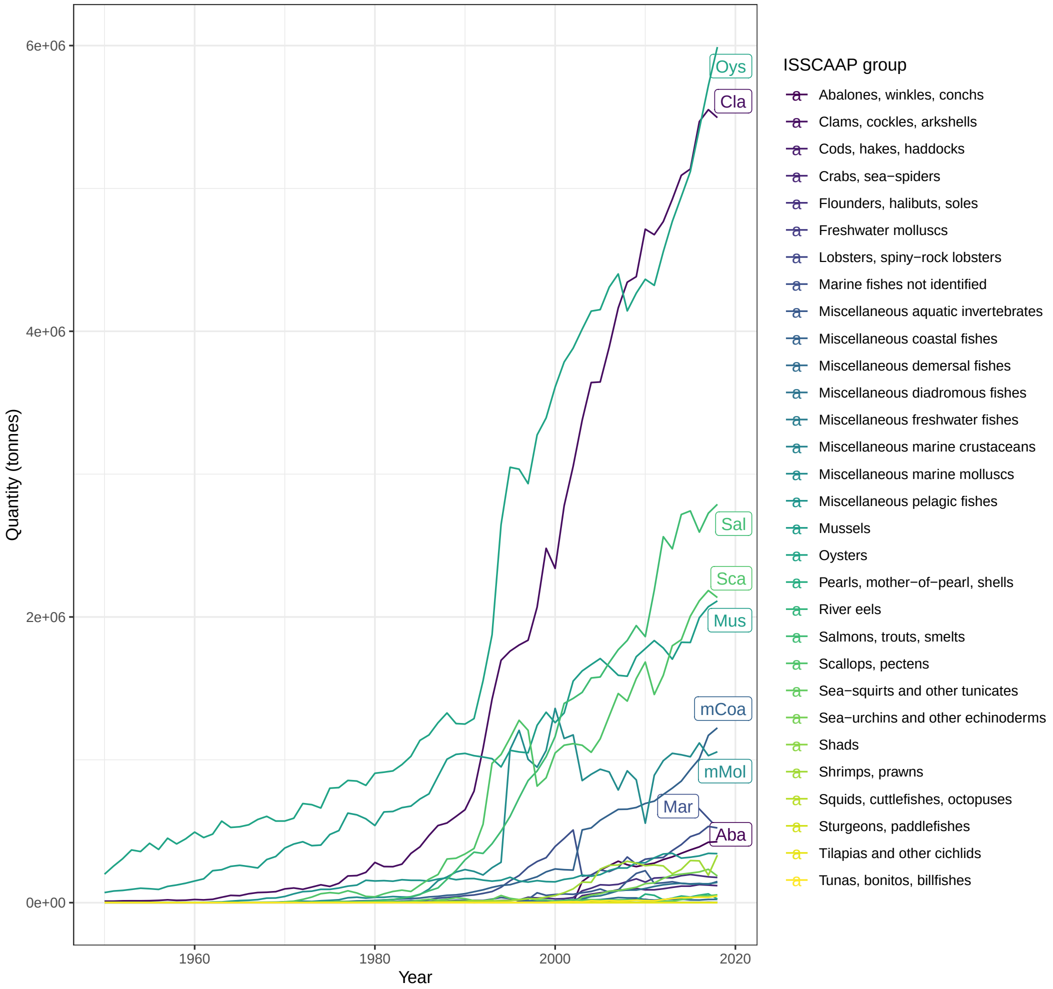
[4] See: fao.org/fishery/statistics-query/en/aquaculture.

Figure 1: Trends in global aquaculture expansion



Notes: Graph shows the quantity of seafood supplied by aquaculture over time (data source: FAO). Labels, where shown, correspond to the first 3 letters of the species group name, labels in “m...” correspond to “miscellaneous...” groupings.

correspond to the prices that fishers receive directly for their catch, are expected to reflect the economic incentives that determine fishing decisions. We use ‘ex-vessel price’ and ‘price’ interchangeably for the rest of the paper. Nominal prices were converted to USD per kilogram using the 2012 US GDP implicit price deflator from the Bureau of Economic Analysis (2021).

1.6 Preliminary analysis

Table 1 reports summary statistics for the main variables in the sample of unmanaged fisheries. Relative harvest has a median value of 1.32 across the sample, while relative biomass has a median value of 0.84. This means that for the median stock, fishing pressure is 32% higher than the biologically sustainable fishing pressure that would eventually lead to MSY, while the biomass is 16% lower than what the equilibrium biomass would be if MSY were caught annually. Mean price per kilogram is $3.39. These statistics mask an important amount of variation across years and stocks as shown in Figure 2. Panel a. shows the downward trend across the 10th, 50th, and 90th percentiles of relative biomass. For example, the median biomass has

Table 1: Summary statistics for unmanaged and managed fisheries, 1990-2012

	Mean	Median	Minimum	Maximum
Ex-vessel price (USD/kg)	3.393	2.581	0.068	27.699
Unmanaged stocks				
Relative biomass	0.963	0.839	0.070	2.420
Relative harvest	1.373	1.320	0.001	8.824
Fishing pressure	1.716	1.585	0.001	6.318
Managed stocks				
Catch (10^6 tonnes)	1.793	0.642	0.000	19.19
TAC-constrained catch (10^6 tonnes)	0.315	0.014	0.000	9.061

Notes: Relative biomass, harvest, and fishing pressure vary at the stock-year level. Ex-vessel prices in USD per kg ($2012) vary at the species-year level. Catch and TAC-constrained catch are in million metric tonnes and vary at the ISSCAAP group-year level. TAC-constrained catch is defined as catch occurring when the catch-to-TAC ratio is between 0.9 and 1.1.

steadily declined from 1.0 in 1990 to 0.7 in 2012, corresponding roughly to a 30% decline. The data also indicate large cross-sectional differences in biomass across stocks: in 2012 the 90th percentile stock had a biomass of 1.49, more than 3.5 times larger than the 10th percentile (0.42). Panel b. shows that in contrast, relative harvest has remained more constant over time, with the median declining from 1.38 in 1990 to 1.15 in 2012 (a 17 % decline), and the 10th and 90th percentiles having similar levels in 1990 and 2012.

Finally, panel c. displays the evolution of the real price of fish per kilogram over time for the species among unmanaged stocks. Here we observe differential trends across the distribution. In particular, the 10th percentile price showed a small increase over time (ranging between $0.49 and $0.73), the 90th percentile price dropped by $1.82 per kilogram (corresponding to a 30% decline in real terms), and the median price remained relatively constant between 1990 and 2012 (ranging between $2.60 and $2.54).

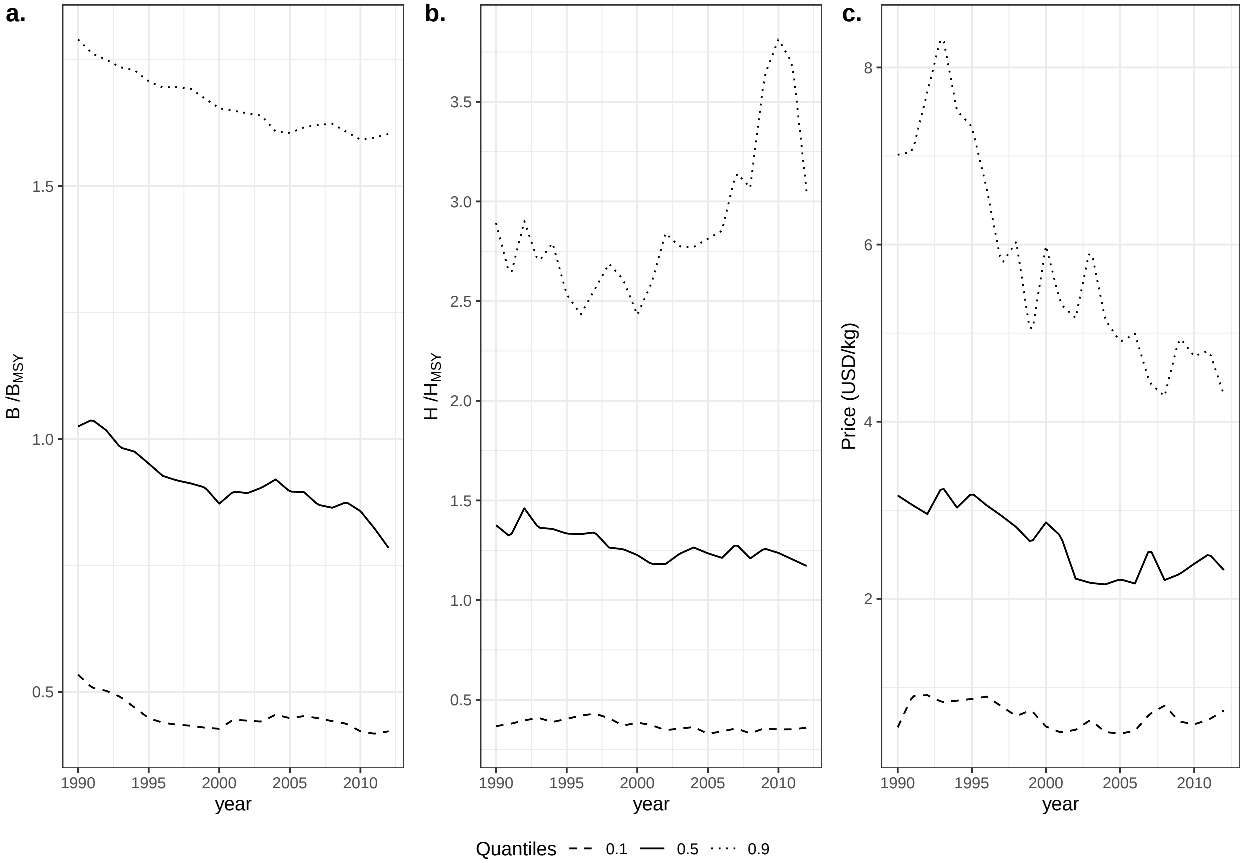
1.6.1 Background for the management-based instrumental variables strategy

Figure 3 illustrates the overlap in the number of stocks by species group in the unmanaged and managed fisheries. A total of 17 species groups (included in the four ISSCAAP divisions listed above) are observed. Good overlap in species that are exploited in both managed and unmanaged fisheries is essential because the identification strategy detailed below will use catch in managed fisheries that are quantity-regulated (and therefore presumed to be price-independent) as instruments for the global price of fish species that are part of the same species group.

There is strong overlap for several species groups as evidenced by the large number of stocks with data in both the unmanaged and managed fisheries. For example, there are 144 unmanaged stocks and 101 managed stocks in the 'flounders, halibuts, and sole' group. Similarly, we see notable overlap for 'herrings, sardines, and anchovies', 'tunas, bonitos, and billfishes', and 'cods, hakes, haddocks' among others. Overlap is poor in other species groups, in particular for 'squids, cuttlefishes, octopuses' and 'salmons, trouts, smelts', which have few managed fisheries compared to the number of unmanaged fisheries.

Figure 4 completes the preliminary analysis by reporting the fraction of stock-years in the managed RAMLDB data where the catch falls within 90% to 110% of the TAC. As we describe in more detail in the next section,

Figure 2: Trends in relative biomass, harvest, and ex-vessel price for unmanaged stocks



Notes: Figure shows the time series trends for unmanaged stocks (1990-2012). Panel a. (left) shows relative biomass (B/B_{MSY}), panel b. (center) displays relative harvest (H/MSY), and panel c. (right) shows ex-vessel prices in real USD per kilogram. In all panels, the solid line corresponds to the median, and the dotted and dashed lines the 90th and 10th percentiles, respectively.

within this range we assume that the actual catch was quantity-constrained by the TACs, allowing for slight overages or underages of 10 percentage points in catch relative to the TAC, which is common across a fleet in any given fishing season. The row labelled 'All' shows that across all managed stocks with a TAC, about 35% of stock-years are quantity-constrained by the TAC according to our definition, with 47% of stock-years having catch below 90% of the TAC and 18% of stock-years having catch above 110% of the TAC. There is substantial variation in these shares across species groups. For example 'abalones, winkles, and conchs' are within 90-110% of the TAC in 73% of stock-years, while 'sharks, rays, and chimaeras' are quantity-constrained by the TAC in only 13% of stock-years. This rich variation will contribute to the identification of the instrumental variables estimates below.

Figure 3: Overlap between unmanaged and managed stocks, by species group

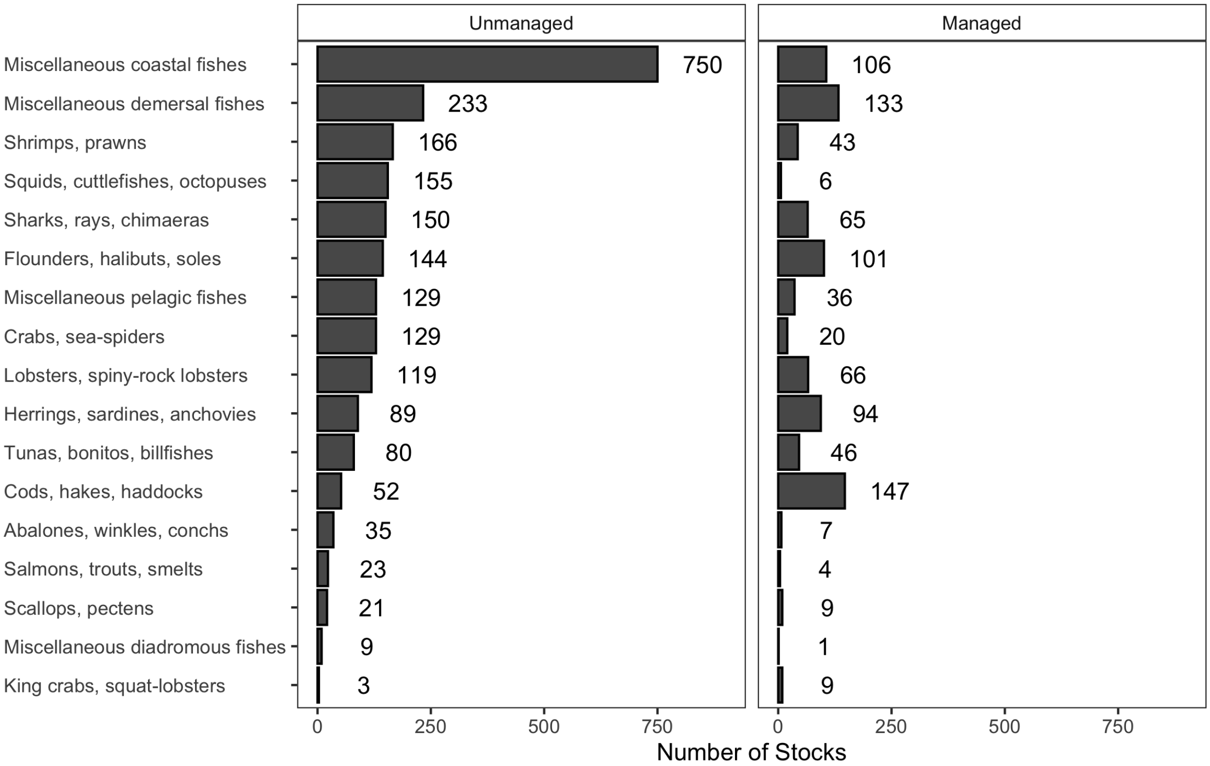
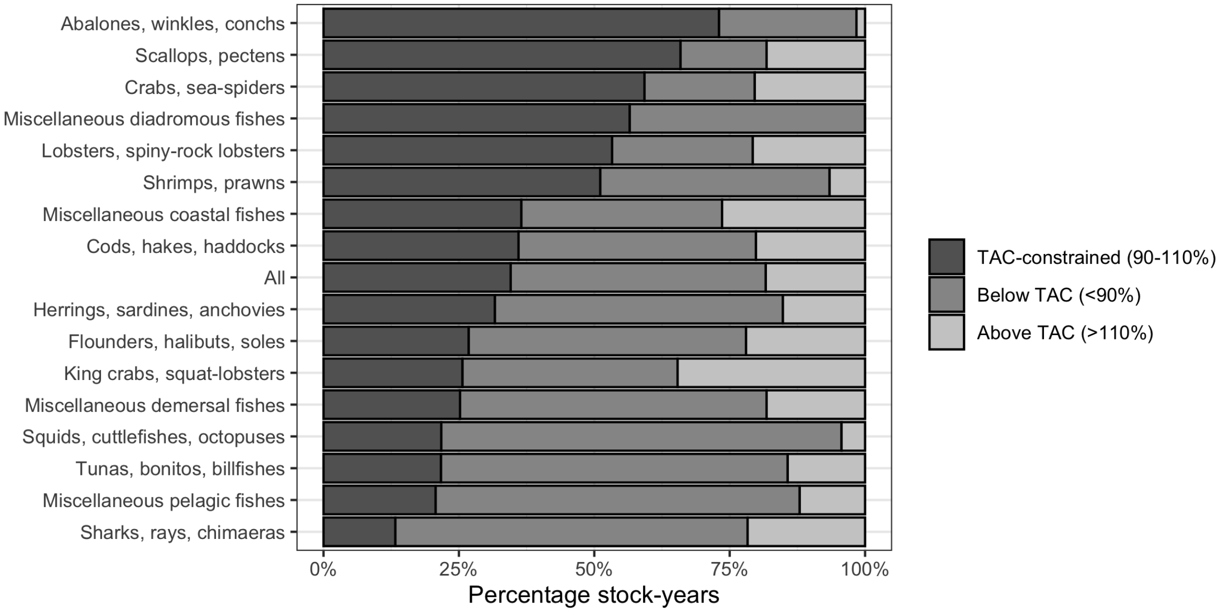


Figure 4: Variation in total allowable catch (TAC) constraints, by species group

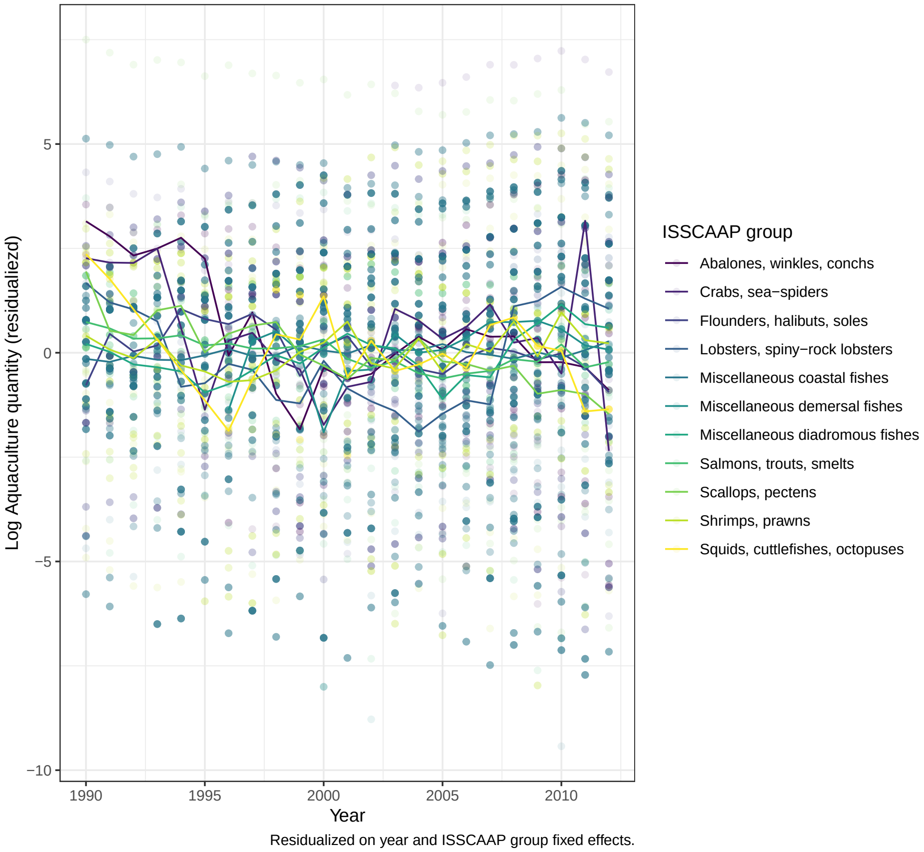


Notes: This figure shows the percentage of stock-years that are Total Allowable Catch (TAC)-constrained (defined as stock-years where the fraction of the TAC caught is 90-110%, in dark grey), below the TAC (fraction of TAC caught is below 90%, in middle grey), or above the TAC (fraction of TAC caught is above 110%, in light grey), by species group.

1.6.2 Background for the aquaculture-based instrumental variables strategy

Figure 1 presented in the Data section shows the evolution over time of farmed seafood quantities, by species group. Of note are the quasi-exponential growth experienced by some groups; the diversity of growth rates across groups, and over time; the ruggedness of these trajectories. Indeed the identification strategy for the aquaculture-based instrumental variables strategy hinges on variations in the supply of this substitute to wild-caught seafood, as they should act as price-shifters (first stage) for the ex-vessel prices we observe for wild-caught and unmanaged seafood. The variation *per se* is represented graphically in Figure 5.

Figure 5: Identifying variation (first stage)



Notes: The figure shows (logged) aquaculture quantities demeaned by year and species group fixed effects; dots show aggregation at the year-group-country level, lines show aggregation at the year-group level.

2 Empirical Framework

The first goal of this paper is to estimate the price responsiveness of supply for unmanaged fisheries. As the simple model above shows, this amounts to estimating the parameter β_1 from the unmanaged supply curve. In practice, we measure the quantity supplied in the unregulated segment with the annual relative harvest (by stock) among unmanaged fisheries, h_{ist}. Given the panel nature of our data, where biomass and harvest are observed for the same stock in multiple years, we use an additive fixed-effect specification relating harvest to prices and a quadratic profile in biomass:

$$h_{ist} = \beta_0 + \beta_1 p_{st} + \gamma_1 b_{ist} + \gamma_2 b_{ist}^2 + \varepsilon_{ist} \tag{1}$$

Where i represents stocks, s represents species, and t represent year. The parameter β_1 captures the price-responsiveness of supply and represents how relative harvest changes when the price changes by one unit, holding biomass constant. Importantly, the price data only varies at the species-level, which precludes the inclusion of stock fixed effects. The quadratic profile in biomass allows for the possibility that fishing pressure (which, along with biomass, determines harvest) is not constant in biomass. Further, biomass is a slow-moving stock-specific outcome that controls for different biological conditions across stocks, holding prices constant. In this sense, it is akin to a stock fixed effect.

A natural starting point would be to estimate β_1 using an OLS regression on Equation (1). While we report these estimates below for completeness, it is well-known that the estimate of β_1 will be biased due to the endogeneity of prices. Therefore we now propose an instrumental variables approach to identify the price responsiveness of global fisheries supply. We outline two complementary approaches in what follows.

In order to estimate the price responsiveness of supply using an instrumental variables approach, one needs to find an instrument that predicts the global price p_{st}, but is otherwise independent of the determinants of unmanaged supply ε_{ist}^U, conditional on the other controls and fixed effects.

2.1 Instrumental variables approach: Aquaculture quantities

We argue that quantities of seafood produced in aquaculture provide such an instrument. Indeed, quantities farmed and caught in the wild are close (if not perfect) substitutes – therefore variations in quantities produced in aquaculture (at the species group or species level) will affect prices in the capture fishery sector (*relevance*). On the other hand, supply in aquaculture cannot adjust as easily to prices and other demand-side factors as the capture fishery sector, and variations in aquaculture production does not affect wild capture otherwise than through prices and the incentives to fish they convey (*exclusion restriction*).

More specifically, Bjørndal and Guillen (2016) suggest that aquaculture production influences seafood prices, as long as the products considered are close substitutes: they find no relationship between white fish prices (or production) and that of salmonids – but quantities of farmed salmonids (respectively, white fish) influence the price of wild-caught salmonids (white fish, resp.). Basurco (2001) mentions that when seeking to develop new species for aquaculture one should assume *a priori* "the expected price and acceptance of a given species [to] be correlated with their fisheries counterparts," also indicating strong substitutability between wild and farmed products, in most cases.

Conversely, industry constraints prevent farmed production volumes from being influenced by short-term price fluctuations of their wild substitutes. Licensing, rules and local regulations, grow-out times, all impede instantaneous adjustment of production to prices. In a 2013 report, the European Commission states that "*in several Member States authorisation procedures often take around 2-3 years to complete; examples of substantially longer times have also been reported*" (European Commission, 2013). The report cites as exemplary the case of Norway,[5] where average licensing time for new salmon farms went from 12 to 6 months. But even then, biological constraints prevent short-term adjustments of production: farmed salmon quantities produced in a given year depend on how many salmon juveniles were hatched (intended scale of the operation) a few years prior, and on environmental conditions during their development.[6] As a result, Asheim et al. (2011) find that quantities produced are very inelastic to prices.

2.2 Instrumental variables approach: Quota-regulated quantities

In order to estimate the price responsiveness of supply using an instrumental variables approach, one needs to find an instrument that predicts the global price p_{st}, but is otherwise independent of the determinants of unmanaged supply ε^U_{ist}, conditional on the other controls and fixed effects. Such an instrument is given by the quantities caught in regulated fisheries: variation in catch (q^M_t above) mostly reflects changes in the TAC across years, which are determined by biological variations in stock size and other factors that are independent of prices. Indeed, in those fisheries, fisheries scientists propose each year a quota based on stock assessments and the species' biology, such that it ensures the persistence, or the recovery of the fishery (e.g., the MSY). It is of course influenced by factors such as the weather, to the extent that it affected or is anticipated to affect recruitment. Fishery managers in turn enforce the quota. The management of the iconic Bristol Bay sockeye salmon fishery in Alaska, the largest salmon fishery in the world, illustrates this principle. The fishery is managed with what is called a "constant escapement" policy, whereby a fixed number of fish are allowed to "escape" upstream to spawn each year, and the rest are harvested by the fishery. Still, quotas fluctuate wildly (over the 2010s, catch has ranged from 15 million in 2013 to 44 million in 2019, with a mean of 28 million individuals), but escapement is the same year in and year out. This implies that the TAC is completely determined by biological conditions, and is insulated from economic effects such as price.

But not all fisheries are as precisely regulated as the Bristol Bay sockeye fishery and two concerns remain regarding the exogeneity of our instrument. First, even when limited by a quota, catch could still respond to prices if fishers decide to fish under the quota or above. Second, the fishery manager could be influenced by stakeholders (fishers) and the quota might thus not be completely immune from price considerations. To address the first concern and ensure that the catch in TAC-regulated fisheries is not responsive to price, we focus on stock-years where the regulated catch falls between 90% and 110% of the TAC. As previously shown in Figure 4, this condition is met for roughly 35% of all the stock-year data we observe, and varies across species groups. To address the second, we note that most TACs are set *before* the fishing season begins, so any potential price information contaminating the TAC would come from the previous year. Since fishers respond to contemporaneous prices to decide their effort levels, there is a measure of independence between the pre-determined TACs and contemporaneous prices.

The relevance of managed catch for the global fish price is evident in Figure 6: shifts in the managed supply

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[5] Norway is not part of the European Union.

[6] Note that the effects of environmental fluctuations just mentioned are visible on Figure 1 – they eventually determine how many from the initial pool will make it to the mature, market-ready age and size.

curve lead to shifts in the total supply curve and therefore to a change in price. We test for instrument relevance and for weak instruments in the empirical analysis and find that managed catch is a strong predictor of global fish prices in the same species group. To proceed, consider the first-stage relationship between the global price of fish species s, in species group g, in year t, and managed, TAC-constrained catch in group g in year t (q^M_{gt}) as:

$$p_{sgt} = \pi_0 + \pi_1 q^M_{gt} + \theta_1 b_{sgt} + \theta_2 b^2_{sgt} + \lambda_t + u_{sgt} \tag{2}$$

See also the first-stage F-statistics reported in Table 5; a weak instruments problem might have been a concern had the F-statistics been lower than 10 (Andrews et al., 2019).

The market equilibrium diagram in Figure 6 suggests that π_1 in Eq. (2) is negative: an increase in managed catch should reduce global fish prices, everything else being the same. The independence assumption for TAC-constrained catch to be a valid instrument requires that shifts in managed supply across years are driven by factors that are independent of the shifters of unmanaged supply. However, our model of managed and unmanaged supply implicitly allows for a correlation between managed supply shocks and unmanaged supply shocks (through the parameter ρ). This implies, as we mentioned above and show in the Online Appendix, that the standard TSLS estimator does not directly recover β_1, but instead recovers a function of β_1, ρ, and α_1 (the slope of the demand curve): the TSLS estimator of β_1 converges to $\frac{\beta_1 - \rho\alpha_1}{1+\rho}$. Naturally, when $\rho = 0$, the managed supply shocks are uncorrelated with the unmanaged supply shocks, and the TSLS estimator identifies β_1. Otherwise, we will derive the value of β_1 under different assumptions for the value of ρ and use our global data to estimate α_1 in order to recover β_1. We describe our approach to this in what follows.

3 Conceptual framework

In order to illustrate the challenges to the causal identification of the effect of prices on fishing pressure, we first develop a conceptual framework of the global supply and demand of fish and seafood. We treat year t as the time step for consistency with the data. Thus, this simple model and the empirical analysis below focuses on annual snapshots of the global fish market rather than on examining the long-term equilibrium (which, for example, could induce a backward-bending supply curve in unmanaged fisheries (Copes, 1970)).

The global quantity supplied corresponds to the catch among managed and unmanaged fisheries and allows the global supply function to be segmented, with one segment where supply is price-independent (which we refer to as the managed segment M) and the remaining segment where the supply curve is allowed to be price-responsive (the unmanaged sector U). We assume the managed supply is vertical at the amount specified by the TAC.[7] The aggregate supply curve is the horizontal sum of the managed and unmanaged segments. On the demand side of the market, there is a single demand curve that represents the global demand function. This assumes consumers demand fish independently of whether they are harvested by managed or unmanaged fisheries. To proceed with a simple model, we ignore the possibility of an upward-sloping segment of the managed supply curve (at least in the short run) and represent the demand and supply curves for a given species group level as follows:

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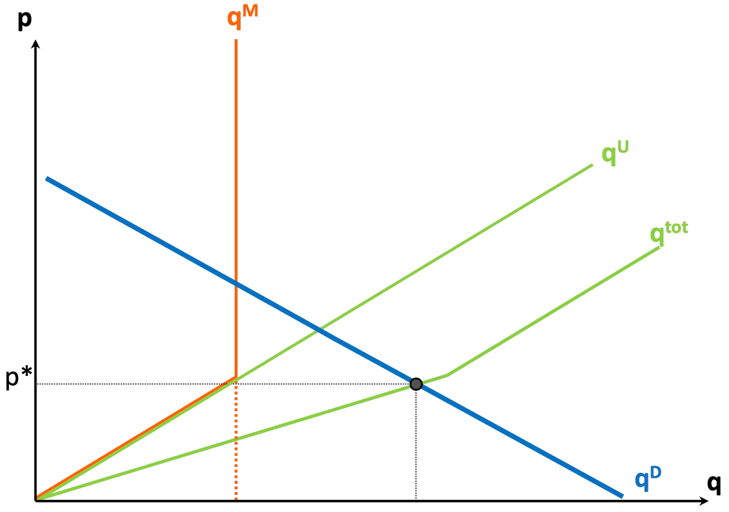
[7] As shown in Figure 6, the managed supply curve could be upward-sloping (i.e., price-responsive) up to the TAC. In the empirical analysis below we focus on stock-years where the catch is within 10% of the TAC to center on the vertical segment of the managed supply curve.

$$
\begin{aligned}
q_t^D &= \alpha_0 - \alpha_1 p_t + \varepsilon_t^D && (3)\\
q_t^U &= \beta_0 + \beta_1 p_t + \varepsilon_t^U && (4)\\
q_t^M &= \bar{S}_t + \varepsilon_t^M && (5)
\end{aligned}
$$

The parameter β_1 captures the price responsiveness of supply in unmanaged fisheries and the goal of the empirical analysis is to estimate it. Figure 6 illustrates the various components of the model, where the total supply q_t^{tot} is the sum of the managed inelastic supply q_t^M and an unmanaged, upward-sloping supply q_t^U. While inelastic, the managed supply q_t^M can vary from year to year due to the shock ε_t^M (depending on variation in stock biomass, environmental conditions, etc.). Similarly, the unmanaged supply q^U and the demand curve q^D can also shift from year to year (due to unmanaged supply shifter ε_t^U or to the demand shifter ε_t^D). Given the segmented nature of the total supply curve, we allow for a dependence between random supply shifters as follows: $\varepsilon_t^U = \rho\varepsilon_t^M + (1-\rho)\,\tilde{\varepsilon}_t^U$, where $\tilde{\varepsilon}_t^U$, ε_t^M, ε_t^D are assumed to be uncorrelated, thus allowing the random shocks to managed supply to also impact the unmanaged supply shifters.

Figure 6: Market equilibrium with segmented supply curves



Notes: The diagram represents the segmented global supply with the managed and unmanaged segments. For each group of substitutable fish species (species group), a portion of the supply is covered by stocks where harvest is managed, hence q^M (regulated) vertical. The rest is covered by unmanaged fisheries q^U, where fishing effort *can* be price-responsive. The horizontal sum of q^M and q^U gives the total supply curve, q^{tot}, and its intersection with the global demand curve q^D determines the price (p*) and quantity for that species group.

In practice, we identify managed fisheries where supply is assumed price-independent (represented by q_t^M) using information on the ratio of fishery actual catch to total allowable catches (TAC) or other catch limits among regulated fisheries. For those fisheries, TACs are set by national or regional management agencies, typically on the basis of meeting stock sustainability objectives, often on maximum sustainable yield (MSY) or similar proxies (Methot Jr. et al., 2014). The estimates of MSY upon which TACs are determined depend on current stock status and biological productivity of a fishery; they involve considerations of what catch can be safely caught with respect to biologically sustainable criteria. The setting of TACs does not typically involve fish price or other economic considerations, and therefore when catches are constrained by TACs, we can presume that those catches are also independent of price.

Fisheries rarely catch the TAC exactly; slight overages or underages across a fleet in any given fishing season are common. Therefore, we consider ratios of catch/TAC in the range of 0.9-1.1 to represent stock-years in which management regulations have constrained the catch. Below this range (catch/TAC < 0.9), market incentives for fully harvesting the TAC may be limiting. Above this range (catch/TAC > 1.1), catch regulations may be ineffective and incentives for over-harvesting may be present. At both of these extremes, fish prices may play a role in determining managed supply. Within the range of 0.9-1.1, however, we assume that catches are constrained by the TAC and are insensitive to price. And as a result, in that range, we expect the supply curve in managed fisheries to be vertical, as shown by q_t^M supply curve above.

4 Empirical Results

4.1 Supply elasticity with an aquaculture production instrument

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Ln price	0.078^{***}	0.074^{***}	0.078^{***}	0.078^{**}	0.078^{***}	0.172^{***}	0.075^{***}
	(0.009)	(0.009)	(0.021)	(0.029)	(0.020)	(0.021)	(0.009)
Biomass b_{it}	-0.873^{***}	2.160^{***}	-0.873^{***}	-0.873^{***}	-0.873^{***}	-1.040^{***}	0.280^{***}
	(0.019)	(0.079)	(0.090)	(0.074)	(0.083)	(0.085)	(0.021)
Biomass b_{it}^2	0.034^{***}	-1.428^{***}	0.034^{***}	0.034^{***}	0.034^{***}	0.044^{***}	-0.017^{***}
	(0.001)	(0.036)	(0.005)	(0.004)	(0.004)	(0.004)	(0.002)
Dep. var.	LnEffort	LnEffort	LnEffort	LnEffort	LnEffort	LnEffort	LnCatch
Sample	all	Upsides	all	all	all	all	all
FEs	year	year	year	year	year	year+group	year
Clustering	none	none	clust1+iso3	clust2+spp	clust3+year	clust1+iso3	none
Num. obs.	21,542	20,649	21,542	21,542	21,542	21,542	21,542
R^2 (proj model)	0.142	0.216	0.142	0.142	0.142	0.196	0.016

Notes: $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{cdot}p < 0.1$. Table shows OLS regression of wild catch prices (logged, in USD/kg) on logged fishing effort (columns 1-6) or catch (column 8), with year fixed effects, and in column (6) ISSCAAP group fixed effects in addition. The standard errors are robust (columns 1-2 and 7), or clustered at the species x year and country (columns 3, 6), the country x year and species (column 4), the species x country and year (column 5) level. Wild catch data comes from the Upsides database only (column 2), or both RAM and Upsides (all others), restricting the samples to stocks-years where no catch shares are implemented.

Table 2: OLS: prices on effort and catch

	(1)	(2)
Quantity (kg)	-0.000^{***}	
	(0.000)	
Ln quantity		-0.045^{***}
		(0.002)
Biomass b_{it}	0.015	0.006
	(0.014)	(0.013)
Biomass b_{it}^2	0.001	$0.002^{\cdot}$
	(0.001)	(0.001)
F-stat	37.303	180.045
Num. obs.	21,542	21,542
R^2 (proj model)	0.011	0.024
Num. groups: year	33	33

Notes: $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $\cdot p < 0.1$. Table shows OLS regression of aquaculture quantities (aggregated at the ISSCAAP group x country x year level) on wild catch prices, with year fixed effects. The independent variable is either the quantity (column 1) or the logged quantity (column 2). The dependent variable is the logged price (in USD/kg).

Table 3: First stage: predicting prices with aquaculture quantities

Table 2 shows the naïve OLS regressions of price on (normalized) fish mortality (columns 1–7) and catch (column 8) using various samples and clustering schemes. As expected, price coefficient is positive, and fairly stable across specifications. Nevertheless these OLS estimates are likely plagued with endogeneity, as prices and quantities are determined jointly.

First, the binscatter plot in Figure 7 provides suggestive evidence that aquaculture quantity, after controlling for year fixed effects and a quadratic in biomass, is negatively related to seafood prices in 1990-2012, which

	(1)	(2)	(3)	(4)
$\widehat{\text{Ln price}}$	0.575^{***}	0.575^{*}	0.575^{**}	0.575^{***}
	(0.056)	(0.254)	(0.203)	(0.153)
Biomass b_{it}	-1.048^{***}	-1.048^{***}	-1.048^{***}	-1.048^{***}
	(0.019)	(0.080)	(0.076)	(0.073)
Biomass b_{it}^2	0.043^{***}	0.043^{***}	0.043^{***}	0.043^{***}
	(0.002)	(0.004)	(0.004)	(0.004)
F-stat 1st stage	104.753	5.121	8.049	14.128
Clustering	none	clust1 + iso3	clust2 + cmnname	clust3 + year
Instrument	LnQuantity	LnQuantity	LnQuantity	LnQuantity
Sample	all	all	all	all
Num. obs.	$21,542$	$21,542$	$21,542$	$21,542$
R^2 (proj model)	0.099	0.099	0.099	0.099

Notes: $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$. Table shows IV regression of seafood prices (logged, USD/kg) instrumented by aquaculture quantities (at the ISSCAAP level), on fishing effort (logged), with year fixed effects. The instrument is the quantity of aquaculture. Standard errors are either robust (column 1) or clustered at the species x year and country (column 2), the country x year and species (column 3), the species x country and year (column 4).

Table 4: IV: instrumented prices on effort

corroborates the mechanism proposed: farmed seafood increases supply and depresses prices, and as a result wild catch decreases.

The insights from the binscatter plot are confirmed by the first stage regressions, presented in Table 3. They show that the instrument (aquaculture quantities) is reasonably strong (F-stat $>$ 30), and gives sensible results (prices for wild-caught seafood decrease as farmed quantities increase). Finally Table 4 shows the IV results deriving from that first stage. Prices now have a much stronger effect on fishing mortality (or effort), confirming the attenuation bias caused by the endogeneity of the OLS. The results survive various clustering schemes (at the country, species, year, and combinations thereof, level).

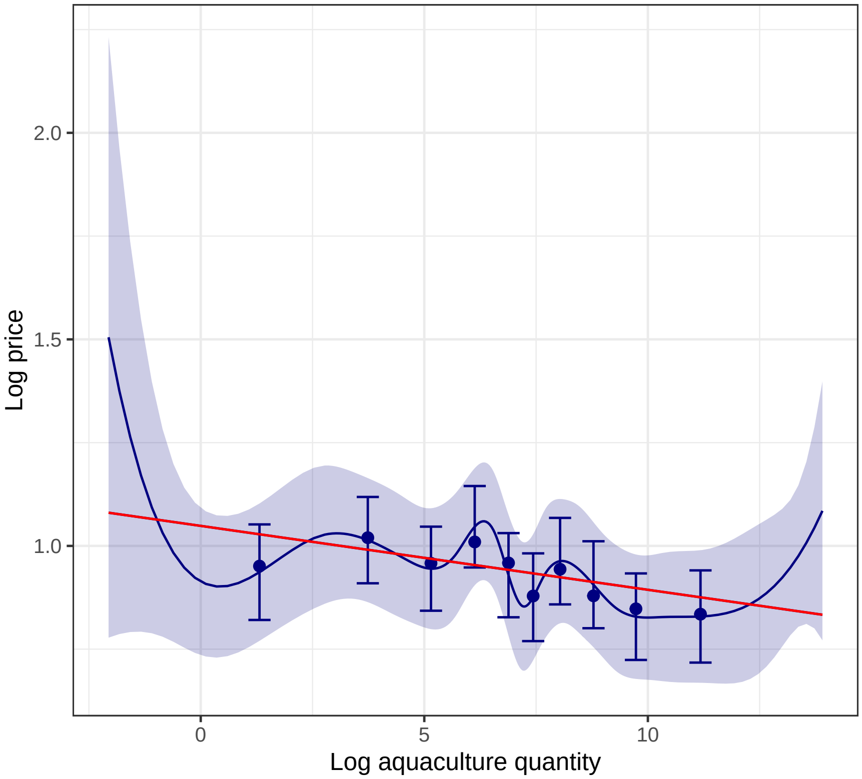
Following Reiss (2016), we investigate the sensitivity of the IV approach to the functional form of the instruments. The instrumental variable (q_A below) is transformed using a Box-Cox transformation along a sequence of λs to test the sensitivity of the elasticity estimate to log ($\lambda = 0$) or other transformation ($\lambda \in [-1, 2] \setminus \{0\}$):

$$q_A(\lambda) = \begin{cases} \frac{q_A^{\lambda} - 1}{\lambda} & \lambda \neq 0 \\ \ln q_A & \lambda = 0 \end{cases}$$

The values of λ that yield an estimate with a p-value below 0.05 lie between -1 and 1.8 (i.e., most of the range), and produce estimates between 0.54 and 0.96 (see Figure 8), with a mean and a median of 0.65 and 0.64, respectively. The estimation is fairly stable in sign and significance to transformation of the instrumental variable.

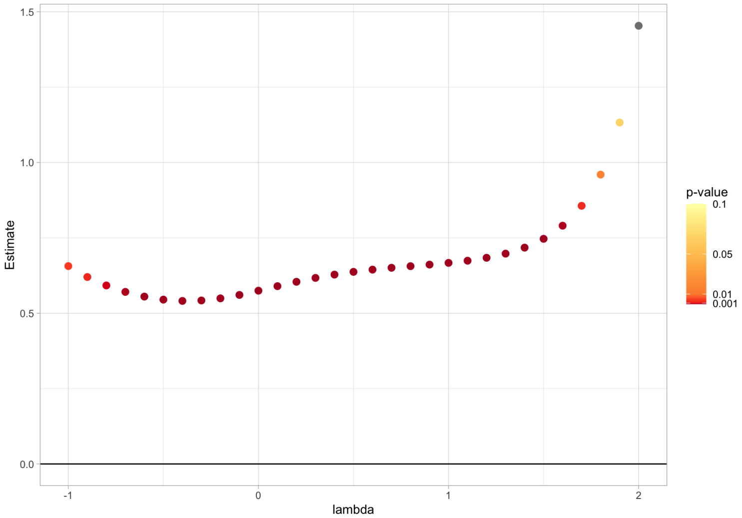
[*We are currently working on disaggregating the price elasticity by species group. It is indeed to be expected that different gear, fishing grounds, crew requirements, etc., will lead to different supply elasticities for different commercial groups. It is doable with both IV strategies; results look more reasonable with the aquaculture IV, though the aquaculture shock concerns fewer species (commercial) groups so it does not allow us to recover an elasticity for each group.*]

Figure 7: Mean relationship between aquaculture production and seafood prices, 1990-2012



Notes: Binscatter plot following Cattaneo et al. (2024), with prices in USD (logged) as the dependent variable and aquaculture quantities (logged) as the independent variable, controlling for year fixed effects and a quadratic in normalized biomass using the optimal bins (i.e., data-driven selection of bins and number of bins).

Figure 8: Price coefficient estimates along Box-Cox transformations of the instrument



Notes: In abscissa are values of λ in the Box-Cox transformation; in ordinate, point estimates for the coefficient associated with the log-price variable (price elasticities of supply) instrumented by a Box-Cox transformation of aquaculture quantity (see text) of corresponding λ. The color scale indicates the p-value associated with each estimate, from garnet-coloured (0) to pale yellow (0.1) (through 0.001, 0.01, 0.5, with corresponding breaks); values in grey are statistically not significant ($p > 0.1$).

4.2 Supply elasticity with a regulated harvest (TAC) instrument

Table 5 reports the estimates of the parameters in equations (1) and (2), along with the estimated standard errors.[8] Column (1) reports the OLS estimates of β_1, γ_1, and γ_2. The estimates suggest a quadratic relationship between harvest and biomass, consistent with the predictions of most bioeconomic models. The estimated slope of the unmanaged supply curve is statistically different from zero but small: 0.01, which corresponds to a short-run (annual) elasticity of 0.03. This indicates that among unmanaged fisheries, harvest increases when prices increase, but in a fairly weak manner.[9] By comparison, supply elasticities in other natural resource sectors such as timber and agricultural commodities can sometimes be one order of magnitude larger (see Fally and Sayre (2018) for a survey).

Column (2) reports the estimates from the first-stage regression relating global fish prices to the TAC-constrained catch in the managed sector as in 2. As expected, the estimated π_1 is negative and statistically significant. The coefficient indicates that a one million metric ton increase in harvest in TAC-constrained stocks reduces fish prices by $0.62 per kilogram. The F-statistic testing the null hypothesis that the effect of regulated catch is zero is 260, indicating the instrument is relevant and outside of the critical range for weak instrument concerns. The corresponding elasticity is -0.05, indicating that a 1% increase in harvest in TAC-constrained fisheries leads to a 0.05% decrease in the global price of fish.

Column (3) shows the TSLS estimates of the parameters in 1, using TAC-constrained catch in the managed sector as an instrument for price. The relationship between relative harvest and biomass is again quadratic and similar to the one estimated by OLS in column (1). As noted earlier, the TSLS estimate of the price coefficient (β_1) presented here is consistent if and only if $\rho = 0$ (i.e., if the shocks to managed and unmanaged supplies are uncorrelated). We find an estimate of 0.05, with a standard error of 0.01, which corresponds to an elasticity of 0.11. While the elasticity obtained with TSLS is larger than that obtained with OLS, it remains indicative of a fairly weak relationship between harvest and prices in unmanaged fisheries. This finding foreshadows limits to the ability of demand-side intervention to lead to sizable changes in catch in response to price fluctuations.

Lastly, we might expect fishers to respond to short-term (year-on-year) price variations differently from longer-term price variations, for instance one might be reluctant to make capital adjustments in the short run, but might consider making them in the long run. This is important when considering the effect of permanent or long-lived policies, especially if overcapacity is believed to be part of the issue. We tackle this issue empirically by using 5-year price averages (and the 5-year average value of the instrument) instead of contemporaneous prices in the estimation. The results are reported in columns (4)-(6) of Table 5. The TSLS coefficients (and all the others) are strikingly similar to those obtained with same-year prices. Thus as far as we can judge from that analysis, long-run elasticities are not very different from short-term elasticities, and we therefore stick to the short-term estimates for the remainder of the paper.

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[8] Standard errors are two-way clustered at the stock and species-year levels to account for possible serial correlation specific to each stock, and to account for possible annual species-specific shocks.

[9] Recall that these OLS estimates potentially suffer from endogeneity bias; we report them here for completeness.

Table 5: OLS, first-stage, and TSLS estimation results for price on relative harvest

	OLS (1)	First-stage (2)	TSLS (3)	OLS (4)	First-stage (5)	TSLS (6)
Annual ex-vessel price (USD/kg)	0.01^{***}	—	0.05^{***}	—	—	—
	(0.00)		(0.01)			
Ex-vessel price, 5y avg. (USD/kg)	—	—	—	0.01^{***}	—	0.05^{***}
				(0.00)		(0.01)
Biomass b_{it}	3.12^{***}	0.16	3.25^{***}	3.13^{***}	-0.16	3.26^{***}
	(0.14)	(0.81)	(0.14)	(0.14)	(0.82)	(0.14)
Biomass b_{it}^2	-1.42^{***}	-0.47	-1.43^{***}	-1.43^{***}	-0.36	-1.44^{***}
	(0.06)	(0.32)	(0.06)	(0.06)	(0.33)	(0.06)
TAC-constrained catch (10^6 tonnes)	—	-0.62^{***}	—	—	-0.63^{***}	—
		(0.04)			(0.04)	
Implied elasticity	0.03	—	0.11	0.03	—	0.11
1st stage F-stat.	—	—	1,447.8		—	1,514.3
Observations	52,601	45,852	45,852	52,571	45,822	45,822

Notes: $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$. This table shows regression estimates for our preferred specification of the effect of fish price on relative harvest. The dependent variable in columns (1), (3), (4) and (6) is the relative harvest (h_{it}). The first three columns use contemporaneous prices (the prices of year t on the quantities of year t) in order to obtain a short-term elasticity, while the last three aim at getting at a long-term elasticity of supply and thus use as independent variable the average of prices in years t through $t-4$ (5-year rolling average). Columns (1) and (4) show OLS estimates, columns (2) and (5) report the the first stage estimates (managed quantities on global prices), and columns (3) and (6) show TSLS estimates (instrumented prices on relative harvest in unmanaged fisheries). Standard errors are two-way clustered at the stock and species-year level.

5 Simulations: Approach and Results

Our empirical results indicate a relatively price-inelastic global supply curve for unmanaged fisheries. What does this imply for the efficacy of demand-side interventions? To answer this question, we embed our empirical estimates in a structural simulation of global fish supply and demand. This allows us to tease apart the relative efficacy of demand-side interventions (which shift the demand curve) vs. supply-side interventions (which constrain supply responses directly). Once parametrized, the model enables us to derive counterfactual estimates of fishing mortality, catch, ex-vessel price, and biomass under different scenarios for management and price regimes for our sample of 2,287 unmanaged fisheries over the 1990-2012 period.

The model takes as starting conditions the relative biomass of each stock and the ex-vessel price for each species in 1990 and endogenously derives the values of these variables for each year through 2012. For each time step (year), we construct a global demand curve for each of the 17 fish and seafood species groups using the parametrization from Costello et al. (2020), and intersect them with a global supply curve, inclusive of a managed and unmanaged segment, and constructed using the conditions specific to each scenario. To infer the unmanaged segment supply curve, we rely on the TSLS estimates of β_1 derived using the annual price variation and reported in column (3) of Table 5. Finally, for each fish class and time step, the model outputs global quantities of harvest and biomass as well as the ex-vessel price (Figure 9). We then aggregate this information in each time step across all fish classes.

Using this simulation framework, we model four alternative assumptions about management representing different supply-side policies (through regulated quantity management, Q) and a demand-side intervention (through price changes that shift the global demand curve, P). Each scenario requires either constructing a counterfactual supply curve for unmanaged stocks, or a counterfactual global demand curve, which we intersect to derive the harvest, equilibrium ex-vessel prices, and biomass for the stocks that are currently unmanaged. The four scenarios we consider are as follows:

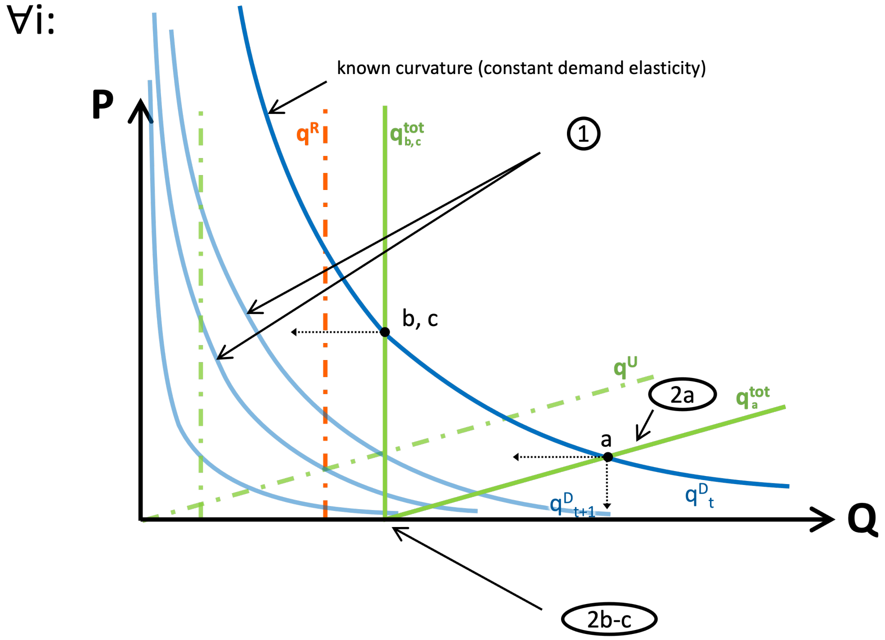
- **‘No intervention’**: All currently unmanaged stocks remain unmanaged throughout the duration of the simulation, and so catch is price-responsive, following the empirical estimates of the unmanaged supply curve. This corresponds to our modelled baseline.
- **‘Q-optimal’**: All currently unmanaged stocks are managed to maximize long-term sustainable yield. From 1990 onward, a relative fishing pressure $F_{it} = F_{MSY\,it}$ (i.e., $f_{it} = 1$) is applied to all stocks, and so catch does not respond to prices.
- **‘Q-average’**: All currently unmanaged stocks are managed at the average fishing pressure observed in managed stocks (from RAMLDB) for the same species group and year. From 1990 onward, fishing pressure $F_{it} = \frac{1}{N_M} \cdot \sum_{j=1}^{N_M} \frac{F_{jt}}{F_{MSY\,jt}}$ (N_M the number of managed stocks in group i) is applied to all stocks. This implies that catch does not respond to prices, and that all stocks are managed as well as comparable managed stocks were in the same year.
- **‘P-unit’**: All currently unmanaged stocks remain unmanaged (catch is price-responsive) but we include a permanent negative demand shock, specifically a unit tax of \$2 per kilogram, that shifts the demand curve downwards. Recall the observed mean ex-vessel price of fish is \$3.39 per kilogram, so this is a large unit tax.

5.1 Simulation procedure

Our simulation assumes that ex-vessel prices are determined by the global demand for a species category and the aggregate supply for that category. The aggregate supply is the horizontal sum of the managed and unmanaged supply. The intersection of the species group-level supply and demand curves deliver a market-clearing price, and the harvest in each individual fishery within that species category is determined by the supply curve. The end result is a market-clearing fishery-level harvest in each year. Naturally, since our interventions affect either the supply or the demand curve, the fishery-level harvest will depend on the intervention. And since the biomass of a fishery affects the supply curve for that fishery, biomass must be tracked over time because it endogenously affects supply, and therefore market equilibrium.

We begin by calculating demand curves specific to each species group i and year t assuming an isoelastic demand of the form $Q_{it} = k_{it} \times P_{it}^{-r}$ with $r = 0.382$, following Costello et al. (2020). Under this form, a single point on the curve suffices to fully specify the demand curve in any given year. To proceed, we use for each species group the total quantities harvested (across managed and unmanaged stocks) for Q_{it}, and average observed ex-vessel price for P_{it}. This allows us to back out k_{it}, and yields a global demand function for each time step and species group.

Figure 9: Schematic illustration of the simulation procedure



Notes: Figure illustrates the simulation procedure for any species group i. **(1)** Assuming an isoelastic demand curve, a pair (P_{it}, Q_{it}) (from the data, total catch and price in year t) suffices to pin down the demand curve. **(2-a)** No-management scenarios: No intervention and P-unit. The intersection of the demand curve and the empirically derived unmanaged segment supply curve yields an endogenously determined fish price and harvested quantity for year t and species group i. Dash-dot lines correspond to supply curves for either the regulated or the unregulated segment; solid supply curves correspond to the total supply. **(2-b,c)** Management scenarios: Q-optimal, Q-average. The quantity harvested is fixed at $f_{it} = 1$ (b) or $\bar{F}_M$ (c, see text), and its image by the demand curve endogenously gives the price for that year and species group. **(3)** With the quantity caught from step (2), the next period biomass is given by the Pella-Tomlinson model of stock dynamics, and the operation can be repeated for all groups and years from 1991 to 2012.

For each time step and species group we calculate the equilibrium price and quantity by intersecting the demand curve for species group i and year t with the corresponding aggregate supply curve for i. The aggregate supply is the horizontal sum of managed supply (which is perfectly inelastic at the observed quantity of harvest) and the empirically estimated unmanaged supply curve, as shown schematically in Figure 9. Note also that each of these supply curves is the aggregation of the fishery-level supply curve for the fisheries contained in that species group.[10] For the scenarios without management (No intervention and P-unit), the unmanaged supply curve is constructed using the TSLS estimates based on annual price variation and reported in column (3) of Table 5. The demand-side intervention scenario (P-unit) involve shifts in the demand curve, leading to new equilibrium prices and supplied quantities in each time step. Once the equilibrium price for species group i is determined, the harvest for fish stock $j \in i$ (denoted h_{jt}) can be read off of j's supply curve. This allows us to update the biomass for fish stock j according to fishery-specific biological growth equation. For scenarios that impose supply-side management on currently unmanaged stocks (Q-optimal, Q-average), the new unmanaged supply curve is perfectly inelastic and constructed based on the catch resulting from the level of fishing pressure h_{jt} prescribed by the management regime.

For the scenario involving a shift in the demand curve (P-unit), we express the shift in terms of an equivalent per-unit tax levied on the buyers in the ex-vessel market. Using the same notation as before, the effect of a unit tax τ on demand for species group i would therefore be: $Q_{it} = k_{it} \cdot \left(\tilde{P}_{it} + \tau\right)^{-r}$ where $\tilde{P}_{it}$ correspond to the untaxed (ex-vessel) price for species group i in year t.

In each time step, the above procedure delivers a market-clearing price for each species group, i. That price determines catch in each fishery, j. We then simulate the biomass dynamics fishery-by-fishery where biomass is projected to the next time step by applying the Pella-Tomlinson model of stock dynamics: $b_{jt+1} = b_{jt} + \frac{\phi+1}{\phi} \times g_j \times b_{jt}(1 - \frac{b_{jt}^{\phi}}{\phi+1}) - g_j \times h_{jt}$, with ϕ and g_j biological parameters, where $\phi = 0.188$ for all fisheries and g_j is a fishery-specific growth parameter (Costello et al., 2016).

5.2 Simulation results

The results of the simulations are shown in Figure 10. Each of the five panels corresponds to a variable of interest aggregated across all currently unmanaged fisheries: total catch in million tonnes (panel a), median ex-vessel price in USD/kg (panel b), total biomass in million tonnes (panel c), median relative catch (panel d), and median relative biomass (panel e). In each panel, the gray line corresponds to the historically observed trajectory of the variable plotted for unmanaged stocks for 10 years pre-simulation and continuing through the 1990-2012 simulation period. Later, we summarize the results of the simulation for each scenario at the 2012 endpoint.

We begin with the business-as-usual (No intervention) scenario, where the catch for each unmanaged stock responds to ex-vessel price as estimated in Equation (2). The outcomes are represented by the purple line Figure 10. Not surprisingly, in the absence of any interventions to curtail fishing, the median biomass continues to decline following the historical trend (panel e), resulting in a 35% decline of total biomass compared to 1990. Indeed, catch (panel a) remains high initially, further depleting healthy and overfished stocks alike, but eventually falls as relatively high prices (panel b) keep incentivizing higher fishing effort on increasingly depleted stocks, leading to a decline in quantities landed.

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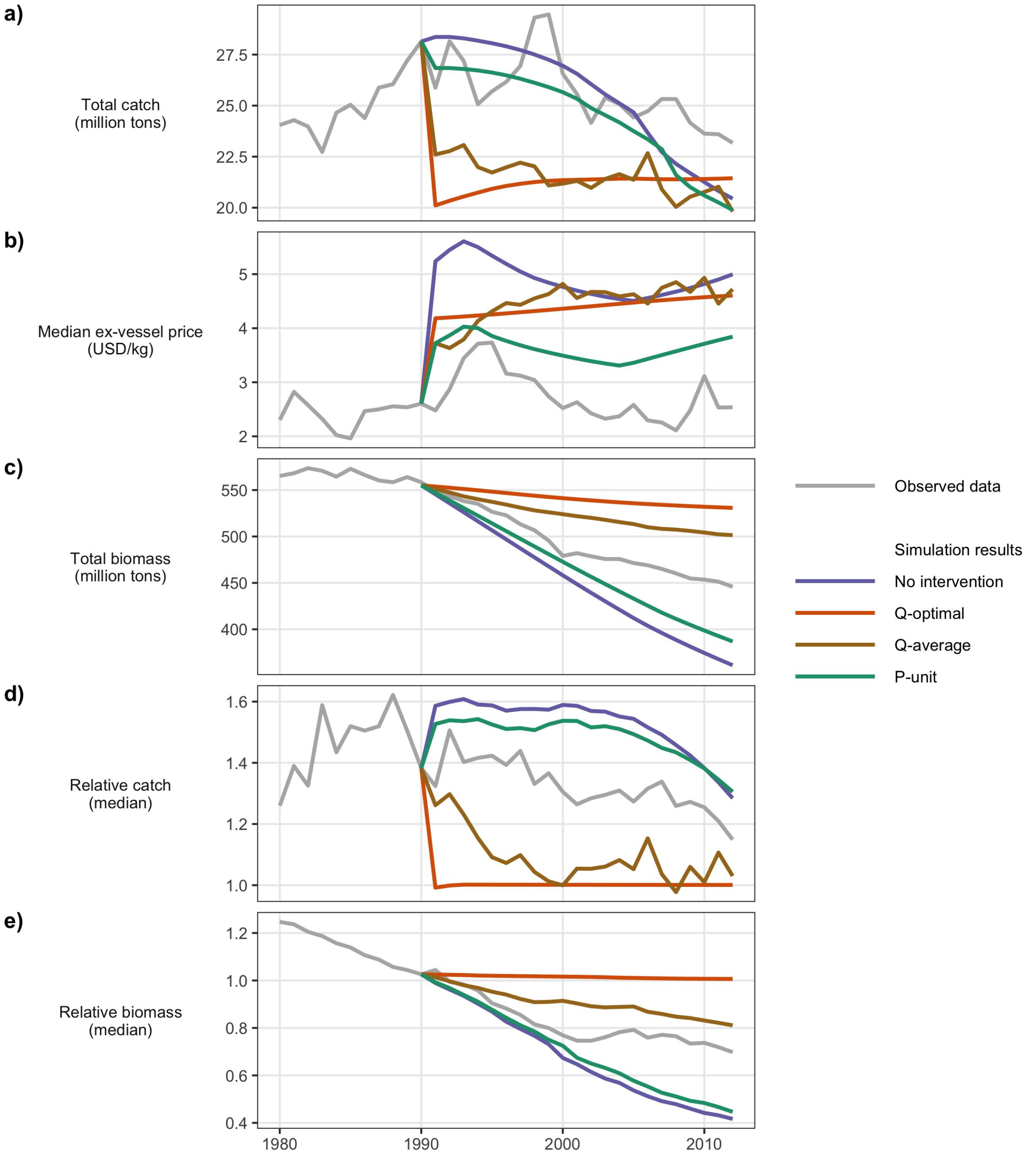
[10] This procedure excludes the possibility of demand substitution across species groups, while it considers all species within the same species group as substitutes. Note that spillovers across groups are not explicitly considered in the supply side either, but for the empirical part they are less of a concern.

Figure 10: Simulation results



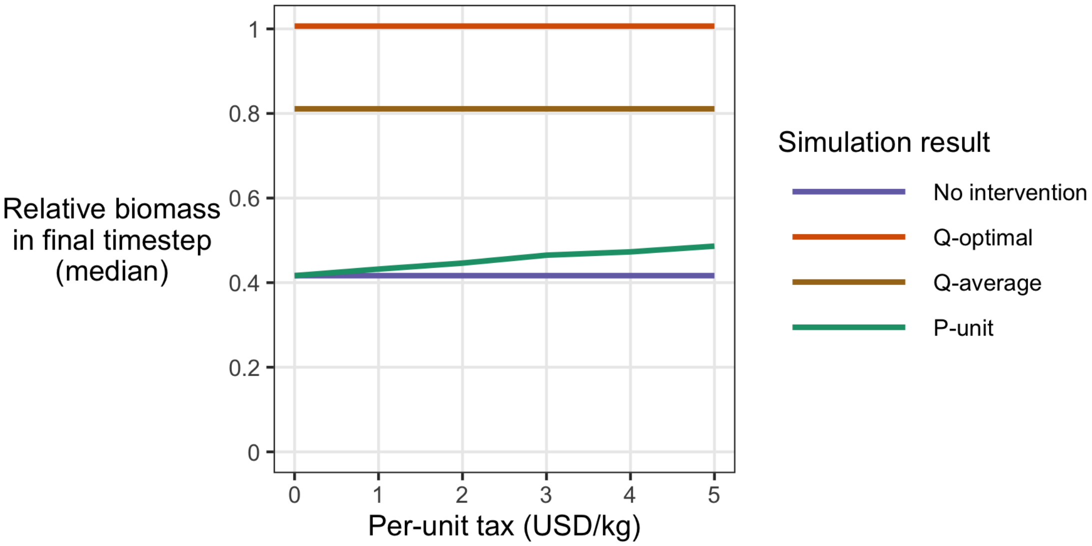
Notes: The figure shows simulation results for different management and demand intervention scenarios: in panel **a)** the total catch (in million metric tonnes), panel **b)** median ex-vessel price (USD per kilogram), panel **c)** total biomass (million metric tonnes), panel **d)** median relative catch ($^{H}/_{H_{MSY}}$), and panel **e)** median relative biomass ($^{B}/_{B_{MSY}}$). The gray line plots the actual observed data for currently unmanaged fisheries. The purple line corresponds to the modelled baseline scenario, where unmanaged stocks remain unmanaged and are fully price-responsive (**No-intervention**). The orange line and dark yellow lines correspond to the management scenarios **Q-optimal** and **Q-average**. Finally, the green line corresponds to a scenario where fisheries are not managed but demand is shifted with a unit tax (τ =2 USD/kg) (**P-unit**). Note that vertical axes do not begin at 0.

The two management scenarios, Q-optimal (orange line) and Q-average (brown line) lead to stock recovery owing to the quantity-based management; this results in smaller declines in total biomass, with median biomass and catch converging rapidly to 1 in the case of Q-optimal (panels d and e). In the Q-average scenario, median biomass continues to decline from 1990 to 2012, eventually reaching a value of 0.81 in 2012, notably higher than the endpoints reached under the No intervention or P-unit demand-side scenarios, and also higher than historic observed levels. Management also leads to a substantial (roughly 20-30%) initial reduction in total catch (panel a, recalling that this applies to unmanaged fisheries only), with dynamics that differ from the other scenarios. The dynamics of median ex-vessel prices are also noteworthy (panel b). From 1990 to 2012 ex-vessel prices are typically lower in the scenarios with fisheries management (Q-optimal and Q-average) compared to the No intervention case, reflecting the complex and dynamic interactions between supply, demand, and fishery stock.

Our demand-side scenario represents a case where demand for fish and seafood at the ex-vessel market drops, and thus the economic incentive for catching fish is reduced. We consider a fairly extreme scenario where demand is considerably reduced through a \$2 per kilogram tax (P-unit). The magnitude of the demand shift is evident when looking at the median ex-vessel price, where the the equilibrium price is less than the No intervention baseline scenario (panel b). Interestingly, this decline in price does not lead to a commensurate response in terms of total catch (panel a) or total biomass (panel c), reflecting the weak empirical connection between harvest and price we documented in section §4. As for the physical quantities landed (panel a) and biomass in the ocean (panel c), their paths remains close to that of the baseline No intervention (slightly below, and slightly above, respectively), and markedly apart (far higher, for catch, and far lower, for biomass) than Q-average and Q-optimal scenarios for most of the simulation (noting however the convergence in total catch towards the end). A similar pattern is observed for median catch and biomass (panels d and e). The takeaway is that even with extreme measures to reduce demand (and the economic incentives to catch fish), over a 22 year period, biomass recovery is substantially less than what our model estimates would instead arise from fishery management interventions.

Figure 11 examines the impact of a demand-side intervention further by considering a wider range of unit-tax scenarios. To compare across increasingly stronger demand-side interventions, we report the simulated biomass at the last time step (2012) derived under a range of values for the unit tax (0-5 USD/kg). The figure shows that increasing the tax beyond 2 USD/kg only marginally changes the outcome in terms of stock health, since the final-step (2012) biomass only reaches at best 0.49 (as opposed to 0.45 with the baseline tax of 2 USD/kg). From this analysis we conclude that conventional fishery management approaches (Q-average) continue to outperform demand-side interventions, even in the most aggressive versions of such interventions.

Figure 11: Median relative biomass in 2012 under varying stringency of the unit tax



Notes: For the P-unit tax scenario we vary the per-unit tax from 1 USD/kg to 5 USD/kg (green line, **P-unit**). The purple line corresponds to the baseline scenario, where unmanaged stocks remain unmanaged, i.e., fully price-responsive (**No intervention**). The orange line corresponds to an optimal management scenario (**Q-optimal**), whereas the dark yellow line (**Q-average**) corresponds to the scenario where all stocks are managed at the average fishing pressure observed in managed stocks (from RAMLDB) for the same species group.

We end this section with a brief sensitivity analysis of the simulation results for different values of ρ, the parameter capturing the correlation between supply shocks in managed versus unmanaged segments. More details are presented in the Online Appendix. As explained in section §2, when shocks to managed and unmanaged supply functions are correlated, the TSLS estimator we recover converges to $\frac{\beta_1-\rho\alpha_1}{1+\rho}$, in which case it is incorrect to interpret the coefficient estimate as the slope of supply (which is β_1). Thus if $\rho \neq 0$, we need to adjust the TSLS estimate in order to recover the slope of the supply curve β_1. To proceed we calculate the parameter α_1 and then derive β_1 for a range of values of ρ. Recall that α_1 is the slope of the demand function in our model; in 3 it is expressed as a linear function of price for simplicity, but in our simulations we used a more realistic isoelastic function (see above) and thus α_1 is the slope of the tangent to the demand curve evaluated at the equilibrium price, divided by the MSY as our model uses quantities relative to MSY, i.e., $\alpha_1 = \frac{rk}{MSY} \cdot P^{-(1+r)}$. We use the average values of k and P to get α_1 values for each species group and then average them to obtain a single value (we find $\alpha_1 = 0.78$). This gives $\beta_1 \in \{0.13, 0.46, 0.79\}$ for $\rho \in \{0.1, 0.5, 0.9\}$. This simple procedure allows us to examine the implication of correlated suppy shocks for the qualitative conclusions of our simulation exercise. For example, if $\rho = 0.5$, we can back out the implied supply slope (which turns out to be $\beta_1 = 0.46$), and conduct the simulation described above.

Online Appendix Figure S2 summarizes the simulation results when varying ρ from 0 to 0.9; the dynamics are shown in Figure S1. For the no-management scenarios (No intervention and P-unit), varying ρ from 0 to 0.9 only leads to a marginal change in relative biomass, and overall does not alter qualitatively the results obtained above when ρ is assumed to be 0. Therefore the conclusions from the simulations in this paper are not qualified by any specific assumption about the correlation between supply shocks in the managed and unmanaged sectors.

6 Discussion and Conclusion

The declining status of many of the world's fisheries is one of the leading ecological and economic challenges of the 21st century. About half of the world's fish catch comes from fisheries managed with quantity-based regulations; by and large, these fisheries are in good, and improving, health. The other half of the world's fish catch comes from fisheries with little or no management; many of these fisheries are in poor health and continue to decline.

Because the dire condition of these latter fisheries has grave consequences for food security, livelihoods, and ecosystem health, they are the focus of tremendous international attention, primarily aimed at identifying how to put them on a path to sustainability. One candidate solution is to bestow on these fisheries similar management to that applied, largely successfully, on the managed fisheries. An alternative is to shift demand away from unsustainable stocks via seafood campaigns, eco-labels, and supply chain commitments. This paper provides the first empirically grounded, causal-inference evidence on the possible efficacy of demand-side interventions for the world's unmanaged fisheries.

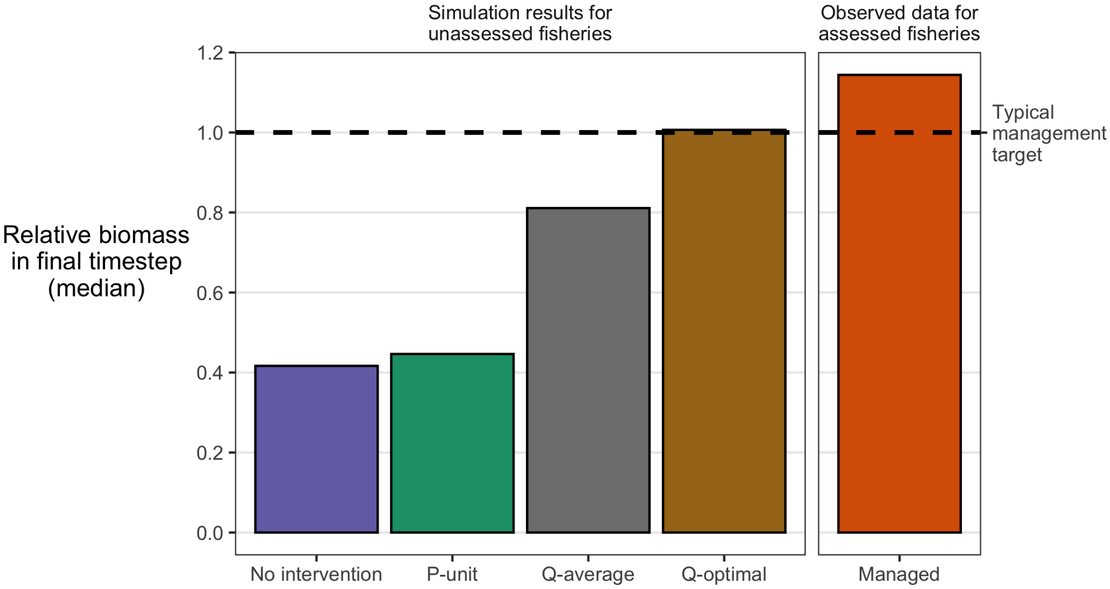
We show theoretically that effective demand-side interventions hinge critically on the degree of price-responsiveness of the supply curve in unmanaged fisheries. However, the supply elasticity of unmanaged fisheries remains to date mostly unknown, due to the lack of appropriate data and research design to causally identify supply responses to price variation.

We remedy this knowledge gap by combining global fisheries data on stocks, prices, and catch between 1990 and 2012 for 2,287 unmanaged stocks (166 countries) and 900 managed stocks (51 countries). We leverage the insight that catch in quantity-regulated (managed) fisheries is determined primarily by ecological conditions, and not by prices. We find that the catch in these managed fisheries has a strong effect on global fish prices within species categories. We use this result as the first stage of an instrumental variables strategy to uncover the causal effect of prices on catch in unmanaged fisheries. This produces the first causal estimate of the global short-term supply elasticity for seafood, which is about 0.11.

Implicit in the demand-side intervention approach to sustainable fisheries is the assumption that the prescribed change in consumers' demand will translate into a change in harvest which in turn will lead to the ecological recovery of depleted stocks. We use our causally identified empirical results in a quantitative simulation exercise to examine the likely consequences of various interventions on biomass, harvest, and prices. We use this simulation to compare demand-side interventions, traditional quantity-based regulation, and a benchmark case of no intervention. Specifically, we develop a model of global demand and supply of seafood parametrized with our estimate of the supply functions, demand elasticities from the literature, and coupled with bioeconomic (Pella-Tomlinson) stock dynamics, and run it under four scenarios.

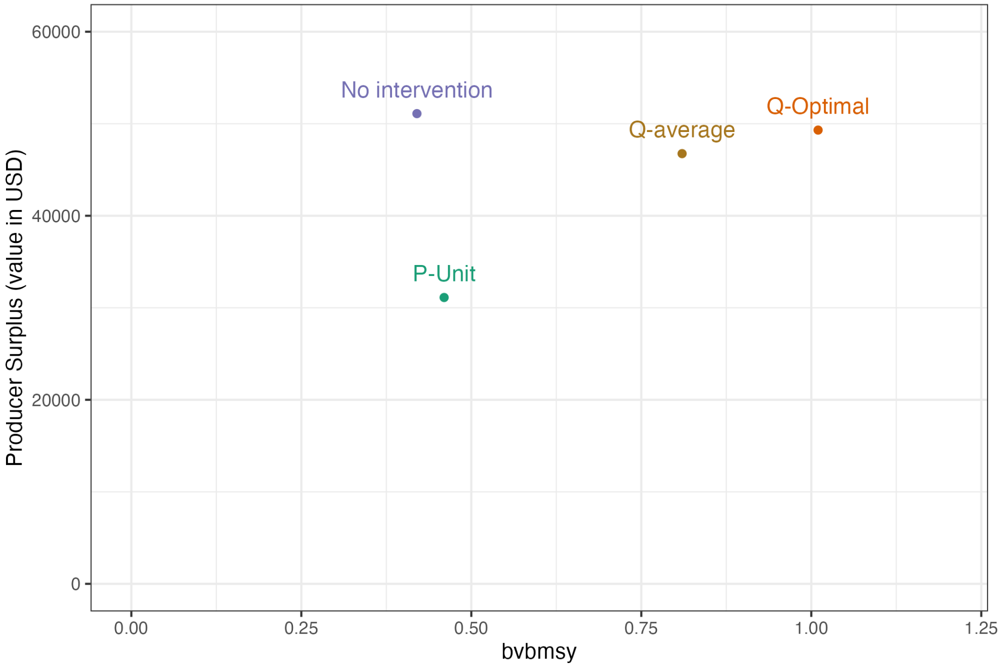
Figure 12 provides a graphical summary of these results (left panel) in comparison to what we observe empirically for managed stocks (right panel). The No intervention scenario delivers the worst outcome (relative biomass at 0.4), but the demand-side intervention (P-unit) offers only modest improvements. This is in sharp contrast with the supply-side quantity management interventions, which produce roughly twice the ending biomass (0.8) for perhaps "realistic" management effectiveness, Q-average, or even larger biomass (1.0), for optimized fishery management. Thus, we find that even drastic demand-side interventions (in isolation of other interventions), deliver only modest improvements and fall short of management targets whereas quantity-based management can deliver substantial improvements. Figure 13 shows that these improvements in biological status do not come at the expense of economic performance: given that the demand-side intervention ("P-Unit") reduces the prices received by the producers and fails to improve the health of the stocks, it does poorly compared to both the business-as-usual (no-intervention) and to the quotas (supply-side) scenarios.

Figure 12: Simulated and observed median biomass in 2012



Notes: Figure shows median relative biomass at the end of the simulation run for each scenario, and the corresponding actual biomass observed in managed fisheries in 2012. The purple bar corresponds to the baseline simulation scenario, where unmanaged stocks remain unmanaged, i.e., fully price-responsive (**No intervention**). The green bar corresponds to a simulation scenario where unmanaged fisheries are not managed but demand is shifted either with a unit tax (2 USD/kg) (**P-unit**). The dark yellow bar corresponds to an imperfect, realistic management simulation scenario applied to unmanaged fisheries (**Q-average**). The orange bar corresponds to an optimal management scenario (**Q-optimal**) applied to unmanaged fisheries. The gray bar corresponds to observed data for assessed and managed fisheries from RAMLDB. The horizontal dashed line at 1 represents a typical sustainable management target.

Figure 13: Economic and biological outcomes: Producer surplus and biomass



Notes: Figure plots final time step (2012) producer surplus (in USD) against relative biomass ("bvbmsy") for the various scenarios implemented: business-as-usual ("No intervention"), quotas ("Q-optimal", "Q-average"), a unit tax ("P-unit").

A natural concern is that the important improvements in stock levels under the management scenario could come at the expense of total seafood catch, possibly leading to food insecurity or to high prices. Our simulation model allows us to track these important variables and found that neither supply-side intervention scenario caused prices to exceed those of the No intervention scenario. In fact, total quantities caught reached comparable levels at the end of the simulation period across all scenarios. This implies that stronger management does not harm consumers (nor to producers, recall Figure 13), on the contrary, we find that better management ensured the sustained replenishment of the exploited stocks, which ultimately leads to lower prices. Taken together, these results provide further support for the expansion of quantity-based fisheries management (such as quotas), and strongly qualify calls for demand-side interventions as a panacea to rebuild global fisheries. Further, by greatly reducing ex-vessel prices, demand-side interventions also depress incomes in the fishing sector and impact the livelihood of many.

It is important to note that in real-world applications, interventions such as eco-labels often involve a mixture of demand and supply-side incentives. For example, most certification programs require explicit changes in management, and can thus simultaneously improve management and shift demand. While we do not explicitly model these blended approaches, we emphasize that to be effective, such programs must contain the supply-side link.

The findings and methods presented in this paper contribute both to the academic research on natural resources and to the policy and management debates around them. Several promising avenues arise for future research and policy exploration. First, the elasticities of supply estimated here are not species- or group-specific, although it is clear that different fish ecology, fishing gear, and institutional context would likely result in different fishing responses to prices. Refining those estimates would likely uncover heterogeneity, which is interesting in its own right, and might reveal that for some species, and in some contexts, demand-side intervention may be worth pursuing, if higher supply elasticities are uncovered. Second, our results raise interesting questions about why supply elasticities are so low and fishers so unresponsive to prices. Other studies have suggested that fixed costs and subsidies might play a role (Martini and Innes, 2018, among others) but the exact contribution of each is unclear, and importantly for policy and management, vary by fishery or species. Clarifying and subsequently altering those dimensions to the extent that they are responsible for the muted response of fishers might tip the scales in favor of supply-side interventions. Efforts to blend causal inference, fishery dynamics, and concepts of market equilibrium will continue to help deliver practically relevant insights about how to restore the productivity of the ocean, and will be instrumental in addressing one of the leading ecological and economic challenges of the 21st century.

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Online Appendix

A Deriving an instrument for price in the unmanaged supply function

Recall from equations (3)–(5) in the main text:

$$\begin{aligned} q_t^D &= \alpha_0 - \alpha_1 p_t + \varepsilon_t^D \\ q_t^U &= \beta_0 + \beta_1 p_t + \varepsilon_t^U \\ q_t^M &= \bar{S}_t + \varepsilon_t^M, \end{aligned}$$

with q_t^D, q_t^U, q_t^M the quantities demanded, supplied by the unmanaged segment, supplied by the TAC-constrained managed segment, respectively, and $\varepsilon_t^U = \rho\varepsilon_t^M + (1-\rho)\,\tilde{\varepsilon}_t^U$ where $\tilde{\varepsilon}_t^U$, ε_t^M, ε_t^D are uncorrelated, but ε_t^U and ε_t^M are potentially correlated. At market equilibrium, for all t and group i (indices omitted for clarity), supply equals demand and thus:

$$p^* = \frac{\alpha_0 - \beta_0 - \bar{S} + \varepsilon^D - (\rho+1)\,\varepsilon^M - (1-\rho)\,\tilde{\varepsilon}^U}{\alpha_1 + \beta_1}.$$

We can now back out ${dq^U}/{dp^*}$ from ${\partial q^U}/{\partial \varepsilon^M}$, ${\partial q^U}/{\partial p^*}$, ${d\varepsilon^M}/{dp^*}$ and get:

$$\frac{dq^U}{dp^*} = \beta_1 - \frac{\rho}{1+\rho}\cdot(\alpha_1+\beta_1) = \frac{\beta_1 - \rho\alpha_1}{1+\rho}$$

If $\rho = 0$, our two-stage least squares (TSLS) estimate ($\frac{dq^U}{dp^*}$) will converge towards β_1 the parameter of interest.

However if the supply shocks are correlated, i.e., $\rho \neq 0$ and ε^U is correlated with ε^M, the TSLS estimator of β_1 will be biased downwards, even with a valid instrument. In the main text, we report empirical and simulation estimates that assume $\rho = 0$ for the simplicity of exposition, and then relax that assumption in the Online Appendix (see section §B).

B Robustness: non-zero correlation between managed and unmanaged supply shocks

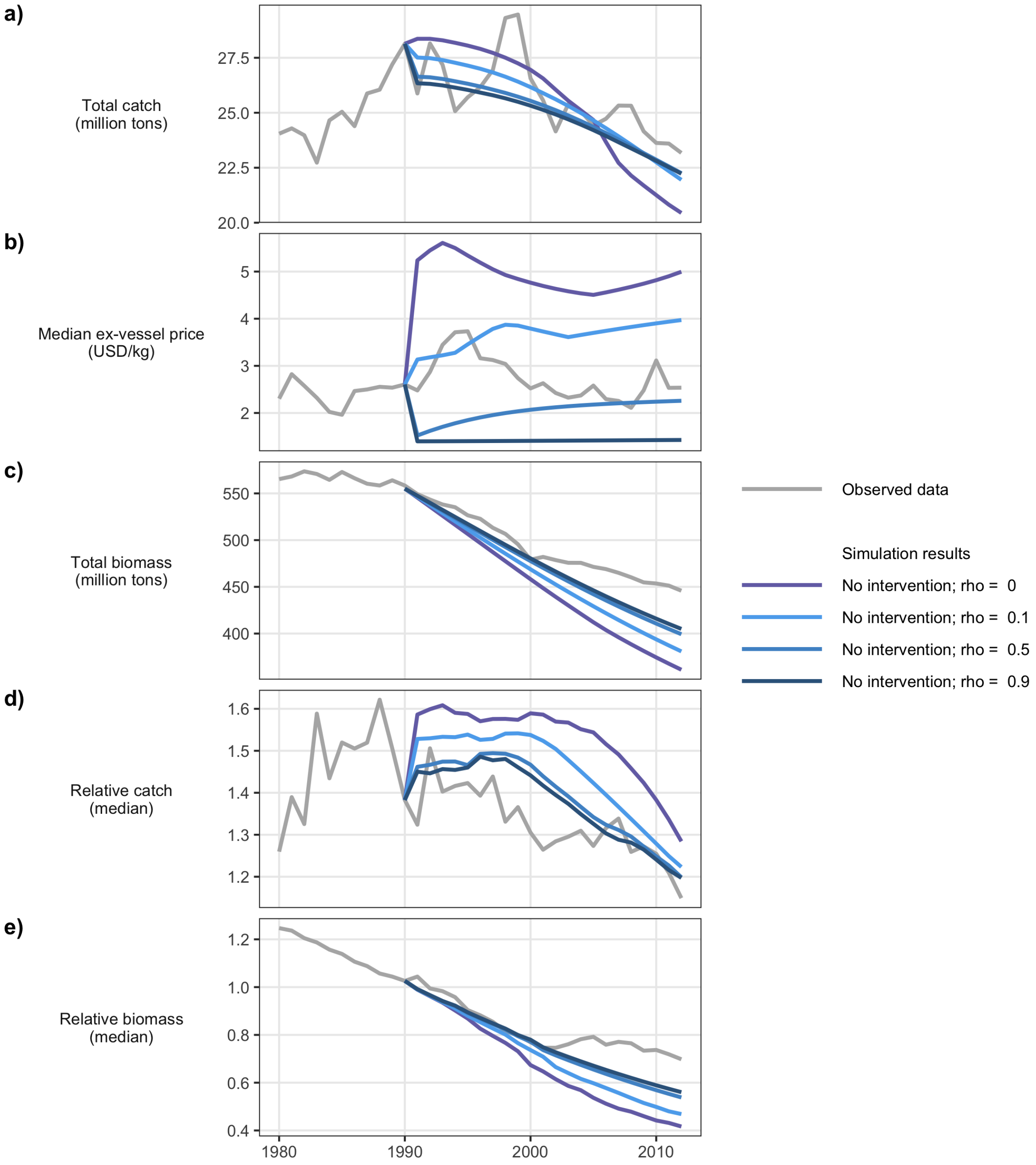
As a robustness check, we re-run the simulations described in Section 5 for unmanaged stocks in which we vary ρ (see section 3) from 0 (baseline results) to 0.9. The results are shown for all outcome variables in Figure S1, and the endpoint biomass for a continuum of values of ρ in Figure S2. They are also summarized in Table S1 for $\rho = 0.5$.

Table S1: Simulations with $\rho = 0.5$: summary

	No intervention	Q-optimal	Q-average	P-unit
Median ex-vessel price (USD/kg)	2.26	4.60	4.72	1.10
Total biomass (million tonnes)	399.32	530.80	501.47	419.40
Total catch (million tonnes)	22.25	21.44	19.81	21.82
Relative fishing pressure (median)	2.19	1.00	1.30	2.04
Relative biomass (median)	0.54	1.01	0.81	0.57
Relative catch (median)	1.20	1.00	1.03	1.19
Collapsed stocks	1.00	1.00	1.00	1.00
Variance of weighted rel. fishing pressure	0.92	0.18	0.56	0.83
Variance of weighted relative biomass	0.76	0.42	0.58	0.76
Median post-tax price (USD/kg)	2.26	4.60	4.72	4.10
Change in total biomass (%)	-28.06	-4.37	-9.66	-24.44
Change in total catch (%)	-20.92	-23.80	-29.59	-22.47

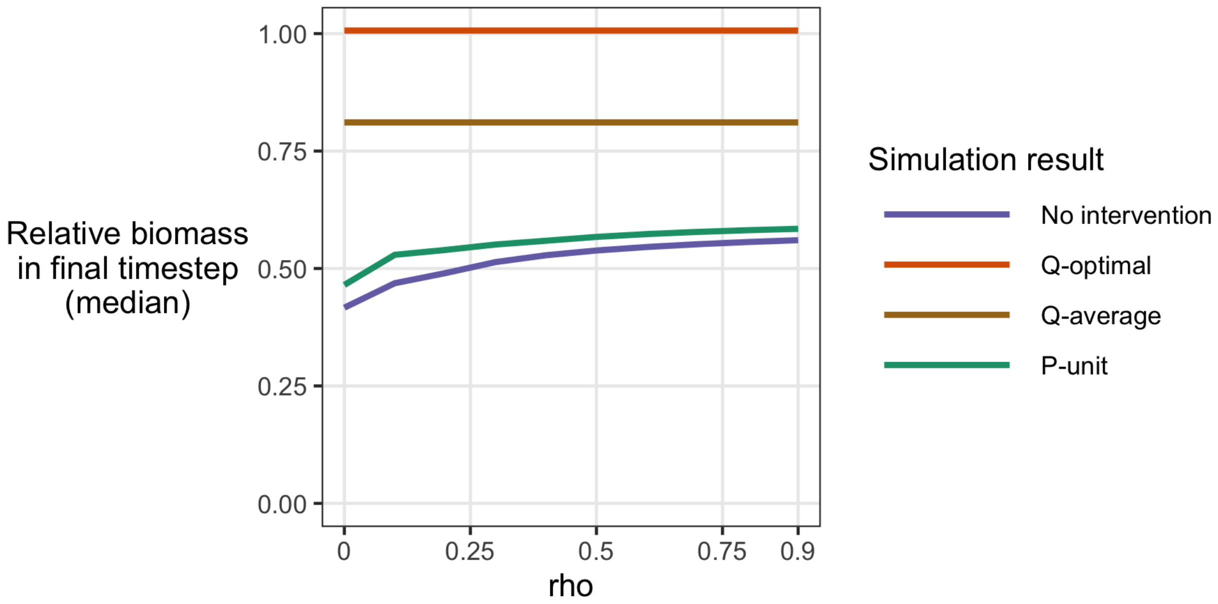
Summary statistics from simulations using a value of rho=0.5. Percent change statistics represent the change in values from 1990 to 2012, while all other statistics represent the value in 2012, the final time step.

Figure S1: Simulations under the business-as-usual (No intervention) scenario using different values of ρ



Notes: The figure shows simulation results (see Section 5) for the 'No intervention' scenario (where all unmanaged stocks remain unmanaged) with different values of ρ, the parameter that captures the correlation between the managed and unmanaged supply functions. Panel **a)** displays the total catch (in million metric tonnes), panel **b)** the median ex-vessel price (USD per kilogram), panel **c)** total biomass (million metric tonnes), panel **d)** median relative catch ($^{H}/_{H_{MSY}}$), and panel **e)** median relative biomass ($^{B}/_{B_{MSY}}$). The dark gray line represents historical data (1980-1990). All the modelled trajectories correspond to the baseline, 'No intervention' scenario, i.e., where unmanaged supply remains price-responsive as modelled by our adjusted TSLS estimate of β_1: the dark violet line corresponds to $\rho = 0$ (also shown in the main text, see Figure 10); the sky blue line to $\rho = 0.1$; the steel blue line to $\rho = 0.5$; and the Prussian blue line to $\rho = 0.9$.

Figure S2: Sensitivity of the endpoint (2012) median relative biomass to alternative assumptions for ρ



Notes: The figure shows the simulated relative biomass under different assumptions for ρ (ranging from 0 to 0.9) at the simulation endpoint (2012). We consider the same 4 scenarios as in Section 5. Specifically, the purple line corresponds to the **No intervention** scenario, the orange line to an optimal management scenario (**Q-optimal**, $\rho = 0$), the dark yellow line, corresponds to the case where stocks are managed at the average fishing pressure observed in managed stocks (from RAMLDB) for the same species group and year (**Q-average**, $\rho = 0$), and the green line to a scenario where fisheries are not managed but demand is shifted with a unit tax (2 USD/kg, **P-unit**).