ENVIRONMENTAL STUDIES

The economics of fishing the high seas

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While the ecological impacts of fishing the waters beyond national jurisdiction (the "high seas") have been widely studied, the economic rationale is more difficult to ascertain because of scarce data on the costs and revenues of the fleets that fish there. Newly compiled satellite data and machine learning now allow us to track individual fishing vessels on the high seas in near real time. These technological advances help us quantify high-seas fishing effort, costs, and benefits, and assess whether, where, and when high-seas fishing makes economic sense. We characterize the global high-seas fishing fleet and report the economic benefits of fishing the high seas globally, nationally, and at the scale of individual fleets. Our results suggest that fishing at the current scale is enabled by large government subsidies, without which as much as 54% of the present high-seas fishing grounds would be unprofitable at current fishing rates. The patterns of fishing profitability vary widely between countries, types of fishing, and distance to port. Deep-sea bottom trawling often produces net economic benefits only thanks to subsidies, and much fishing by the world's largest fishing fleets would largely be unprofitable without subsidies and low labor costs. These results support recent calls for subsidy and fishery management reforms on the high seas.

INTRODUCTION

Fishing in the marine waters beyond national jurisdiction (the "high seas" covering 64% of the ocean's surface) is dominated by a small number of fishing countries, which reap most of the benefits of fishing this internationally shared area (*1*). The rationality of widespread high-seas fishing has been questioned because of its environmental impacts and uncertain economic profitability (*2*). Deep-sea bottom trawling can damage fragile habitats containing unique biodiversity including millenary deep-sea corals (*3*). Highly migratory species such as tuna and sharks that move between the high seas and countries' jurisdictional waters [exclusive economic zones (EEZs)] tend to be intensely fished and overexploited (*4*). Although the International Seafood Sustainability Foundation indicates that 57% of managed tuna stocks are considered to be at a healthy level of abundance, 13% are overfished (*5*), and even those that are not overfished show slight declines in biomass over time (*6*) and may benefit from increases in biomass. Oceanic sharks, of which 44% are threatened (*7*), spend a great deal of time in the high seas, where shark fishing is largely unregulated and unmonitored (*8*).

Although the environmental impacts of fishing on the high seas are well studied, the lack of transparency and data has precluded reliable estimates of the economic costs and benefits of high-seas fishing. Fisheries data suggest that fish catch in this vast area amounted to around 6% of global catch and 8% of the global fishing revenue in 2014 (see www.seaaroundus.org/data/#/global). However, the high level of secrecy around distant-water fishing has impeded the calculation of fishing effort and associated costs. Nevertheless, recent technological developments in machine learning and satellite data now allow us to obtain a far more accurate picture of fishing effort across the globe at the level of individual vessels (*9*). This capability provides a more transparent and novel method to examine high-seas fisheries and answer key questions such as whether fishing in the high seas is profitable and whether government subsidies enable current levels of fishing.

Here, we characterize the global high-seas fleet in detail and estimate the net economic benefit of high-seas fishing using (i) reconstructed estimates of the global fishing catch and its landed value, (ii) the costs of fishing based on satellite-inferred fishing effort and vessel characteristics, and (iii) estimates of government subsidies per country. We report high-seas fishing profits by fishing gear type, flag state, and Food and Agriculture Organization of the United Nations (FAO) region, with the goal of understanding whether fishing the high seas is economically rational.

RESULTS

Global patterns

Until very recently, the composition of the high-seas fishing fleet has been largely unknown, and this lack of transparency has prevented any serious analysis of the economic rationality of fishing in that vast swath of Earth's surface. New technologies are now shedding light on this previously dark corner of Earth. Using the Global Fishing Watch (GFW) database, which uses automatic identification systems (AIS) and vessel monitoring systems (VMS) to track individual vessel behavior, fishing activity, and other characteristics in near real time, we identified a minimum of 3620 unique fishing vessels operating in the high seas in 2016 (Fig. 1). In addition to the actual fishing vessels, we tracked 35 bunkers (tankers that refuel fishing vessels) and 154 reefers (refrigerated cargo ships onto which fishing vessels transfer their catch at sea, a process called transshipment), vital to the operation of the high-seas fishing fleet (fig. S2 and table S6). Only six countries (China, Taiwan, Japan, Indonesia, Spain, and South Korea) accounted for 77% of the global high-seas fishing fleet and 80% of all AIS/VMS-inferred fishing effort (measured in kilowatt-hours; table S1). Fifty-nine percent of the vessels active in the high seas used drifting longlines and represented 68% of all fishing days. The top four fishing gears operating in the high seas are drifting longliners, purse seiners, squid jiggers, and trawlers (Fig. 1 and table S2).

The global high-seas fishing fleet identified here spent an aggregate 510,000 days at sea in 2016; 77% of these days were spent fishing, with an average of 141 days at sea per vessel (table S1). The time spent by vessels fishing in the high seas versus fishing in EEZs varied according to the type of fishing they conduct (fig. S1).

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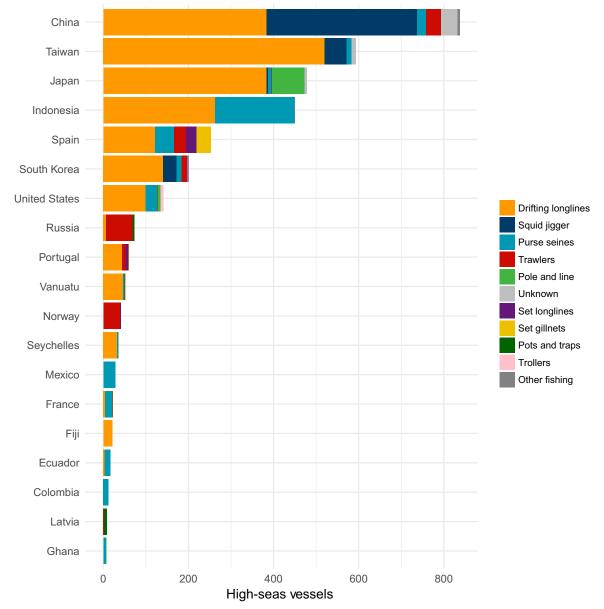*Corresponding author. Email: esala@ngs.org

Fig. 1. The high-seas fishing fleet. High-seas vessels by flag state and gear type, as detected by GFW in 2016.

This characterization of the global high-seas fleet enables a detailed estimation of the total cost of fishing the high seas. Using vessel-level data on ship length, tonnage, engine power, gear, flag state, trip-level fishing and transit tracks, speed, and other factors that affect the costs of fishing, we estimate that total costs of fishing in the high seas in 2014 (the most recent year for which spatially allocated global reconstructed catch data are available) ranged between $6.2 billion and $8.0 billion (Table 1). The uncertainty around total costs was driven mainly by labor costs, particularly for China and Taiwan, which exhibited the highest total costs, but for which fisheries data are often scarce.

The total fisheries catch from the high seas in 2014 was 4.4 million metric tons, with an aggregate revenue (landed value of the catch in US$) of $7.6 billion (Table 1). Five countries alone accounted for 64% of the global high-seas fishing revenue: China (21%), Taiwan (13%), Japan (11%), South Korea (11%), and Spain (8%). High-seas

catch by country and FAO region significantly and positively increased with rising fishing effort ($R^2 = 0.46$, $P < 0.001$) (fig. S4). Subtracting our estimated costs from the landed value of catch provides the first empirically based estimates of the net economic profit of fishing the high seas.

Globally, our estimates of high-seas fishing profits (without accounting for subsidies) ranged between −$364 million and +$1.4 billion (Table 1). We estimated that governments subsidized high-seas fishing with $4.2 billion in 2014, far exceeding the net economic benefit of fishing in the high seas. This result suggests that without subsidies, high-seas fishing at the global scale that we currently witness would be unlikely (at the aggregate level), and that most of the negative returns accrue from China, Taiwan, and Russia (Table 1). Coupling our estimates of profits with country-level subsidies suggests that subsidy-distorted high-seas profits range between $3.8 billion and $5.6 billion.

Table 1. The economics of fishing in the high seas. Catch (in thousand metric tons), revenue, costs, subsidies, and profits without subsidies (π) and with subsidies (π*) for each country. All monetary values reported in million US dollars. These 14 countries accounted for 90% of the high-seas catch.

	Catch	Revenue	Costs		π		Subsidies	π*	
			Lower bound	Upper bound	Lower bound	Upper bound		Lower bound	Upper bound
Global	4391	7656	6228	8020	−364	1428	4185	3821	5613
China	1523	1624	1563	2041	−418	60	418	1	479
Taiwan	545	983	1048	1220	−237	−65	244	6	179
South Korea	403	807	553	605	202	254	409	612	664
Spain	248	637	434	492	145	203	603	749	807
Japan	213	816	639	639	177	177	841	1018	1018
Ecuador	194	271	95	186	85	176	22	107	198
Indonesia	192	384	178	260	123	206	102	226	308
Russia	188	195	153	309	−114	42	12	−102	54
Mexico	107	252	81	184	68	170	32	100	202
United States	93	377	100	162	216	278	256	471	533
Norway	86	107	77	88	19	30	14	33	43
France	58	235	78	86	148	157	195	344	352
Seychelles	55	50	26	50	−1	24	10	9	33
Panama	55	104	32	66	38	72	25	63	98

We conducted these calculations spatially, revealing that, even with subsidies and our lowest estimate of labor costs, 19% of the currently fished high seas cannot be exploited profitably at current rates (Fig. 2). Assuming higher labor costs, and the fact that companies still receive subsidies, the area of unprofitability jumps from 19 to 30%. Finally, without subsidies and low wages to labor, the area of unprofitability shoots to 54%, implying that without subsidies and/or low labor compensation, more than half of the currently fished high-seas fishing grounds would be unprofitable at present exploitation rates.
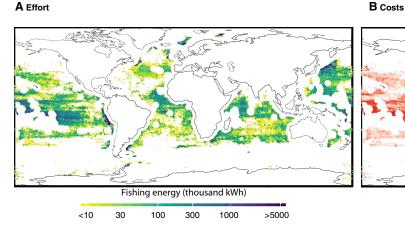
The countries that provided the largest subsidies to their high-seas fishing fleets are Japan (20% of the global subsidies) and Spain (14%), followed by China, South Korea, and the United States (Table 1). It is remarkable that in these cases, the subsidies far exceed fishing profits, with the extreme being Japan, where subsidies represent more than four times our estimate of their high-seas profits. For 17 countries, contributing 53% of the total high-seas catch, current extraction rates would not be profitable without government subsidies (Table S5). Among these countries, China and Taiwan alone account for 47% of the total high-seas catch, which is significant. Whether subsidies enable profitability or not, the magnitude of subsidies and the fact that many of these subsidies lower the marginal cost of fishing suggest that high-seas fishing activity could be markedly altered in their absence.
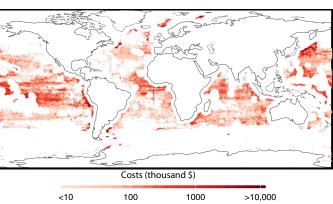
In what fisheries do these high-seas dynamics play out? We find that drifting longliners and purse seiners, targeting mainly large mobile, high-value fishes such as tuna and sharks, are the most profitable high-seas fisheries (Fig. 3). All other fisheries are either barely profitable or unprofitable. We estimate that deep-sea bottom trawling would not be globally profitable at current rates without government subsidies,

with maximum annual losses of $230 million before subsidies. Similarly, squid jiggers would be, on average, very unprofitable without subsidies, with maximum annual losses estimated at $345 million, but when we look at the spatial economic patterns per country, type of gear, and fishing grounds, the picture becomes much more complex.
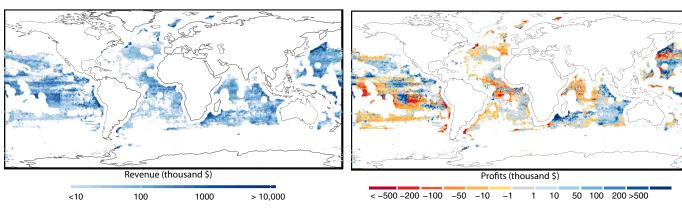
Spatial fishing patterns and profitability

While fishing is geographically extensive on the high seas, it is perhaps less so than previously assumed. Using a spatial grid with 0.5° resolution, we estimate that fishing occurred in 132 million km² or 57% of the high seas in 2016; this number reduces to 48% with a grid of 0.25° resolution. Fishing effort in the high seas occurs mostly between latitudes 45°N and 35°S (Fig. 2). Hot spots of fishing effort were detected at the EEZ boundaries of Peru, Argentina, and Japan, dominated by the Chinese, Taiwanese, and South Korean squid jiggers; deep-sea bottom trawling off Georges Bank and in the Northeast Atlantic; and to a lesser extent in the Central and Western Pacific, associated mostly with tuna longline/purse seine fleets. The spatial footprint of high-seas fishing was most extensive for longliners; purse seiners were restricted to the equatorial zone; squid jiggers operated mostly on the EEZ boundaries of Peru, Argentina, and Japan; and deep-sea bottom trawlers were restricted to the continental shelf edge and seamounts (fig. S3).

China and Taiwan had the largest spatial footprints, followed by Japan, Spain, and South Korea (Fig. 4). A global pattern emerged in which unprofitable high-seas fishing (without subsidies) transformed into profitable fishing (with subsidies) in most areas for Japan, Spain, and South Korea. However, the global map of profits after subsidies still showed many areas with an apparent economic loss for China and
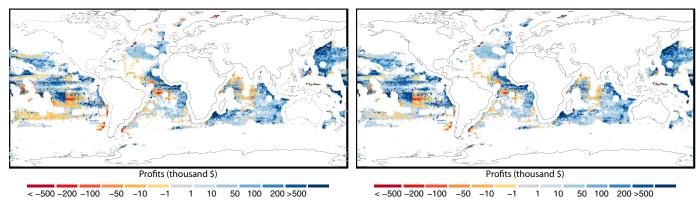
Fig. 2. Global patterns of fishing in the high seas. (**A**) Fishing effort, (**B**) economic costs, (**C**) revenue (landed value of the catch), (**D**) profits before subsidies, (**E**) profits after subsidies, and (**F**) profits after subsidies and low labor costs. Values for costs and profits are scaled averages between lower and upper bound estimates.

Taiwan, such as the Western Indian Ocean. Fishing by China and Taiwan became profitable at many locations only after assuming low labor costs, that is, by lowering average labor costs from these countries by 30 and 53%, respectively (table S5).

Economic profitability also varied markedly between countries, fisheries, and FAO regions (Fig. 5). The analysis at this level is most important for understanding the economics of individual fisheries, with direct management implications. The following are the results for the most important high-seas fishing countries.

China

China shows the highest economic contrasts of fishing in the high seas, as it deploys some of the most and least profitable fisheries (Fig. 5 and table S7). The most profitable of the high-seas operations by China and globally were in the Northwest Pacific, where we estimate that fuel expenditures are only a fraction of those elsewhere because of the proximity to mainland China. Longlining and bottom trawling in the Northwest Pacific showed an estimated average profit (before subsidies) of $325 million and $111 million, respectively. Most other
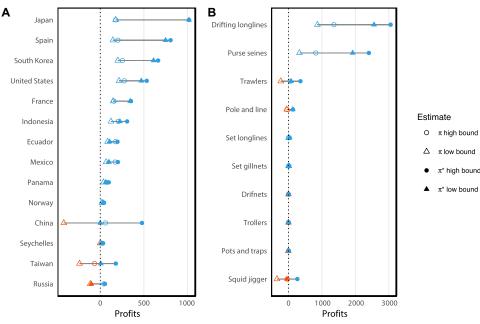
Fig. 3. Net economic benefit of high-seas fishing. Range of estimates of fishing profits (US$ millions) before (π) and after (π*) subsidies for (**A**) major fishing countries and (**B**) gear types.

Chinese fisheries appeared to be unprofitable, and the worst were in the Southwest Atlantic, where estimated fishing costs are four times greater than near mainland China. The most unprofitable of all Chinese fisheries was bottom trawling in the Southwest Atlantic, which exhibited an average net loss (even after subsidies are taken into account) of $98 million. China's squid fishing was consistently unprofitable, and subsidies made it profitable only off Peru's EEZ.

Taiwan
Similar to mainland China, Taiwan's high-seas fisheries in the Northwest Pacific are its most profitable (Fig. 5 and table S7). Taiwanese longlining and squid jigging in the Northwest Pacific are among the most profitable high-seas fisheries globally without subsidies (average profit $193 million and $63 million, respectively). Taiwanese longlining elsewhere appears to be unprofitable. We estimate that in the Western Central Pacific and Eastern Central Pacific, longlining results in average annual losses of $65 million and $63 million, respectively. Similar to China, only after assuming low labor costs does Taiwanese high-seas fishing produce profits (table S7).

Japan
In contrast to China and Taiwan, Japanese fishing in the high seas was mostly profitable, especially in the Eastern Central and Western Central Pacific (Fig. 5 and table S7), with longlining profits before subsidies estimated at $205 million and $113 million, respectively. Japanese pole and line fishing in the Western Central Pacific and longlining in the South Atlantic and Eastern Indian Ocean were also profitable even without subsidies. Surprisingly, the least profitable Japanese tuna fishing occurs in the Northwest Pacific, close to Japan, with net economic losses unless subsidies make that fishery profitable.

South Korea
South Korea's most profitable high-seas fishing was longlining in the Western Central Pacific ($173 million on average before subsidies), followed by bottom trawling in Atlantic Antarctic waters ($129 million) (Fig. 5 and table S7). Korean squid jigging off the EEZ of Argentina and off the Falkland Islands (Malvinas) is also profitable ($91 million on

average before subsidies). The least profitable South Korean high-seas fishery was bottom trawling in the Southeast Atlantic, where costs exceeded revenue even after subsidies were subtracted. Longlining in the Southeast Pacific was the second most unprofitable of South Korean fisheries.

Spain
Spain's most profitable fishery was longlining in the Western Indian Ocean, followed by longlining in the Southeast Pacific, off West Africa, and the Southwest Pacific (Fig. 5 and table S7). However, Spain's purse seining in the Eastern Central Pacific, the Western Indian Ocean, and the Eastern Central Atlantic (West Africa) would not be profitable at current rates without subsidies. Purse seining in the Southeast Pacific was not profitable even with subsidies, and current bottom trawling effort everywhere in the high seas was unprofitable without subsidies.

Other countries and fisheries
Deep-sea bottom trawling on the high seas showed a broad pattern of unprofitability worldwide (table S7). Sixty-four percent of all national bottom trawling operations in FAO regions were unprofitable without subsidies, and a remarkable 32% of these operations appear to have been unprofitable even with subsidies, which raises obvious questions about the incentives to fish there.

Indonesia, the only flag state that publicly provides VMS data, fished only in the high seas of the Indian Ocean. Tuna fishing using purse seines and longlines in the Eastern Indian Ocean was profitable even without subsidies because of the relatively low costs of fishing off the western edge of their EEZ and the characteristics of the fleet, that is, small vessels with small engines (Fig. 5 and table S7). However, Indonesian fishing in the Western Indian Ocean was unprofitable, as we estimate that costs are 15 times greater than the landed value of the catch. This result may be due to the sharp differences in reported catch across FAO regions of the Indian Ocean.

DISCUSSION
Our results show that, by and large, fishing the high seas is artificially propped up by an estimated $4.2 billion in government subsidies (more
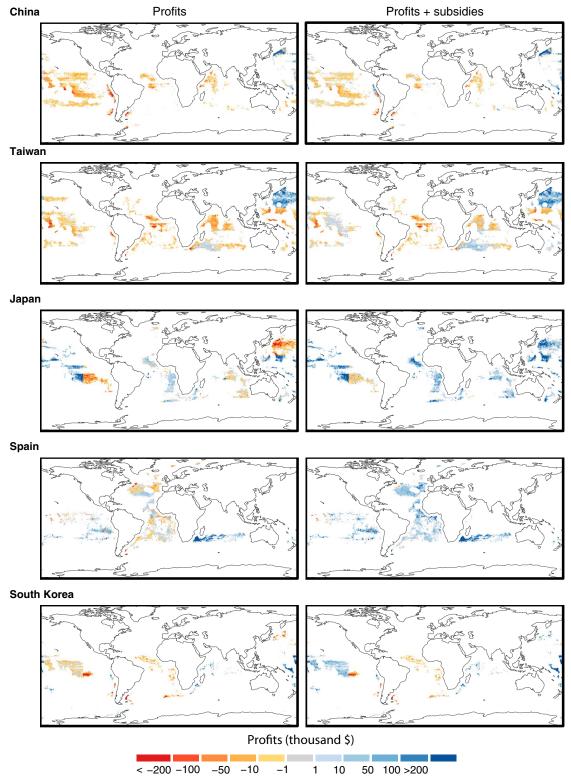
Fig. 4. National patterns of fishing in the high seas. Average high-seas fishing profits with and without subsidies for the five main fishing flag states.

than twice the value of the most optimistic estimate of economic profit before subsidies are taken into account). The economic benefits vary enormously between fisheries, countries, and distance from port. On aggregate, current high-seas fishing by vessels from China, Taiwan, and

Russia would not be profitable without subsidies. This is globally significant since these three countries alone account for 51% of the total highseas catch. Other countries exhibit annual profits ranging from negligible to $250 million, which were increased substantially by subsidies (for
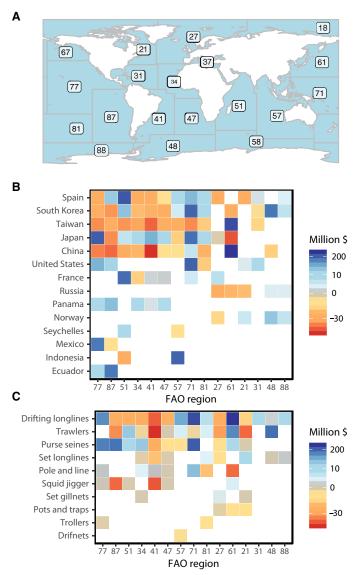
Fig. 5. Spatial patterns of high-seas fishing profits. (**A**) FAO regions, (**B**) profits before subsidies by country, and (**C**) fishing gear.

example, Japan, Korea, Spain, and the United States). Surface fisheries for pelagic species such as tuna were profitable, whereas most other fisheries barely broke even, and squid jigging (mostly concerning Chinese and Taiwanese fleets) and deep-sea bottom trawling were generally unprofitable without subsidies. Some national fisheries in specific regions were unprofitable even after government subsidies are taken into account.

The lack of profitability for China and Taiwan may be related to massive overcapacity. After realizing the declining returns from their domestic fishing, China embarked on a vessel construction program in the 1990s destined to "distant-water fishing," which continued through the 2000s, when China declared its interest in developing high-seas fisheries (10), although GFW data suggest a recent sharp decline in its fishing fleet. Japan, on the other hand, has undertaken well-documented vessel-scrapping programs to decrease the overcapacity of its large-scale tuna longline fleet (11). Scrapping means that vessels are decommissioned and dismantled, which results in effective reduction of the fleet.

How is it possible that some countries continue to fish in certain high-seas regions while exhibiting an apparent economic loss? For this behavior to be incentive-compatible, there must be a net benefit for individual companies to continue operating in the high seas. The most obvious reason is underreporting the catch, which would result in an underestimate of fishing revenue and profits. The data used in our analysis are reconstructed catch data that attempt to correct for underreporting (12, 13). Some analysts have criticized catch reconstructions on a methodological basis, suggesting high uncertainty about the reliability of the reconstructions and claiming that FAO's annual catch reports are "the only validated source of global fisheries landings" (14), but see (15). Reconstructed data suggest catches perhaps 30% larger than those reported by FAO (13), which makes our estimates of fishing revenue and profits larger than they would be had we used FAO's raw data. However, global catch reconstructions mainly address unreported catches within countries' EEZs. The data for industrially caught tuna and other large pelagic fishes were largely on the basis of officially reported data provided by the various tuna Regional Fisheries Management Organizations to which major discards were added before spatial allocation (16). Therefore, catches for some high-seas areas may still be underreported.

Overall, we conjecture that fishing the high seas could become rational for the most unprofitable fisheries due to a combination of factors including the following: (i) currently available catch data continue to underrepresent real catches, (ii) vessels fish only part of the time in the high seas and make most of the economic benefit from fishing in EEZs, (iii) government subsidies not accounted for in this analysis, (iv) reduced costs because of unfair wages or forced labor, and (v) reduced costs because of transshipment at sea. There may be additional market factors that are fishery-specific, that is, squid fishing by Chinese vessels in South America. Our results suggest that this fishery is unprofitable, but over 100 Chinese squid jiggers amass in January at the limit of Argentina's EEZ to catch small *Illex* squid, before Argentina opens the season inside its EEZ. The low stock size and high demand for squid may allow Chinese companies fishing early in the season to charge higher prices than those used in our analysis (17). To these factors, we could add geostrategic reasons, where countries may fish in some regions as part of their long-term foreign policy strategy, regardless of the economic benefit. Examples of this strategy have been documented for Chinese and Russian fleets fishing in Antarctica (18, 19).

Previous studies showed that total government subsidies equaled 30 to 40% of the global landed value of catch (20), but this study allows us to compare subsidies to the actual profits in the absence of subsidies, specifically for fishing in the high seas. Even under the lowest estimates of high-seas fishing costs, subsidies more than double the net economic benefit of fishing in the high seas. For some fishing fleets, subsidies make the difference between negative and positive profits, but for a few countries, subsidies are extremely large (especially Japan and Spain) and appear to play a central role in economic outcomes. Some of the Japanese and Spanish fishing fleets do not appear to require subsidies to be profitable, yet they collect the highest sums globally. To the extent that government subsidies enhance fishing activity (for example, through fuel or other subsidies that affect the marginal cost of fishing) (20, 21), they artificially boost the bottom line of fishing companies, perhaps at the expense of sustainability of the underlying resource stocks.

Forced labor or modern slavery is a key cost-reducing factor in long-distance fishing, which manifests itself both at sea (using forced labor) and on land (using child slavery) (22–24). In some countries, high-seas fisheries are profitable only after assuming government subsidies and

low labor costs (mainly for China and Taiwan). Thus, it seems possible that unfair labor compensation, or no compensation at all, allows seemingly unprofitable fisheries to be economically viable. High-seas fishing has also been linked to illegal activities (that is, smuggling of drugs, weapons, and wildlife) by transnational organized criminal groups that use flags and ports of convenience, poor regulation of transshipments, and offshore shell companies and tax havens (25, 26). These illegal activities may also justify the rationality of some of the fishing in the high seas.

Refueling and transshipment at sea also reduces the costs of fishing in the high seas because it allows fishing vessels to continue fishing for months or years without having to return to port (27). Without bunkers and reefers, fishing in the high seas would be far less profitable, especially for China, which showed the largest number of encounters with reefers for transshipment. These results also show how chronically unprofitable some fisheries are, such as Chinese squid jigging, which appears to be profitable only through the provision of subsidies, the use of transshipment, and low compensation for labor.

A caveat of our analysis is that GFW data are not able to detect all fishing vessels because some of them do not carry or will simply deactivate AIS or VMS. However, including more vessels in our analyses would only further increase the estimated costs of fishing the high seas and reduce the per-vessel subsidies. Comparing our data with the best available estimates of the number of active vessels per country, gear type, and Regional Fisheries Management Organization, we estimated the proportion of the fleet detected by satellites, and calculated scaling factors to correct for underobserved fishing effort (see the Supplementary Materials). This calculation assumes that the vessels not in the GFW data are as active as and behave similarly to those in the data set. If this assumption does not hold, and undetected vessels are less active and/or fish more inside EEZs than on the high seas, then our scaled estimates may overestimate high-seas effort. For many of the major fleets, including China's longline and purse seine fleet in the Western Central Pacific, we observed >90% of the active fishing vessels, resulting in small correction factors to account for vessels we could not track (table S3). However, a number of fleets have notably bad coverage, including Taiwan's small-scale longline fleet in the Western Central Pacific (40%) and China's squid fleet operating in the South Atlantic (48%). In aggregate, scaling up for undetected vessels augments effort by 20%.

Labor costs are the largest source of uncertainty in our analysis, accounting for 68% of the uncertainty around our estimate of total profits. Wages and labor compensation schemes are highly variable across fleets and nations, and violations of human rights and modern slave labor have been documented in some high-seas and distant-water fleets. We address this uncertainty by providing conservative upper and lower bound estimates of labor costs for each country. Nevertheless, unfair wages or unpaid labor could further decrease our lower bound of costs and increase profitability for some fleets. For example, if crew wages were 20% lower than our current low bound estimate, our highest estimate of total profits would increase by 26%. Fuel costs account for the remaining uncertainty (32%), which is determined by the assumed fuel consumption factor of each vessel (see Materials and Methods). Last, we used the global average price of fuel, which may not reflect regional price variability. While this may affect our results (for example, a 10% change in fuel price would result in a 7% change in our estimate of total costs), tracing the origin of the fuel each vessel uses and the price it pays for it would require strong assumptions and is further complicated by the common practice of refueling while at sea.

For our calculation of fishing profits, we use the landed value of the reconstructed catch for 2014, which is the latest year for which both global FAO statistics and global reconstructed data are available (15, 28, 29). To estimate costs, we use effort data from 2016 (the year for which we have the most complete AIS and VMS databases) combined with 2014 global average fuel prices. Using data 2 years apart might result in some discrepancies, but we believe that high-seas fishing effort in 2016 is a good proxy for effort in 2014. Evidence to support this claim is the small short-run price elasticity of fuel demand of the large-scale industrial fishing fleet (9). Assuming that the spatial distribution of effort has remained constant, we used the estimate of elasticity (−0.06) to adjust fishing effort in response to higher fuel prices in 2014.

Fishing profits are likely to vary over time as factors such as fuel price, fish price, climate, and fish stocks fluctuate. While our analysis is for a single year, the slight increase in high-seas catch and revenue, coupled with the high and constant price of fuel between 2010 and 2014, suggests that our estimate of profits is likely to be representative of, or slightly higher than, the average state during the first half of this decade. In addition, we have likely underestimated the costs of fishing in the high seas because our calculations do not include capital investments. For example, the capital invested in Japan's distant-water fisheries in 2014 (the only country for which this information is available) corresponds to around 40% of total annual expenditures, which would decrease the country's profits (before subsidies) from $177 million to virtually zero. However, since 2014, fuel prices have decreased by ~50% and we estimate that total profits may have increased (before subsidies) by up to $720 million. If current fuel prices remain stable, the second half of this decade may be considerably more profitable for high-seas fisheries, and their dependency on government subsidies may be reduced. As more recent effort, catch, and costs data become available, we will be able to better assess the temporal dynamics of the economics of fishing the high seas.

Satellite data and machine learning technology have opened up a new era of transparency that allows us to evaluate quantitatively what we previously could only speculate about. This study opens a window into the economic profitability of high seas fishing across spatial scales, countries, and fisheries, which can be updated in near real time going forward. Our results show that, in many locations, the current level of fishing pressure is not economically rational, despite the overall profitability of major pelagic fisheries such as tuna fishing. Potential food security arguments in favor of continued or ramped-up high-seas fishing seem misguided because high-seas fisheries mainly target catches of high-value species such as tuna, squid, and deep-sea fishes, which are primarily destined for markets in high-income countries (30).

Our findings provide economic evidence that supports growing calls for substantial reforms of high-seas fisheries to align conservation and economic potential. These reforms could include combinations of better fisheries management including capacity reduction, marine reserves, and innovative financing (31), but our most direct finding is that subsidy reform could substantially alter fishing behavior in the high seas. Strong fishery management reform could act as a kind of substitute, even in the presence of subsidies, provided strong catch limits were adhered to. In a similar manner, several authors have suggested that closure of large areas, and even all of the high seas, could both achieve conservation goals and increase the economic benefits of fishing migratory species, particularly when they are overfished (1, 32). The uncertainties in our analysis highlight the need for increased monitoring and transparency in fisheries, particularly regarding labor

practices. The additional evidence presented here can serve as a starting point for targeting policies in the most efficient manner, as the United Nations starts discussions in 2018 to negotiate a new agreement for conservation of biodiversity in the high seas (33).

MATERIALS AND METHODS

High-seas fishing fleet

We defined the global high-seas fleet as fishing vessels that spend more than 5% of their fishing effort in the high seas and that either (i) self-report as fishing vessels in their AIS messages, (ii) were matched to official fishing vessel registries, or (iii) were classified as fishing vessels by the neural net models of the GFW (9). In addition, we included bunker and reefer vessels that met at sea with the high-seas fishing fleet based on AIS data. We complemented these data with Indonesian VMS data to incorporate all Indonesian vessels that operate more than 5% of their time in the high seas. For details on vessel characteristics, crews, speed, and fuel consumption, see the Supplementary Materials.

Fishing effort

We estimated and reported vessel activity and fishing effort for 2016 in units of days, hours, kilowatt-days, and kilowatt-hours. Days were calculated by summing the number of days a vessel was actively transmitting AIS or VMS signals. We excluded time at port by filtering out positions where a vessel is closer than 1000 m from shore and traveling at a speed under 0.1 knots. For each vessel, energy in kilowatt-days was estimated by multiplying active days by the vessel's engine power. We estimated the hours at each AIS/VMS position as half the time elapsed between the previous and next position and calculated energy in kilowatt-hours by multiplying hours by the vessel's engine power. Each position was classified as fishing or not fishing using GFW's neural net model, and we used this classification to distinguish active fishing effort from transiting and other activities. We removed noise in AIS/VMS data by filtering out positions that had invalid coordinates (for example, >90°N) and kept only track segments that had over five positions.

The fraction of vessels detected by GFW relative to the total number of vessels varied by country and gear type (see the Supplementary Materials). For example, for China, we likely saw 100% of purse seiners and 95% of longliners in the Western and Central Pacific in 2016, but only 70% of all squid jiggers. We report scaled estimates of high-seas fishing costs and profits for the entire high-seas fishing fleet plus reefers and bunkers (tables S5 and S6).

To calculate fishing costs in 2014, we adjusted total fishing effort using a published estimate of the short-run price elasticity of fuel demand of the global large-scale industrial fleet (9). This resulted in an estimated 5.8% reduction of the total high-seas effort in 2016.

Fishing costs

We built an activity-based model of the cost of fishing that takes into account individual vessel behavior and characteristics to estimate the total fuel and labor costs per vessel per year. To estimate total costs, we then used estimates of the fraction of the total costs that fuel and labor costs represent and scaled them up accordingly. The total costs for each vessel were apportioned spatially in proportion to the energy spent fishing in each 0.5° cell.

Fuel costs

For each vessel (i) and AIS/VMS position (j), we calculated fuel cost (FC) for the main and auxiliary engines by multiplying the time in each position (T) by an estimated fuel consumption (C) and the global average quarterly price of fuel (p).

$$\mathrm{FC}_{i,j} = T_{i,j} \times C_{i,j} \times p$$

The time associated to each position (T) was estimated as the average between time to next position and time from last position.

$$T_{i,j} = \frac{t_{j+1} - t_{j-1}}{2}$$

Fuel consumption (C) was estimated on the basis of the methodology used by the European Environmental Agency (EEA) to estimate emissions from the shipping industry (34). The general formula to estimate fuel consumption for the main and auxiliary engine is

$$C_{i,j} = P_i \times \mathrm{SFC}_i \times \mathrm{LF}_{i,j}$$

where P is engine power (in kilowatts), SFC is the specific fuel consumption (in grams per kilowatt-hour), and LF (in percentage) is known as the load factor, which represents the engine loading relative to its maximum continuous rate.

Main engine power was obtained from official vessel registries and inferred from the neural net. Data on the auxiliary engine power of 1156 European Union (EU) fishing vessels were used to train conditional inference random forests and fill in gaps for the remainder of the high-seas fleet.

The SFC parameter measures the efficiency of an engine and varies with engine type (for example, medium speed versus high speed), type of fuel [for example, marine diesel oil (MDO) versus bunker oil], engine age, vessel size, and type of activity (for example, maneuvering and cruising) (35). It has been estimated that 96% of the world's fishing fleet installed engine power uses MDO and 84% uses medium-speed diesel engines (35). For this type of engine and fuel, SFC factors range from 203 to 280 g/kWh (36).

Given this information, we estimated upper and lower bound estimates of fuel costs using (i) country-specific estimates of SFC when available and the size-specific SFC for remaining countries (high bound) and (ii) only the size-specific SFC (low bound). In both cases, we used a constant SFC of 217 for auxiliary engines and used the difference in SFC between cruising and maneuvering (9% higher SFC when maneuvering) as a proxy of SFC when fishing versus transiting (35).

The load factor (LF) is calculated from the cubed ratio of a vessel's instantaneous speed (v) and its design speed (d). This is bounded between a minimum load (20%) when engines are idling to a maximum load assumed when vessels operate at design speed (90%) (37). For trawlers, we need to account for high LFs at relatively low speeds when vessels are towing gear in the water, so we used a LF of 0.75 to all trawlers during fishing activities as suggested by Coello et al. (37).

$$\mathrm{LF}_{i,j} = L_{\max} \times \frac{\frac{v_{i,j}{}^3}{d_i} + \frac{L_{\min}}{L_{\max} - L_{\min}}}{1 + \frac{L_{\min}}{L_{\max} - L_{\min}}}$$

Instantaneous vessel speed (v) was obtained from AIS/VMS messages and also inferred using time and distance from AIS/VMS data. The design speed of each vessel was estimated using a linear regression of engine power versus design speed using vessel characteristics of

23,000 fishing vessels from the IHS Fairplay database (N. Olmer, International Council on Clean Transportation, personal correspondence, April 2017; see eq. S1). For auxiliary engines, we used the average LF reported by the EEA for cruising (0.3) and maneuvering (0.5) (34). Last, annual averages of global fuel prices were calculated with daily data of the price of MDO ($/metric ton) obtained from the Bunker Index for 2010–2016 (www.bunkerindex.com/prices/bixfree.php?priceindex_id=5).

To account for gaps in AIS transmission, we applied the average fuel consumption per hour of each vessel to the total time it spends in the gaps. The costs associated with gaps represented ~16% of total fuel cost. This same methodology was used to estimate the fuel costs of reefers and bunkers that support the high-seas fishing fleet (table S6).

Labor costs
We built a database of labor costs using different sources such as government reports, gray literature, and estimates of mean wages for fishers and similarly skilled workers reported by the International Labor Organization (ILO). This search often yielded two different metrics of labor cost: (i) labor cost per day and (ii) labor cost per crew member per day. We used these to estimate total labor cost for each vessel (LC_i) with the following two equations

$$LC_i = N_i \times W_i$$

or

$$LC_i = N_i \times w_i \times C_i$$

where N_i is the total number of days at sea for vessel i, W_i is the estimated labor cost per day assigned to that vessel, w_i is the labor cost per day per crew member, and C_i is the estimated crew size of vessel i.

For a subset of countries, representing 25% of total high-seas fishing effort—the EU, Japan, South Korea, and Chile—we were able to obtain reliable estimates of labor costs per day. For China, we obtained information on the average labor costs per month of crew members onboard the country's squid jigger fleets (J. Ho, Maritima Oceánica S.A.C., personal communication, December 2017). For Taiwan, we used the country's minimum wage. Given that fleets often use labor from similar nationalities (for example, Philippines and Indonesia), and assuming that labor costs are mostly determined by a vessel's gear type and size, we used the average labor costs from these countries to estimate the labor costs of the remaining high-seas fleet. We considered this our high bound estimate.

Realizing that fleets often use the cheapest labor available and that it is not uncommon for human rights violations to take place on board high seas and distant-water vessels [for example, (22–24)], we searched for additional—often less reliable—information on labor costs to estimate a lower bound. For China, Taiwan, the United States, and Vanuatu, we obtained gray literature estimates of labor cost, and for several other countries, we used the mean wages for fishers or similarly skilled workers as reported by the ILO. For the remaining countries, we filled in data gaps with regional, gear type, and size-specific averages. All monetary values have been converted to US dollars.

Total fishing costs
The EU Annual Economic Report and Japan's Fisheries Yearbook provide detailed information on the cost structure of distant-water fleets by vessel size class. Using these data, we estimated the fractions that fuel and labor cost represent from the total costs (f). These costs include depreciation, opportunity costs of capital, repair, maintenance, rights, other variable costs, and other nonvariable costs.

$$TC_i = \frac{FC_i + LC_i}{f}$$

After estimating the total fishing costs of each vessel, we distributed it spatially proportionally to the fishing energy spent at each position

$$TC_{i,j} = \frac{TC_i \times E_{i,j}}{\sum_j E_{i,j}}$$

where TC_i is the total cost of vessel i, and $E_{i,j}$ is the fishing energy by vessel i on position j defined as

$$E_{i,j} = h_{i,j} \times P_i \times F_{i,j}$$

where $h_{i,j}$ is the time associated with each position, P_i is the vessel's engine power, and $F_{i,f}$ is a binary variable that represents whether or not a vessel is fishing at a particular position (that is, 0, not fishing; 1, fishing). This methodology allows us to determine the fraction of total fishing costs associated with fishing activity on the high seas.

Reefers and bunkers
We used the same methodology as above, with slight modifications, to estimate the costs of the reefers (transshipment vessels and fish carriers) and bunkers (fuel replenishment vessels) that support the high-seas fishing fleet. To estimate fuel costs, we used the same formula as for fishing vessels, excluding the rules that increase engine LFs during fishing behavior (that is, 0.75 LF for trawlers, 9% increase in LF during fishing behavior for other gears, and 0.5 LF for auxiliary engines). This approach likely results in an underestimate of the fuel costs of these vessels because it does not account for the potential increase in power needed during rendezvous events. For labor costs, we used the same average upper and lower bounds of labor costs per day by vessel size class used to fill in gaps as described in the Labor costs section above (see also the Supplementary Materials). Similarly, we used the same fractions of total cost by vessel size class to estimate total costs. The main difference in methodology is apportioning high-seas costs from total cost. To do this, we calculated the fraction of total encounters that involved vessels from the high-seas fleet and used this estimate as the fraction of total costs associated with the high seas (C_{hs_i})

$$C_{hs_i} = \frac{TC_i \times R_{hs_i}}{TR_i}$$

where TC_i is the total costs of vessel i, TR_i is the total number of rendezvous of vessel i, and R_{hs_i} is the number of rendezvous of vessel i with fishing vessels of the high-seas fleet.

Catch and revenue
We used high-seas catch and landed value data from the Sea Around Us research initiative for 2014, aggregated by fishing country and FAO region. Global catch data were reconstructed separately for every maritime country and its territory by the Sea Around Us or by over 300 colleagues around the world, following a general catch reconstruction approach (38). In principle, this approach evaluates and reviews a country's official reported catch data to ascertain what fisheries components are missing from official reported data. These identified gaps are then filled in using all available data and information sources to derive time series of unreported catches. This may include the use of

assumption-derived estimates [see (12) and references therein]. Thus, the Sea Around Us reconstructed catch data complement official reported data as presented by the FAO on behalf of countries with best estimates of unreported catches and major discards. The Sea Around Us reconstructed catch database contains three layers of catch data: layer 1, domestic catches within the home EEZ; layer 2, non-tuna catches taken by fleets outside of home (domestic) waters (that is, foreign catch); and layer 3, industrial tuna and other large pelagic fisheries catches. The domestic data in layer 1 was the major focus for reconstructions, and thus data within EEZs have the most comprehensive coverage for unreported catches. These data, while of no direct relevance in the present context of high-seas areas, suggest that around 30% of total EEZ catches are unreported (13). Layer 2 (foreign non-tuna catches) and layer 3 (industrial tuna and other large pelagic catches) have so far received less attention on unreported catches, although discards have been added to all data. Thus, the catch data used here for high-seas areas, although reconstructed, need to be considered as minimal estimates of the likely actual high-seas catches.

Catch reconstructions are now widely documented in the peer-reviewed literature [for example, (39–43)] and increasingly used, for example, as part of the Environmental Performance Index (44) or in global studies on human nutrition and health (45). The landed value of catches was derived by multiplying the reconstructed catches by the global ex-vessel price database first derived by Sumaila et al. (46), and since updated by Swartz et al. (47) and Tai et al. (48).

The reconstructed catch data for high-seas areas were combined with effort data to estimate ratios of landed value per fishing energy (in dollars per kilowatt-hour)

$$RR_{k,f} = \frac{LV_{k,f}}{E_{k,f}}$$

where $RR_{k,f}$ represents the revenue per unit of energy spent fishing by country k on FAO region f, $LV_{k,f}$ is the total landed value of high-seas catch by country k on FAO region f, and $E_{k,f}$ is the total energy spent fishing by country k on FAO region f.

We then used these ratios to apportion fishing revenue across high-seas positions

$$R_{i,j,k,f} = RR_{k,f} \times E_{i,k,f,j}$$

where $RR_{k,f}$ represents the revenue per unit of energy spent fishing by country k on FAO region f, and $E_{i,k,f,j}$ is the fishing energy spent by vessel i on position j. This process was species-agnostic for all gear types except for squid jiggers, for whom mapping species to gear type is a direct link. Of the total landed value of $8.5 billion for the 2014 reconstructed catch by the Sea Around Us, we were able to match $7.6 billion (that is, 89%) to GFW effort by country and FAO region.

Fishing profits

We estimated fishing profits on the high seas without (π) and with (π^*) subsidies by combining costs, revenues, and subsidies at each position

$$\pi_{i,j} = R_{i,j} - TC_{i,j}$$
$$\pi^*_{i,j} = R_{i,j} - TC_{i,j} + S_{i,j}$$

where $R_{i,j}$ represents high-seas revenue, $TC_{i,j}$ denotes cost, and $S_{i,j}$ indicates subsidies from vessel i at position j.

We present two scenarios, with and without scaling for unseen vessels, and for each we estimated upper and lower bounds of profits with and without subsidies. The principal driver of the uncertainty that makes the upper and lower bounds is labor costs (especially for Chinese and Taiwanese vessels). In the upper bound, we assumed that labor costs from the EU, Japan, South Korea, and Chile are representative of the average labor cost per day across all fleets. In the lower bound, we used gray literature estimates of average labor costs of crew on Chinese and Taiwanese distant-water fleets, as well as estimates of mean wage of fishers or similarly skilled workers from the ILO.

Government subsidies

We made the reasonable assumption that high-seas fisheries are large scale and used this to estimate high-seas fisheries subsidies for each country that is known to have vessels operating in the high seas. We applied two steps. First, we computed the amount of fisheries subsidies to large-scale fisheries (LSF) per landed value (LV) they generate for countries identified to be fishing in the high seas. In other words, we calculated subsidy per landed value, $x_n = y_n/z_n$, where y is subsidies to LSF and z is LV generated by LSF of high-seas fishing country, n. Second, we estimated the amount of subsidies provided by each high-seas fishing country, s_n, to its fleet operating in this area of the ocean by multiplying subsidy per landed value, x_n, to the estimated landed value generated in the high seas (l_n): $s_n = x_n * l_n$.

To accomplish the first step, we needed data on the total landed values and the proportion thereof that was generated by LSF versus small-scale fisheries (SSF) by each high-seas fishing country (n), and the total amount of fisheries subsidies and the proportion thereof that was received by SSF compared to LSF. To implement the first step, we needed data on the total landed values and the proportion thereof that was generated in the high-seas versus within-country EEZs.

Subsidies to LSF (that is, y_n) were taken from Sumaila et al. (20, 49) and Schuhbauer et al. (50), while LVs generated by LSF (that is, z_n) by high-seas fishing countries were taken from the Sea Around Us and Fisheries Economics Research Unit databases (46–48) (www.seaaroundus.org). The estimated landed values generated in the high seas (l_n) were obtained from the same database.

For each country, we then apportioned total high-seas subsidies across high-seas vessels ($S_{i,k}$) proportionally to a vessel's fraction of the country's installed capacity (engine power)

$$S_i = \frac{S_k \times P_{i,k}}{\sum_i P_{i,k}}$$

where $S_{i,k}$ is the high-seas subsidies of vessel i from country k, S_k is the total high-seas subsidies of country k, and $P_{i,k}$ is the engine power of vessel i from country k.

Last, similarly to the method used to apportion costs spatially, we apportioned subsidies proportionally to the energy spent fishing at each AIS/VMS position on the high seas

$$S_{i,j} = \frac{S_i \times E_{i,j}}{\sum_j E_{i,j}}; \text{ for } j \text{ on high seas}$$

where $S_{i,j}$ represents the subsidies from vessel i allocated to high-seas position j, S_i is the total subsidies allocated to vessel i, and $E_{i,j}$ is the energy spent fishing by vessel i on high-sea position j.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/6/eaat2504/DC1

Supplementary Materials and methods

fig. S1. Distributions of vessel characteristics, high-seas fishing effort relative to total fishing effort, and nonlinear relationships between length, tonnage, and engine power.

fig. S2. Vessel encounters on the high seas (2016).

fig. S3. Fishing effort by gear type.

fig. S4. Effort versus catch.

table S1. High-seas fishing fleets and effort by country (2016).

table S2. High-seas fishing fleets and fishing effort by gear type.

table S3. AIS coverage of high-seas fleet and scale factors by country, Regional Fisheries Management Organization, gear type, and vessel size in 2016.

table S4. Average labor costs per day by country, gear type, and vessel size class.

table S5. High-seas costs, catch, revenue, subsidies, and profits by country.

table S6. High-seas fishing costs by reefers and bunker vessels per flag state.

table S7. Summary of high-seas economics by country, gear type, and FAO region (scaled results).

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The economics of fishing the high seas

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