ENVIRONMENTAL STUDIES

Far from home: Distance patterns of global fishing fleets

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Postwar growth of industrial fisheries catch to its peak in 1996 was driven by increasing fleet capacity and geographical expansion. An investigation of the latter, using spatially allocated reconstructed catch data to quantify "mean distance to fishing grounds," found global trends to be dominated by the expansion histories of a small number of distant-water fishing countries. While most countries fished largely in local waters, Taiwan, South Korea, Spain, and China rapidly increased their mean distance to fishing grounds by 2000 to 4000 km between 1950 and 2014. Others, including Japan and the former USSR, expanded in the postwar decades but then retrenched from the mid-1970s, as access to other countries' waters became increasingly restricted with the advent of exclusive economic zones formalized in the 1982 United Nations Convention on the Law of the Sea. Since 1950, heavily subsidized fleets have increased the total fished area from 60% to more than 90% of the world's oceans, doubling the average distance traveled from home ports but catching only one-third of the historical amount per kilometer traveled. Catch per unit area has declined by 22% since the mid-1990s, as fleets approach the limits of geographical expansion. Allowing these trends to continue threatens the bioeconomic sustainability of fisheries globally.

INTRODUCTION

Distant-water fishing, that is, fishing in areas far removed from a country's domestic waters, existed well before the 19th century industrialization with, for example, Europeans fishing for Atlantic cod (*Gadus morhua*) off Newfoundland from the early 16th century (*1*) and Indonesians first fishing for *trepang* (sea cucumber) in northern Australia in the late 17th century (*2*). However, the practice accelerated with the deployment of the first steam trawlers around the British Isles in the 1880s (*3*). The increased fishing capacity of engine-powered trawlers led to greatly improved catches, but their introduction was soon followed by signs of depletion in coastal fish stocks and conflict with smaller inshore fishers (*4*). Vessels capable of moving further offshore did so, targeting less heavily exploited fishing grounds and beginning a process of progressive spatial expansion, first into the open North Sea, then south to the coasts of Spain and Portugal, and north into the North Atlantic waters around Iceland (*4*). The latter move ultimately led to a series of Cod Wars between 1958 and 1976, which culminated in the expulsion of British fishers from Icelandic waters (*5*). The industrial fleets of other developed countries followed similar patterns of expansion, interrupted only by wars and other crises (*6*, *7*). Increasing competition between domestic and foreign fishing vessels for national fisheries resources was one of the motivations behind the series of international negotiations in the 1970s and 1980s, leading to the adoption of the United Nations Convention on the Law of the Sea (UNCLOS) in 1982 (*8*). Key to UNCLOS was its permission for maritime countries to declare 200–nautical mile exclusive economic zones (EEZs), within which they have exclusive responsibility and control over resource exploitation, management, and conservation. Although UNCLOS did not come into force until 1995, countries began asserting their sovereign rights to fisheries resources in unilaterally declared EEZs or exclusive fisheries zones after the early rounds of UNCLOS III discussions began in 1973, and

EEZ declarations accelerated in the 1980s. The expansion of sovereign claims to fisheries marked the beginning of the end of unrestricted and uncontrolled open-access fishing for distant-water fleets (*9*). However, this formalization of resource ownership and control affected the activities of the distant-water fishing fleets of major industrialized countries only briefly, as countries quickly moved to negotiate extensive access agreements for their fishing vessels, particularly in the waters of developing countries (*10–12*).

While a long history of expansion is well documented (*3*, *6*), the second half of the 20th century saw an unprecedented increase in catching power, as industrial fisheries reaped a peace dividend from wartime technologies such as LORAN [long-range navigation; a precursor to Global Positioning System (GPS)], radar, and sonar (*13–15*). The postwar period also marked the start, in 1950, of detailed record collection at the global scale by the Food and Agriculture Organization (FAO) of the United Nations (*16*). However, while a huge and laudable undertaking, the FAO data ultimately derive from the annual reports of flag states, which have differed greatly in quality and scope of the data submitted, both between countries and years. These data are characterized by poor spatial resolution.

The Sea Around Us addresses several shortcomings in the data reported by FAO on behalf of flag states by reconstructing unreported catches using complementary data sources and in-country expertise to extend and harmonize official reported data. This catch data reconstruction process also allows Sea Around Us data to separate wider-ranging industrial from relatively local artisanal, subsistence, and recreational fisheries (*17–19*). Furthermore, the sector-specific reconstructed catches have been spatially allocated to a half-degree latitude-longitude resolution spatial grid system, using both biological probability distributions for each taxon in the catch data sets and detailed information on EEZ fishing access agreements and available spatial catch information (*20*). These high-resolution spatial and temporal reconstructed catch data have allowed the geographical expansion of industrial fisheries over time to be quantified and visualized. Here, we have examined, for the first time, the trends since 1950 in the mean distances traveled to fish by the industrial fleets of the 20 largest fishing countries, collectively accounting for 80% of global industrial catches, and the trend in total industrial catch relative to the growth in the total area fished.

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RESULTS

Analysis of the mean distance traveled by the industrial fleets of the world's 20 largest fishing countries between their home countries and the locations where catches were taken illustrates three distinct patterns: rapid and largely continuous expansion (Fig. 1A), early expansion followed by stabilization or retrenchment (Fig. 1B), and limited or no expansion (Fig. 1C). The fishing fleets of Taiwan, South Korea, Spain, and China have continuously expanded their mean distance to fishing grounds by at least 2000 km since the 1950s, with the first three of these now fishing, on average, more than 3000 km from their home ports (Fig. 1A). These are globally operating distant-water fleets and flag states, accounting for nearly 20% of the global industrial catch over the last decade (Fig. 1A). Spain was already fishing, on average, nearly 1500 km from home at the start of global data records in 1950 (Fig. 1A), largely driven by the country's long history of fishing for Atlantic cod off the Canadian east coast. Five countries or former countries that currently account for about 27% of global industrial catches showed expansion during the early postwar decades but appear to have curtailed or consolidated their distant-water operations since then (Fig. 1B). This includes the former USSR, which had a large distant-water fleet during the 1950s and 1960s, operating, on average, more than 2000 km from home. In scale and early timing of expansion, the former USSR is only exceeded by Spain, South Korea, and Japan (Fig. 1, A and B). However, while Spain and South Korea have continued a fairly monotonic expansion, the countries of the former USSR began to retrench in the 1970s. Japan, after rapid postwar industrial expansion, also consolidated its fishing effort within the Indo-Pacific region starting in the 1970s (Fig. 1B). The remaining 11 of the 20 largest fishing countries, accounting for 33% of global industrial catches, have shown little or no expansionist efforts over the last 65 years (Fig. 1C). Norway has begun to fish relatively further afield in recent years, likely driven by the rapid growth in contribution of its Antarctic krill (*Euphausia superba*) fishery from <1% of the national total catch in 2006 to 7% in 2014 (www.seaaroundus. org). For the top 20 fishing countries, catches caught on the high seas or in the EEZs of other countries grew by more than 600% between 1950 and 2014, increasing their contribution to global catches from 16 to 23% over this period (www.seaaroundus.org). Catches by distant-water or "foreign" vessels have therefore grown faster than catches by countries within their own waters, illustrating the increasing importance of distant-water fishing among the countries that supply most of the world's wild-caught seafood.

Driven strongly by the trends in fishing distance among the 20 largest fishing countries, the net effect since 1950 is a global doubling of the mean distance fished from port (fig. S1). However, this net expansion has been associated with a strong decline in the catch obtained per kilometer traveled over the 65-year time period. Catches declined from more than 25 metric tons per 1000 km traveled in the early 1950s to approximately 7 metric tons per 1000 km traveled by 2014 (Fig. 2). The global industrial fishing catch increased fivefold between 1950 and its peak of 100 million metric tons in 1996 but has declined steadily by around 18% over the two decades since (Fig. 3A). In contrast, the percentage of total ice-free ocean area used for industrial fishing increased rapidly from 60 to 90% during the 1950s and 1960s, plateaued through the mid-1990s, and has expanded by less than 5% in the last two decades (Fig. 3B). The combination of these two patterns suggests that industrial catch per unit area of ocean fished expanded through peak catch in 1996 but has since declined by 22% (Fig. 3C).

A comparison of the spatial distribution of industrial catches between the 1950s and the 2000s illustrates and confirms the predominance of continental shelf waters as the source of most fish (Fig. 4, A and B). Expansions were most pronounced along the coasts and archipelagic waters of Southeast Asia, Africa, South America, and the South Asian subcontinent (Fig. 4, A and B). However, offshore and high seas waters have also become increasingly exploited in the past 65 years, with essentially no waters other than those at extreme high latitudes presently unfished to some degree (Fig. 4B).

DISCUSSION

The trends in the spatial expansion of industrial fisheries and their overall catch together indicate that we may be approaching the physical limits of expansion in capture fisheries (Figs. 3B and 4). Similar concerns have been raised by work showing the rapidly growing proportion of marine primary productivity being redirected to human consumption (6).
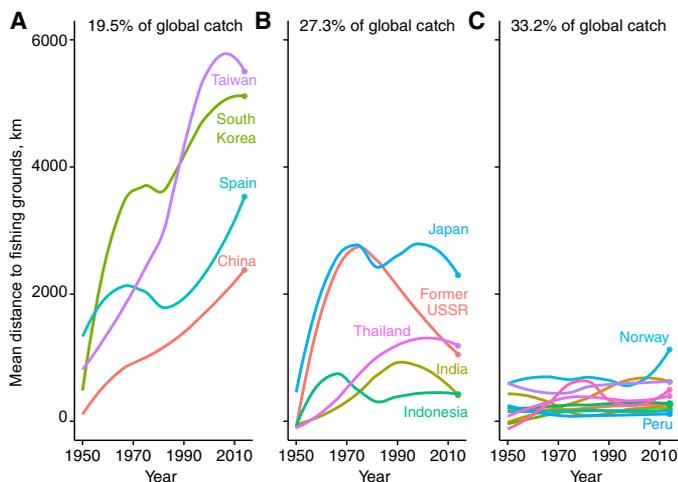
Fig. 1. Trends in the distance traveled to fish from 1950 to 2014. Mean distance to fishing grounds for the world's 20 largest industrial fishing countries (by tonnage) grouped by expansion history: (**A**) rapid and continuous expansion, (**B**) expansion followed by retrenchment, and (**C**) limited expansion. Percentage of global catch over the past decade is shown at the top of each panel. Countries not labeled in (C) are Argentina, Chile, Iceland, Malaysia, Mexico, Morocco, Philippines, and United States.
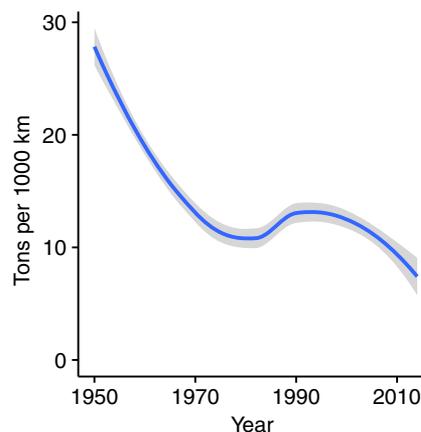

Fig. 2. Trend in mean global industrial catch per 1000 km traveled from 1950 to 2014. Gray band indicates ±95% confidence interval of LOWESS smoothed time series.
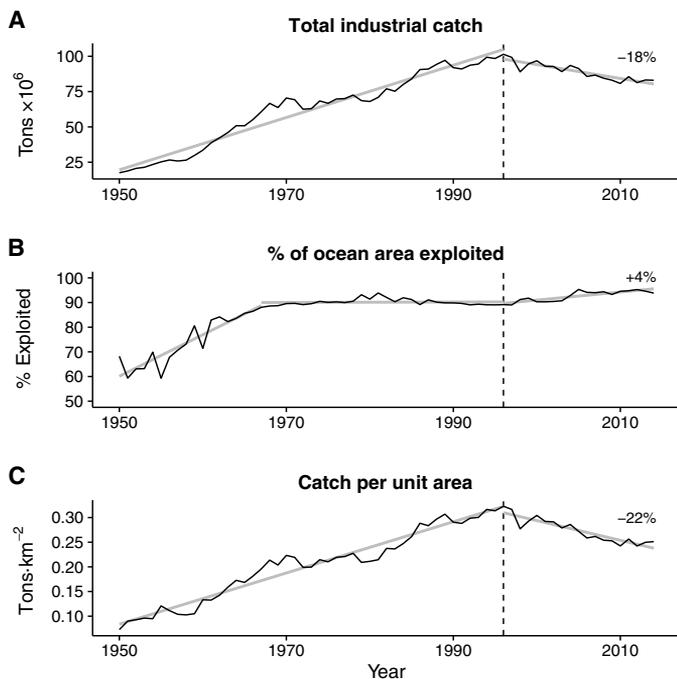
Fig. 3. Trends in total catch and area fished by global industrial fisheries, 1950–2014. (**A**) Global industrial fisheries catch (8), (**B**) percentage of ice-free ocean area exploited, and (**C**) industrial catch per unit ocean area. Dashed line indicates year of peak global catch in 1996, with percentage growth/decline since 1996 labeled on each time series.

Fig. 4. Spatial mapping of the distribution and intensity of industrial fishing catch. Mean industrial fisheries catch in metric tons per square kilometer by catch location during the (**A**) 1950s and (**B**) 2000s.

The trends in catch and effort data presented here suggest that the continuous increase in global catches to peak catch in 1996 (17) resulted from a combination of intensifying fishing effort and geographical expansion, which together masked underlying declines in the stocks being targeted (21). Between 1950 and 1970, the fraction of the global ocean exploited by fisheries grew by half and catches increased strongly. We suggest that this continued expansion and the concurrent intensification of fishing effort sequentially depleted new areas of the ocean such that catches peaked in 1996 when the rate at which new stocks were discovered could no longer keep up with the declines in existing stocks (17, 18, 22). This mechanism of serial discovery and depletion of fishing grounds is exemplified by the correlation between time series of fishing pressure and ecosystem regime change in large marine ecosystems (23) and the "boom and bust" trends documented in deep sea trawl fisheries over the last 65 years (24). By our measure, total industrial catch per unit ocean area has declined by 22% since 1996, despite spatial expansion having continued, albeit slowly. Further expansion into the remaining accessible areas of the polar seas, even if it were ecologically justifiable, seems unlikely to reverse this trend (Figs. 3B and 4).

Distance trends observed here imply that most of the fishing countries concentrate their effort in relatively local waters, with Peru, for example, largely focusing on its domestic fishery for Peruvian anchoveta (*Engraulis ringens*) (25). In addition, several former distant-water fishing fleets either have retrenched to domestic or regional waters near home countries or have been reduced or abolished (Fig. 1, B and C). For example, the countries of the former USSR fished extensively in the waters of the southwest Atlantic and the EEZs of Argentina, Uruguay, and Brazil before the collapse of the Soviet Union with its state support of distant-water fisheries. They have since reduced their distant-water activities to concentrate on northeast Atlantic, European, and western
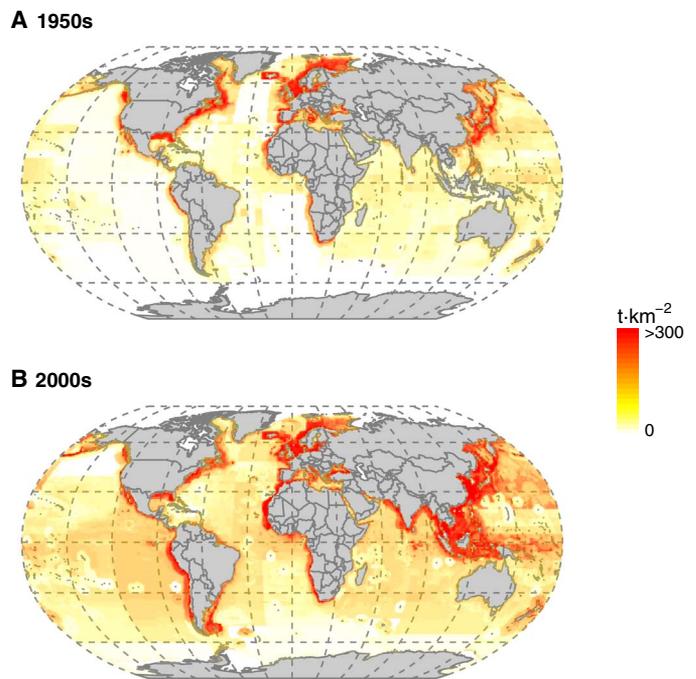
Pacific waters closer to domestic ports (23). Japan, after rapid postwar expansion aimed at improving domestic food supply, began consolidating its distant-water fishing effort from the mid-1970s, as access to many of its traditional fishing grounds became increasingly restricted with the emergence of the EEZ regime and increasing competition from low-cost fishing countries. Rising domestic labor costs and growing wealth also shifted Japanese food supply policy toward imports, paving the way for fleet reductions and spatial retrenchments that have helped remaining Japanese distant-water fishing to be relatively profitable (26, 27). For the few countries seemingly locked into the expansionist strategy, such as China and South Korea, distant-water fleets have become the mainstay of their industrial fisheries, with catches from outside their EEZs contributing 39 and 45%, respectively, of national total catches (www.seaaroundus.org). However, returns from this activity, in terms of catch per unit distance traveled, appear to have declined sharply, likely a combined result of declining fish stocks and the greater distances required to access them (Fig. 2). Long-haul distant-water fishing also incurs significantly higher fuel and crew costs (28) due to the long travel times to fishing grounds [for example, (29)]. To keep vessels fishing, fuel costs may be partly offset by generous government subsidies (30–32), and there is a good correlation between the distance a country fishes from home and the level of subsidies paid for fuel, vessel, and fleet support. In the case of Taiwan, these payments amount to more than 80% of the landed value of the industrial fishing catch (fig. S2). The relationship between subsidies and fishing distance suggests that expansion has been driven, in large part, by national policies that actively promote distant-water fishing through the provision of fuel and vessel subsidies. A recent analysis of the economics of high seas fishing found that profits from these activities for the major distant-water fishing countries would be greatly reduced, or even disappear completely, if fleets were not subsidized (33). While governments continue to subsidize fleet expansion,

the labor costs of these operations can typically only be reduced by cutting back on crew numbers, pay, or working conditions, which may be contributing to the growing tally of human rights and labor abuses that have been recorded on fishing vessels (28, 34). Illegal fishing and the use of flags of convenience can also serve to reduce the cost component for vessels suffering diminishing returns (35).

Continuing distant-water fishing activities are also increasingly viable only due to the growing number of refrigerated transshipment and resupply vessels (or "reefers") that allow individual fishing vessels to remain at sea for extended periods and avoid the fuel expenditure and lengthy breaks in fishing required to return to port or their home countries (34, 36). However, by transshipping and aggregating catches, and thus allowing fishing vessels to avoid port visits, reefers may also facilitate the "laundering" of illegally caught fish and permit other crimes at sea to remain undetected (37, 38). Transshipment also denies developing countries that host distant-water fleets (for example, in West Africa) the revenue from port activities and the processing and exporting of seafood associated with foreign fleets (36).

Our findings on the spatial expansion of industrial fishing are consistent with previous estimates by the Sea Around Us using only the FAO reported landings data (6). The spatial allocation of reconstructed fisheries data reported here assumes that fish are caught wherever a species' spatial distribution overlaps the operating sphere of a fishery targeting it, in proportion to its habitat preference–driven probability distribution (20). Therefore, this approach likely constitutes an upper bound to the current spatial coverage of fisheries, with some locations at the fringes of a taxon's distributional range likely not commercially viable for fisheries. For comparison, a recent analysis of vessel automatic identification system (AIS) data by Global Fishing Watch (GFW) and partners estimated that up to 73% of the oceans was fished in 2016, based on identifying gear-specific vessel movements assumed to indicate fishing activity and after taking into account spatial variations in AIS satellite coverage (34). Given that not all vessels carry or consistently use AIS transponders, for example, turning them off to preserve commercial secrecy around fishing grounds or during illicit activities, it is likely that the GFW figure is a lower-bound estimate of the area currently in use by industrial fisheries. Our analysis is able to provide historical context to the more precise but incomplete and temporally limited AIS data, showing how different countries have risen and fallen as distant-water fishing powers. The GFW study found that China, Spain, Taiwan, Japan, and South Korea dominate global industrial fishing effort; our results confirm that these five are also the world's most important distant-water fishing countries in terms of distance traveled (34). Collaborative research efforts combining AIS data and catch reconstructions will further refine our understanding of the spatial distribution of catch and effort in these fisheries.

Global catch per unit of effort has halved since FAO records began in 1950, despite a steady improvement in fishing power and technology (39). Our analysis corroborates this evidence of diminishing returns, showing that, while fisheries have extended their reach into all but the polar extremes of the global oceans, catch per unit area and per kilometer traveled have declined continuously for over two decades. Considered alongside the well-documented increase in the number of overfished stocks (21), these trends warrant an urgent reduction in fishing effort if declines in fisheries productivity are to be halted and reversed. Reducing the high levels of fuel and capacity-enhancing subsidies paid by fishing countries, in particular by the very small number of countries that fish the furthest from home (Fig. 1, A and B), would be a powerful first step in addressing our global overfishing problem and

returning an element of economic rationality to commercial fisheries (33). Reducing the subsidies that enable unprofitable fishing on the high seas would also reduce income inequality among maritime countries (40). Fish are a vital component of global food and economic security, and further degrading the productive capacity of the oceans puts both at risk for hundreds of millions, if not billions, of people and increases the risk of fisheries conflict (41). As with other spheres of human endeavor, recognizing that there are physical limits to growth on a finite planet is vital to humanity's long-term well-being. The oceans, once thought boundless and inexhaustible, may at last now also be proving a barrier to our quest for endless growth.

MATERIALS AND METHODS
The data were extracted from the global reconstructed fisheries catch database of the Sea Around Us (18). All Sea Around Us data and associated documentation and descriptions are freely accessible and downloadable at www.seaaroundus.org. Data can also be accessed through an R package via the Sea Around Us GitHub site at https://github.com/seaaroundus/. These data consist of more than 270 country-level catch reconstructions that currently cover 1950–2014 and that account for all fishing sectors (industrial, artisanal, subsistence, and recreational) as well as landed and discarded catches (42). These reconstructed data include best estimates of all unreported catches by year, fishing sector, and taxon for each country, following the established and well-documented catch reconstruction methodology (20, 43). It should also be noted that the baseline data for the Sea Around Us catch reconstructions are the data reported by member states to the FAO. Hence, all catches are assigned to a flag state (country) rather than that of the country of beneficial ownership. Thus, catch by vessels flagged to Togo but owned by a South Korean company, for example, will be assigned to Togo in both the original FAO data and the Sea Around Us reconstructed catch data. Had we been able to assign flag of convenience and open registry catches to beneficial owners, the average fishing distance of countries with significant numbers of foreign flagged vessels, such as Taiwan, Spain, and South Korea, would likely increase because, in many cases, those catches are treated as "local" catches of the flag state in our analysis rather than distant-water fishing by the beneficial owner country.

These reconstructed catch data sets were mapped onto a grid of $1/2° × 1/2°$ latitude and longitude cells overlaid over the global oceans to generate data for more than 150,000 oceanic grid cells. Allocations of catch data to individual cells take into account spatial variation in species' abundance, as well as political and historical accessibility of EEZ waters by the fleets of each fishing country (20). For the current analyses, only industrial sector data were used, as these represent the catches of fleets, including distant-water fleets, that fish domestically and internationally, that is, also outside of national EEZ waters. The nonindustrial catches from the small-scale artisanal, subsistence, and recreational sectors are excluded here as they are assumed to be spatially restricted to the inshore fishing areas within each home country's EEZ (20). Larger "artisanal" operators capable of operating further out to sea would be included as "industrial" vessels under the Sea Around Us classification [for example, the large semi-industrial pirogue fleets of Senegal that fish throughout many West African countries (44)]. Filtering for industrial fishing only, >62 million cell/fishing entity/catch/year allocation records were extracted from the Sea Around Us database, together with grid cell metadata (latitude and longitude of cell centroid and total water area). These data formed the basis for all spatial analyses. Catch locations were deemed to be spatially represented by the cell centroids.

Distances to fishing grounds were calculated from each relevant cell centroid to the nearest major port of each fishing country. Port locations were obtained from the World Ports Index (WPI) (https://msi.nga.mil/MSISiteContent/StaticFiles/NAV_PUBS/WPI/WPI_Shapefile.zip). For a small number of island fishing countries without port listings in the WPI, the geographical center of their landmass was used instead of port locations. Geographical centers for the relevant island entities were downloaded from the Center for International Development at Harvard University (https://sites.hks.harvard.edu/cid/ciddata/geographydata.htm).

The catch-weighted average distance between the major ports of each fishing country and fishing grounds (cells with catch taken by each country in question) was calculated for each fishing country and year as follows (fig. S3):

1) Catches were summed within each $^1/_2° × ^1/_2°$ grid cell (Catch in cell). The great circle distance from each grid cell centroid to the fishing country's nearest domestic port (Distance to cell) was then calculated using the function distGeo() in the R package geosphere.

2) The catch-weighted mean distance traveled to fish, for each country and year (1950–2014), was calculated as the weighted mean of all catch distances as follows

$$\frac{\sum_{i=1}^{180,000}(\text{Distance to cell}_i × \text{Catch in cell}_i)}{\text{Total catch}}$$

The purpose of the calculation was to generate a measure that captured relative changes over time in geographic reach of the fisheries of the major fishing countries, and the distance measure derived here is therefore a simplification of the actual distances traveled by industrial fishing vessels. In particular, the great circle distance used here is the shortest straight-line distance between a country's major ports and the location of allocated fishing catches. This calculated distance thus ignored realities affecting actual vessel travel distances, including landmasses, shipping routes, and other navigational complexities. In addition, distances moved within a given $^1/_2°$ cell to achieve the catch within that cell (that is, smaller-scale "searching" and fishing operation patterns) were not included here. We also omitted factors that would likely reduce an individual vessel's actual distance to fish, such as temporary or seasonal "home-porting" in ports outside a vessel's flag country, or the use of support vessels for catch transshipment and refueling at sea.

The mean distance traveled to fish was visualized for the 20 largest fishing countries, as ranked by total catch. The fishing countries of the former USSR (Estonia, Georgia, Latvia, Lithuania, Russia, and Ukraine) were treated as a single fishing entity to capture the expansion history of the Soviet Union, given its significant role in postwar industrial fisheries. Distance trends for each country were plotted as smoothed time series using locally weighted regression (LOWESS) (45) with a span coefficient of 0.75, implemented in the stat_smooth() function in the R package ggplot2. Plots were grouped according to three distance trends over the 65-year time period: steady and rapid increase, initial increase followed by stagnation or decline, or little or no increase.

The mean fishing distance for the global industrial fleet in each year was calculated as the catch-weighted mean of all individual country fishing distances, as calculated above. A smoothed time series (±95% confidence interval) was plotted as per the method above. Tons of fish caught per 1000 km traveled were calculated by year for all countries' industrial fisheries by dividing the global industrial catch by the total distance traveled to fish by all countries, with individual country's fishing distances calculated using the methodology described above.

Total industrial catch and total area fished were calculated by summing total catch and total cell area with industrial catch by year for the entire data set. Only the water area of each cell was used, where cells crossed coastlines. The trend in total area fished was presented as a percentage of the total ice-free ocean area. This was taken to be the total ocean area, 361.9 million km², minus the combined mean summer minimum ice coverage for the Arctic and Southern Oceans of 9.6 million km² (https://nsidc.org/cryosphere/seaice/index.html). Total ice-free ocean area available to fish was therefore estimated to be 352.3 million km². Industrial catch per unit area (metric tons per square kilometer) was calculated as the total industrial catch divided by the total area fished in each year. The data were plotted as line charts overlaid with broken stick regression lines showing points of inflection in the trend lines, notably the point of peak fish in 1996.

The global geographical distribution of industrial catch was mapped for the first and last decades of the time series (1950–1959 and 2005–2014) by averaging total industrial catch in each cell for each 10-year period and plotting the resulting values as a spatially defined raster superimposed on the world map. Since the distribution of cell catch values was highly skewed, catch per unit area in each cell was color-coded using a logarithmic scale, to give greater visual resolution among the smaller values.

To examine the relationship between fishing distance and government subsidies, mean distance to fish was plotted against harmful (fuel and capacity-enhancing) subsidies as a percent of landings. Subsidies were taken from Sumaila et al. (31). The relationship was tested using linear regression, and the line of best fit (±95% confidence interval) was added to the scatterplot. All analyses were performed using the R Statistical Language and packages in RStudio.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/8/eaar3279/DC1

Fig. S1. Mean distance traveled to fishing grounds by the world's industrial fisheries.
Fig. S2. Mean distance traveled to fishing grounds versus harmful subsidies.
Fig. S3. Schematic of methodology used for great circle distance calculations.

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Far from home: Distance patterns of global fishing fleets

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