FISHERIES

Tracking the global footprint of fisheries

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Although fishing is one of the most widespread activities by which humans harvest natural resources, its global footprint is poorly understood and has never been directly quantified. We processed 22 billion automatic identification system messages and tracked >70,000 industrial fishing vessels from 2012 to 2016, creating a global dynamic footprint of fishing effort with spatial and temporal resolution two to three orders of magnitude higher than for previous data sets. Our data show that industrial fishing occurs in >55% of ocean area and has a spatial extent more than four times that of agriculture. We find that global patterns of fishing have surprisingly low sensitivity to short-term economic and environmental variation and a strong response to cultural and political events such as holidays and closures.

Agriculture, forestry, and fishing are the main activities by which humans appropriate the planet's primary production (*1*, *2*) and reshape ecosystems worldwide (*3*). Recent advances in satellite-based observation have allowed high-resolution monitoring of forestry and agriculture, creating opportunities such as carbon management (*4*), agricultural forecasting (*5*), and biodiversity monitoring (*6*) on a global scale. In contrast, we lack a precise understanding of the spatial and temporal footprint of fishing, limiting our ability to quantify the response of global fleets to changes in climate, policy, economics, and other drivers. Although fishing activities have been monitored for selected fleets using electronic vessel monitoring systems, logbooks, or onboard observers, these efforts have produced heterogeneous data that are neither publicly available nor global in scope. As a result, the global footprint of fishing activity, or "effort," could be inferred only from disaggregated catch data (*7*, *8*).

Recent expansion of the automatic identification system (AIS) (*9*) presents an opportunity to fill this gap and quantify the behavior of global fleets down to individual vessels (*10*). Although AIS was originally designed to help prevent ship collisions by broadcasting to nearby vessels a ship's identity, position, speed, and turning angle every few seconds, these messages are also recorded by satellite- or land-based receivers. Whereas its usefulness as a tracking tool has been established locally (*11*–*13*), we use AIS to directly map global fishing activity.

We processed 22 billion global AIS positions from 2012 to 2016 and trained two convolutional neural networks (CNNs): one to identify vessel characteristics and a second to detect AIS positions indicative of fishing activity (fig. S1). The vessel characterization CNN was trained on 45,441 marine vessels (both fishing and nonfishing) that were matched to official fleet registries. The resulting model identifies six classes of fishing vessels and six classes of nonfishing vessels (tables S1 and S2) with 95% accuracy

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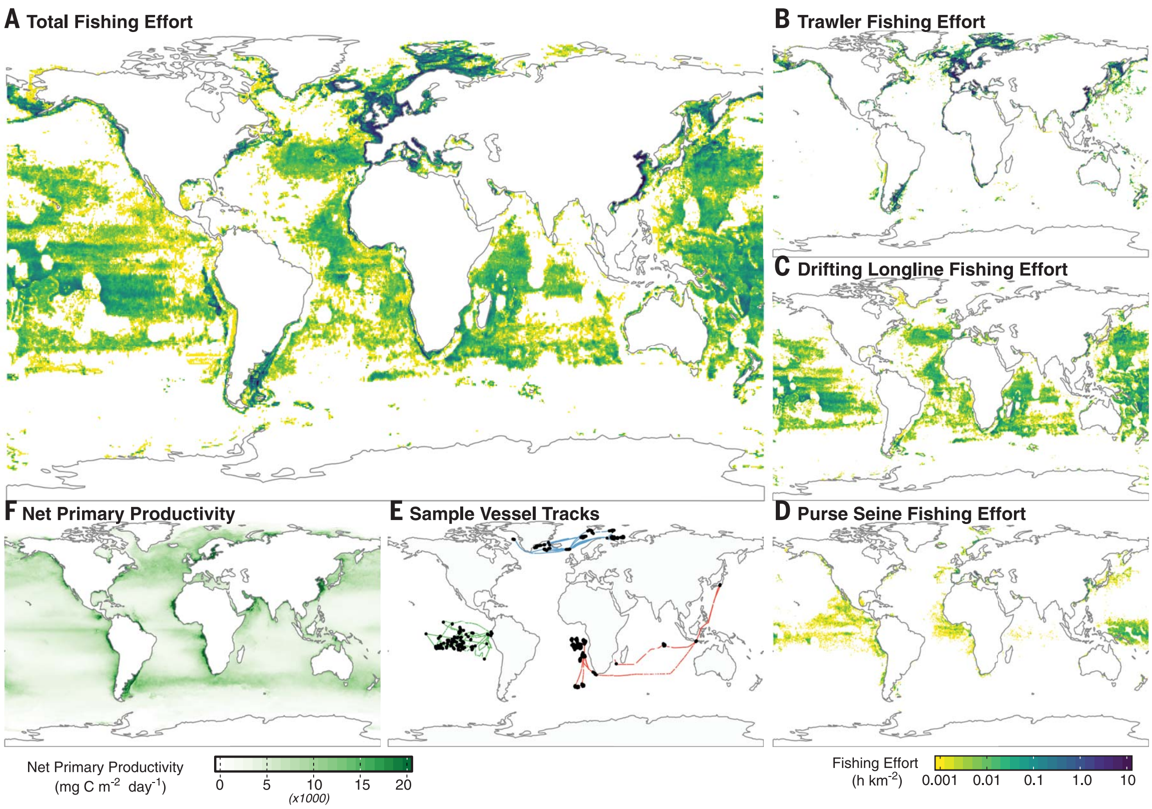

Fig. 1. The spatial footprint of fishing. (**A** to **D**) Total fishing effort [hours fished per square kilometer ($h\ km^{-2}$)] in 2016 by all vessels with AIS systems (A), trawlers (B), drifting longliners (C), and purse seiners (D). (**E**) Examples of individual tracks of a trawler (blue), a longliner (red), and a purse seiner (green). Black symbols show fishing locations for these vessels, as detected by the neural network, and colored lines are AIS tracks. (**F**) Global patterns of average annual NPP [expressed as milligrams of carbon uptake per square meter per day ($mg\ C\ m^{-2}\ day^{-1}$)] are shown for reference.

and performs well at predicting vessel length [R^2 (coefficient of determination) = 0.90], engine power (R^2 = 0.83), and gross tonnage (R^2 = 0.77) (fig. S2). The fishing detection model was trained on AIS data from 503 vessels and identified fishing activity with >90% accuracy (fig. S3 and table S3).

The resulting data set contains labeled tracks of more than 70,000 identified fishing vessels that are 6 to 146 m in length. We aggregated fishing effort by fishing hours (the time spent fishing) and by kilowatt-hours (kWh) (the estimated energy expended). This effort can be mapped at hour- and kilometer-level resolution, or two to three orders of magnitude higher than previous global maps of catch-derived effort (*14*, *15*). Although the data set includes only a small proportion of the world's estimated 2.9 million motorized fishing vessels (*16*), it contains 50 to 75% of active vessels larger than 24 m (tables S4 and S5) and >75% of vessels larger than 36 m, the size at which most vessels are mandated by the International Maritime Organization to transmit AIS signals. We empirically estimate that vessels with AIS account for 50 to 70% of the total energy expended while fishing beyond 100 nautical miles from land (fig. S4). The fraction of fishing captured closer to shore varies strongly by region, largely on the basis of national AIS usage rates (tables S4 and S5). For pelagic ecosystems, we cross-referenced AIS data with effort data reported by regional fisheries management organizations (RFMOs) and found strongly positive relationships (fig. S5). Regional deviations from this relationship can help identify zones of poor satellite coverage, limited AIS usage, or potential misreporting of fishing effort to RFMOs.

Over the course of 1 year (2016), our data set captured 40 million hours of fishing activity by vessels that consumed 19 billion kWh of energy and covered a combined distance of more than 460 million km, equivalent to traveling to the Moon and back 600 times. The spatial footprint of fishing, as determined with AIS, is unevenly distributed across the globe (Fig. 1A). Global hot spots of fishing effort were seen in the northeast Atlantic (Europe) and northwest Pacific (China, Japan, and Russia) and in upwelling regions off South America and West Africa (Fig. 1A). Areas with minimal fishing effort included the Southern Ocean, parts of the northeast Pacific and central Atlantic, and the exclusive economic zones (EEZs) of many island states, forming conspicuous "holes" in the global effort map (Fig. 1A).

Dividing the ocean into an equal-area grid with 0.5° resolution at the equator, we observed fishing in 55% of cells in 2016. The total area fished is likely higher, as we did not observe some fishing effort in regions of poor satellite coverage or in EEZs with a low percentage of vessels using AIS (figs. S6 and S7 and table S6). If we generously assume that these regions are fully fished, we would calculate that 73% of the ocean was fished in 2016. There may also be some regions of the high seas with good satellite coverage where we are missing effort due to vessels not having AIS. However, given that AIS captures the

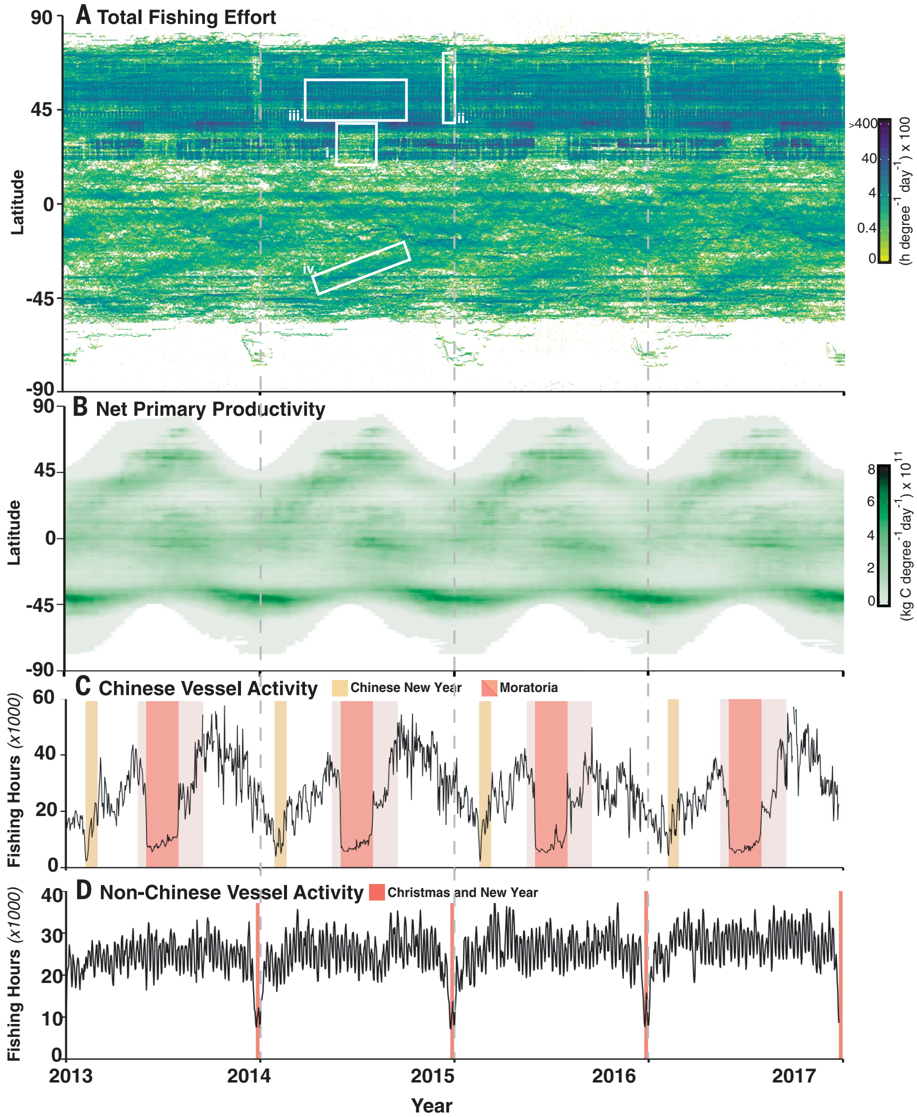

Fig. 2. The temporal footprint of fishing. Fishing hours by day and latitude (**A**) and seasonal patterns of marine net primary production (**B**). (**C**) Fishing hours per day for the Chinese fleet, with annual moratoria and the Chinese New Year highlighted. Light pink shading shows where some regions in the Chinese EEZ observe fishing moratoria, and dark pink shading shows where most of the Chinese EEZ is under moratorium. (**D**) In contrast, non-Chinese vessels show a strong weekly pattern and a drop in effort due to the Christmas holiday. Insets in (A) highlight periods of low effort around (i) annual fishing moratoria in Asian waters, (ii) Christmas in North America and Europe, and (iii) weekends, as well as (iv) a seasonal signal for longline fishing in the Southern Hemisphere (Fig. 3C).

majority of fishing effort in the high seas (fig. S4), this missing effort is unlikely to substantially affect our estimate. Previous work, based on ocean basin–scale landing data, estimated that >95% of the ocean may be fished when using a similar grid size (*15*). Though our estimate is lower, the percentage of the ocean fished is still much higher than the fraction of land used in agriculture or grazing (~34%) (*17*), covering more than 200 million km^2, compared with 50 million km^2 for agriculture.

This large spatial footprint varies by gear type and fleet. Longline fishing was the most widespread activity and was detected in 45% of the ocean (Fig. 1B), followed by purse seining (17%) (Fig. 1C) and trawling (9.4%) (Fig. 1D). Different gear types had distinct latitudinal distributions, with trawling confined mostly to higher latitudes, purse seining concentrated in tropical regions, and longlining in between. Longliners had the greatest average trip length between anchorages (7100 km) and displayed transoceanic circumglobal movements, whereas purse seiners (average trip length, 750 km) and trawlers (average trip length, 510 km) were typically active on a more regional scale (Fig. 1E). Analyzing the spatial distribution of individual fleets, we found

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that most nations fished predominantly within their own EEZ, with five flag states (China, Spain, Taiwan, Japan, and South Korea) accounting for more than 85% of observed fishing effort on the high seas (fig. S8).

The temporal footprint of fishing was surprisingly consistent through time (Fig. 2A). A large annual drop in mid-latitude effort coincides with annual fishery moratoria in China, a smaller drop at higher latitudes corresponds to the Christmas vacation in Europe and North America, and breaks in effort occur during the weekends for many Northern Hemisphere fisheries (Fig. 2A, insets). In stark contrast, temporal patterns of net primary productivity (NPP) present a seasonal "heartbeat" of biological activity (Fig. 2B) that is not reflected by human activity at this scale (Fig. 2A). For non-Chinese vessels (Fig. 2D), the largest contributors to variations in the overall temporal footprint were the Christmas holiday and weekends, with the remaining seasonal variation explaining a small amount of the temporal footprint (fig. S9). In contrast, Chinese vessels show little weekly variation, and their yearly pattern is dominated by the Chinese New Year and the annual moratoria during the summer months (Fig. 2C). Although some fleets display seasonal movements (Fig. 3), the work week, holidays, and political closures are much more influential than natural cycles in determining the temporal footprint of fishing on a global scale. This pattern stands in stark contrast to agriculture, which is focused on plants and nonmigratory herbivores tied to seasonal cycles of terrestrial primary production (*18*).

We further inspected how the spatial and temporal footprint of fishing responds to other environmental or economic drivers—namely, annual NPP, sea surface temperature (SST), and fuel prices. Annual NPP predicts fish catch from coastal ecosystems (*19*) but has not been analyzed as a predictor of effort across the global ocean. Using a general additive model that accounts for spatial autocorrelation, we found a highly significant but relatively weak relationship between fishing hours (Fig. 1A) and NPP (Fig. 1F) (slope = 0.58, $P < 0.001$), with only 1.7% of spatial deviance explained. This relationship was strongest for purse seiners [slope = 0.74,

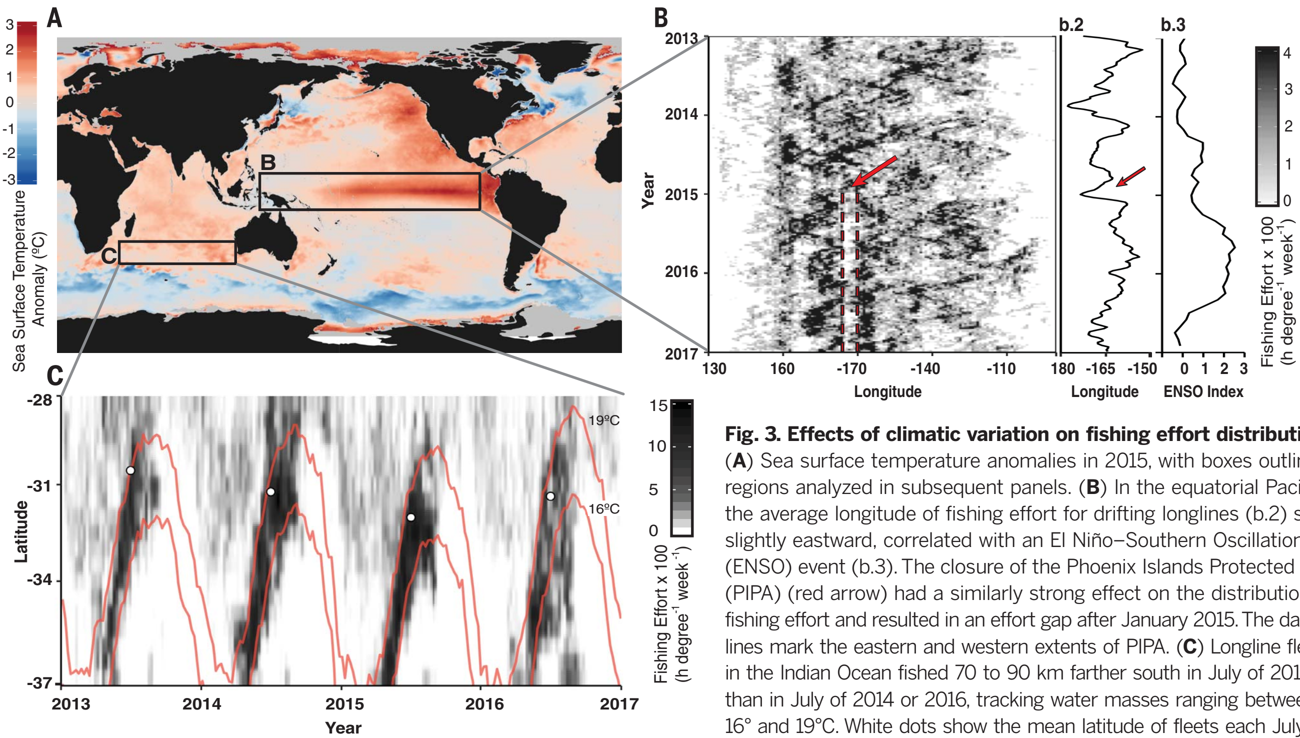

Fig. 3. Effects of climatic variation on fishing effort distribution. (**A**) Sea surface temperature anomalies in 2015, with boxes outlining regions analyzed in subsequent panels. (**B**) In the equatorial Pacific, the average longitude of fishing effort for drifting longlines (b.2) shifts slightly eastward, correlated with an El Niño–Southern Oscillation (ENSO) event (b.3). The closure of the Phoenix Islands Protected Area (PIPA) (red arrow) had a similarly strong effect on the distribution of fishing effort and resulted in an effort gap after January 2015. The dashed lines mark the eastern and western extents of PIPA. (**C**) Longline fleets in the Indian Ocean fished 70 to 90 km farther south in July of 2015 than in July of 2014 or 2016, tracking water masses ranging between 16° and 19°C. White dots show the mean latitude of fleets each July.

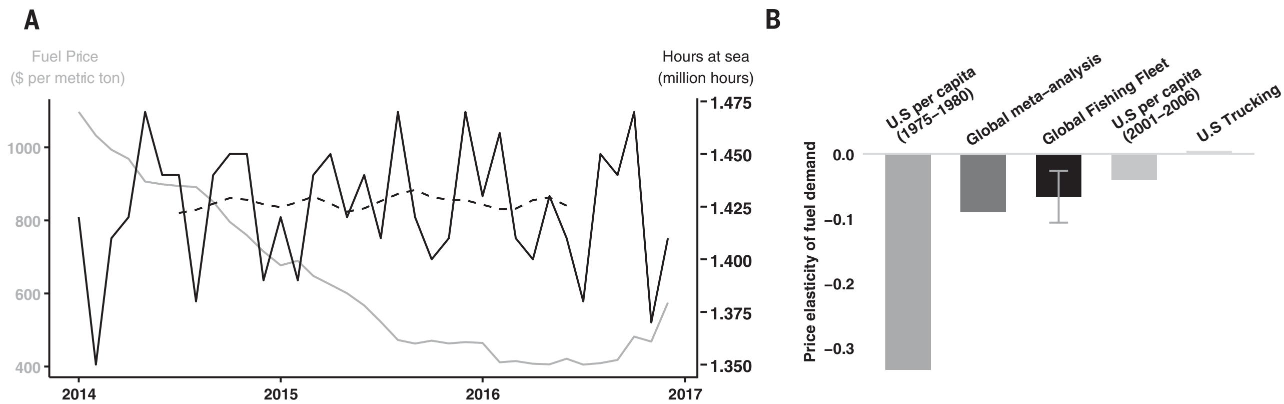

Fig. 4. Response to economic forcing. (**A**) Monthly averages of the global price of marine diesel oil (gray line) and total hours at sea by the global fishing fleet after removing seasonality (solid black line) reveal that a large decrease in fuel price from 2013 to 2016 corresponded to minimal change in fishing activity (the dashed line corresponds to the trend component via additive decomposition). (**B**) The short-run price elasticity of fuel demand (−0.06, $P < 0.001$; error bar denotes 95% confidence interval) is comparable to those in other sectors.

P < 0.001, deviance explained (DE) = 2.5%] and trawlers (slope = 0.69, P < 0.001, DE = 2.1%), which are commonly found in highly productive coastal areas, and weakest for drifting longlines (slope = 0.37, P < 0.001, DE = 0.6%), which operate largely in medium- to low-productivity waters. Although these relationships may be strengthened by incorporating additional drivers and different scales, global fishing effort corresponds only loosely to NPP.

We further explored the response to elevated SST in 2015 (Fig. 3), when a positive Indian Ocean dipole mode index and an El Niño event warmed the Indian and Pacific Oceans, respectively (*20*). In the Indian Ocean, we found longline fishing concentrated between the 16° and 19°C isotherms [r (correlation coefficient) = 0.8 between average latitude of fishing effort and the 19°C isotherm]. Fishing effort in this region was an average of 70 to 90 km farther south in July of 2015 than in July of 2014 or 2016 (Fig. 3C). In the equatorial Pacific, previous studies have shown that regional warming during El Niño years correlates with a shift in the catch of skipjack tuna of up to 40° longitude (*21*). By analyzing effort across all fleets in the region, we find a more modest response. The total fleet shifts by ~3.5° per unit of the El Niño–Southern Oscillation (ENSO) index (second-order autoregression model, P < 0.001), with purse seiners responding more strongly than longlines. This shift corresponds to a movement of ~10° longitude of the average location of fishing effort over ~2 years (Fig. 3B, b.2). This shift, likely due to a strong El Niño, was similar in magnitude to the effect of a change in policy. When the Phoenix Islands Protected Area (PIPA) was closed to industrial fishing in 2015 (Fig. 3B), the average longitude of fishing effort moved by ~10° over a month as fleets recalibrated to new regulations (Fig. 3B, b.2).

Changes in fuel price may also drive variation in fishing effort, as fuel represents, on average, 24% of costs (*22*). Previous research regarding the effects of fuel price on the structure (*23*), economic performance (*24*), and behavior (*25*) of European fishing fleets suggests that, at a regional level, fishing fleets respond to fuel price. To measure elasticity globally, we built a monthly time series of the average price of marine diesel matched with tracking data for all fishing vessels active since 2014. The resulting sample includes 5933 vessels from 82 flag states (table S7). We found that a >50% drop in fuel price corresponded to a minimal change in fishing effort (measured as the time spent at sea) (Fig. 4 and table S8). These data suggest that the short-run price elasticity of fuel demand for the global fishing fleet is –0.061 (P < 0.001) (Fig. 4B), implying that a 10% increase in the price of fuel would correspond to a 0.6% decrease in global fishing activity. This elasticity is smaller than that implied by previous studies in fisheries but is comparable to those in other commercial sectors (*26*–*28*) (Fig. 4B). It is possible that abundant fuel subsidies decouple fisheries from energy costs, masking the true price elasticity of fuel demand.

These results provide insight into the spatial and temporal footprint of global fishing fleets. Fishing vessels exhibit behavior with little natural analog, including circumglobal movement patterns and low sensitivity to energy costs or seasonal and short-term interannual oceanographic drivers. It appears that modern fishing is like other forms of mass production that are partially insulated from natural cycles and are instead shaped by policy and culture. The absolute footprint of fishing is much larger than those of other forms of food production, even though capture fisheries provide only 1.2% of global caloric production for human food consumption (*29*), ~34 kcal per capita per day (*16*). We also find that large regions of the ocean are not heavily fished, and these areas may offer opportunities for low-cost marine conservation. To further the understanding and monitoring of global fisheries, we are making daily high-resolution global rasters of effort publicly available. These data provide a powerful tool for improved global-scale ocean governance and are well positioned to help assess the effectiveness of existing management regimes while accelerating the development of novel dynamic management approaches (*30*) that respond in real time to changing ocean conditions, management issues, or conservation concerns.

REFERENCES AND NOTES

1. H. Haberl *et al*., *Proc. Natl. Acad. Sci. U.S.A.* **104**, 12942–12947 (2007).
2. W. Swartz, E. Sala, S. Tracey, R. Watson, D. Pauly, *PLOS ONE* **5**, e15143 (2010).
3. P. M. Vitousek, H. A. Mooney, J. Lubchenco, J. M. Melillo, *Science* **277**, 494–499 (1997).
4. V. De Sy *et al*., *Curr. Opin. Environ. Sustain.* **4**, 696–706 (2012).
5. M. Burke, D. B. Lobell, *Proc. Natl. Acad. Sci. U.S.A.* **114**, 2189–2194 (2017).
6. W. Turner *et al*., *Trends Ecol. Evol.* **18**, 306–314 (2003).
7. J. A. Anticamara, R. Watson, A. Gelchu, D. Pauly, *Fish. Res.* **107**, 131–136 (2011).
8. R. A. Watson *et al*., *Fish Fish.* **14**, 493–503 (2013).
9. International Telecommunication Union (ITU), "Technical characteristics for an automatic identification system using time division multiple access in the VHF maritime mobile frequency band" (Recommendation ITU-R M.1371-5, ITU, 2014); www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.1371-5-201402-I!!PDF-E.pdf.
10. D. J. McCauley *et al*., *Science* **351**, 1148–1150 (2016).
11. F. Natale, M. Gibin, A. Alessandrini, M. Vespe, A. Paulrud, *PLOS ONE* **10**, e0130746 (2015).
12. E. N. de Souza, K. Boerder, S. Matwin, B. Worm, *PLOS ONE* **11**, e0158248 (2016).
13. T. D. White *et al*., *Biol. Conserv.* **207**, 64–71 (2017).
14. D. Pauly, D. Zeller, Eds., Sea Around Us concepts, design, and data (2015); www.seaaroundus.org.
15. R. A. Watson, *Sci. Data* **4**, 170039 (2017).
16. Food and Agriculture Organization of the United Nations (FAO), *The State of World Fisheries and Aquaculture 2016* (FAO, 2016).
17. J. A. Foley *et al*., *Nature* **478**, 337–342 (2011).
18. L. Guanter *et al*., *Proc. Natl. Acad. Sci. U.S.A.* **111**, E1327–E1333 (2014).
19. E. Chassot *et al*., *Ecol. Lett.* **13**, 495–505 (2010).
20. P. L. Barnard *et al*., *Nat. Commun.* **8**, 14365 (2017).
21. P. Lehodey, M. Bertignac, J. Hampton, A. Lewis, J. Picaut, *Nature* **389**, 715–718 (1997).
22. World Bank, *The Sunken Billions Revisited: Progress and Challenges in Global Marine Fisheries* (World Bank, 2017).
23. H. Stouten, K. Van Craeynest, A. Heene, X. Gellynck, H. Polet, "The effect of fuel price scenarios on Belgian fishing fleet dynamics," paper presented at the International Council for the Exploration of the Sea (ICES) Annual Science Conference, Halifax, Canada, 22 to 26 September 2008 (CM 2007/M:04); www.vliz.be/imisdocs/publications/135276.pdf.
24. A. Cheilari, J. Guillen, D. Damalas, T. Barbas, *Mar. Policy* **40**, 18–24 (2013).
25. D. J. Beare, M. Machiels, *ICES J. Mar. Sci.* **69**, 1064–1068 (2012).
26. J. E. Hughes, C. R. Knittel, D. Sperling, "Evidence of a shift in the short-run price elasticity of gasoline demand" (Working paper 12530, National Bureau of Economic Research, 2006).
27. J. J. Winebrake *et al*., *Transp. Res. D* **38**, 166–177 (2015).
28. T. Havranek, Z. Irsova, K. Janda, *Energy Econ.* **34**, 201–207 (2012).
29. FAO, *FAO Statistical Pocketbook 2015* (FAO, 2016).
30. R. Lewison *et al*., *Bioscience* **65**, 486–498 (2015).

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/359/6378/904/suppl/DC1
Materials and Methods
Figs. S1 to S9
Tables S1 to S8
References (*31*–*46*)

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More than half the fish in the sea

As the human population has grown in recent decades, our dependence on ocean-supplied protein has rapidly increased. Kroodsma *et al.* took advantage of the automatic identification system installed on all industrial fishing vessels to map and quantify fishing efforts across the world (see the Perspective by Poloczanska). More than half of the world's oceans are subject to industrial-scale harvest, spanning an area four times that covered by terrestrial agriculture. Furthermore, fishing efforts seem not to depend on economic or environmental drivers, but rather social and political schedules. Thus, more active measures will likely be needed to ensure sustainable use of ocean resources.

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