APPLIED ECOLOGY

Global hot spots of transshipment of fish catch at sea

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A major challenge in global fisheries is posed by transshipment of catch at sea from fishing vessels to refrigerated cargo vessels, which can obscure the origin of the catch and mask illicit practices. Transshipment remains poorly quantified at a global scale, as much of it is thought to occur outside of national waters. We used Automatic Identification System (AIS) vessel tracking data to quantify spatial patterns of transshipment for major fisheries and gear types. From 2012 to 2017, we observed 10,510 likely transshipment events, with trawlers (53%) and longliners (21%) involved in a majority of cases. Trawlers tended to transship in national waters, whereas longliners did so predominantly on the high seas. Spatial hot spots were seen off the coasts of Russia and West Africa, in the South Indian Ocean, and in the equatorial Pacific Ocean. Our study highlights novel ways to trace seafood supply chains and identifies priority areas for improved trade regulation and fisheries management at the global scale.

INTRODUCTION

Seafood is the world's most traded food commodity, with global exports worth more than US$148 billion in 2014 (*1*). The vast majority of fish and shellfish (78%) is processed and traded internationally through complex supply chains that connect fishing vessels with individual consumers (*1*). Most of the global catch estimated at 100 million metric tons year^{-1} (*2*) is landed directly by fishing vessels in port, particularly from vessels that operate closer to the coast and in national waters. However, larger fishing vessels and those fishing further offshore and on the high seas often offload catch to refrigerated cargo vessels ("reefers") instead while often also being resupplied with food, water, bait, crew, and fuel; this common practice is known as transshipment of catch at sea (hereafter referred to as "transshipment").

It has been previously reported that most of the species subject to transshipment are high seas–related species such as tuna, sharks, and billfishes (*3*), but other species including groundfish, salmon, and crustaceans also get transshipped in both national and international waters (*4*). Transshipment increases the efficiency of fishing by eliminating trips back to port for fishing vessels while maintaining product quality, but it can also obscure the origin of the catch and may or may not be legal, depending on local regulations (*5*). Thus, transshipment can be problematic from a regulatory, business, or consumer perspective because it decreases transparency; it may also facilitate human-rights abuses and has been implicated in other crimes such as weapon and drug trafficking (*4*, *6*). The situation is further complicated by the fact that transshipment often occurs in regions of unclear jurisdiction where policy-makers and enforcement agencies may be slow to act against a challenge that they cannot see.

Transshipment is also thought to be a factor in enabling illegal, unreported, and unregulated (IUU) fishing, which is a global problem, extracting an estimated 11 to 26 million metric tons from the oceans each year (*2*, *7*). In addition to incurring an annual revenue loss of US$10 billion to US$23.5 billion for legal fisheries, IUU fishing undermines fisheries management and conservation efforts and contributes to global overfishing (*7*). It has been estimated that about a quarter to a third of all wild-caught seafood imports into major markets, such as the United States and Japan, could have been caught illegally (*8*, *9*). Vessels transshipping part of their catch at sea or the mixing of catches from several fishing vessels from different regions can obscure the traceability of seafood through the supply chain and introduce IUU catch into the global market under false labeling. The United Nation's Food and Agriculture Organization (FAO) acknowledged this possible link between transshipment and IUU and developed guidelines and procedures for transshipment at sea to minimize illegal activities (*10*). In addition, FAO launched an international plan of action to prevent, deter, and eliminate IUU fishing, calling on flag states to improve monitoring and control of transshipments or to prohibit it entirely (*11*). To date, transshipment is individually regulated by coastal and flag states and by Regional Fisheries Management Organizations (RFMOs). Some RFMOs, especially concerned about the laundering of high-value species such as tuna, restrict transshipment to ports (*12*), prohibit certain fishing vessels from transshipping, or require onboard observers to be present (*13*).

With increasing global demand for better seafood supply chain transparency and traceability, transshipment has become an important yet poorly quantified focal point in the international trade of seafood. This can be addressed and resolved if each transshipment event is monitored and documented appropriately. New tools have emerged lately with the application of machine learning technology to analyze vessel tracks on the basis of satellite-based Automatic Identification System (AIS) data, tracking the behavior of fishing vessels at a global scale and even in remote waters (*14*, *15*). Recently, researchers at Global Fishing Watch have expanded these methods to analyze the behavior of reefers, making it possible to detect and monitor transshipment at sea (*16*, *17*).

Here, we build and extend on this method to map and better understand the extent, spatial distribution, and role of transshipment for different fleets, gear types, and supply chains at a global scale. Using AIS data, we ask where and when transshipment occurs, which fisheries and fleets are most involved in this practice, and what proportion of high-seas catch is transshipped versus landed directly. We also apply this methodology to trace detailed seafood supply chains for tuna fisheries in the Indo-Pacific.

RESULTS

Likely transshipment events (fishing vessel–reefer encounters at sea detected from AIS positions of vessels within 500 m of each other and lasting longer than 2 hours, traveling at less than 2 knots while at least 10 km from shore, hereafter called "encounters") were identified from

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22 billion individual AIS position signals where AIS data were available for both the reefer and fishing vessel engaged in the encounter (Fig. 1). AIS messages provide detailed information on vessel identity and behavior and have become more widely available since 2012 (*14*, *15*). Novel machine learning algorithms allowed us to automatically detect and map encounters between fishing and refrigerated cargo vessels at sea. Using a subset of the global database developed by Global Fishing Watch (*17*) including AIS tracks from both reefers and fishing vessels, we quantified the spatial distribution of encounters between fishing vessels (focusing on four major gear types) and refrigerated cargo vessels and estimated the fishing effort (in hours spent fishing) as a proxy for the catch that was accumulated between encounters or port calls (see Materials and Methods below for more details). Between 2012 and the end of 2017, we observed 501 reefers meeting up with 1856 fishing vessels in 10,510 likely transshipment events worldwide. The refrigerated cargo vessels involved comprise a variety of types, including fish carriers, fish processors, and a small number of fish tenders.

Together, 35% of all observed transshipment encounters occurred on the high seas, while 65% took place within exclusive economic zones (EEZs) where most global fishing occurs (*15*). A large fraction (39%) of all detected encounters occurred in the Russian EEZ, with the remainder (61%) spread over 41 other nations' EEZs. Excluding Russia, 57% of likely encounters took place on the high seas.

Fishing vessels engaged in transshipping were mostly trawlers (53%) and longliners (21%), the former being more active in shallow continental shelf waters, the latter concentrating on the high seas. Squid jiggers (13%), fishing vessels using pots and traps (7%), and purse seiners (1.2%) contributed less to global transshipment events detected from AIS data.

Transshipping from trawlers was most common in EEZs in the Northern Hemisphere, most notably in Russian waters, whereas most

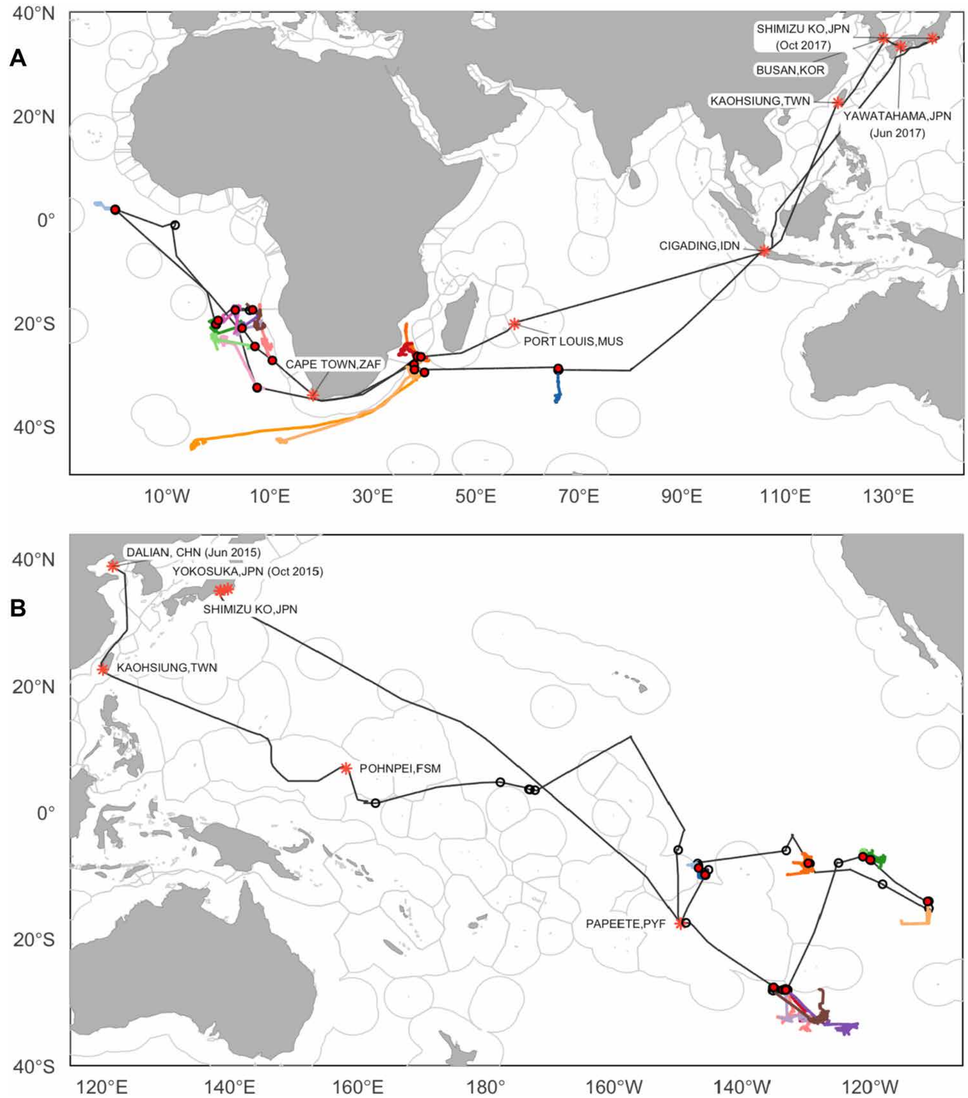

Fig. 1. Transshipment of catch at sea. Example AIS tracks of reefer (black) and fishing vessels (colors), port calls (asterisks), likely transshipment encounters (red circles), and potential encounters (white circle) in the (**A**) Atlantic and (**B**) Pacific are shown. EEZs are outlined in light gray. Note that tracking data for fishing vessels are missing for some likely encounters, but reefers exhibited behavior consistent to an encounter.

of the transshipments from longliners, purse seiners, and squid jiggers occurred on the high seas, with hot spots off West Africa, in the South Indian Ocean, and the equatorial Pacific (Fig. 2).

The average duration of likely transshipment events identified in the AIS data was 11.6 hours (median, 7.3 hours), which is close to the 9.5 hours reported in transshipment documentation (see below). Fishing vessels transshipped their catch to a reefer roughly once a month. Most reefers traveled to meet the fishing vessels at or close to the fishing grounds (Fig. 1), whereas fishing vessels only traveled relatively short distances (mean distance, 122 km; median distance, 42 km) to meet a reefer.

For most of the time vessels spent fishing before meeting a reefer, they were located in EEZs (Fig. 3, A and B). Catch from more than three-quarters of all observed fishing in EEZs (86%) was landed directly, whereas only 14% was transshipped. Transshipment was much more prevalent on the high seas, with nearly half (45%) of catch from observed fishing effort on the high seas being transshipped (Fig. 3). In EEZs, trawlers predominated landings and transshipment events, whereas on the high seas, longline fishing dominated both in terms of landed and transshipped catch, followed by squid jiggers (Table 1 and Fig. 4). Trawlers predominantly fished and transshipped in Northern Hemisphere temperate waters, whereas longliners operated globally in tropical and subtropical waters, and squid jiggers were observed in international waters along the EEZs of South American countries both in the Pacific and Atlantic (Fig. 2).

A fishing vessel's voyage may be broken into three segment types of varying durations. For short daily fishing trips, the entire voyage might be characterized by the segment of time between two anchorages (docking in port or anchoring nearby). Longer trips, which include likely transshipment encounters, can be divided into additional segments such as the time between an anchorage and an encounter at sea or the time between two sequential encounters. Excluding the upper and lower 5% of the data to eliminate implausible outliers caused by data gaps (fig. S1), we found that fishing vessels that undertook voyages characterized solely by an anchorage exit and a return (no transshipment involved) spent about 18 days at sea (median, 6 days) and fished about 46 hours (median, 23.5 hours). Short coastal fishing trips with vessels returning to port every day influence this estimate. For fishing vessels engaging in transshipment, we found that the time between an anchorage exit and a fishing vessel's first likely transshipment encounter was about 50 days (median, 37 days), during which time the vessel fished for an average of 100 hours (median, 74 hours). Between transshipment encounters, we found that fishing vessels met with a reefer about every 31 days (median, 19.5 days) and fished about 132 hours (median, 135.5 hours). The longer time between anchorages and first transshipment encounters is likely due to the time fishing vessels spent traveling to their fishing grounds and the fact that some encounters are not identified because of missing AIS signals (lack of satellite coverage and/or switching off of AIS transponder).

Of 33 flag states observed to operate reefers, Russia accounted for almost a third (32%), followed by Panama (20%) and Liberia (7%), the latter two representing so-called flags of convenience (FoCs), flags of states characterized by loose regulation and limited oversight (fig. S2A). About 41% of all reefers were flagged to FoCs,

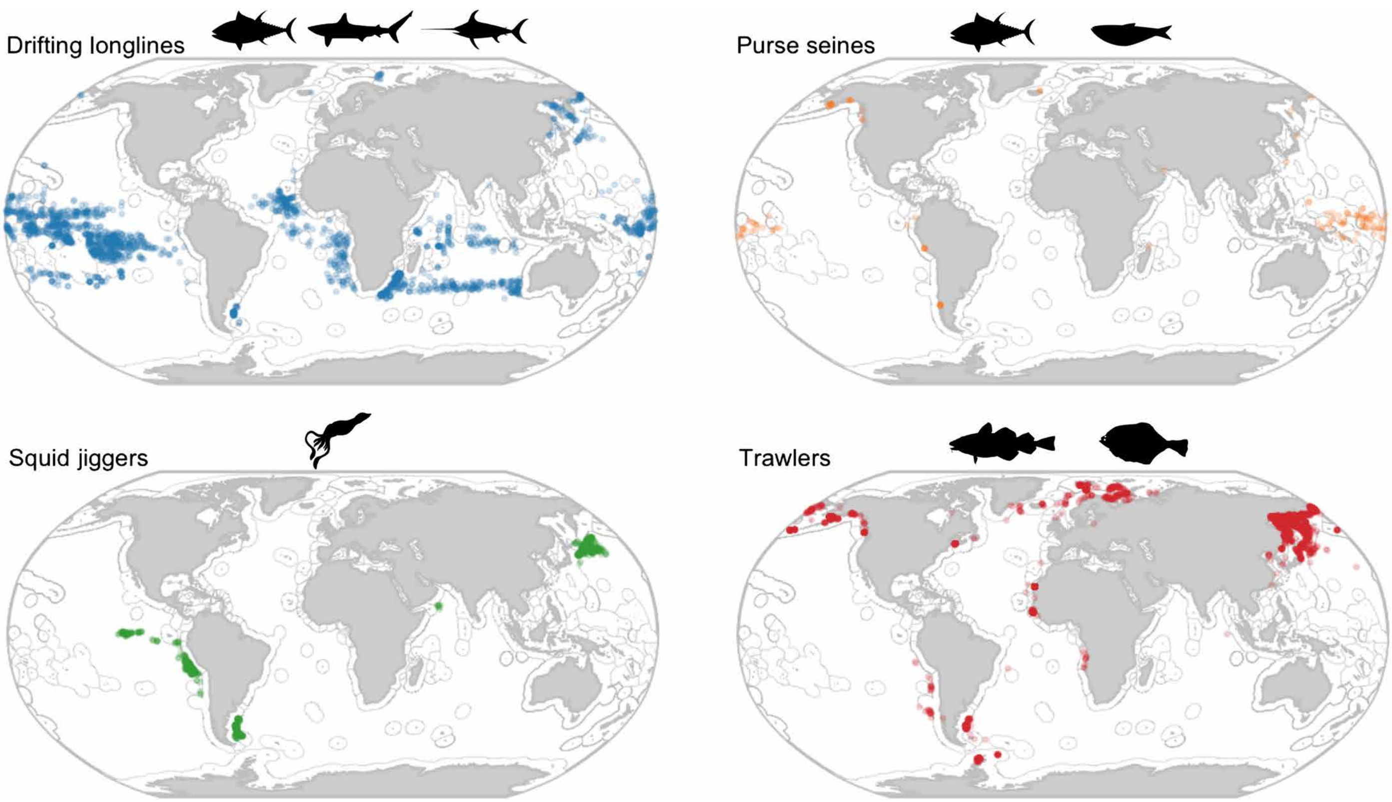

Fig. 2. Global patterns of transshipment for different fishing gears. All likely encounters (colored dots) between reefers and fishing vessels as identified from AIS data spanning 2012 to 2017 and separated by fishing gear type are shown. EEZs are outlined in light gray, and pictograms illustrate major target species.

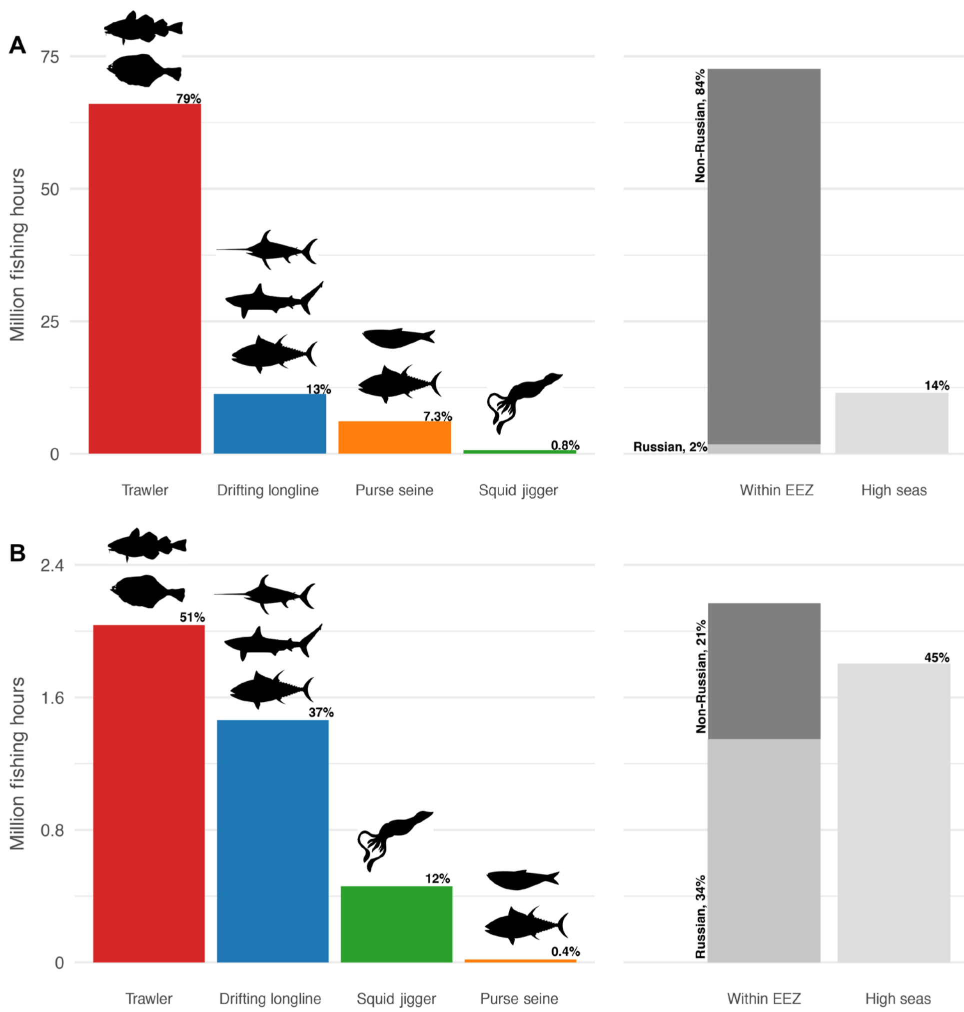

Fig. 3. Relative extent of transshipment for different types of fishing gear. The fishing effort (estimated fishing hours) that is (**A**) landed directly in port versus (**B**) transshipped and brought to port by reefer is shown. Data are separated by fishing gear type (left) and for EEZs versus the high seas. Data include fishing vessels that, at least once, have met up with a reefer. Gears represent more common gears used by fishing vessels involved in encounters. Pictograms denote major target species by gear type.

Table 1. Direct landing or transshipment of catch in EEZs versus the high seas. The percentages of fishing hours landed directly in port by fishing vessel or transshipped at sea and landed by reefer are shown. Data are separated by fishing gear and for EEZs and the high seas (HS; bold). Percentages are given for fishing in all EEZs and for the Russian EEZ separately because of outstanding importance of transshipment for Russian fleets.

	In EEZ				In HS	
	Landed directly (%)	Landed directly from Russian EEZ (%)	Transshipped (%)	Transshipped from Russian EEZ (%)	Landed directly (%)	Transshipped (%)
Trawler	84.3	97.9	81.2	97.2	**41.8**	**15.3**
Longliner	8.1	1.2	13.7	1.8	**47.0**	**64.5**
Purse seiner	7.1	0.5	0.6	0.06	**8.3**	**0.1**
Squid jigger	0.5	0.4	4.4	0.9	**2.9**	**20.1**

or 60% when excluding Russia. Fishing vessels from 47 nations were found to encounter those reefers and engage in a likely transshipment, again, a majority from Russia (26%), followed by China (20%) and Taiwan (15%) (fig. S2B). Encounters of fishing vessels with reefers flying FoCs were more prevalent on the high seas than in EEZs for all gear types, especially for squid jiggers (78% of all high-sea encounters compared to 27% within EEZs) and longliners (62% to 25%, respectively).

Testing for a correlation between the number of likely transshipment encounters and regional extent of IUU estimated for each FAO area (*7*), we found a weak positive but nonsignificant relationship ($P = 0.1626$) (fig. S3). FAO area 61 (Northwest Pacific) emerged as

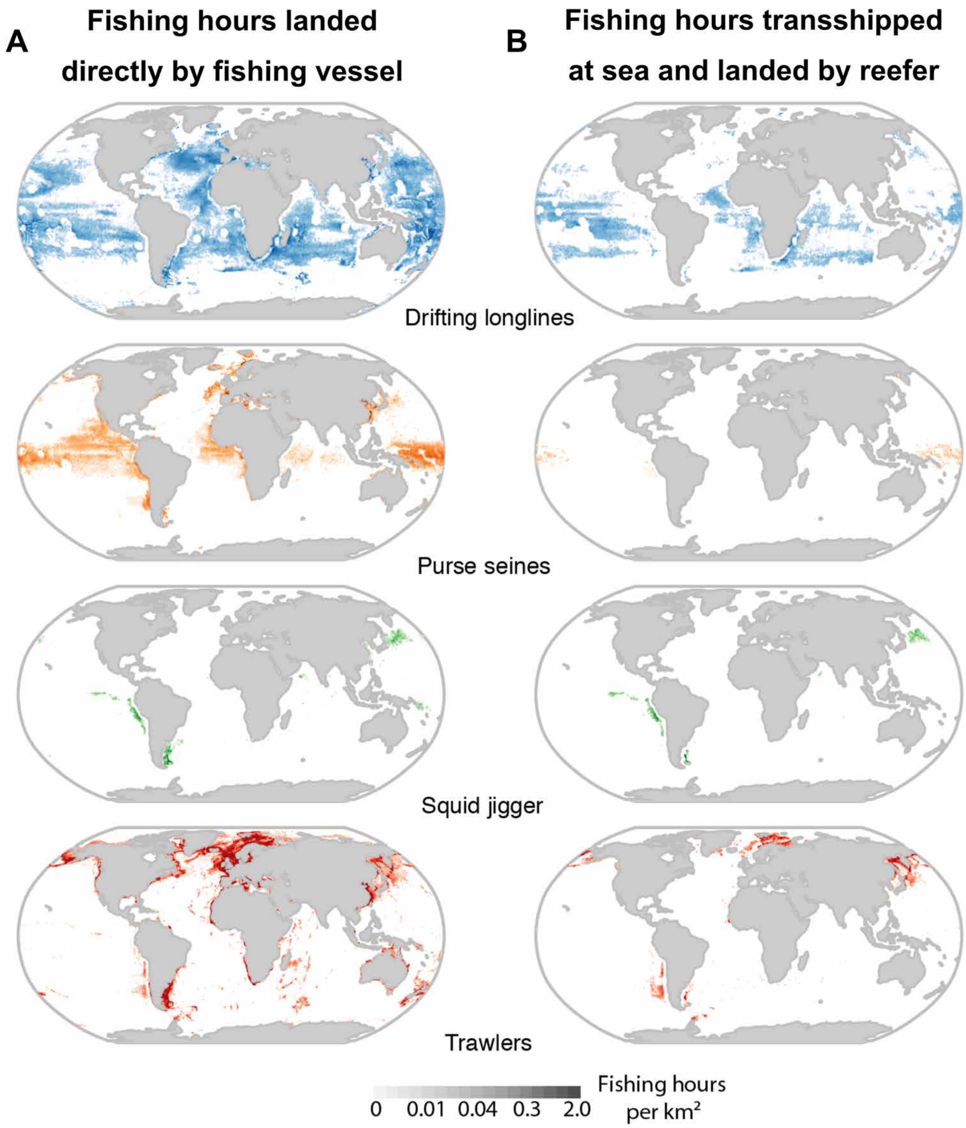

Fig. 4. Spatial patterns of landed versus transshipped fishing effort. The spatial distribution and intensity (fishing hours per square kilometer) of fishing effort for each gear type landed directly (**A**) by fishing vessel or (**B**) by reefer after transshipment at sea between 2012 and 2017 are shown.

a notable outlier of this analysis, with both a high percentage of IUU (33%) and by far the highest number of likely transshipment events (44% of total).

Tuna case study

On the basis of information provided from a tuna processor and retailer, we were able to reconstruct detailed supply chains for tuna transshipped to and landed by three reefers flagged to China, Taiwan, and Panama and operating in two of the global hot spots that we identified here: the south Indian Ocean and the equatorial Pacific (Fig. 5). These three vessels spent an average of 8 days (1 to 23 days) in port and about 50 days at sea (23 to 96 days, excluding short transits from port to port) and received an average amount of 57,500 kg of catch [mostly albacore tuna (*Thunnus alalunga*)] per transshipment from 16 fishing vessels flagged to either China or Taiwan. Of these fishing vessels, AIS data were available for 13 (Fig. 5). Using the transshipment location as noted in the reefer's documentation, we were able to match 7 of the 13 documented transshipment events to the AIS data used in this paper. For six events, it was not possible to identify a likely transshipment event (within a 100-km radius) from the AIS data.

On the basis of AIS tracks and industry documentation, we estimate that tracked tuna fishing vessels fished for about 2 to 3 weeks before meeting with a reefer to offload their catch. The reefer returned to port to land the transshipped catch about once a month, depending on the distance from port and the number of fishing vessels encountered. In processing facilities in or close to the port of landing, the whole fish was processed into loins and shipped in sealed containers to canning facilities, in this case located in the United States. This takes 4 to 8 weeks, depending on the location of the port. Reprocessing and canning happen over another 4 weeks with a subsequent distribution to retail within 2 to 12 weeks. It thus takes about half a year on average (18 to 35 weeks) from the catch of albacore tuna to the canned final product on the shelf. Along the entire supply chain, the fish have traveled an average 17,000 km (13,000 to 20,000 km, excluding traveling on the fishing boat and transport to final retail)

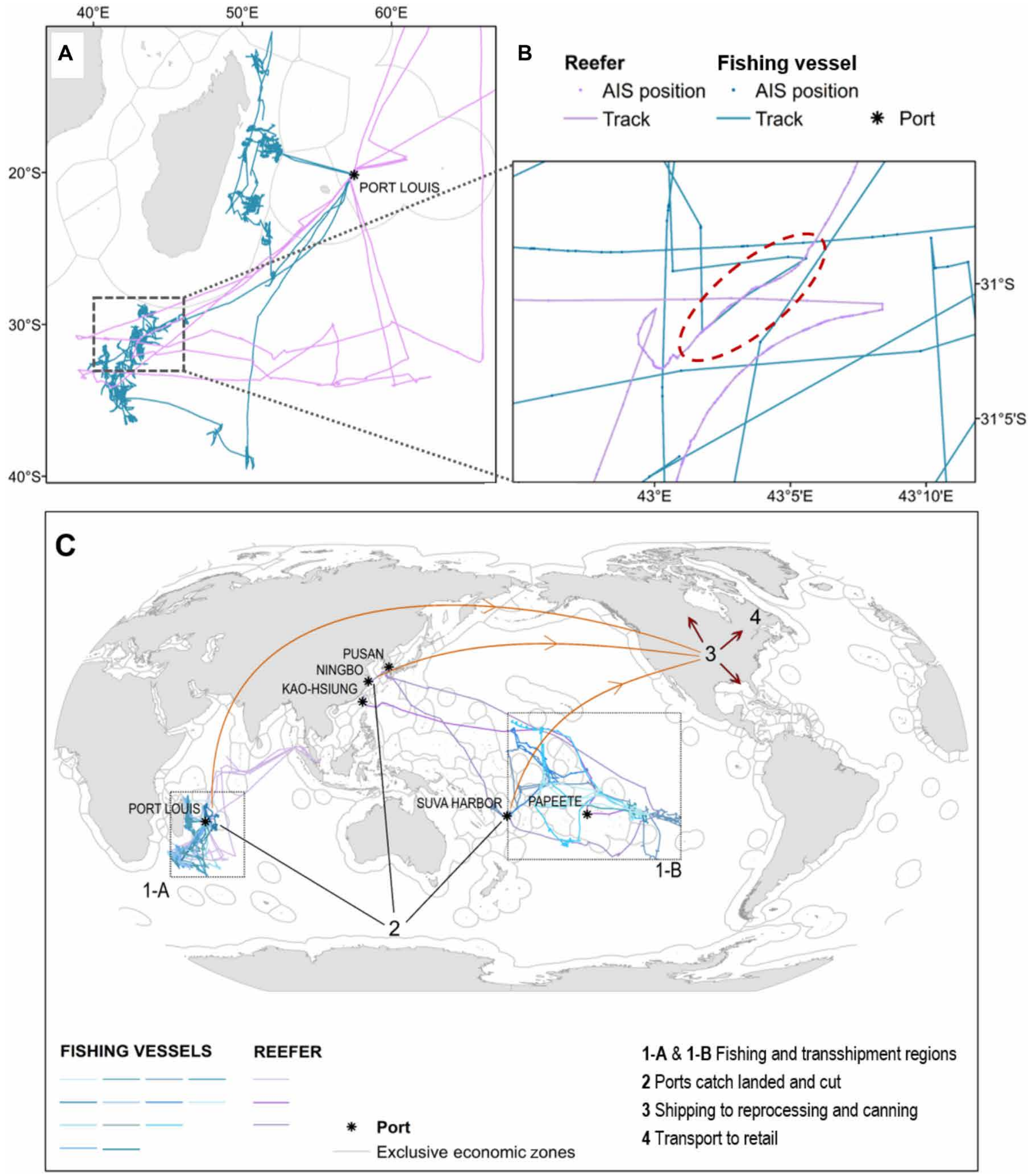

Fig. 5. Tuna case study. The path of albacore tuna from fishing location to retail shelf is shown. Reefer and fishing vessel tracks are in purple and blue, respectively, the area of fishing and transshipment is denoted by a dashed black rectangle, and EEZ boundaries are in light gray. (**A**) Fishing and transshipment off Mauritius, port call into Port Louis, (**B**) close-up of transshipment event (dashed red circle). (**C**) Tracks of three reefers and 13 fishing vessels from January 2017 to February 2018. (1-A) and (1-B) (dashed rectangles) denote fishing and transshipment areas, (2) ports (asterisks) where reefers landed whole fish and fish is cut, (3) transport to reprocessing and canning facilities, and (4) transport of final product to retail.

with about five discrete steps involved, including postproduction steps such as shipment of cans (Fig. 5).

DISCUSSION

In the last decade, transshipment of catch at sea has become a focal point in the international discussion surrounding seafood supply chain transparency, especially for fisheries operating in distant waters and featuring complex supply chains. Fish commonly pass from producers (individuals/companies operating fishing vessels) to fish brokers, who aggregate catches upon landing or transshipment to a reefer and arrange for sale to processors and distributors. Unsurprisingly, traceability of products becomes more complicated with increasing supply chain length, complexity, and levels of aggregation of catch. While fish landed directly in port by fishing vessels is usually documented by vessel before aggregation of catches from multiple sources, this documentation is less precise for catches transshipped at sea.

Here, we build on a global database of transshipment encounters developed by Global Fishing Watch (*16*, *17*), mapping empirical observations of transshipment at sea by gear and region and connecting it to supply chains to highlight the role, scale, and importance of transshipment in the global seafood trade. We found that, while transshipment is occurring in all oceans and across 42 EEZs (*16*), it is more common in distinct hot spot areas on the high seas (for example, south Indian Ocean and equatorial Pacific), in some EEZs (for example, off Russia and West Africa), for some gear types (trawlers and longliners), and involving few dominant states that flag a majority of reefers (Russia, Panama, and Liberia).

Transshipment is mostly seen close to fishing grounds (Fig. 2), as it is common practice for fish traders to arrange for the reefer to meet the fishing vessels. The distribution of transshipment activity and the types of fishing vessels transshipping catch depend on the nature, value, and volume of target species and can be useful indicators for fisheries managers to pinpoint areas and fisheries where monitoring and documentation should be enhanced.

Observed transshipment events within EEZs largely involved trawlers, likely fishing on the continental shelves for demersal- or coastal-pelagic species. As these fisheries generate high-volume catches, transshipment enables vessels with limited hold capacities to continue fishing. On the high seas, more than half (excluding Russia) likely transshipment events involved longline fishing vessels, presumably transshipping highly migratory species such as tuna, sharks, and billfishes (swordfish and marlins) (*3*, *18*). Few longline vessels have adequate deep-freezing facilities; thus, quick transshipment to reefers is essential to maintain high quality and market prices (*5*). This suggests that the type of catch (high volume or high value) and its location shape the infrastructure of the supply chain involved and thus can be an indicator which fisheries and supply chains might be the most susceptible to illicit activities surrounding transshipment, thus warranting closer monitoring, control, and surveillance.

Some fishing fleets rely heavily on the use of reefers regardless of the type of fishing. More than a third of all observed transshipments were conducted between Russian-flagged reefers and fishing vessels in the Russian EEZ and the Bering Sea, which are areas with poor monitoring of transshipment (*4*) and a history of illegal fishing. Russia's fishing fleet largely dates back to the Union of Soviet Socialist Republics, and struggling to meet targets set to close a gap in food supply after World War II, Soviet fishing fleets were restructured in the 1950s and 1960s to increase operation time and range (*19*, *20*). Fishing operations were centered around mother ships and fish carriers to supply the fishing fleet and process their catch (*20*); these historical developments may, in part, explain the importance of transshipment and the central role of reefers in Russian fisheries today (*16*). In addition, a strong link to the nearby Chinese market (57% of all fish imports to China come from Russia) further favors transshipment in Russian waters and under Russian flag (*9*). Relatively poor monitoring, low compliance, weak enforcement, and high levels of transshipment enable IUU fishing for Russian pollock, crab, and salmon, which are imported to the United States and Europe following reprocessing in China (*9*). These fisheries are contributing to high estimated prevalence of IUU (33%) in the Northwest Pacific (FAO area 61) (fig. S3) (*7*, *9*). However, the overall correlation between AIS-detected transshipment and estimated IUU fishing is weak (fig. S3), possibly owing to large uncertainties in quantifying both processes and a scale mismatch between localized transshipment observations and FAO-area IUU estimates. For improved analysis, more regional knowledge on IUU fishing is required.

No comprehensive global regulations or codes of conduct for transshipment exist. Next to regulations by RFMOs for their convention areas (see below), it is up to individual states to regulate transshipment within their own EEZ and for vessels flying their flag. Following FAO recommendations (*11*), some nations, such as Thailand, Nauru, and Indonesia, have temporarily or permanently banned transshipment in their waters or for vessels flying their flags (*4*). Some flags feature weaker regulations and enforcement and less oversight, particularly so-called FoCs [following definition by (*21*)]. The high prevalence of FoC-flagged reefers found in this study (41% of total observed, 60% if excluding Russia) and the fact that they primarily engage in transshipments in areas beyond national jurisdiction might compromise transparent documentation of seafood supply chains and warrants further consideration.

In the international waters of the high seas, responsibility for fisheries management lies with the RFMOs. While some RFMOs have developed measures to document and regulate transshipment such as required onboard observers and an electronic vessel monitoring system (VMS) (*14*), this is not globally coordinated (*4*). A recent study found that, of the 17 RFMOs active on the high seas, 5 have mandated a partial and only 1 has a total ban of transshipment at sea (*4*). Thirteen RFMOs mandate some form of vessel tracking in relation to transshipment such as VMS, and 10 require an onboard observer. For example, the Western and Central Pacific Fisheries Commission requires observer coverage and a notice of planned transshipments at least 36 hours prior (*13*), while the Indian Ocean Tuna Commission allows transshipments from large tuna longliners only (*22*). Fishing vessels using certain gear types, such as purse seines, are prohibited to transship in some areas, which is likely one reason why only 1.2% of all fishing vessels involved in encounters seen in this study are purse seiners.

How these mandates and regulations are enforced on the water, however, remains questionable, and documentation by authorities is hard to access. For instance, more than 100 likely encounters between fishing vessels and reefers were observed between 2012 and 2017 in the convention area of the South East Atlantic Fisheries Organization (SEAFO) where all transshipment of fishery resources covered by the Convention is banned (Fig. 1) (*23*). One such instance involving a likely encounter between a Japanese longline vessel and a Liberian reefer is highlighted in fig. S4. It remains unclear whether the likely encounters observed within the convention area are transshipping fish from resources covered by the SEAFO convention and resources covered by another convention with overlapping area (in this case, the International Commission for the Conservation of Atlantic Tunas and the Commission for the Conservation of Southern Bluefin Tuna, both regulating tuna and tuna-like species) or whether the encounter constitutes a mere resupplying of the fishing vessel by the reefer (which, however, appears not to be exempt from the term transshipment by SEAFO). This highlights the importance of proper monitoring and transparent documentation of all encounters at sea, whether they are to transship catch or to resupply.

Monitoring of remote waters and the high seas can be facilitated through the use of AIS data, complementing existing monitoring, control, and surveillance tools (*24*). This combination of various tools is useful to create a complete picture of global fisheries and seafood supply chains. Looking at tuna fisheries in two global hot spot areas (south Indian Ocean and equatorial Pacific; see below) and tracking known transshipment events using AIS data, we found that only 7 of 13 (or 54%) documented transshipment events could be reconstructed using AIS. This is likely due to a combination of gaps in the AIS data and poorly recorded transshipment locations. Hence, our estimates of the global prevalence of transshipment should be seen as very conservative; the true extent is evidently much higher.

As discussed in detail elsewhere (*15*, *25*, *26*), some important caveats and limitations apply to the use of AIS data in general: While coverage by AIS-capable satellites is continuously increasing, some areas may not be covered 100% of the time, and transshipment events in these areas might go unnoticed some of the time. Furthermore, AIS transponders can be manually switched off, or location data can be manipulated (*15*). For the detection and subsequent classification of a likely transshipment event in this study, AIS data of both the reefer and the fishing vessel need to be available and correspond to the chosen characteristics of an encounter. Where no AIS data for fishing vessels involved in encounters are available, "loitering" behavior of the reefer may still be indicative of likely transshipment events (*16*). However, because of the missing AIS data for fishing vessels involved in those events, we excluded these from our data. This reduces the numbers of encounters analyzed and may bias results toward transshipment events including large, AIS-equipped vessels operating offshore. However, global patterns of other potential transshipments events are largely similar to those shown here and discussed in (*16*). Last, gaps in the AIS data might also influence the calculations of fishing hours landed versus transshipped. If an encounter or port call is not included because of missing data, then fishing hours might be overestimated or wrongly allocated to the following transshipment or encounter.

Tuna case study

On the basis of a fully documented industry supply chain, we illustrated the voyage of albacore tuna from the hook to a retailer's shelf. In this case, individual fish travel roughly 17,000 km after catch, over a time span of about half a year, changing boats, owners, and processing facilities several times (Fig. 5). Ideally, every step of this complex supply chain is documented and recorded electronically, at sea and in port, and the documentation that we received from industry illustrates how this can be done. At-sea documentation includes fishing location, gear used, and amounts caught by species (ideally also recording bycatch), time, date, and location of all transshipment events during that trip, as well as identity of vessels involved, catch already transported by the reefer, and all ports visited. Some of this information was not included in the transshipment documentation used in this study: Fishing locations were recorded only by RFMO or ocean area, and overall information on the origin of all catches transshipped by reefers servicing fishing vessels for more than one buyer appears to be generally not available.

The entry of fish to the market via port is a key point in supply chains to require and verify documentation and preclude IUU catch from landing, as included in the recent Port State Measures Agreement (*27*). On land, further documentation includes the method of delivery (fishing vessel direct, by reefer, containerized via another port) and the production code or lot numbers specific to the fishing vessel trip the fish was caught. Following landing, catches ideally are binned in sealed containers corresponding to these codes and lot numbers, which are carried through all levels of processing to maintain traceability of the fish to the final product.

As we presented here, satellite-based AIS enables independent verification of vessel activities, including transshipment (*14*), expanding and complementing existing monitoring and documentation tools. Ultimately, improved legislation and transboundary management may want to include mandatory AIS to ensure increased traceability and transparency in supply chains (*5*, *24*).

CONCLUSIONS

In this analysis, we have highlighted global hot spots of transshipments such as the Russian EEZ and the high seas, especially off West Africa, in the southern Indian Ocean, and (most prominently) in the tropical Pacific where high-value species such as tuna are fished. Trawlers in territorial waters and longliners on the high seas contributed a large majority of likely transshipment events. To reduce the probable introduction of IUU catch into the supply chain, strict monitoring and documentation of each transshipment event are needed, especially if it takes place in international waters. AIS data are ideally suited for long-range monitoring and surveillance of vessel movements, and new methods are available to independently detect and document likely transshipment events, in addition to documentation provided by vessels and observers. Therefore, AIS-based monitoring of transshipment, coupled with improved regulation and oversight, holds promise for improving fisheries management and trade practices on the high seas and elsewhere.

MATERIALS AND METHODS

Likely encounters and fishing effort

Likely transshipment events (encounters) were detected using satellite and tower-based AIS data between 2012 and 2017, as described by (*17*). AIS was designed as a tool of maritime safety to avoid ship collisions. Transponders installed aboard vessels send position and vessel identification messages to receivers on other ships, land, and satellites every few seconds. These messages can be used to reconstruct vessel tracks with high precision and allowed us to analyze their activity on the basis of an automated analysis of movement patterns.

Likely encounters were identified by Global Fishing Watch as locations where two vessels remained within 500 m of each other for longer than 2 hours, traveling at less than 2 knots while at least 10 km from an anchorage (including ports). These parameters balance the need to detect vessel pairs in close proximity while recognizing our ability to identify long periods in which vessels are in immediate contact is limited by satellite coverage and inconsistent AIS transmission rates. Some vessels are known to tranship within ports, but these events are more likely to be subject to surveillance, and therefore, we focused on events that do not occur within the vicinity of port and the accompanying oversight. Here, we used a subset of the data analyzed by (*16*), only including encounters where AIS data are available for both the reefer and the fishing vessel engaged in the encounter.

To exclude vessel meetings that occur within port, encounters were filtered to be more than 10 km from an anchorage (defined as docking in port or anchoring close by) by using a global anchorage data set developed by Global Fishing Watch and made publicly available at http://globalfishingwatch.org/datasets-and-code/anchorages/. Briefly, the anchorage data set was developed by applying an approximately 0.5-km grid to the globe using S2 grid cells (level 14) (http://s2geometry.io/). Using AIS messages from 2012 to 2016 from all vessel types, those grid cells where at least 20 vessels remained stationary for at least 48 hours were identified. For each grid cell, the mean location of the stationary periods was calculated, and this point was labeled as an anchorage. This method identified 102,974 anchorages, and the mean location of an encounter was required to be at least 10 km from any anchorage.

A maximum encounter duration of 3 days was chosen to exclude encounters too short to offload catch and encounters that significantly exceed expected catch offload durations. These events likely represent vessels meeting for other reasons, such as repairs. This upper bound resulted in the removal of 97 events, representing less than 1% of the identified encounters.

Fishing vessels, refrigerated cargo vessels, fish carriers, and fish tender vessels were identified using vessel lists from the International Telecommunications Union and major RFMO fleet registries. Additional vessels were identified by a vessel classification neural network developed by Global Fishing Watch to predict vessel types based on movement patterns. Vessels that were identified as likely reefers by this neural network were manually reviewed through web searches and national, as well as RFMO registries. We do not expect that this list includes all vessels capable of receiving catch at sea, but it likely includes a majority of large specialized reefers that transport fishing for much of the offshore fishing fleet. Of the 641 refrigerated vessels identified in this manner (*17*), 501 were involved in likely transshipment events with AIS-tracked fishing vessels.

Fishing vessels included in this study were cross-checked for gear types through web searches using fleet registries and other reliable sources such as fishing company websites. To estimate the amount of catch landed directly by a fishing vessel versus catch brought to port via a reefer, we identified encounters and port/anchorage visits longer than 24 hours for each fishing vessel. For this analysis, a vessel was not considered to have "visited" a port or anchorage if it did not remain for longer than 24 hours to avoid assigning fishing effort to a port where a vessel was not present long enough to offload significant catch. For reefers, we identified the port visited following an encounter and the hours of fishing per fishing vessel that took place between events (the hours of fishing since the previous encounter or port visit). The fishing that preceded a port visit was assumed to have been landed in that port. Fishing hours that preceded an encounter were assumed to have been transferred from the fishing vessel to the reefer and offloaded in the next port that the reefer visited. The total fishing hours were aggregated by gear and attributed accordingly to ports (Russia considered separately from Asia and Europe).

Fishing activity and vessel gear type were classified following the methods described by (*15*). Briefly, two convolutional neural networks were trained on data from fleet registries, logbooks, and data labeled by experts to identify vessel types and classify their behavior (transiting and fishing) based on movement characteristics as seen in the AIS data.

Tuna supply chain

Data on supply chains for three reefers and 16 fishing vessels transshipping catch at sea were supplied by industry and consisted of official transshipment documentation and captain's statements. On the basis of the vessel identification numbers and details on date, location, and vessels involved in the transshipment given, AIS tracks were reconstructed for the three reefers and 13 of the 16 fishing vessels from raw AIS data supplied by Global Fishing Watch. Industry-recorded encounters were compared against the AIS-based detection method for transshipments, as described above.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/7/eaat7159/DC1

Fig. S1. Activity profiles of fishing vessels at sea.

Fig. S2. Reefers and fishing vessels involved in likely encounters between 2012 and 2017 worldwide by flag.

Fig. S3. Correlation between the number of rendezvous from 2012 to 2017 and IUU fishing by FAO region ($P = 0.1626$).

Fig. S4. Likely encounter between reefer flagged to Liberia (orange) and a Japanese longline fishing vessel (blue) off the west coast of Southern Africa.

REFERENCES AND NOTES

1. Food and Agriculture Organization (FAO), *The State of World Fisheries and Aquaculture 2016. Contributing to Food Security and Nutrition for All* (FAO, 2016).
2. D. Pauly, D. Zeller, Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nat. Commun.* **7**, 10244 (2016).
3. M. Gianni, W. Simpson, *The Changing Nature of High Seas Fishing: How Flags of Convenience Provide Cover for Illegal, Unreported and Unregulated Fishing* (Australian Department of Agriculture, Fisheries and Forestry, International Transport Workers' Federation, and WWF International, 2005).
4. C. Ewell, S. Cullis-Suzuki, M. Ediger, J. Hocevar, D. Miller, J. Jacquet, Potential ecological and social benefits of a moratorium on transshipment on the high seas. *Mar. Policy* **81**, 293–300 (2017).
5. The Pew Charitable Trusts, "Transshipment reform needed to ensure legal, verifiable transfer of catch" (2018); www.pewtrusts.org/en/research-and-analysis/issue-briefs/2018/02/transshipment-reform-needed-to-ensure-legal-verifiable-transfer-of-catch.
6. A. Telesetsky, Laundering fish in the global undercurrents: Illegal, unreported, and unregulated fishing and transnational organized crime. *Ecol. Law Q.* **41**, 939–997 (2015).
7. 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).
8. G. Pramod, T. J. Pitcher, G. Mantha, Estimates of illegal and unreported seafood imports to Japan. *Mar. Policy* **84**, 42–51 (2017).
9. G. Pramod, K. Nakamura, T. J. Pitcher, L. Delagran, Estimates of illegal and unreported fish in seafood imports to the USA. *Mar. Policy* **48**, 102–113 (2014).
10. FAO, *FAO Technical Guidelines For Responsible Fisheries - Fisheries Management Suppl. 4. Marine Protected Areas and Fisheries* (FAO, 2011).
11. FAO, *Implementation of the International Plan of Action to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing* (FAO, 2002).
12. International Commission for the Conservation of Atlantic Tunas (ICCAT), *Recommendation by ICCAT Establishing a Programme for Transshipment* (ICCAT, 2006).
13. Western and Central Pacific Fisheries Commission (WCPFC), *Conservation and Management Measure 2009-06: Regulation of Transhipment* (WCPFC, 2009).
14. 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).
15. 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).
16. N. A. Miller, A. Roan, T. Hochberg, J. Amos, D. A. Kroodsma, Identifying global patterns of transshipment behavior. *Front. Mar. Sci.* 10.3389/fmars.2018.00240 (2018).
17. D. A. Kroodsma, N. A. Miller, A. Roan, "The global view of transshipment: Preliminary findings" (Global Fishing Watch and SkyTruth, 2017); http://globalfishingwatch.org.
18. S. Cullis-Suzuki, D. Pauly, Failing the high seas: A global evaluation of regional fisheries management organizations. *Mar. Policy* **34**, 1036–1042 (2010).
19. FAO, *National Fishery Sector Overview: The Russian Federation* (FAO, 2007).
20. T. S. Sealy, Soviet fisheries: A review. *Mar. Fish. Rev.* **36**, 5–22 (1974).
21. D. D. Miller, U. R. Sumaila, Flag use behavior and IUU activity within the international fishing fleet: Refining definitions and identifying areas of concern. *Mar. Policy* **44**, 204–211 (2014).
22. Indian Ocean Tuna Commission (IOTC), *Resolution 14/06 on Establishing a Programme for Transhipment by Large-Scale Fishing Vessels* (IOTC, 2014).
23. South East Atlantic Fisheries Organisation (SEAFO), *System of Observation, Inspection, Compliance and Enforcement* (SEAFO, 2016).
24. 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.* 1–11 (2018).
25. F. Natale, M. Gibin, A. Alessandrini, M. Vespe, A. Paulrud, Mapping fishing effort through AIS data. *PLOS ONE* **10**, e0130746 (2015).
26. 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).
27. J. Swan, *Implementation of Port State Measures* (FAO, 2016).

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