APPLIED ECOLOGY

The global network of ports supporting high seas fishing

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Fisheries in waters beyond national jurisdiction ("high seas") are difficult to monitor and manage. Their regulation for sustainability requires critical information on how fishing effort is distributed across fishing and landing areas, including possible border effects at the exclusive economic zone (EEZ) limits. We infer the global network linking harbors supporting fishing vessels to fishing areas in high seas from automatic identification system tracking data in 2014, observing a modular structure, with vessels departing from a given harbor fishing mostly in a single province. The top 16% of these harbors support 84% of fishing effort in high seas, with harbors in low- and middle-income countries ranked among the top supporters. Fishing effort concentrates along narrow strips attached to the boundaries of EEZs with productive fisheries, identifying a free-riding behavior that jeopardizes efforts by nations to sustainably manage their fisheries, perpetuating the tragedy of the commons affecting global fishery resources.

INTRODUCTION

Fish stocks are a paradigmatic example of a resource vulnerable to the tragedy of the commons (*1*–*3*), referring to the risk of depletion of shared, unregulated but finite resources by the drive of individuals to maximize their benefits (*4*). Effective management of fishery resources requires regulation on a collective scale. While traditional practices at the artisan level are unlikely to disturb the equilibrium of fisheries stocks (*5*), the opposite case stands for industrial fisheries, dominated by wealthy nations (*6*) operating globally (*7*). The first step to prevent the depletion of fish stocks with the advent of industrial fishing was, therefore, to progressively restrict access to the resources by expanding national marine jurisdictions, which had remained limited to three nautical miles from the coastline, under the so-called cannonball rule, until World War II. Iceland progressively extended their national jurisdiction to 4, 12, and 50 nautical miles, triggering the Cod Wars, to reach the current limit of 200 nautical miles adopted by the United Nations (UN) Law of the Sea Convention in 1982 (*3*). Yet, the Food and Agriculture Organization (FAO) estimates that global fisheries catches, which peaked during the mid-1990s, have declined 9% below that level, with 53% of monitored fish stocks fully exploited, 28% overexploited, and 3% depleted (*8*). This decline suggests that limiting international entry into the fishery has not sufficed to solve the tragedy of the commons. Shared stocks are more prone to overexploitation (*2*), with illegal, unreported fishing estimated at 23 million tons (*9*), representing about 20% of the total catches (*10*). Control of foreign and illegal fishing is fundamental to allow local people to benefit from their own management efforts (*11*), avoiding free-riding on efforts to rebuild these stocks (*12*). Although it only represents a fraction of the total catches, the governance of fishing in the high seas is particularly difficult and consequently inefficient (*13*, *14*), leading to uncertainty in the future of global fisheries (*15*). Furthermore, industrial fishing affects other species, particularly those that are highly migratory and transit between the high seas and exclusive economic zones (EEZs), such as sharks and tunas, through the overlap between fishing hotspots and their core habitats (*16*, *17*).

Whereas management and governance practices are leading to an improved status of fish stocks in some areas (*18*, *19*), problems persist, particularly where highly mobile foreign fleets derive benefit from these efforts in stocks shared in the high seas. Fish stocks shared by multiple countries account for about one-third of world marine capture fishery harvests (*20*), including transboundary fish stocks, which migrate across the EEZ boundaries of two or more coastal states (*21*); straddling fish stocks, found both within coastal state(s) EEZ(s) and the adjacent high seas; and discrete stocks found exclusively in the high seas (*22*). Hence, the bottom-up focus on national reporting to understand global fisheries needs to be complemented with a top-down approach capturing the broader global fishing network and the use of shared fish stocks.

Here, we infer the global network of ports supporting fishing in the high seas and quantify the distribution of fishing effort in hotspots across the high seas. We base our analysis on reported positions of fishing vessels equipped with marine automatic identification systems (AISs) during 2014 (*23*). AIS, a tool developed to increase shipping safety and traffic control, has been used to predict vessel trajectories (*24*), assess Arctic occupation by shipping (*25*), or detect anomalies in ship traffic (*26*) and has the potential to assist in efforts to ensure ecological, environmental, and social sustainability of ocean use (*27*, *28*) and to minimize conflicts for space and resources within and among sectors (*29*). AIS data were recently used as a basis to assess the global distribution of fishing effort (*30*). Here, we specifically analyze the trajectories of fishing vessels to objectively identify provinces of highly modular fishing activity in the high seas and the ports that support the vessels fishing within each province. The resulting network describes the connections between the high seas fishing areas coherently used by fishing vessels and the

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ports associated with their fishing effort, defined as the ports visited before and after the visits to the fishing areas.

RESULTS

The AIS tracking system, mandatory for all fishing vessels capable of operating in the high seas, reported the trajectories of a total of 112,535 fishing vessels in 2014. The speed distribution of fishing vessels was bimodal, with modes at 5.9 and 15.2 km/hour (3.2 and 8.2 knots, respectively; fig. S1), corresponding to fishing and cruising speeds, respectively (*31*), allowing to classify the vessel activity in each reported location. Locations with reported observations associated with speeds lower than 5 knots in high seas were gathered into discretized grid cells (0.5° in latitude and longitude), aggregating the time spent fishing by all the tracked vessels in each grid cell to compute the fishing effort (Fig. 1A). This approach represents a simplified version of more complex approaches using machine learning tools to classify the tracked locations as belonging to fishing and cruise modes (*32*). However, we find a strong correlation between both approaches (r^2 = 0.903), particularly so in areas of relatively high fishing effort (fig. S2). The resulting distribution of fishing effort was very heterogeneous and skewed (fig. S3), characterized by a broad distribution of time spent in each location, with 80% of the observed fishing effort associated with the top 20% of grid cells supporting the highest fishing effort, and a median effort of 0.85 (5th to 95th percentiles = 0.05 to 9.10 days) fishing days in each high seas grid cell in 2014. This implies that most of the grid cells support low effort, with most effort concentrated in fishing hotspots, which we define as the top 10% grid cells with the highest fishing effort in the high seas. This 10% of hotspot locations represent 66.6% of the total global fishing effort in the high seas (Fig. 1A and fig. S3).

EEZ borders and free-riding

We observed large coherent regions of high fishing effort at high seas locations adjacent to the borders of EEZs, indicating concentrated fishing effort near those borders, as they represent locations where fish stocks mostly contained within specific EEZs can be accessed by the high seas fleet (Fig. 1, B to E). Specifically, 47% of the global fishing effort in the high seas was concentrated along the edges of productive EEZs, between 325 and 525 km of distance to the nearest shore (Fig. 1, F and G). This observation denotes a free-riding behavior (*33*), where vessels operating in the high seas benefit from efforts to achieve sustainable fishing of nations holding productive fisheries within their EEZs, by reaping the benefits of these efforts by harvesting fish that move beyond the EEZ boundaries,

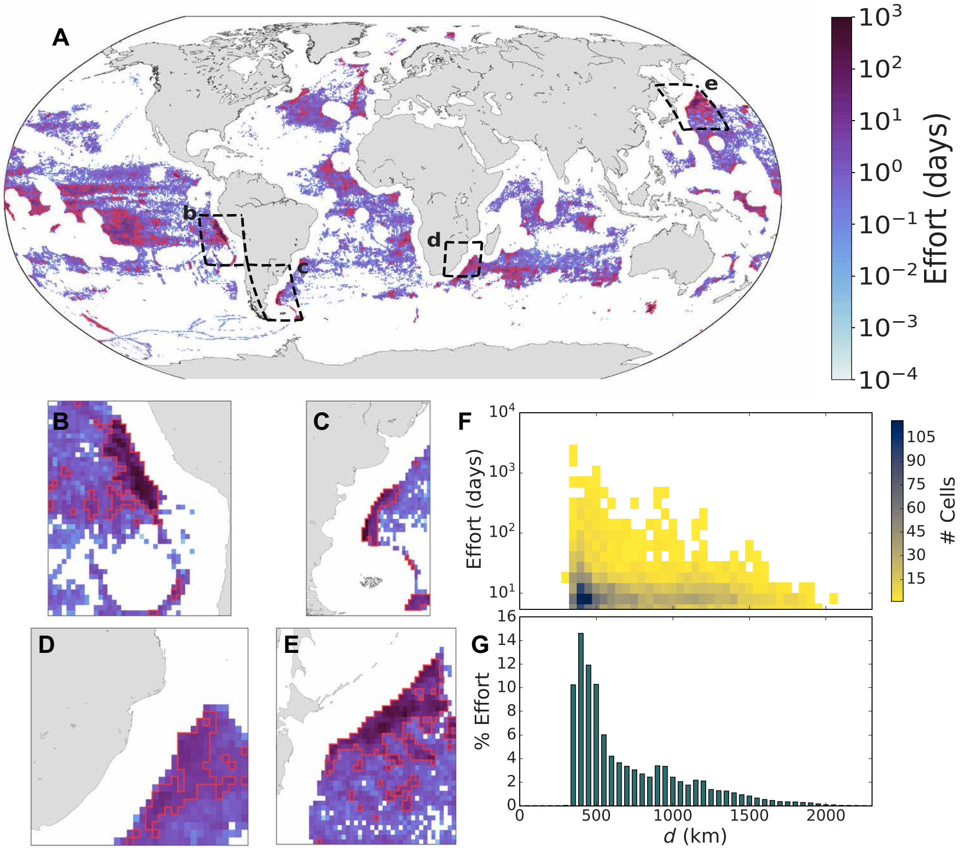

Fig. 1. Fishing effort in the high seas. (**A**) Fishing effort, as total days of fishing activity in 2014, at each grid cell (of size 0.5°lat × 0.5°lon) in the high seas. Red contours delimit the areas including the grid cells with the top 10% fishing effort. (**B** to **E**) Zooms on the regions enclosed by the dashed lines in (A), where high fishing effort concentrates along the outer edge of productive EEZs. (**F**) Number of cells for each observed fishing effort value classified according to the distance *d* to the closest shore. (**G**) Fraction of the global fishing effort in the high seas observed at a distance *d* to the closest shore; bars represent the fraction along bands of 50-km width.

therefore undermining efforts to rebuild and sustainably harvest these fish stocks. An assessment of the stability of this pattern with fishing effort data between 2012 and 2016 (*30*) reveals that these areas are less coherent in the early years, when the AIS displays lower penetration rates, keeping a stable coherence in the period 2014–2016 (figs. S4 to S8).

Marine provinces

We obtained 14 high seas provinces of elevated fishing effort based on the distribution of fishing effort and the trajectories of the vessels active in the high seas (Fig. 2). Some provinces present a high agreement with FAO zones, such as the South Eastern Atlantic and Southern Pacific provinces, mostly associated with a single FAO zone (fig. S9). However, there are notable differences in other regions. For example, we identify four large provinces in the Equatorial Pacific (fig. S9), largely comprising fishing targeting tuna and billfish, which the FAO classification assigns to two zones. Hence, we argue that a modification of FAO zones, including merging of those sharing a cluster to yield 14 instead of the current 19 FAO major zones, would provide reporting and management units consistent with the clusters emerging from the empirical data, which represent coherently visited fisheries, across the ocean (fig. S9). Assuming that each vessel specializes in one province, this modification would create management regions that are associated with the same set of vessels, targeting the same fish stocks and supported by a given set of harbors, facilitating the catch verification in the identified ports that support the vessels fishing in that province. Although the connections between high seas fishing areas were highly modular, consisting of well-defined provinces, we found connections among different provinces, such that these 14 provinces belong to the largest connected component of a global network (fig. S10), and those connections are associated with a geographical structure where fishing hotspots that are close in space are connected through vessels moving between them.

The global fishing network

The global fishing network is defined based on the trajectories connecting the 14 fishing provinces in high seas with the harbors from which the vessels departed and arrived. The fishing effort in high seas was supported by 296 harbors, with the top 10 harbors supporting 41% of the global fishing effort in high seas (Fig. 3, A and B, fig. S11, and table S1). Most of the fishing trips initiated or finished in a harbor involved fishing by the vessel in the same province, that is, from a network perspective, most of the harbors have degree one or a strong link (Fig. 3C), with 38.5% of the trajectories departing and arriving in the same harbor. This hierarchy among harbors was translated into a hierarchy in fishing effort when harbors were grouped by countries (Fig. 4A). Both harbors and countries directed their effort toward a few (one or two) high seas fishing provinces in most cases, although there are some countries (e.g., the United States and South Africa) for which the effort is distributed between several provinces (Fig. 4, B and C, and fig. S12).

DISCUSSION

Overexploitation of coastal waters and restrictions to access stocks within EEZs led to increased exploitation of fish on the high seas (*34*). Captures in the high seas have been estimated to represent 12% of the global average annual marine fisheries catch, with an estimated value of US$16 billion annually, about 15% of the total global marine landed value (*34*), although more recent analyses report that only 4.2% of the global fishing catch occurred in the high seas (*35*). Highly migratory, pelagic species such as tunas, billfishes, and sharks are particularly vulnerable to exploitation in the high seas, as their home ranges typically extend across great distances, along several EEZs [67% of a sample of 938 commercially valuable marine species; (*36*)] and the high seas (*37*). Moreover, many species have home ranges extending from EEZs to high seas, so that efforts to rebuild the stocks in EEZs may be undermined by captures

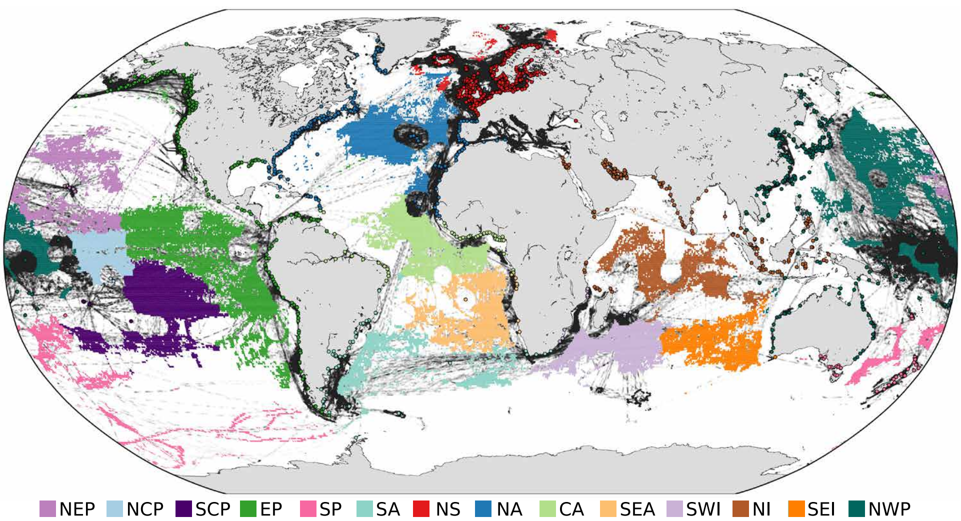

Fig. 2. Global fishing network composed of ports and high seas fishing provinces. Provinces (represented with different colors) of strongly connected locations are identified with Infomap. Ports are depicted as circles with colors identified with the provinces they support. The 14 fishing provinces are North Eastern Pacific (NEP), Northern Central Pacific (NCP), Southern Central Pacific (SCP), Eastern Pacific (EP), Southern Pacific (SP), Southern Atlantic (SA), Northern Seas (NS), Northern Atlantic (NA), Central Atlantic (CA), South Eastern Atlantic (SEA), South Western Indian (SWI), Northern Indian (NI), South Eastern Indian (SEI), and North Western Pacific (NWP). Gray traces represent the trajectories of the vessels connecting ports and fishing locations.

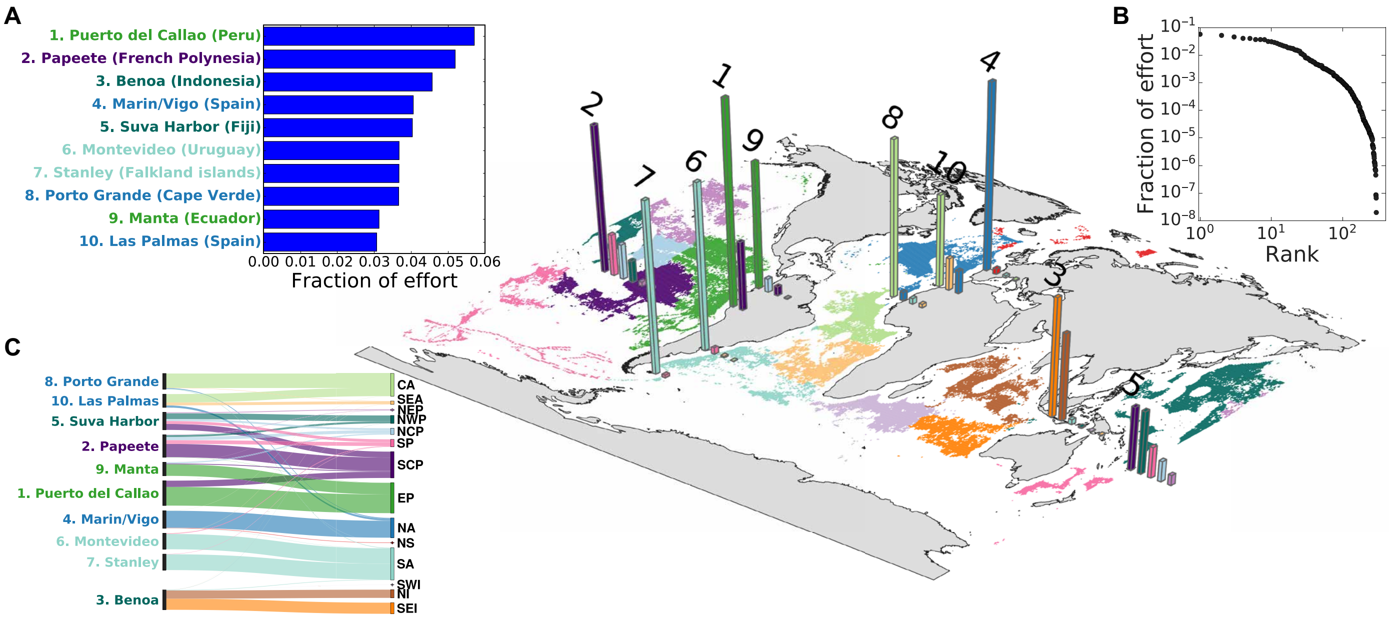

Fig. 3. Distribution of high seas fishing effort among provinces and harbors. Central panel: Effort (vertical axis) of the top 10 harbors in each province, which are depicted in the horizontal plane. Label numbers correspond to their global rank according to (A). (**A**) Fraction of effort supported by the top 10 harbors. (**B**) Ranking plot of the fraction of the global fishing effort supported by each harbor. (**C**) Bipartite network linking the top 10 harbors used by vessels operating in the high seas and the fishing provinces they exploit therein. Links connect the ports with the hotspots visited immediately before and after the detected presence of each vessel in each port, and their widths are proportional to the estimated fishing efforts in the hotspots before and after the presence in ports.

in the adjacent high seas. The concentration of fishing effort along the outer edges of EEZs supporting productive fisheries represents clear evidence of free-riding behavior by the fleet operating in the high seas that undermines the efforts of the nations to manage their fish stocks for sustainability. It also reflects the arbitrary nature of the uniform 200–nautical mile EEZ delineation, which does not recognize the distribution and dimensions of fish stocks. Many of the heavily fished areas correspond to relatively narrow strips of ocean lined along the boundaries of the fish-rich EEZs where the stocks are located, from the Arctic region to tropical areas (Fig. 1, B to E). Particularly revealing are the intense concentrations of high seas fishing off the EEZs of some of the most productive fisheries in the world, including those of Ecuador and Peru, South Africa, Argentina, and Japan (Fig. 1, B to E).

The results obtained are affected by limitations due to the coverage of AIS, as a recent estimation of nondeclared fishing revealed that one-third of vessels operating at high seas did not use AIS (*38*). Moreover, vessels involved in illegal activities probably hide their positions permanently or while fishing certain areas of the ocean or might modify their AIS identifier, making it difficult to extract their real trajectory (*39*). Hence, the estimates of fishing effort in the high seas reported here represent underestimates, and the delineation of high seas provinces and harbors supporting the vessels operating in those areas may be biased if vessels not reporting their position using AIS are concentrated in a particular region of the ocean and/or operate from specific supporting harbors. Our results are also based on classifying the activity of the vessels as fishing or cruising based on speed, but yield consistent results with those of other classifications based on machine learning (r^2 = 0.903; fig. S2) (*30*, *32*). The flow of fish may be affected by transshipment at sea (*40*, *41*), which will be reflected as errors in the assignment of fishing effort to different ports. The vessels catching 40% of fish in the high seas in the period 2012–2017 had at least one encounter with a transshipment vessel (*40*). Our results refer to 2014, but although the estimations of fishing effort grew between 2012 and 2016 due to the higher penetration of AIS (fig. S13), the distribution among the 14 provinces remains stable (fig. S14). This allows us to, according to the trajectories data in 2014, define the weights between fishing provinces in the high seas and the harbors and use these weights to distribute the effort from fishing provinces to harbors, reproducing the global fishing network for the latest available dataset (fishing effort on 2016) (figs. S15 and S16) (*30*). We observe that the distribution of fishing effort among different regions in the high seas displays higher fluctuations across seasons than across different years (fig. S14) (*42*, *43*), such that the aggregation of the data describing fishing vessels' trajectories along a whole year provides a global understanding of worldwide fishing in the high seas.

The machine learning classified data have been used to characterize the economics of fishing at high seas, finding that the high seas fishing effort is distributed among a hierarchy of countries according to the vessels' flag (*44*). However, we find substantial differences when we group harbors by countries. For example, if we compare the ranking of fishing by countries according to their flag (*44*) and according to the support their harbors provide to vessels contributing to fishing effort in the high seas, only Spain, Japan, and Indonesia are included in the top 10 in both rankings. In contrast, Peru, France (through harbors located in French Polynesia), and Uruguay, which we identified in the top 10 countries whose harbors support the highest fishing effort in the high seas, are absent in assessments based on the flags of the vessels (*44*), implying that the flag alone does not provide enough information for a global description of the process and, specifically, where the fish caught may

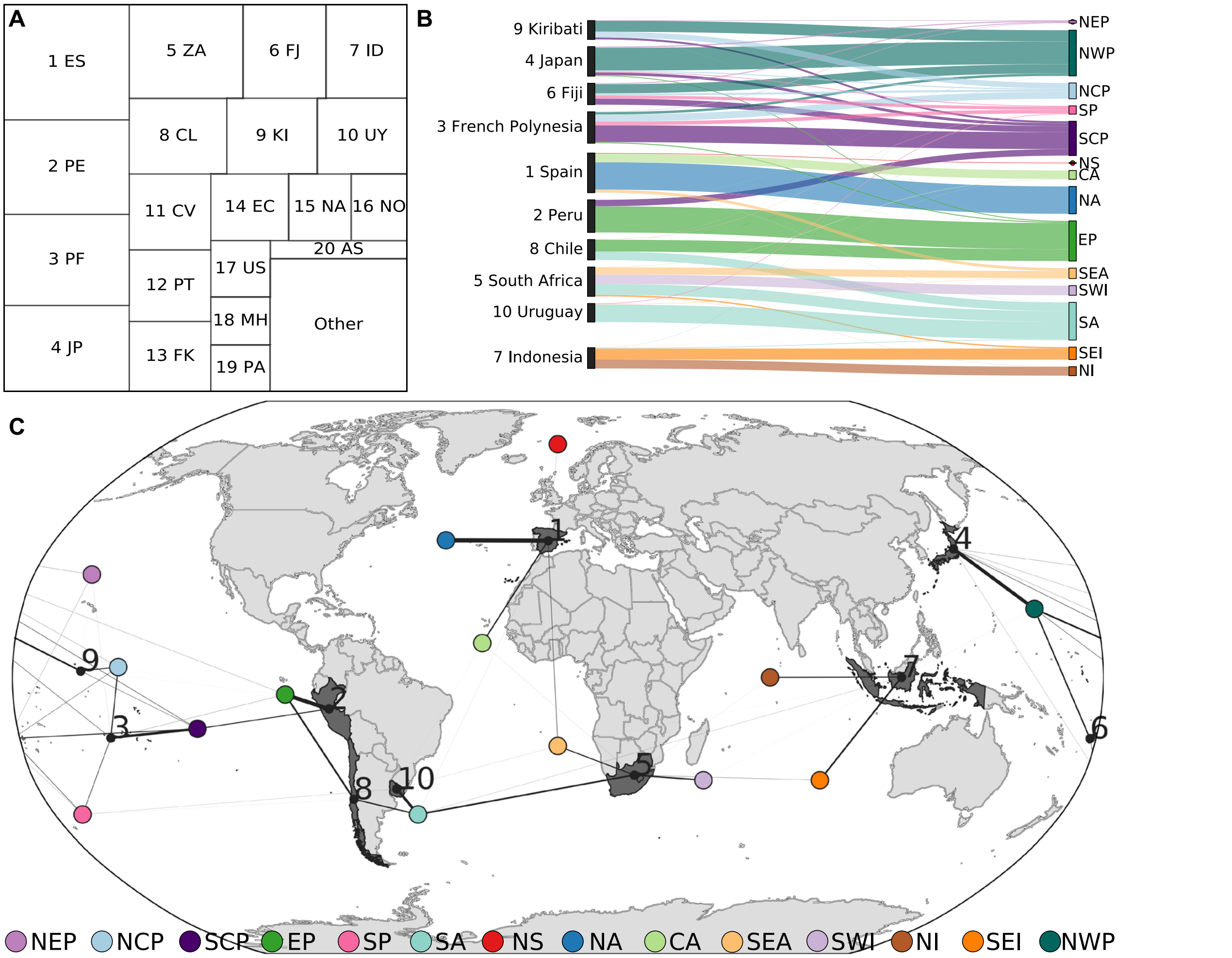

Fig. 4. Distribution of fishing effort in high seas among the countries supporting it. (**A**) Area plot depicting the fraction of the global fishing effort supported by each of the 88 countries with at least one harbor supporting fishing effort at the high seas, specifying the acronyms of the top 20 nations (ES: Spain, PE: Peru, PF: French Polynesia, JP: Japan, ZA: South Africa, FJ: Fiji, ID: Indonesia, CL: Chile, KI: Kiribati, UY: Uruguay, CV: Cape Verde, PT: Portugal, FK: Falkland Islands, EC: Ecuador, NA: Namibia, NO: Norway, US: United States, MH: Marshall Islands, PA: Panama, AS: American Samoa). (**B**) Network between the top 10 countries (left) and fishing provinces (right). Each link groups the effort of the harbors located in each country, and the width is proportional to the fishing effort. (**C**) Geographical distribution of the links between the top 10 countries [colored in dark gray and ranked according to (A)] and the 14 fishing provinces in the high seas (represented by colored dots). Lines link countries to the fishing provinces, with their thickness being proportional to the fishing efforts associated with each link.

be landed. In addition, corporations that fish in the high seas are other important actors that provide a complementary perspective (*45*). Accordingly, we suggest considering at least both the flag and the geographical location of the supporting harbors in future assessments. This result highlights the role of low- and middle-income countries as hubs for fishing in the high seas, supporting fishing vessels with other countries' flags (*44*), suggesting opportunities for new strategies to partner with these nations to improve inspection, monitoring, and management of a significant fraction of high seas fisheries.

The high seas represent approximately 64% of the global ocean surface, but our analysis shows that the catches are concentrated in 14 distinct fishing provinces, rather than being randomly distributed across this area. The top harbors supporting high seas fisheries are adjacent to some of the most productive fisheries, for example, Argentina, Peru, and Ecuador, but also in tropical locations, such as Cape Verde islands, and, remarkably, in Galicia, Spain (Fig. 3A; the complete list of harbors is reported in table S1 and fig. S10). The proximity to harbors, which provide the logistic and commercial support to fishing vessels, provides an important element structuring the fishing network in the high seas, similar to other transport networks, such as the worldwide air transportation network (*46*) and the cargo shipping network (*47*). The modularity in the connections between ports and fishing areas in the high seas represents the likelihood of vessels to fish in the most proximal areas beyond national jurisdiction. This indicates that an extension of the EEZs would reduce the fishing effort associated with these locations while also reducing the free-riding behavior associated with fishing along the EEZ boundary. However, the management of fisheries within EEZs presents highly contrasting effectiveness (*48*), leading to a decline in fish stocks in poorly managed EEZs (*49*).

The results presented provide evidence of how high seas fisheries are structured, identifying 14 hot spot provinces of high seas fisheries along with strips along the outer edge of EEZs supporting rich fisheries, which are characteristically exploited by vessels using different harbors for logistic and commercial support. Targeting these harbors for monitoring and inspections, with the help of international treaties involving the corresponding nations, can help, therefore, regulate high seas fisheries. Our analysis also shows evidence for free-riding behavior by fishing vessels exploiting fish stocks at the edge of EEZs. This behavior potentially undermines the efforts of nations to sustainably manage fish stocks, as these efforts are diluted and the fish stocks are jeopardized. Fish trespass the boundaries of the EEZs, which are entirely arbitrary and inconsistent with the movement and home ranges of fish stocks. A plausible mechanism to fight the tragedy of the commons in this context might come from game theory and the role of diversity of the agents (*50*–*52*), which can be leveraged by penalizing first the agents that are most probable to cooperate, which, in this case, are the countries with smaller economies (*50*). The network on high seas fishing reported here provides a foundation to inform fisheries regulation in the high seas, which is a major focus of the ongoing UN Intergovernmental Conference to reach a new legally binding treaty to protect marine life in the high seas by 2020.

MATERIALS AND METHODS

Vessel tracking dataset

The fishing vessel data, consisting of raw data including trajectories, have been obtained from the AIS for the year 2014 from MarineTraffic (http://marinetraffic.com), under a commercial license. The whole dataset contains around 250M tracking entries, each one containing the following information: timestamp, latitude, longitude, International Maritime Organization (IMO) number of the vessel, name of the vessel, heading, speed, status, length, and breadth.

AIS was developed during the 1990s with the main objective of increasing shipping safety and traffic control. This system is a ship-to-ship and ship-to-shore messaging system sent without human intervention over marine Very High Frequency radio. On 31 December 2004, the International Maritime Organization (*53*), proposed a new rule in the International Convention for Safety of Life at Sea, establishing the obligation for seagoing vessels larger than 300 gross tonnage (GT) to carry AIS (*54*). Whereas the limit imposed by the treaty is of global compliance, Europe imposed more restrictive rules, requiring all fishing vessels with an overall length of more than 15 m to carry AIS (*54*).

Ports dataset

The list of ports is obtained from the World Port Index, which is freely available from the web page of the National Geospatial Intelligence Agency (https://msi.nga.mil/Publications/WPI). This database contains the geographical locations and characteristics of the main 3685 ports and terminals in the world. The complete list of harbors is reported in table S1 and fig. S11. We considered port locations as the grid cells (0.5°latitude × 0.5°longitude) that contain at least one port and are visited by at least one fishing vessel (296 locations).

Boundaries in the ocean datasets

The data on the boundaries of EEZs were downloaded from the Maritime Boundaries Geodatabase from the Flanders Marine Institute (*55*). They contain 282 records corresponding to the boundaries of EEZs. The data for the boundaries of the FAO of the UN were downloaded from the Geonetwork webpage of the FAO of the UN (*56*) and contained the boundaries of the 19 major regions that are used for statistical data gathering, management of fisheries, and jurisdictional purposes.

Preprocessing fishing vessel data

To avoid inconsistencies in the data, such as different vessels using the same ID, we considered as splitting points of trajectories those for which two consecutive tracking locations correspond to one of the following cases: (i) There are no reported positions for more than 1 day, and/or (ii) the distance between consecutive positions is larger than 2000 km (an apparent velocity of at least 2000 km/day). When we detected a pair of locations belonging to a splitting point, the former is analyzed as the end of a trajectory, and the latter is considered as the beginning of another independent trajectory.

Fishing effort and hot spot identification

We aggregate fishing events in high seas, which we identify as fishing points with speeds lower than 5 knots, on a regular grid of 0.5° in latitude and longitude and measure the time spent in each grid cell. The data with speeds higher than 5 knots are considered as cruising events. The fishing effort is estimated through the assignment of half of the time difference between two consecutive fishing events (not separated by any cruising event), belonging to the same trajectory, to the grid cell containing the first location, and the other half to the grid cell containing the second. The effort is then aggregated for all the vessels. This method for quantifying the fishing effort is statistically compatible with other methods that classify the locations according to the inference of stages, such as fishing or cruising, through artificial intelligence algorithms (fig. S2) (*32*). Fishing hot spots are then identified as the top 10% grid cells with the largest effort.

Clustering of fishing provinces

To cluster the locations into coherent hot spot areas, we built a network connecting the consecutively visited areas (grid cells classified as hotspots and ports). When a fishing vessel's trajectory connects consecutively first the area i and then the area j, the weight of the directed link from i to j is increased in one unit. Considering the whole recorded period for all the datasets, this method leads to a directed weighted network. Applying the community detection algorithm Infomap (*57*) to this network, we obtained several clusterization levels and selected that being most similar to the FAO zones (fig. S9). We compare a partition obtained from the global fishing network and the FAO zones with the Frobenius distance between the copresence matrices, whose entries are 1 for grid cells in the same partition or FAO zone and 0 otherwise.

Global fishing network

We detected sequences of fishing activities between two consecutive visits to two ports. Then, half of the fishing effort was associated with each of these two ports if they are identified. See fig. S17 for the different cases in the assignment of fishing effort to harbors. This association will be affected by transshipment (*40*, *41*), which we do not take into account here.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/7/9/eabe3470/DC1

REFERENCES AND NOTES

1. E. Ostrom, *Governing the Commons: The Evolution of Institutions for Collective Action* (Cambridge University Press, 1990).
2. S. F. McWhinnie, The tragedy of the commons in international fisheries: An empirical examination. *J. Environ. Econ. Manag.* **57**, 321–333 (2009).
3. I. K. Heidbrink, The oceans as the common property of mankind from early modern period to today. *Hist. Compass* **6**, 659–672 (2008).
4. G. Hardin, The tragedy of the commons. *Science* **162**, 1243 (1968).
5. F. Berkes, Fishermen, and 'the tragedy of the commons'. *Environ. Conserv.* **12**, 199–206 (1985).
6. D. J. McCauley, C. Jablonicky, E. H. Allison, C. D. Golden, F. H. Joyce, J. Mayorga, D. Kroodsma, Wealthy countries dominate industrial fishing. *Sci. Adv.* **4**, eaau2161 (2018).
7. W. Swartz, E. Sala, S. Tracey, R. Watson, D. Pauly, The spatial expansion and ecological footprint of fisheries (1950 to present). *PLOS ONE* **5**, e15143 (2010).
8. *FAO Yearbook of Fishery and Aquaculture Statistics*, (Fisheries and Aquaculture Department, Food and Agriculture Organization of the United Nations, Rome, 2010).
9. D. J. Agnew, J. Pearce, G. Pramod, T. Peatman, R. Watson, J. R. Beddington, T. J. Pitcher, Estimating the worldwide extent of illegal fishing. *PLOS ONE* **4**, e4570 (2009).
10. C. Costello, D. Ovando, T. Clavelle, C. K. Strauss, R. Hilborn, M. C. Melnychuk, T. A. Branch, S. D. Gaines, C. S. Szuwalski, R. B. Cabral, D. N. Rader, A. Leland, Global fishery prospects under contrasting management regimes. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 5125–5129 (2016).
11. J. Alder, U. R. Sumaila, Western Africa: A fish basket of Europe past and present. *J. Environ. Dev.* **13**, 156–178 (2004).
12. S. Miller, B. Nkuiya, Coalition formation in fisheries with potential regime shift. *J. Environ. Econ. Manag.* **79**, 189–207 (2016).
13. S. Cullis-Suzuki, D. Pauly, Failing the high seas: A global evaluation of regional fisheries management organizations. *Mar. Policy* **34**, 1036–1042 (2010).
14. E. Druel, K. M. Gjerde, Sustaining marine life beyond boundaries: Options for an implementing agreement for marine biodiversity beyond national jurisdiction under the United Nations Convention on the Law of the Sea. *Mar. Policy* **49**, 90–97 (2014).
15. T. J. Pitcher, W. W. Cheung, Fisheries: Hope or despair? *Mar. Pollut. Bull.* **74**, 506–516 (2013).
16. N. Queiroz, N. E. Humphries, A. Couto, M. Vedor, I. Da Costa, A. M. M. Sequeira, G. Mucientes, A. M. Santos, F. J. Abascal, D. L. Abercrombie, K. Abrantes, D. Acuña-Marrero, A. S. Afonso, P. Afonso, D. Anders, G. Araujo, R. Arauz, P. Bach, A. Barnett, D. Bernal, M. L. Berumen, S. B. Lion, N. P. A. Bezerra, A. V. Blaison, B. A. Block, M. E. Bond, R. Bonfil, R. W. Bradford, C. D. Braun, E. J. Brooks, A. Brooks, J. Brown, B. D. Bruce, M. E. Byrne, S. E. Campana, A. B. Carlisle, D. D. Chapman, T. K. Chapple, J. Chisholm, C. R. Clarke, E. G. Clua, J. E. M. Cochran, E. C. Crochelet, L. Dagorn, R. Daly, D. D. Cortés, T. K. Doyle, M. Drew, C. A. J. Duffy, T. Erikson, E. Espinoza, L. C. Ferreira, F. Ferretti, J. D. Filmalter, G. C. Fischer, R. Fitzpatrick, J. Fontes, F. Forget, M. Fowler, M. P. Francis, A. J. Gallagher, E. Gennari, S. D. Goldsworthy, M. J. Gollock, J. R. Green, J. A. Gustafson, T. L. Guttridge, H. M. Guzman, N. Hammerschlag, L. Harman, F. H. V. Hazin, M. Heard, A. R. Hearn, J. C. Holdsworth, B. J. Holmes, L. A. Howey, M. Hoyos, R. E. Hueter, N. E. Hussey, C. Huveneers, D. T. Irion, D. M. P. Jacoby, O. J. D. Jewell, R. Johnson, L. K. B. Jordan, S. J. Jorgensen, W. Joyce, C. A. K. Daly, J. T. Ketchum, A. P. Klimley, A. A. Kock, P. Koen, F. Ladino, F. O. Lana, J. S. E. Lea, F. Llewellyn, W. S. Lyon, A. M. Donnell, B. C. L. Macena, H. Marshall, J. D. M. Allister, R. M. Auley, M. A. Meÿer, J. J. Morris, E. R. Nelson, Y. P. Papastamatiou, T. A. Patterson, C. Peñaherrera-Palma, J. G. Pepperell, S. J. Pierce, F. Poisson, L. M. Quintero, A. J. Richardson, P. J. Rogers, C. A. Rohner, D. R. L. Rowat, M. Samoilys, J. M. Semmens, M. Sheaves, G. Shillinger, M. Shivji, S. Singh, G. B. Skomal, M. J. Smale, L. B. Snyders, G. Soler, M. Soria, K. M. Stehfest, J. D. Stevens, S. R. Thorrold, M. T. Tolotti, A. Towner, P. Travassos, J. P. Tyminski, F. Vandeperre, J. J. Vaudo, Y. Y. Watanabe, S. B. Weber, B. M. Wetherbee, T. D. White, S. Williams, P. M. Zárate, R. Harcourt, G. C. Hays, M. G. Meekan, M. Thums, X. Irigoien, V. M. Eguiluz, C. M. Duarte, L. L. Sousa, S. J. Simpson, E. J. Southall, D. W. Sims, Global spatial risk assessment of sharks under the footprint of fisheries. *Nature* **572**, 461–466 (2019).
17. T. D. White, F. Ferretti, D. A. Kroodsma, E. L. Hazen, A. B. Carlisle, K. L. Scales, S. J. Bograd, B. A. Block, Predicted hotspots of overlap between highly migratory fishes and industrial fishing fleets in the northeast Pacific. *Sci. Adv.* **5**, eaau3761 (2019).
18. B. Worm, T. A. Branch, The future of fish. *Trends Ecol. Evol.* **27**, 594–599 (2012).
19. C. Duarte, S. Agusti, E. Barbier, G. Britten, J. Castilla, J.-P. Gattuso, R. W. Fulweiler, T. P. Hughes, N. Knowlton, C. E. Lovelock, H. K. Lotze, M. Predragovic, E. Poloczanska, C. Roberts, B. Worm, Rebuilding marine life. *Nature* **580**, 39–51 (2020).
20. G. R. Munro, A. Van Houtte, R. Willmann, *The Conservation and Management of Shared Fish Stocks: Legal and Economic Aspects* (Food and Agriculture Organization, 2004), vol. 465.
21. N. Ramesh, J. A. Rising, K. L. Oremus, The small world of global marine fisheries: The cross-boundary consequences of larval dispersal. *Science* **364**, 1192–1196 (2019).
22. G. R. Munro, Internationally shared fish stocks, the high seas, and property rights in fisheries. *Mar. Resour. Econ.* **22**, 425–443 (2007).
23. D. J. McCauley, P. Woods, B. Sullivan, B. Bergman, C. Jablonicky, A. Roan, M. Hirshfield, K. Boerder, B. Worm, Ending hide and seek at sea. *Science* **351**, 1148–1150 (2016).
24. B. Ristic, B. La Scala, M. Morelande, N. Gordon, Statistical analysis of motion patterns in AIS data: Anomaly detection and motion prediction, in *2008 11th International Conference on Information Fusion* (IEEE, 2008) pp. 1–7.
25. V. M. Eguíluz, J. Fernández-Gracia, X. Irigoien, C. M. Duarte, A quantitative assessment of Arctic shipping in 2010–2014. *Sci. Rep.* **6**, 30682 (2016).
26. P. Last, C. Bahlke, M. Hering-Bertram, L. Linsen, Comprehensive analysis of Automatic Identification System (AIS) data in regard to vessel movement prediction. *J. Navigation* **67**, 791–809 (2014).
27. M. Robards, G. Silber, J. Adams, J. Arroyo, D. Lorenzini, K. Schwehr, J. Amos, Conservation science and policy applications of the marine vessel Automatic Identification System (AIS)– a review. *Bull. Mar. Sci.* **92**, 75–103 (2016).
28. D. C. Dunn, C. Jablonicky, G. O. Crespo, D. J. McCauley, D. A. Kroodsma, K. Boerder, K. M. Gjerde, P. N. Halpin, Empowering high seas governance with satellite vessel tracking data. *Fish Fish.* **19**, 729–739 (2018).
29. S. Jennings, J. Lee, Defining fishing grounds with vessel monitoring system data. *ICES J. Mar. Sci.* **69**, 51–63 (2012).
30. D. A. Kroodsma, J. Mayorga, T. Hochberg, N. A. Miller, K. Boerder, F. Ferretti, A. Wilson, B. Bergman, T. D. White, B. A. Block, P. Woods, B. Sullivan, C. Costello, B. Worm, Tracking the global footprint of fisheries. *Science* **359**, 904–908 (2018).
31. F. Natale, M. Gibin, A. Alessandrini, M. Vespe, A. Paulrud, Mapping fishing effort through AIS data. *PLOS ONE* **10**, e0130746 (2015).
32. E. N. de Souza, K. Boerder, S. Matwin, B. Worm, Improving fishing pattern detection from satellite AIS using data mining and machine learning. *PLOS ONE* **11**, e0158248 (2016).
33. S. Jentoft, B. J. McCay, D. C. Wilson, Social theory and fisheries co-management. *Mar. Policy* **22**, 423–436 (1998).
34. U. R. Sumaila, V. W. Lam, D. D. Miller, L. Teh, R. A. Watson, D. Zeller, W. W. L. Cheung, I. M. Côté, A. D. Rogers, C. Roberts, E. Sala, D. Pauly, Winners and losers in a world where the high seas is closed to fishing. *Sci. Rep.* **5**, 8481 (2015).
35. L. Schiller, M. Bailey, J. Jacquet, E. Sala, High seas fisheries play a negligible role in addressing global food security. *Sci. Adv.* **4**, eaat8351 (2018).
36. J. Palacios-Abrantes, G. Reygondeau, C. C. Wabnitz, W. W. Cheung, The transboundary nature of the world's exploited marine species. *Sci. Rep.* **10**, 17668 (2020).
37. M. J. Juan-Jordá, I. Mosqueira, A. B. Cooper, J. Freire, N. K. Dulvy, Global population trajectories of tunas and their relatives. *Proc. Natl. Acad. Sci. U.S.A.* **108**, 20650–20655 (2011).
38. H. Weimerskirch, J. Collet, A. Corbeau, A. Pajot, F. Hoarau, C. Marteau, D. Filippi, S. C. Patrick, Ocean sentinel albatrosses locate illegal vessels and provide the first estimate of the extent of nondeclared fishing. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 3006–3014 (2020).
39. J. H. Ford, D. Peel, D. Kroodsma, B. D. Hardesty, U. Rosebrock, C. Wilcox, Detecting suspicious activities at sea based on anomalies of automatic identification system transmissions. *PLOS ONE* **13**, e0201640 (2018).
40. K. Boerder, N. A. Miller, B. Worm, Global hotspots of transshipment of fish catch at sea. *Sci. Adv.* **4**, eaat7159 (2018).
41. N. A. Miller, A. Roan, T. Hochberg, J. Amos, D. A. Kroodsma, Identifying global patterns of transshipment behavior. *Front. Mar. Sci.* **5**, 240 (2018).
42. J. Guiet, E. Galbraith, D. Kroodsma, B. Worm, Seasonal variability in global industrial fishing effort. *PLOS ONE* **14**, e0216819 (2019).
43. G. O. Crespo, D. C. Dunn, G. Reygondeau, K. Boerder, B. Worm, W. Cheung, D. P. Tittensor, P. N. Halpin, The environmental niche of the global high seas pelagic longline fleet. *Sci. Adv.* **4**, eaat3681 (2018).
44. E. Sala, J. Mayorga, C. Costello, D. Kroodsma, M. L. Palomares, D. Pauly, U. R. Sumaila, D. Zeller, The economics of fishing the high seas. *Sci. Adv.* **4**, eaat2504 (2018).
45. G. Carmine, J. Mayorga, N. A. Miller, J. Park, P. N. Halpin, G. Ortuño Crespo, H. Österblom, E. Sala, J. Jacquet, Who is the high seas fishing industry? *One Earth* **3**, 730–738 (2020).
46. R. Guimerà, S. Mossa, A. Turtschi, L. N. Amaral, The worldwide air transportation network: Anomalous centrality, community structure and cities' global roles. *Proc. Natl. Acad. Sci. U.S.A.* **102**, 7794–7799 (2005).
47. P. Kaluza, A. Kölzsch, M. T. Gastner, B. Blasius, The complex network of global cargo ship movements. *J. R. Soc. Interface* **7**, 1093–1103 (2010).
48. C. Mora, R. A. Myers, M. Coll, S. Libralato, T. J. Pitcher, R. U. Sumaila, D. Zeller, R. Watson, K. J. Gaston, B. Worm, Management effectiveness of the world's marine fisheries. *PLoS Biol.* **7**, e1000131 (2009).
49. U. T. Srinivasan, R. Watson, U. R. Sumaila, Global fisheries losses at the exclusive economic zone level, 1950 to present. *Mar. Policy* **36**, 544–549 (2012).
50. S. Johnson, Escaping the tragedy of the commons through targeted punishment. *R. Soc. Open Sci.* **2**, 150223 (2015).
51. M. C. V. Perc, A. Szolnoki, Social diversity and promotion of cooperation in the spatial prisoner's dilemma game. *Phys. Rev. E* **77**, 011904 (2008).

52. F. C. Santos, F. L. Pinheiro, T. Lenaerts, J. M. Pacheco, The role of diversity in the evolution of cooperation. *J. Theor. Biol.* **299**, 88–96 (2012).
53. IMO, *International Maritime Organization* (2018).
54. European Union. Directive 2002/59/ec of the European Parliament and of the council community vessel traffic monitoring and information system. 2014/100/eu (2014).
55. S. Claus, N. De Hauwere, B. Vanhoorne, F. Souza Dias, P. Oset García, F. Hernandez, J. Mees, *Flanders Marine Institute* (2018); www.marineregions.org.
56. FAO, FAO Statistical Areas for Fishery Purposes, in *FAO Fisheries and Aquaculture Department [online]* (Rome, 2019); www.fao.org/fishery/area/search/en [accessed Feb 2020].
57. D. Edler, A. Eriksson, M. Rosvall, *The Mapequation Software Package* (2018); mapequation.org.

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