SCIENCE POLICY

Fishing through the cracks: The unregulated nature of global squid fisheries

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While most research has focused on the legality of global industrial fishing, unregulated fishing has largely escaped scrutiny. Here, we evaluate the unregulated nature of global squid fisheries using AIS data and night-time imagery of the globalized fleet of light-luring squid vessels. We find that this fishery is extensive, fishing 149,000 to 251,000 vessel days annually, and that effort increased 68% over the study period 2017–2020. Most vessels are highly mobile and fish in multiple regions, largely (86%) in unregulated areas. While scientists and policymakers express concerns over the declining abundance of squid stocks globally and regionally, we find a net increase in vessels fishing squid globally and spatial expansion of effort to novel areas. Since fishing effort is static in areas with increasing management, and rising in unmanaged areas, we suggest actors may take advantage of fragmented regulations to maximize resource extraction. Our findings highlight a profitable, but largely unregulated fishery, with strong potential for improved management.

INTRODUCTION

Seafood represents one of the most widely traded food products globally (*1*, *2*), yet the movements and activities of global industrial fishing fleets remain notoriously opaque. These fleets are characterized by limited oversight of their activities (*3*), a shifting landscape of national and international policy and regulation (*4*, *5*), and highly globalized commodity chains (*6*), all of which contribute substantially to the challenges of transparency and traceability in the sector (*7*). Within these global fishing fleets, the most opaque and problematic activities are termed "illegal, unregulated, and unreported" (IUU). However, "IUU" fishing masks a huge diversity of problems with different drivers and solutions. To date, scientific literature has largely focused on the illegal aspects of IUU fishing (*8*–*10*), with some research directed toward the challenges of unreported fishing (*11*, *12*), but fairly little work has examined the "unregulated" aspects of IUU fishing. This is further complicated by the fact that fishing labeled as unregulated also encompasses multiple meanings, and in reality, regulation manifests as layers and gradients of rules rather than a binary indicator of regulated or nonregulated activities.

This relative inattention toward unregulated fishing—understood here as the complete lack, or extreme limitation of regulations to manage a fishery—is not because it is less challenging than its illegal and unreported counterparts. Unregulated fishing is problematic and difficult to address for several key reasons. First, a fundamental assumption of resource management is that in the absence of regulation and communication between actors, the incentives of individual users will often lead to overexploitation and underinvestment in the health of the resource system (*13*). While scholars have questioned the frequency with which these "open access" conditions occur in reality (*14*–*16*), globalized fleets of unregulated industrial fishing vessels are a close approximation of the conditions under which this overexploitation is expected to occur. Scholarship further suggests that actors may take advantage of fragmented regulations and missing institutions to extract resource and profit levels unobtainable in more regulated spaces (*17*, *18*). Second, unregulated spaces are often directly adjacent to regulated ones [e.g., coastal states' exclusive economic zones (EEZs)], and different fleets often target the same species and habitats. This creates substantial equity considerations for traditional and small-scale fishers that rely on species targeted by large industrial fleets (*10*) as well as for developing coastal states that rely on revenue from stocks that move between regulated and unregulated areas, for example, stocks of Argentine shortfin squid (*Illex argentinus*) for revenue in Argentina (*19*–*23*), jumbo flying squid (*Dosidicus gigas*) for Peru (*24*–*26*) and Ecuador (*27*–*29*), and unconfirmed species for northwest (NW) Indian Ocean states like Kenya (*30*). Third, unregulated fishing is subject to considerably less scrutiny than regulated activities and, as such, is more likely to be associated with questionable human rights and labor practices (*31*–*33*). Many of the fishing vessels conducting unregulated fishing stay at sea for exceptionally long periods (months to years), bunkering (i.e., obtaining fuel) and transshipping catches at sea, thus avoiding the oversight that accompanies port calls. Last, while unregulated fisheries are often not technically illegal, there are often connections between these fleets and activity deemed illegal elsewhere (*34*, *35*); these connections are critically important to consider.

Here, we evaluate the unregulated nature of global squid fisheries using satellite imagery and vessel tracking and monitoring data from the globalized fleet of light-luring squid fishing vessels. Notably, we consider only unregulated fisheries here and do not evaluate the legality or illegality of this fishing activity. We chose this fishery for several key reasons. First, both the target species and fishing vessels are mobile and transboundary. Squid are migratory species that move over thousands of kilometers to feed, aggregate, and spawn, often straddling multiple EEZs and high seas areas in the process (*36*). Globalized squid fishing fleets are also highly

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nomadic, with vessels moving between management areas based on seasonal abundances, licensed fishing seasons, or migratory patterns of their target species (*37*). Second, fishing for cephalopods such as squid has gained global importance and consequence over the past 70 years (*37*). As of 2020, cephalopod catches constitute about 4.3% of all global marine catches by volume and about 7% by value (*2*). Squid products are important and sought-after components of many national cuisines, such as in Asian (*Illex* squids) and Mediterranean (*Loligo* squids) countries, and represent important dietary contributions, especially in the light of declining finfish catches (*37*). Third, the fishery is subject to limited or no management depending on its location, and thus provides the opportunity to evaluate it as a potential open access property regime. Regulation and management of globalized squid fisheries is a complex and multiscalar endeavor and varies considerably between high seas and coastal areas. For example, out of the 17 global Regional Fisheries Management Organizations (RFMOs), only 2—the North Pacific Fisheries Commission (NPFC) and South Pacific Fisheries Management Organization (SPRFMO)—consider squid species within their mandate (*38*). Notably, the Southern Indian Ocean Fisheries Agreement (SIOFA) may also potentially manage squid in the future but currently does not. These RFMOs present vastly different management regimes for the high seas, and in some high seas areas, there is no RFMO at all [e.g., southwest (SW) Atlantic Ocean]. Moreover, squid also occur in the EEZs of dozens of coastal states, each of which implements its own domestic fisheries regulations. To adequately assess how vessels move between these various resource regimes, we consider the International Plan of Action to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing (IPOA-IUU). Paragraph 3.3.2 of the IPOA-IUU states one definition of unregulated fishing as that which occurs "in areas *or* for fish stocks in relation to which there are no applicable conservation or management measures…" (emphasis added) (*39*). We interpret the second part of this as requiring RFMOs to do more than simply exist or adopt general measures, if their mandated fisheries are to be considered regulated. Therefore, here, we consider regulated fisheries to consist of those that occur within the EEZs of coastal states or that occur within RFMOs that have implemented conservation and management measures (CMMs) pertaining specifically to squid stocks. In contrast, we consider unregulated fisheries to occur on the high seas where there is no RFMO in place or where the competent RFMO has adopted no regulation pertaining specifically to squid stocks. Notably, SPRFMO has adopted some measures to regulate the squid fishery (e.g., reporting of catches, vessel monitoring system (VMS) obligations, and transshipment notifications), but not direct management measures for squid stocks, such as quota or effort limits. Applying the definition above, we categorize activities targeting squid in the SPRFMO area as "unregulated" because CMM 18-2020 on the Jumbo Flying Squid Fishery, adopted by SPRFMO in 2020, does not include specific management provisions such as effort limitations or total catch limits for the squid fishery (*40*). That said, we recognize that this is a stock-specific interpretation, and fishing in this area may be considered regulated in relation to other relevant stocks. Last, concerns for the sustainability, ethics, and legality of the global squid fishery are mounting (*21*, *41*, *42*), demonstrating a growing need to evaluate practices in the fishery.

To conduct this analysis, we combined Automatic Identification System (AIS) data providing vessel tracks and Visible Infrared Imaging Radiometer Suite (VIIRS) data depicting light detections at night, to evaluate the location and activities of globalized squid fishing vessels. We then compared this activity to areas of competence for national and regional management bodies and relevant squid regulations to determine the extent to which this fishing activity is unregulated versus regulated (e.g., EEZ or RFMO with squid regulations). Last, we examined the spatial ranges of vessel movement and fishing activity to consider whether these vessels are highly mobile and, if so, what central characteristics are displayed by their movements. On the basis of this work, we summarize the trends observed in the global light-luring squid fishery, discuss the potential implications of these findings, and point to potential recommendations.

RESULTS

Estimating global light-luring squid fishing

The VIIRS sensor on the Suomi National Polar-orbiting Partnership (NPP) satellite system images the entire ocean every night and can detect squid vessels, which use bright lights. These data allow us to estimate fishing effort independent of vessel tracking or fisheries-dependent data. Using these data within our study area (Fig. 1), we estimate an increase in fishing effort in the globalized light-luring squid fishery of 68% over the study period 2017–2020. The total amount of light-luring vessel effort across the four regions increased over time from an estimated 149,000 vessel days in 2017 to 251,000 vessel days in 2020, of which 61 to 63% were by vessels not broadcasting AIS (Table 1 and Fig. 2). This light-luring vessel effort represents an estimated total of 801,000 vessel days over the period 2017–2020.

Annual total effort estimates from VIIRS for each region (Table 1 and Fig. 2) have increased since 2017 in the NW Indian Ocean and southeast (SE) Pacific Ocean, but remained largely unchanged or slightly reduced in the NW Pacific Ocean and the SW Atlantic Ocean. This indicates a likely increase in squid catch pressure in the NW Indian Ocean and SE Pacific Ocean. In particular, in the NW Indian Ocean, effort has increased rapidly from 13,000 to 56,000 vessel days from 2017 to 2020. This further corresponds to a 4.4-fold increase in terms of the number of vessels, from 57 to 250. Furthermore, a comparison of AIS to our VIIRS estimates in the NW Indian Ocean shows that there are substantially more vessels detected with VIIRS than with AIS, suggesting that AIS adoption for squid vessels in this region is lower than other regions. Notably, the proportion of vessels detected only by VIIRS and not AIS is decreasing annually in all regions except the SE Pacific; however, there is substantial variation in those proportions between regions.

Regulated versus unregulated fishing

The combination of AIS and VIIRS facilitates the most accurate estimates of vessel effort. However, evaluation of detailed fishing activity is only possible for vessels broadcasting AIS. We observed 1394 vessels using AIS, fishing in the target study areas during 2017–2020.

Combining these data with spatial information regarding both nationally and internationally regulated areas, we find that the global fleet of light-luring squid vessels operates overwhelmingly in unregulated areas (Fig. 3A). Between 2017 and 2020, these vessels spent 86% of their aggregate fishing time (4.4 million total hours) fishing in areas subject to no relevant regulations (Fig. 3A). This trend is driven largely by Chinese vessels (Figs. 3B and 4), which dominate the global squid fishery observed in AIS, in both vessel number (1123 vessels) and hours fished (4 million hours; 92% of all fishing hours observed in AIS). While unregulated fishing comprises the vast majority of Chinese fishing observed in AIS in each year, trends are mixed for the other state flags (Fig. 3B). For example, Chinese Taipei and the Republic of Korea predominantly fished within EEZs, almost exclusively driven by fishing activity within the Falkland/Malvinas Islands EEZ (Fig. 3B and fig. S1) (*43*). To conceptualize localized fisheries, we further disaggregated fishing within EEZs into two categories: foreign EEZ (fishing conducted in an EEZ different to a vessel's flag state) and domestic EEZ (fishing conducted in a flag state's own EEZ) (Fig. 3B). The domestic EEZ fishing was exceedingly low, representing 8 to 30% annually in Japan, <0.1 to 1% annually in the Republic of Korea, 0 to <0.001% annually in Chinese Taipei, and 0 to <0.001% annually in China (Fig. 3B). Notably, in November 2019, the NPFC began regulating squid fisheries with the passage of effort controls in CMM 2019-11, so we considered the NPFC convention area to be "regulated" space for squid from the date this policy entered into force on 29 November 2019 (*44*). Therefore, the implementation of these NPFC regulations in late 2019 altered the regulatory status of Japanese and Chinese Taipei vessel activities in particular, as their primary fishing grounds came under NPFC regulation (Fig. 3B). The implementation of these regulations also altered the status of a small subset of Chinese vessel activity and a substantial amount of Korean vessel activity; however, RFMO-regulated activity remained the lowest in absolute prevalence for Korean vessels (Figs. 3B and 4).

Squid vessel mobility and interconnectedness

We also find that light-luring squid fishing vessels tend to be highly mobile, operating in multiple oceans and crossing ocean basins multiple times within a single year (Fig. 5). While there are substantial differences between flag states, the average duration of flag state fishing voyages ranged from 3 months to just over 1 year. This duration is much longer than the average voyage for other vessels engaged in pelagic fishing; according to Welch *et al.* (*45*), the mean voyage of vessels that fish more than 50 nautical miles from shore is under 1 month. This contrasts starkly with globalized squid vessels, which often take several weeks to even reach fishing grounds (*46*). In addition, while only 1% of vessels operated in all four regions within a single year, 52% operated in two or more regions annually (Table 2). Comparing the number of vessels that move between regions with those that are endemic (i.e., they stay within a single region), we find that the majority of vessels are highly mobile, fishing in multiple regions (Table 3). Endemism is low, ranging between 9 and 38% with the exception of the NW Indian Ocean. While the NW Indian Ocean is an exception further explored in Discussion, it is notable that even in this region, while endemism is relatively high (e.g., vessels that fished there only fished in that region), the vast majority of vessels are Chinese and therefore are still not representative of a localized fishery (Fig. 6).

The extreme mobility of these fishing vessels is facilitated by two important factors. First, many of these light-luring squid fishing vessels stay at sea continuously or for extremely long periods, enabling them to shift between regions without making port calls for shore leave or to land catches or obtain provisions. This prolonged sea time enables near continuous fishing activity, shifting from one region to another. Second, and relatedly, the mobility of these fishing vessels is facilitated by the similar movement and connectivity of carrier vessels (refrigerated cargo vessels capable of receiving catch and delivering fuel, supplies, and crew to fishing vessels) (*47*, *48*) between regions (Fig. 7). These carrier vessels provide fishing fleets with fuel and provisions, as well as accept

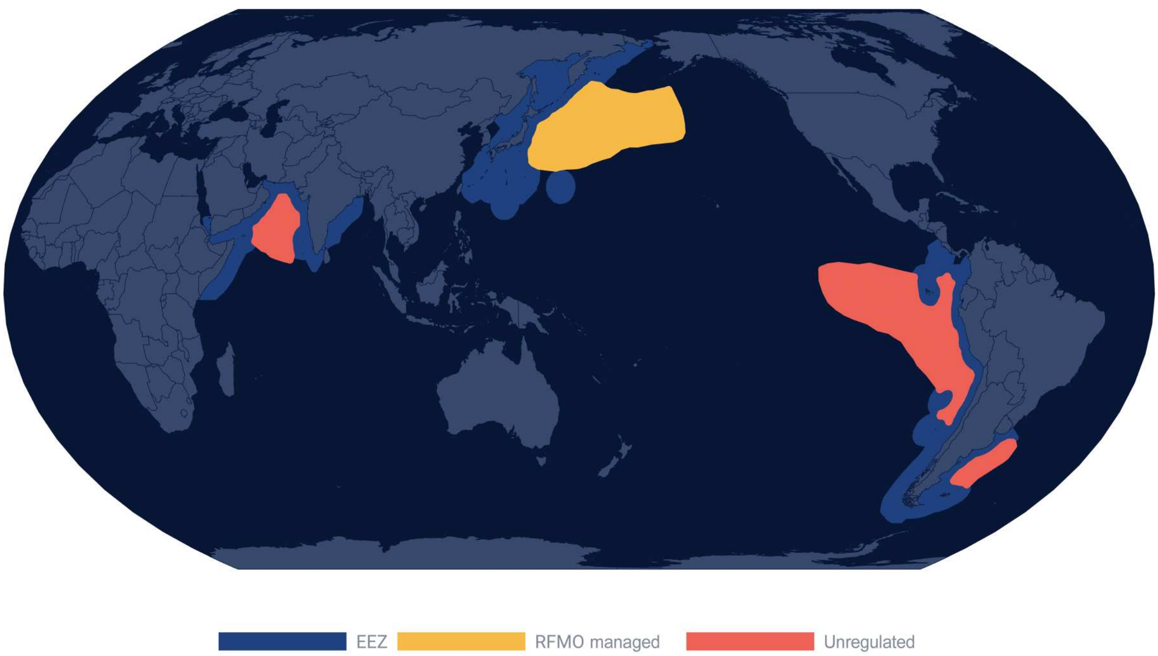

Fig. 1. Study area map. Map of study area and management statuses considered here. Boundaries are based on Marineregions.org (2022) (*98*) and do not necessarily reflect the views of the organizations or countries to which the authors belong (see Materials and Methods).

Fig. 2. Squid fishing effort by region and year. Annual aggregation of effort (vessel days) estimated from VIIRS. The orange bar and the number in the bar indicate the number and the percentage of the vessels detected only by VIIRS, respectively. The blue bar indicates vessels detected by both VIIRS and AIS.

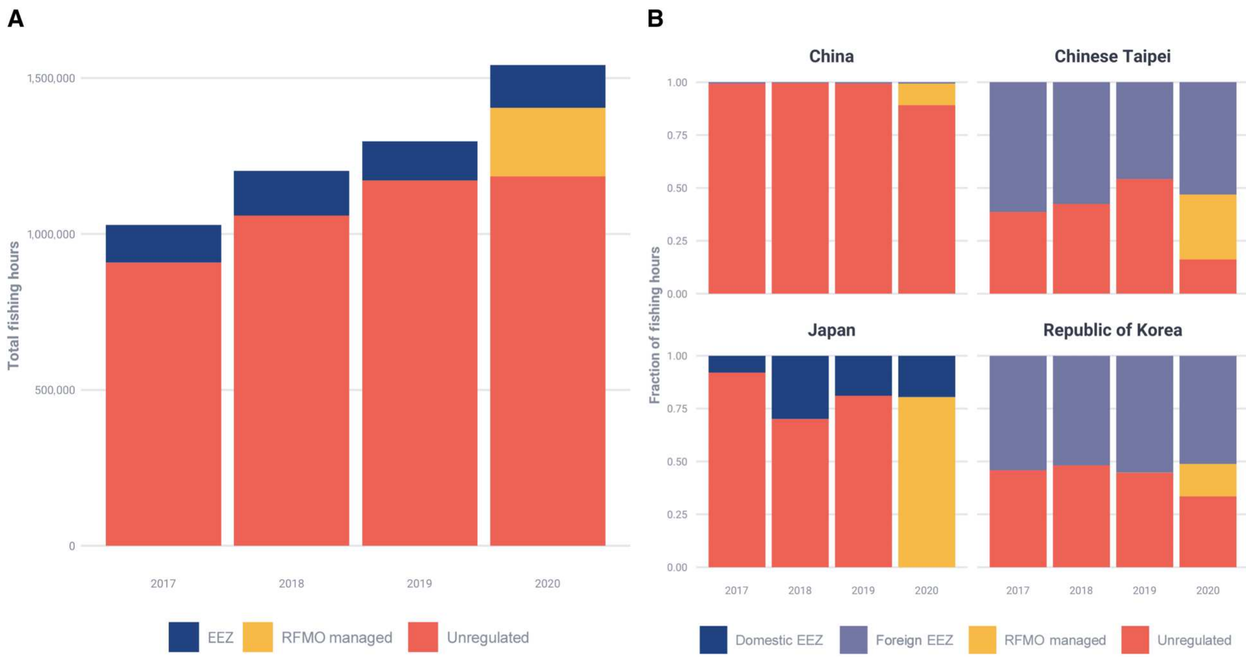

Fig. 3. Fishing effort by regulation zone. (**A**) Annual counts of total fishing hours by EEZ, RFMO managed, and unregulated zones. (**B**) Fraction of fishing hours identified in AIS that were observed within each management zone, by fishing flag (panel) and year.

Table 1. Estimated squid fishing effort and AIS coverage. Estimated effort (vessel days) and the percentage of those not broadcasting AIS in each squid fishing region annually and in total.

Region	2017	2018	2019	2020	Total
NW Indian	13,000 (91.2%)	17,000 (89.9%)	40,000 (89.6%)	56,000 (80.2%)	126,000 (85.6%)
NW Pacific	34,000 (75.9%)	28,000 (68.3%)	32,000 (65.2%)	32,000 (63.6%)	126,000 (68.4%)
SE Pacific	63,000 (49.8%)	92,000 (46.8%)	120,000 (57.8%)	136,000 (56.9%)	410,000 (53.8%)
SW Atlantic	40,000 (64.6%)	43,000 (58%)	28,000 (49.5%)	28,000 (47.2%)	139,000 (56%)
Total	149,000 (63.2%)	180,000 (56.9%)	220,000 (63.6%)	251,000 (61.8%)	801,000 (61.5%)

transshipments of catches, enabling vessels to cover more fishing ground in less time.

Increased effort and expanded spatial exploitation

In addition to vessel mobility, trends in effort are overall growing. In 2017, the number of unique Maritime Mobile Service Identities (MMSIs) belonging to vessels fishing for squid was 887, increasing steadily to approximately 1102 in 2020 (fig. S2). During the study period, annual vessel counts fluctuated between the different regions, with increasing trends in the SE Pacific and mixed trends in the other three regions (figs. S3 and S4). However, on the whole, effort measured by the number of vessels targeting squid shows steady growth (fig. S2). This trend is also visible through the number of total fishing hours, which increases steadily from 1.02 million in 2017 to 1.54 million in 2020 (Fig. 4). Notably, the largest increases in fishing hours occur in spaces that are unregulated, rather than those that are in national or regionally managed waters (Fig. 4), even considering the substantial amount of fishing effort that came under regulation starting in late 2019. This trend of increased global squid fishing effort is supported by evidence from publicly available data in both NPFC and SPRFMO.

In addition to increasing overall effort, evidence also suggests the expanded spatial exploitation of squid fisheries. Several recent reports have highlighted the expansion of Chinese squid fishing fleets in particular, facilitated by the use of advanced remote sensing and communications technologies used to inform and direct Chinese fishing fleets in real time (*5*, *49*–*51*). Chinese officials have been quoted as saying that this expansion is part of a larger geopolitical agenda of high seas squid fishing dominance on the part of Chinese fleets (*21*, *34*, *35*, *50*, *52*, *53*).

DISCUSSION

Our analyses suggest that light-luring fishing vessels operate as a globalized and interconnected fishery targeting squid across multiple oceans. In large part, these vessels fish in unregulated areas and move freely between regulated and unregulated spaces, fishing huge amounts of squid with little to no oversight or data reporting. In some cases, these activities are of lesser concern, as some fleets fish for short periods, fish relatively close to home, and report their catches domestically (e.g., Japan) (*54*). In other cases, these activities raise substantial concerns, as vessels remain continuously at sea, extract estimated huge amounts of squid, do not report catches, and fish directly adjacent to coastal states' EEZs and large marine protected areas (e.g., China) (*29*, *55*). Our analysis also suggests increasing squid fishing effort across regions and the spatial expansion of squid exploitation.

Implications of unregulated fishing for governance, sustainability, and equity

Notably, we also find increasing fishing pressure in the NW Indian Ocean and SE Pacific Ocean, where there is currently no management of squid fishing, and static fishing pressure in the NW Pacific Ocean, where regulation is increasing. Where fishing vessels are less mobile, either fishing a single region (endemic) or fishing heavily in coastal waters (EEZs), we find that these vessels represent foreign rather than local fishing vessels. Therefore, despite being less mobile, these vessels still represent notable behavior, as they move large distances to exploit populations in foreign waters, and would therefore not be expected to demonstrate the localized incentive to conserve fish resources.

The fact that the sizable fishing activity observed here is largely unregulated has substantial implications for resource equity and sustainability, as well as the broader ethics and legality of the fishery. For example, small-scale and traditional fishers in several of these regions have expressed a growing sense of frustration and injustice toward the industrial squid vessels that they perceive to be overfishing right outside their waters and depleting their historically fished stocks. Examples from Peru stress these views that unregulated foreign fishing threatens the squid stocks that support their livelihoods and employment (*55*, *56*). Similarly, coastal developing states have also expressed increasing concern toward these vessels, which often concentrate extensive effort directly outside of their EEZ or immediately adjacent to sensitive and protected areas (e.g., Galápagos) (*27*, *29*, *53*, *55*, *57*). These coastal states often lack sufficient enforcement capacity to prevent incursions into their EEZs and poaching by foreign industrial fleets. In addition to this direct competition for traditionally fished stocks, coastal developing states have also expressed concern for the potential lost revenue from extensive industrial fishing immediately outside their EEZ.

Just as unregulated fishing fails to benefit coastal states, so, too, does it fail to inform sustainable management of stocks. In many cases, these catches are not reported to domestic or international management bodies, nor are they incorporated into estimates of fishing effort, harvest, or stock status. Hence, catches from unregulated fishing—especially in areas with missing or nascent management institutions—result in a consistent underestimation of fishing pressure and correspondingly inaccurate estimates of sustainable exploitation. In addition, since there are currently no data sharing agreements between the countries fishing squid, there is also no regional estimation of squid abundance in any of the four regions in this study, and any estimates of stock status or comprehensive catch per unit effort (CPUE) are not possible (*58*–*60*). While squid fisheries are notoriously difficult to evaluate (*61*–*69*), concerns for stock sustainability are echoed in scientific literature, management statements, and journalism pertaining to the relevant stocks. For example, evidence suggests concerns over the declining abundance of squid stocks both globally (*6*) and within multiple regions: the NW Pacific Ocean (*52*, *70*, *71*), SW Atlantic Ocean (*2*, *37*, *60*), SE

Table 2. Squid fishing vessel mobility. Number and proportion of vessels observed in AIS that visited one or more regions in this analysis.

Number of regions visited	Number of MMSI	Total MMSI	Fraction
1	673	1394	48%
2	585	1394	42%
3	123	1394	9%
4	13	1394	1%

Pacific Ocean (*60*, *72*–*74*), and NW Indian Ocean (*75*). Particular species of concern include the jumbo flying squid (*D. gigas*) in the SE Pacific, Argentine shortfin (*I. argentinus*) in the SW Atlantic, and Japanese flying squid (*Todarodes pacificus*) in the NW Pacific (*2*, *60*, *72*, *76*). These concerns were most recently emphasized by China's declaration of a moratorium on fishing by its fleet in the SW Atlantic Ocean and eastern Pacific Ocean due to concerns over fish stock status and environmental damage (*21*, *42*). In addition, the evaluation of publicly available catch data suggests that CPUE of vessels jigging for squid has been declining in the NPFC and SPRFMO for several years (fig. S5). Within the study time period of 2017–2020, measures of squid CPUE have declined sharply in these two regions and were preceded by steady downward trends from 2012 in NPFC and 2015 in SPRFMO (fig. S5).

In addition to concerns regarding the equity and sustainability of this fishery, there are also substantial questions regarding the ethics of some of these fishing practices. For example, McDonald *et al.* (*77*) suggest that vessels at high risk of labor abuses tend to fish far from ports and have a high number of voyages per year. Yen and Liuhuang (*46*) also suggest that long working hours associated with some fisheries are a primary indicator of forced labor. Many of the fishing practices identified in this study strongly resemble these "at risk" fisheries, and McDonald *et al.* (*77*) find that squid jiggers have the highest percentage of high-risk vessels across examined fleets and years, and all four of the regions examined in this study are considered "hot spots" where high-risk jiggers are commonly active. Last, while this unregulated fishing is not known to be illegal, vessels conducting unregulated fishing are oftentimes connected to, or associated with, illegal activity in other regulated spaces (e.g., EEZs) (*51*). For example, within our study, several fishing vessels were connected via encounters at sea with the carrier vessel Lu Rong Yuan Yu Yun 008. While this vessel similarly moved between regions of several ocean basins, it was also connected with illegal activity in the North Korean EEZ in 2019 (fig. S6). Analytical precision is needed to ensure that fishing deemed unregulated is not erroneously conflated with illegal activity; however, scholars and journalists have noted the frequent associations between illegal, unregulated, and unreported fishing (*51*, *78*, *79*), and our analyses reinforce these connections.

Table 3. Squid fishing vessel endemism. Number and proportion of vessels observed in AIS that were endemic to one region (i.e., they only fish within a single region).

Region	Endemic MMSI	Total MMSI	Percent endemic
NW Pacific Ocean	259	674	38%
SE Pacific Ocean	201	709	28%
SW Atlantic Ocean	50	584	9%
NW Indian Ocean	163	297	55%

Contextualizing regulated squid fisheries

Further, while the implementation of the NPFC CMM 2019-11 in November 2019 resulted in a marked shift in the regulatory status of a substantial amount of squid fishing, this fact merits further exploration (*44*). On the one hand, the passing of this CMM suggests increasing regulation of a previously open access fishery and progress toward improved management. However, since the CMM primarily aims to limit the expansion of fleets targeting Japanese flying squid (*T. pacificus*) within NPFC in advance of an appropriate stock assessment, the substantive contribution toward improved management may be more tempered than at first glance. For example, CMM 2019-11 calls for halting the expansion of fleets for states with "substantial harvest" and "encouraging" a halt to expansion for those without substantial harvest, in addition to requiring VMS and data sharing (*44*). The regulation does not, however, include harvest control measures or other limits to catch or effort. Therefore, while the technical regulatory status of the NPFC convention area in this analysis changed to a regulated fishery, as CMM 2019-11 represents a squid fishery–specific regulation, the potential of these regulations to substantially alter fishing behavior and improve fisheries management is currently limited.

In addition, while we consider areas within the EEZs of coastal states to be nationally regulated, there are substantial differences in fishing regulations between coastal state waters, as well as government capacities to monitor and enforce the regulations within them. Within our analysis, we found that the majority of fishing that occurred within EEZs was conducted by Chinese Taipei and the Republic of Korea in the Falkland/Malvinas Islands EEZ; to a much lesser extent, Japanese fleets fished in Japanese waters, and the Republic of Korea fished in Russian waters (fig. S1). While all of these fleets' activities are classified as regulated in our analysis, as they occur in areas subject to the jurisdiction of coastal states, the relevant fishing regulations and enforcement capacities of Japan, Russia, and the Falkland/Malvinas Islands EEZ are likely to vary widely. For example, squid fishing in Japanese waters has been managed since 1969 and is largely conducted by domestic Japanese fleets (*54*). In contrast, squid fishing in the Falkland/Malvinas Islands EEZ has been managed since 1986 and is predominantly conducted by foreign Chinese Taipei and Korean vessels (*80*). Notably, squid fishing in the Falkland/Malvinas Islands EEZ is also critically important, providing 40% of gross domestic product (GDP) and playing a key role in the ongoing sovereignty dispute (*6*, *80*–*83*). Therefore, while we determine fishing within an EEZ to be regulated for the purposes of this analysis, we do not evaluate the quantity or quality of domestic regulations, nor vessel compliance.

Summary and recommendations

Last, we note that, while the overall trends in this fishery suggest increasing fishing effort focused heavily and preferentially in unregulated areas despite concerns for stock status, it is important to

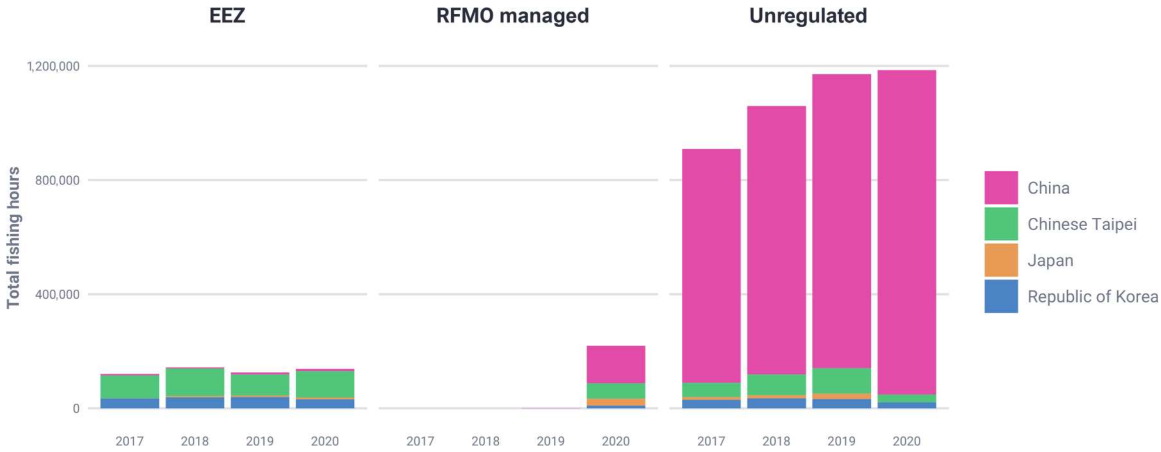

Fig. 4. Total fishing effort by flag state and year. Total fishing hours observed in AIS by fishing flag (stacked) and zone for the period 2017–2020.

point out the strong differences between flag state behavior. The overall trends are driven by Chinese-flagged vessels, which dominate the sector in terms of vessels and hours fished. These vessels fish on long voyages, predominantly in unregulated spaces, and are highly mobile, often targeting three or four regions within a single year. While some scholars have recently noted improvements in the policy and management of Chinese distant water fisheries and suggested specific approaches to address unregulated fishing (*4*, *84*), skepticism remains (*21*). However, not all vessels demonstrate this behavior, and the less numerous vessels flagged to states such as Japan and Chinese Taipei show very different fishing behaviors. For example, Japan predominantly fishes within its own EEZ and the neighboring high seas now regulated by NPFC. Chinese Taipei preferentially fishes in the NW Pacific and the SW Atlantic. These differences are more than anecdotal and instead provide potential insights into the drivers of these fishing behaviors and potential approaches to improved management. For example, in Japan, early fishery expansion was driven by investments in shipbuilding and vessel efficiency, but the fleet has since retrenched because of a combination of geopolitical (e.g., expansion of EEZ claims), institutional (e.g., high safety requirements for Japanese licenses), and economic factors (e.g., high labor and fuel costs) (*54*, *85*). In contrast, Chinese Taipei provides some of the highest rates of fleet subsidies (e.g., for fuel, vessel, and fleet support), and this, combined with a preferential agreement for access to the Falkland/Malvinas Islands EEZ squid fishing grounds, creates substantial institutional and economic incentives for long-distance fishing (*85*). Therefore, the mobility and magnitude of fishing effort can be understood not as an intrinsic characteristic of distant water fishing but rather as being facilitated (e.g., by subsidies and generous access agreements) or constrained (e.g., by high safety standards and labor investments) by specific factors that can be changed.

This study sought to evaluate the characteristics of unregulated fishing using the globalized fleet of light-luring squid vessels. We found that the fleet preferentially fishes in unregulated areas, shifting fishing effort between grounds over large areas. In addition, we found that fishing effort is static in areas with increasing management, and increasing in unmanaged areas, supporting the notion that actors may take advantage of fragmented regulations to maximize resource extraction.

However, while this behavior of squid fishing vessels is concerning, even more alarming are the apparent increases in overall capacity, suggesting not only shifting effort but also the filling of novel areas with new or increased effort. Some potential explanations for this may include the high rate of subsidies in industrial fisheries (*52*), increased demand for seafood products globally (*2*), or the increasingly globalized markets for seafood that often obscure chain of custody and quality controls (*1*). Understanding the factors that facilitate this increase and expansion of fishing effort is a critical next step in addressing the challenges of industrial unregulated fishing.

Fisheries like the light-luring squid fishery are truly globalized and require a globalized approach to governance. This does not suggest that globalized fisheries should necessarily be governed by global institutions (*86*) or even that RFMOs provide a universal solution to wide-ranging transboundary fisheries. Instead, we suggest that a polycentric and adaptive approach might provide the best way forward for governance of these complex fisheries. In some cases, this may indicate the need for new or expanded RFMO institutions (e.g., in the NW Indian Ocean and SW Atlantic Ocean) with the mandate and capacity to effectively manage squid fishing. In other cases, it may mean the strengthening of RFMOs that are currently in place (e.g., NW Pacific Ocean and SE Pacific Ocean); while SPRFMO was established in 2009, it once again failed to adopt measures regulating the squid fishery in 2021 (*87*–*90*), risking "noncooperative" consideration in the fight against IUU (*76*). Squid regulations within coastal state EEZs are continually developing and will also require strong domestic management capacity and the corresponding monitoring, control, and surveillance capacity to ensure their effectiveness. In all of these cases, however, it will certainly require increased cooperation between existing governance regimes and incorporation of the best fisheries science, regardless of jurisdictional boundaries (*60*). For example, compatibility of CMMs between management areas, whether RFMOs or coastal waters, is essential to ensure that mobile actors such as squid vessels are not able to shift locations, targeting areas with fragmented or missing regulations. Comprehensive data sharing agreements between areas of competence are also critical to understand not only the movements of these vessels but also their impact on the squid stocks on which they rely. Flag states are essential for improving the governance of these unregulated

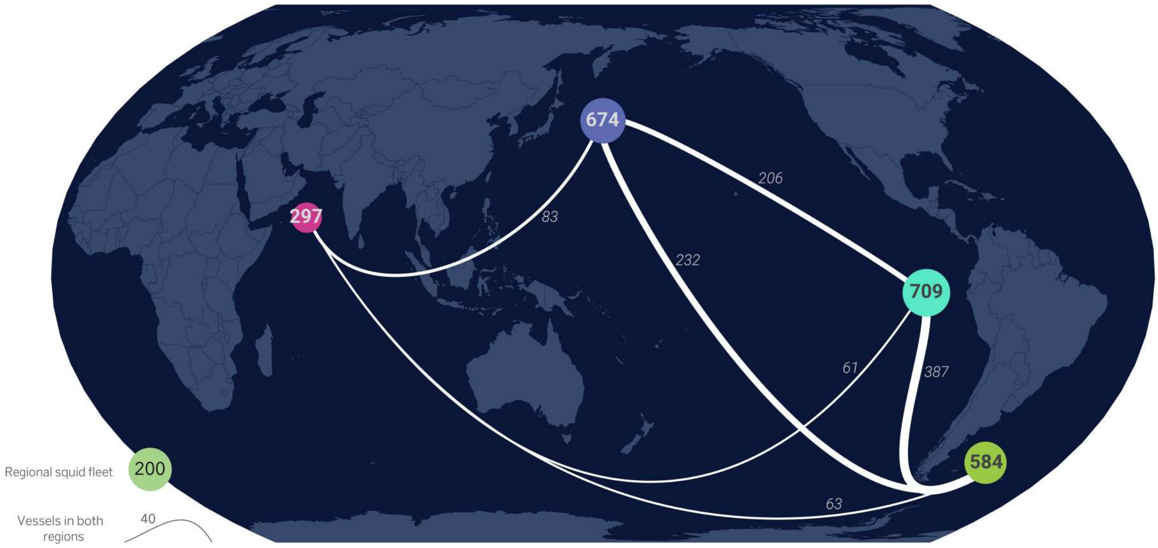

Fig. 5. Squid fishing vessel connectivity. Globalized squid fishing vessel connectivity. The number and size of circles corresponds to the vessels that fished in each ocean region (NW Pacific Ocean, purple; SE Pacific Ocean, teal; SW Atlantic Ocean, green; NW Indian Ocean, pink). The width of white connecting lines and numbers correspond to the vessels that were observed in both regions connected.

fisheries, but corporations, fishing companies, regional and subregional bodies, and scientific organizations will play an indispensable role in governing these activities.

Global and regional governance strategies are foundational for transboundary fisheries; however, governance at multiple scales will be critical to solve the challenges of roving fishing fleets. Literature on institutions and the commons suggest that reinforcing rules at multiple scales and sectors (e.g., international, regional, and national) can improve governance and promote resilience in natural resource governance regimes (*91*–*93*). Specifically, these polycentric systems have been cited as creating enhanced adaptive capacity and good institutional fit in the management of natural resource systems like fisheries (*93*). In light of these insights, innovative and successful governance of these unmanaged fisheries will likely call upon not only regional and national governments but also scientific, nonprofit, and civil society institutions.

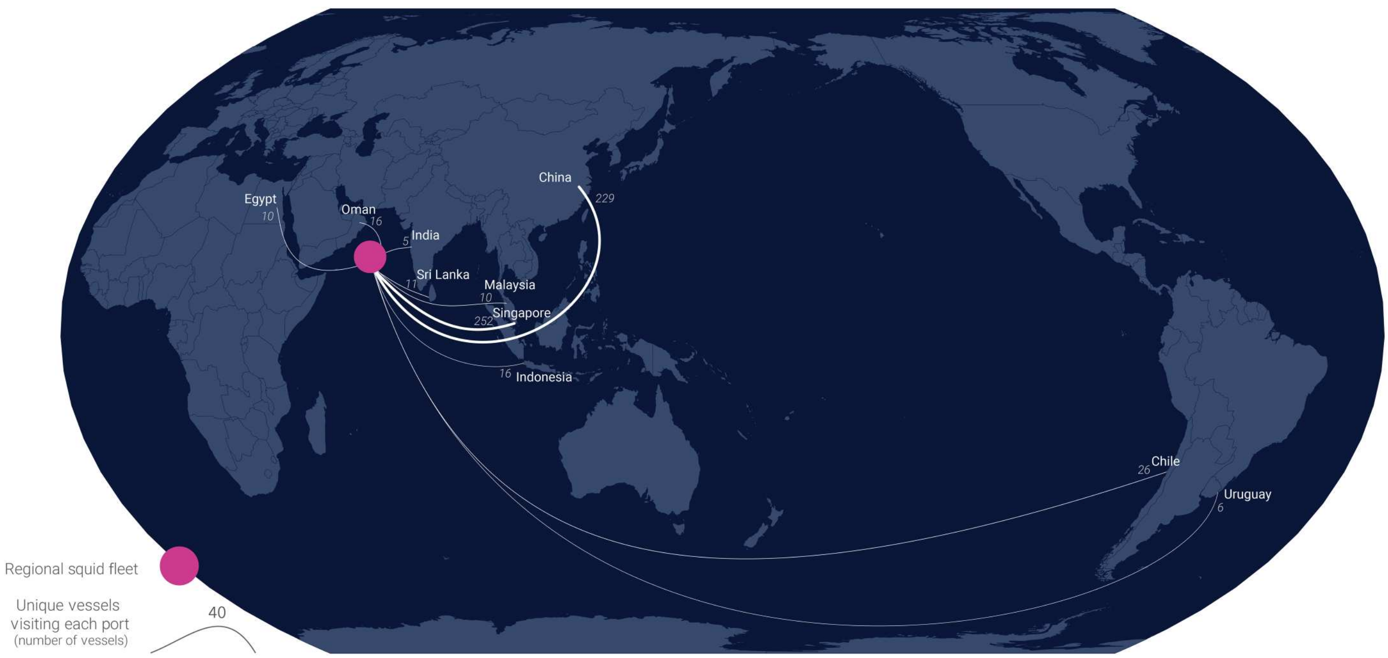

Fig. 6. Port connections to squid vessels fishing in the Indian Ocean. Squid fishing vessel connectivity in the NW Indian Ocean. The number and size of circles corresponds to the vessels that fished in the NW Indian Ocean region; the width of white connecting lines and numbers correspond to the vessels that were observed in port in each country listed.

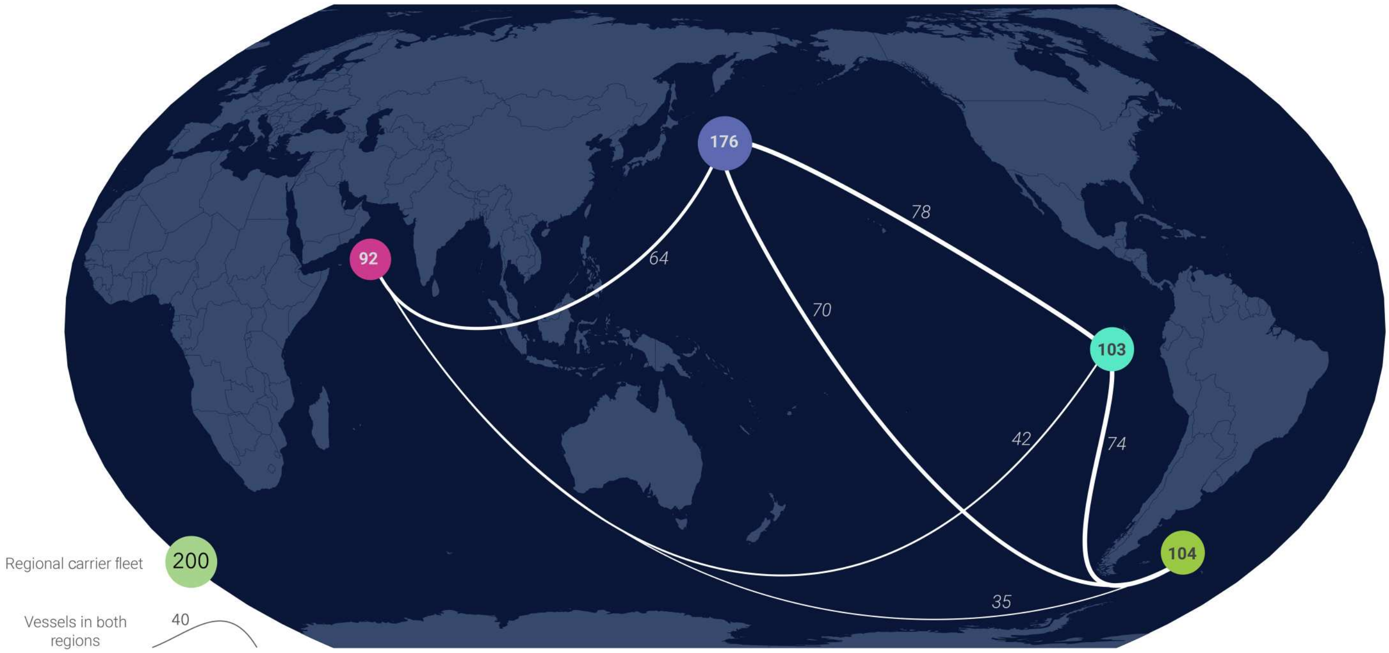

Fig. 7. Carrier vessel connectivity. Globalized carrier vessel connectivity. The number and size of circles corresponds to the vessels observed in AIS in each ocean region (NW Pacific Ocean, purple; SE Pacific Ocean, teal; SW Atlantic Ocean, green; NW Indian Ocean, pink). The width of white connecting lines and numbers correspond to the vessels that were observed in both regions connected.

Within their seminal work, Berkes (*94*) identify a primary solution to the problem of mobile resource extraction as the "self interested, conserving feedback that comes from attachment to place." This suggests that where fishing is conducted by actors and in locations that facilitate attachment, stewardship and resource conservation will follow. While this study demonstrates the globalized nature of the light-luring squid fishery, and the limited observation of localized fleets, it is possible to identify subsets of vessels that might exhibit characteristics that could promote this "conserving feedback." For example, in the NW Pacific region, a large number of vessels are seen transiting to nearby ports to offload catches, obtain provisions, and enable shore leave, suggesting some connection to place and the likelihood of multiple trips to the same fishing ground. To a lesser extent, this is also seen in the SE Pacific, where the majority (70%) of vessels fishing in the area visit ports in Peru, although this is likely for provisioning purposes after transshipping catches at sea. In contrast, in the NW Indian Ocean, the vast majority of vessels travel thousands of miles to dock in the ports of China and Singapore, suggesting limited "attachment to place" and the resources therein (Fig. 6). Analyses such as these, and of the business and policy environments that promote this "attachment," may provide a strong first step in identifying good actors and the conditions under which sustainable globalized fishing will emerge.

MATERIALS AND METHODS

Study areas

Study areas were chosen using the Global Fishing Watch (GFW) fishing algorithm to identify areas of squid jigger fishing effort (as identified by the GFW vessel classification and fishing algorithms) from 2017 to 2020. Using these data on fishing activity, we generated a 0.5° raster of fishing effort (data accessed 25 April 2022; fig. S7). The effort raster was overlain with VIIRS vessel boat detections to more accurately delineate regions in which fishing vessels use light to attract squid. We drew manual polygons around these concentrations of squid and "light lure" fishing using mapview (version 2.10.0) and mapedit (version 0.6.0) packages in R (version 3.6.3) (*95*–*97*). To capture management status considered here, we trimmed each polygon to the high seas using an EEZ shapefile (Marine Regions version 11) (*98*). Notably, in the case of Argentina, there is a small discrepancy in the delineation of their outer EEZ limit; Argentina claims a slightly smaller EEZ limit than Marine Regions, and this is the limit largely acknowledged by the Government of Argentina and relevant fishing vessels. This results in an overestimation of fishing within the Argentine EEZ, which should be considered an artifact of a nonpolitically contested boundary and interpreted with caution (fig. S1). We then joined the polygons onto the EEZ shapefile to identify EEZs with which they immediately abutted. We also joined these polygons to the shapefile delineating the area of competence for the NPFC. We considered those areas within EEZs and abutting concentrations of squid fishing to be state regulated, areas within the mandate of RFMOs with squid management measures in place to be RFMO regulated (see text below), and areas within RFMOs without specific squid management measures as well as non-RFMO high seas areas to be unregulated (Fig. 1). As a matter of convenience solely for scientific, research, and educational purposes, the figure with EEZs shown in the present study is illustrated by using a database, Marineregions.org (2022) (*98*), developed by a nonprofit organization, Flanders Marine Institute (Ostend, Belgium), and does not reflect the views of the organizations or countries to which the authors of manuscript belong (*98*).

List of light-luring vessels

We compiled a list of vessels that use light to catch squid with nets or lines, from multiple sources of vessel information for those operating with AIS. These sources included the Register of Fishing Vessels (RFV) for both NPFC and SPRFMO; we included vessels registered in the NPFC as jiggers, liftnets, or purse seines, as well as vessels registered in the SPRFMO as liners. We matched these vessel lists to AIS using a combination of the MMSI, International Maritime Organization (IMO) number, ship name, and call sign. Vessels from these registries were supplemented by vessels classified as "squid jiggers" by the GFW vessel classification algorithm (*99*), along with vessels identified in reports such as (*100*). To ensure a robust list, we also performed a manual review (using internet searches) of all vessels classified by the GFW vessel classification algorithm as "fishing" with AIS positions within the study areas. All vessel counts were based on the MMSIs (the unique vessel identifier used in AIS).

From this broad list of vessels (n = 2058), we eliminated those vessels that never fished on the high seas or did not operate during the study period (n = 547), as we considered them unrepresentative of the vessel population of interest—those that fished unregulated spaces from 2017 to 2020. To simplify the analysis, we further eliminated vessels with unknown flag state or a flag state whose vessels represented less than 1% of vessels fishing in the high seas (68 MMSIs; see table S1). An additional 32 MMSIs were identified as offsetting their true vessel positions in the southeastern Pacific Ocean to false positions near New Zealand and subsequently were removed to avoid misallocating their fishing effort and to retain conservative estimates. Retained flag states included Chinese Taipei, Republic of Korea, China, and Japan. In addition, recent reports suggest that other flag states (e.g., Iran, India, and Pakistan) actively fish within one or more of the study regions (*101*); however, since they do not transmit AIS, they were omitted for the purposes of this study, and estimates are considered conservative.

AIS vessel counts

To estimate the number of light-luring vessels operating in each region using AIS, we processed AIS data from satellite providers ORBCOMM and Spire for the study period of 2017–2020 through the GFW's data pipeline.

For the analysis of vessel mobility and regional interconnectivity, we used AIS vessel presence, counting any from the list of light-luring vessels with any AIS positions in a region as being present in that region. Two regions were considered interconnected if an MMSI was identified as being present in both regions, with regions possessing more shared MMSI considered more strongly interconnected. MMSI that were only identified in one region were considered "endemic" to that region.

For all the fishing effort analyses, AIS positions were classified as fishing or not fishing using a "night loitering" fishing algorithm. This algorithm more accurately identifies fishing by squid jiggers and other light-luring vessels that fish primarily at night while relatively stationary than the general GFW fishing classifier. This algorithm identified vessel positions as fishing when the average speed of the vessel is less than 1.5 knots for at least 4 hours during the night (between local sunset and sunrise) with an average distance of at least 10 km from shore and/or a GFW defined anchorage.

VIIRS boat detection analysis

Not all squid fishing activity can be observed using AIS as some vessels do not transmit AIS. Therefore, we additionally used VIIRS to create a more complete picture of squid fishing. Since light-luring squid fisheries are characterized by their use of strong light at night, sensitive optical satellite sensors such as VIIRS can capture the activities of squid fisheries that do not transmit AIS. VIIRS has been used to investigate light-luring fishing (*10*, *102*–*107*).

We used the VIIRS boat detection (VBD) data from Colorado School of Mines developed by Elvidge *et al.* (*107*). A limitation of the VIIRS detection data to consider in this context is that it contains more false detections around South America due to the abundance of high-energy particles in the atmosphere in the region [the South Atlantic Anomaly (SAA)] (*108*). To address the prevalence of these false detections, we developed a noise filter that we applied to the SAA. The filter distinguishes true detection and SAA noise based on the value of the radiance and spike height index (SHI), an indicator also used in the VBD algorithm (*107*). We iteratively modified the cutoff value of radiance and SHI and examined the resulting spatial distribution of the extracted VBDs until the final set of detections contained as little SAA noise as possible. Although the noise filter was designed to exclude false detections due to SAA, some true detections are likely removed as well, making the VIIRS detection counts conservative. The noise filter was only applied to a portion of the SE Pacific and the SW Atlantic region. In all other regions, VBDs that are defined as true vessel detections (i.e., QF1, QF2, QF3, and QF10) were used (see the Supplementary Materials and figs. S8 to S12 for detail).

The raw VBD counts are also influenced by cloudiness, which can obscure vessel lights, the lunar cycle, as a full moon makes it more difficult to detect vessel lights, and the fact that some parts of the ocean are imaged multiple times in a night, resulting in some vessels being double counted. To eliminate double counting, in areas with multiple satellite overpasses on a given night, we included only observations from the overpass with the smaller satellite zenith angle. The error in VIIRS detections increases with zenith angle; thus, this operation also helps to exclude erroneous VBDs. To minimize the influence of the moon and clouds, we extracted the dates where we observed the largest daily count of VIIRS in every half month following Park *et al.* (*10*). As in Park *et al.* (*10*), this analysis is reasonable because most of these high seas vessels fish in a given location longer than 2 weeks, so this maximum likely captures the number of vessels in these areas over that period. To calculate the annual aggregation of vessel days for each region, every date in each half-month period was assigned the maximum daily count for that half month and the daily counts were summed across the year. To better identify light-luring fishing vessels, we only extracted VIIRS detections with the radiance larger than 10 nW cm^{-2} sr^{-1}, as vessels engaging in pelagic light-luring activity are generally brighter than this value (*10*) (see also figs. S13 and S14 for the radiance threshold).

Matching VIIRS detections to AIS vessels

VIIRS can be used to analyze the fishing activity of light-luring vessels that do not broadcast AIS signals. However, it was unknown how much of the VIIRS detections were from vessels that do not transmit AIS (so-called "dark vessels"). In this study, we identified overlaps between VIIRS and AIS vessels and determined the percentage of VIIRS detections that are not transmitting AIS signals by using a technique that matches VIIRS detections and AIS vessels.

To match a vessel's AIS position at the time of the VIIRS satellite overpass to a VIIRS detection, we used the method described by Kroodsma *et al.* (*109*), with a few modifications. This method mines AIS data to develop probabilistic estimates of a vessel's location after a given amount of time when traveling at a given speed (probability rasters). For this study, the probability rasters were adjusted to the lower resolution of VIIRS by applying a gaussian filter with a sigma of 300 m (about half the size of a VIIRS pixel) to account for VIIRS lower resolution. These rasters are then used to assign a probability that a given vessel in AIS is at the location of a VIIRS detection at the time of the VIIRS image. In most cases, especially in the pelagic regions of this study, most VIIRS detections match to only one vessel in AIS, but in cases where multiple vessels match, the pair with the highest probability above a minimum probability threshold (score) was identified as the "best" match. The minimum threshold score was determined through manual review of candidate matches across a range of minimum thresholds (see fig. S15 for the sensitivity analysis of score threshold).

Supplementary Materials

This PDF file includes:
Supplementary Text
Figs. S1 to S15
Table S1

REFERENCES AND NOTES

1. J. A. Gephart, M. L. Pace, Structure and evolution of the global seafood trade network. *Environ. Res. Lett.* **10**, 125014 (2015).
2. FAO, *The State of World Fisheries and Aquaculture 2020* (Food and Agriculture Organization of the United Nations, 2020).
3. E. H. Allison, H. R. Bassett, Climate change in the oceans: Human impacts and responses. *Science* **350**, 778–782 (2015).
4. H. Shen, S. Huang, China's policies and practice on combatting IUU in distant water fisheries. *Aquac. Fish.* **6**, 27–34 (2021).
5. J. Yu, Q. Han, Exploring the management policy of distant water fisheries in China: Evolution, challenges and prospects. *Fish. Res.* **236**, 105849 (2021).
6. A. Ospina-Alvarez, S. de Juan, P. Pita, G. B. Ainsworth, F. L. Matos, C. Pita, S. Villasante, A network analysis of global cephalopod trade. *Sci. Rep.* **12**, 322 (2022).
7. K. L. Seto, N. A. Miller, M. Young, Q. Hanich, Toward transparent governance of transboundary fisheries: The case of Pacific tuna transshipment. *Mar. Policy* **136**, 104200 (2020).
8. 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).
9. R. B. Cabral, J. Mayorga, M. Clemence, J. Lynham, S. Koeshendrajana, U. Muawanah, D. Nugroho, Z. Anna, A. G. Mira, N. Zulbainarni, S. D. Gaines, C. Costello, Rapid and lasting gains from solving illegal fishing. *Nat. Ecol. Evol.* **2**, 650–658 (2018).
10. J. Park, J. Lee, K. Seto, T. Hochberg, B. A. Wong, N. A. Miller, K. Takasaki, H. Kubota, Y. Oozeki, S. Doshi, M. Midzik, Q. Hanich, B. Sullivan, P. Woods, D. A. Kroodsma, Illuminating dark fishing fleets in North Korea. *Sci. Adv.* **6**, eabb1197 (2020).
11. Q. Hanich, F. Teo, M. Tsamenyi, A collective approach to Pacific islands fisheries management: Moving beyond regional agreements. *Mar. Policy* **34**, 85–91 (2010).
12. MRAG, "Towards the quantification of illegal, unreported and unregulated (IUU) fishing in the Pacific Islands region" (MRAG, 2016), pp. 1–101.
13. D. Feeny, F. Berkes, B. J. McCay, J. M. Acheson, The tragedy of the commons: Twenty-two years later. *Hum. Ecol.* **18**, 1–19 (1990).
14. I. G. Baird, Chapter 3: Open to all?: Reassessing capture fisheries tenure systems in southern Laos, in *Managing Coastal and Inland Waters: Pre-existing Aquatic Management Systems in Southeast Asia*, K. Ruddle, A. Satria, Eds. (Springer Science+Business Media B.V., 2010), pp. 57–75.
15. E. H. Allison, B. Horemans, "Poverty alleviation, sustainable livelihoods and management in small-scale fisheries" (FAO Fisheries Report 782, 2005), p. 307.
16. R. I. Arthur, Small-scale fisheries management and the problem of open access. *Mar. Policy* **115**, 103867 (2020).
17. H. Eriksson, M. de la Torre-Castro, P. Olsson, Mobility, expansion and management of a multi-species scuba diving fishery in East Africa. *PLOS ONE* **7**, e35504 (2012).
18. A. Merrie, D. C. Dunn, M. Metian, A. M. Boustany, Y. Takei, A. O. Elferink, Y. Ota, V. Christensen, P. N. Halpin, H. Österblom, An ocean of surprises–Trends in human use, unexpected dynamics and governance challenges in areas beyond national jurisdiction. *Glob. Environ. Chang.* **27**, 19–31 (2014).
19. MercoPress, Argentina's EEZ "flooded" by Chinese jiggers catching tons of squid. *MercoPress*, 2020; https://en.mercopress.com/2020/04/28/argentina-s-eez-flooded-by-chinese-jiggers-catching-tons-of-squid.
20. BBC, Argentina sinks Chinese fishing boat Lu Yan Yuan Yu 010. *BBC*, 2016; https://www.bbc.com/news/world-latin-america-35815444.
21. M. Godfrey, Argentine coast guard opens fire on Chinese fishing vessel. *SeafoodSource*, 2019; https://www.seafoodsource.com/news/supply-trade/argentine-coast-guard-opens-fire-on-chinese-fishing-vessel.
22. Greenpeace, "The Wild West Atlantic: The impact of overfishing in the South-West Atlantic Ocean" (Greenpeace, 2019), p. 20.
23. C. Woody, Fleets of fishing ships are going 'dark' in the South Atlantic, and China is the leading culprit. *Business Insider*, 2021; https://www.businessinsider.com.au/chinese-fishing-vessels-going-dark-off-argentina-waters-2021-6.
24. M. Mereghetti, Chinese fleet continues to threaten Peru's giant squid fishery, group alleges. *Undercurrent News*, 2020; https://www.undercurrentnews.com/2020/12/11/chinese-fleet-continues-to-threaten-perus-giant-squid-fishery-group-alleges/.
25. Nikkei Asia, Fleet of 250 Chinese fishing boats monitored by Peru navy. *Nikkei Asia*, 2020; https://asia.nikkei.com/Politics/International-relations/Fleet-of-250-Chinese-fishing-boats-monitored-by-Peru-navy.
26. MercoPress, Some 270 Chinese jiggers catching giant squid in Peruvian EEZ; Navy monitoring the fleet. MercoPress, 2020; https://en.mercopress.com/2020/09/29/some-270-chinese-jiggers-catching-giant-squid-in-peruvian-eez-navy-monitoring-the-fleet.
27. M. Youkee, China wary of image crisis after Galapagos fishing scrutiny. *China Dialogue Ocean*, 2020; https://chinadialogueocean.net/14750-china-wary-of-image-crisis-after-galapagos-fishing-scrutiny/.
28. Y. Garcia, Chinese fishing vessels leave area near Ecuador's Galapagos. *Reuters*, 2020; https://www.reuters.com/article/us-ecuador-environment-china/chinese-fishing-vessels-leave-area-near-ecuadors-galapagos-idUSKCN26D2VK.
29. D. Collyns, Chinese fishing armada plundered waters around Galápagos, data shows. *The Guardian*, 2020; https://www.theguardian.com/environment/2020/sep/17/chinese-fishing-armada-plundered-waters-around-galapagos-data-shows.
30. Stop Illegal Fishing, China flagged vessels target unregulated North West Indian Ocean squid fishery. *Stop Illegal Fishing*, 2020; https://stopillegalfishing.com/news-articles/china-flagged-vessels-target-unregulated-north-west-indian-ocean-squid-fishery/.
31. D. Tickler, J. J. Meeuwig, K. Bryant, F. David, J. A. H. Forrest, E. Gordon, J. J. Larsen, B. Oh, D. Pauly, U. R. Sumaila, D. Zeller, Modern slavery and the race to fish. *Nat. Commun.* **9**, 4643 (2018).
32. J. S. Brashares, B. Abrahms, K. J. Fiorella, C. D. Golden, C. E. Hojnowski, R. A. Marsh, D. J. McCauley, T. A. Nuñez, K. Seto, L. Withey, Wildlife decline and social conflict. *Science* **345**, 376–378 (2014).
33. B. D. Ratner, B. Åsgård, E. H. Allison, Fishing for justice: Human rights, development, and fisheries sector reform. *Glob. Environ. Chang.* **27**, 120–130 (2014).
34. Trygg Mat Tracking, "Squid fishing in the northwest Indian Ocean: Clear as ink" (2021), p. 28.
35. Trygg Mat Tracking, WWF, "Unregulated fishing on the high seas of the Indian Ocean" (2020); https://wwfeu.awsassets.panda.org/downloads/wwftmt_unregulated_fishing_on_the_high_seas_of_the_indian_ocean_2020.pdf.
36. R. K. O'Dor, Big squid in big currents. *South Afr. J. Mar. Sci.* **12**, 225–235 (1992).
37. A. I. Arkhipkin, P. G. K. Rodhouse, G. J. Pierce, W. Sauer, M. Sakai, L. Allcock, J. Arguelles, J. R. Bower, G. Castillo, L. Ceriola, C.-S. Chen, X. Chen, M. Diaz-Santana, N. Downey, A. F. González, J. G. Amores, C. P. Green, A. Guerra, L. C. Hendrickson, C. Ibáñez, K. Ito, P. Jereb, Y. Kato, O. N. Katugin, M. Kawano, H. Kidokoro, V. V. Kulik, V. V. Laptikhovsky, M. R. Lipinski, B. Liu, L. Mariátegui, W. Marin, A. Medina, K. Miki, K. Miyahara, N. Moltschaniwskyj, H. Moustahfid, J. Nabhitabhata, N. Nanjo, C. M. Nigmatullin, T. Ohtani, G. Pecl, J. A. A. Perez, U. Piatkowski, P. Saikliang, C. A. Salinas-Zavala, M. Steer, Y. Tian, Y. Ueta, D. Vijai, T. Wakabayashi, T. Yamaguchi, C. Yamashiro, N. Yamashita, L. D. Zeidberg, World squid fisheries. *Rev. Fish. Sci. Aquac.* **23**, 92–252 (2015).
38. A. M. Cabanelas, G. D. Quelch, K. V. Kistowski, M. Young, G. Carrara, A. R. Aneiros, R. F. Artés, S. Ásmundsson, B. Kuemlangan, M. Camilleri, "Transshipment: A closer look—An in-depth

study in support of the development of international guidelines" (FAO Fisheries and Aquaculture Technical Paper No. 661, 2020), p. 661.
39. FAO, "International plan of action to prevent, deter and eliminate illegal, unreported and unregulated fishing" (FAO, 2001); https://www.fao.org/documents/card/en/c/71be21c9-8406-5f66-ac68-1e74604464e7.
40. SPRFMO, CMM 18-2020 conservation and management measure on the management of the jumbo flying squid fishery (SPRFMO, 2020).
41. Sustainable Fisheries Partnership Global Squid Supply Chain Roundtable Squid IUU Prevention Group, Public statement on squid IUU issues in global supply chains (2022); https://sustainablefish.org/roundtable/global-squid/.
42. A. Wang, China to limit squid fishing fleet over environmental concerns. *South China Morning Post*, 2021; https://www.scmp.com/news/china/diplomacy/article/3155316/china-limit-size-squid-fishing-fleet-over-environmental.
43. A. R. Rey, F. Huettmann, Telecoupling analysis of the Patagonian Shelf: A new approach to study global seabird-fisheries interactions to achieve sustainability. *J. Nat. Conserv.* **53**, 125748 (2020).
44. NPFC, Compendium of Active Conservation and Management Measures for the North Pacific Fisheries Commission (NPFC, 2019).
45. H. Welch, T. Clavelle, T. D. White, M. A. Cimino, J. V. Osdel, T. Hochberg, D. Kroodsma, E. L. Hazen, Hot spots of unseen fishing vessels. *Sci. Adv.* **8**, eabq2109 (2022).
46. K.-W. Yen, L.-C. Liuhuang, A review of migrant labour rights protection in distant water fishing in Taiwan: From laissez-faire to regulation and challenges behind. *Mar. Policy* **134**, 104805 (2021).
47. K. Boerder, N. A. Miller, B. Worm, Global hot spots of transshipment of fish catch at sea. *Sci. Adv.* **4**, eaat7159 (2018).
48. N. A. Miller, A. Roan, T. Hochberg, J. Amos, D. A. Kroodsma, Identifying global patterns of transshipment behavior. *Front. Mar. Sci.* **5**, 50–59 (2018).
49. X. Chen, B. Liu, Y. Chen, A review of the development of Chinese distant-water squid jigging fisheries. *Fish. Res.* **89**, 211–221 (2008).
50. C. T. Masuo, China's "National Spatial Infrastructure" and global governance: Chinese way of Military–Civil Fusion (MCF) over the ocean. *Marit. Aff. J. Natl. Marit. Found. India* **17**, 27–42 (2021).
51. J. Goodman, Great Wall of Lights: China's sea power on Darwin's doorstep. *Associated Press*, 2021; https://apnews.com/article/china-oceans-overfishing-squid-294ff1e489589b2510cc806ec898c78f.
52. S. Chen, How China's squid fishing programme is squeezing its neighbours and creating global sea change. *South China Morning Post*, 2018; https://www.scmp.com/news/china/society/article/2150956/how-chinas-squid-fishing-programme-squeezing-its-neighbours-and.
53. Oceana, "Oceana finds 300 Chinese vessels pillaging the Galapagos for squid" (Oceana, 2020), pp. 1–8.
54. K. Miki, N. Miki, "Development and structure of Japan's squid fishing industry: Globalized production, distribution, processing, and consumption" (Agriculture and Forestry Statistics Publishing Inc., 2021), p. 488.
55. Instituto del Mar del Perú, "Situación del calamar gigante durante el 2020 y perspectivas de pesca para el 2021" (Instituto del Mar del Perú, 2021); https://cdn.www.gob.pe/uploads/document/file/2065465/Informe-correspondiente-Oficio-199-2021-IMARPE-PCD.pdf.
56. L. M. Custodio, "Artisanal squid fishing in Peru threatened by international fleets" (Latin America's Environmental Policies in Global Perspective, Wilson Center, 2021); https://www.wilsoncenter.org/sites/default/files/media/uploads/documents/Artisanal%20Squid%20Fishing%20by%20Leslie%20Moreno%20Custodio%2011.1.pdf.
57. C4ADS, "Who controls the distant water squid fishing fleet? An investigation into the ownership of squid fishing vessels operating in the Southeast Pacific Ocean" (C4ADS, 2022).
58. A. I. Arkhipkin, L. C. Hendrickson, I. Payá, G. J. Pierce, R. H. Roa-Ureta, J.-P. Robin, A. Winter, Stock assessment and management of cephalopods: Advances and challenges for short-lived fishery resources. *ICES J. Mar. Sci.* **78**, 714–730 (2021).
59. R. Wiff, R. ´en H. Roa-Ureta, Regional stock assessment of the flying jumbo squid in the South-Eastern Pacific: A conceptual proposal, in *SPRFMO 9th Meeting of the Scientific Committee* (SPRFMO, 2021), *SC9-Obs04*.
60. A. I. Arkhipkin, C. M. Nigmatullin, D. C. Parkyn, A. Winter, J. Csirke, High seas fisheries: The Achilles' heel of major straddling squid resources. *Rev. Fish Biol. Fish.* **235**, 1 (2022).
61. J. Wang, Y. Jiang, J. Zhang, X. Chen, D. Kitazawa, Catch per unit effort (CPUE) standardization of Argentine shortfin squid (*Illex argentinus*) in the Southwest Atlantic Ocean using a habitat-based model. *Int. J. Remote Sens.* **41**, 9309–9327 (2020).
62. P. Chen, X. Chen, W. Yu, D. Lin, Interannual abundance fluctuations of two oceanic squids in the Pacific Ocean can be evaluated through their habitat temperature variabilities. *Front. Mar. Sci.* **8**, 770224 (2021).
63. H. Han, C. Yang, H. Zhang, Z. Fang, B. Jiang, B. Su, J. Sui, Y. Yan, D. Xiang, Environment variables affect CPUE and spatial distribution of fishing grounds on the light falling gear fishery in the northwest Indian Ocean at different time scales. *Front. Mar. Sci.* **9**, 939334 (2022).
64. H. Moustahfid, L. C. Hendrickson, A. Arkhipkin, G. J. Pierce, A. Gangopadhyay, H. Kidokoro, U. Markaida, C. Nigmatullin, W. H. Sauer, P. Jereb, G. Pecl, T. de la Chesnais, L. Ceriola, N. Lazar, C. J. Firmin, V. Laptikhovsky, Ecological-fishery forecasting of squid stock dynamics under climate variability and change: Review, challenges, and recommendations. *Rev. Fish. Sci. Aquac.* **29**, 1–36 (2021).
65. F. Powell, A. Levine, L. Ordonez-Gauger, Climate adaptation in the market squid fishery: Fishermen responses to past variability associated with El Niño Southern Oscillation cycles inform our understanding of adaptive capacity in the face of future climate change. *Clim. Change* **173**, 1 (2022).
66. P. G. K. Rodhouse, G. J. Pierce, O. C. Nichols, W. H. H. Sauer, A. I. Arkhipkin, V. V. Laptikhovsky, M. R. Lipiński, J. E. Ramos, M. Gras, H. Kidokoro, K. Sadayasu, J. Pereira, E. Lefkaditou, C. Pita, M. Gasalla, M. Haimovici, M. Sakai, N. Downey, Environmental effects on cephalopod population dynamics: Implications for management of fisheries. *Adv. Mar. Biol.* **67**, 99–233 (2014).
67. S. Nishijima, H. Kubota, T. Kaga, S. Okamoto, H. Miyahara, H. Okamura, State-space-modeling clarifies productivity regime shifts of Japanese flying squid. *Popul. Ecol.* **63**, 27–40 (2021).
68. W. Yu, J. Wen, X. Chen, Y. Gong, B. Liu, Trans-Pacific multidecadal changes of habitat patterns of two squid species. *Fish. Res.* **233**, 105762 (2021).
69. Y. Zhang, W. Yu, X. Chen, M. Zhou, C. Zhang, Evaluating the impacts of mesoscale eddies on abundance and distribution of neon flying squid in the Northwest Pacific Ocean. *Front. Mar. Sci.* **9**, 862273 (2022).
70. Q. Ren, M. Liu, Assessing Northwest pacific fishery stocks using two new methods: The Monte Carlo Catch-MSY (CMSY) and the Bayesian Schaefer Model (BSM). *Front. Mar. Sci.* **7**, (2020).
71. Y. Liu, X. Xia, Y. Tian, I. D. Alabia, S. Ma, P. Sun, S.-I. Saitoh, Influence of spawning ground dynamics on the long-term abundance of Japanese flying squid (*Todarodes pacificus*) winter cohort. *Frontiers Mar. Sci.* **8**, 659816 (2021).
72. Z. Chun, China announces closed season on squid spawning grounds. *China Dialogue Ocean*, 2020; https://chinadialogueocean.net/14146-china-announces-closed-season-squid-spawning-grounds/.
73. L. Hao, Independent fishing moratorium on squid fisheries on the high seas. *Zhoushan Daily*, 2020; http://www.zhoushan.cn/newscenter/zsxw/202004/t20200419_969166.shtml.
74. H. Siyi, Squid off the menu. *News China*, 2020; https://www.pressreader.com/china/newschina/20201024/281569473099178.
75. L. Harkell, New Indian Ocean squid fishery sees drop in catch. *Undercurrent News*, 2022; https://www.undercurrentnews.com/2022/04/13/new-indian-ocean-squid-fishery-sees-drop-in-catch/.
76. C. Molinari, SPRFMO risks "non-cooperative" consideration in fight against IUU, CALAMASUR warns. *SeafoodSource*, 2022; https://www.seafoodsource.com/news/environment-sustainability/sprfmo-risks-non-cooperative-consideration-in-fight-against-iuu-calamasur-warns?utm_source=marketo&utm_medium=email&utm_campaign=newsletter&utm_content=newsletter&mkt_tok=NzU2LUZXSi0wNjEAAAGCoyLfnqfbVBYITp7N0guXPAkH_Am8qftdiVr78e7ckUoYiSdesm9_dAZKLvV_2C9iS27t8GAO64eznWGigOx9a6ho6LU0MefkrTUXxBr63cCWdRo.
77. G. G. McDonald, C. Costello, J. Bone, R. B. Cabral, V. Farabee, T. Hochberg, D. Kroodsma, T. Mangin, K. C. Meng, O. Zahn, Satellites can reveal global extent of forced labor in the world's fishing fleet. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2016238117 (2021).
78. A. M. Song, J. Scholtens, K. Barclay, S. R. Bush, M. Fabinyi, D. S. Adhuri, M. Haughton, Collateral damage? Small-scale fisheries in the global fight against IUU fishing. *Fish Fish* **21**, 831–843 (2020).
79. B. L. Gallic, A. Cox, An economic analysis of illegal, unreported and unregulated (IUU) fishing: Key drivers and possible solutions. *Mar. Policy* **30**, 689–695 (2006).
80. Falkland Islands Fisheries Department, Managing Falkland Islands fisheries since 1987; https://www.falklands.gov.fk/fisheries/.
81. J. J. A. Blair, South Atlantic universals: Science, sovereignty and self-determination in the Falkland Islands (Malvinas). *Tapuya: Latin Am. Sci. Technol. Soc.* **2**, 220–236 (2019).
82. S. Dunne, thesis, University of Edinburgh (2017).
83. Falkland Islands Government, "Fisheries Statistics 2020 Volume 25 (2011–2020)" (Stanley, FIG Fisheries Department, 2021), p. 98.
84. J. Yu, Q. Han, Exploring the management policy of distant water fisheries in China: Evolution, challenges and prospects. *Fish. Res.* **236**, 105849 (2021).

85. D. Tickler, J. J. Meeuwig, M.-L. Palomares, D. Pauly, D. Zeller, Far from home: Distance patterns of global fishing fleets. *Sci Adv.* **4**, eaar3279 (2018).
86. J. S. Barkin, E. R. DeSombre, Do we need a global fisheries management organization? *J Environ Stud Sci.* **3**, 232–242 (2013).
87. SPRFMO, G10-2022 Decisions adopted by the 10th Meeting of the SPRFMO Commission.pdf (2022).
88. Government of Ecuador, G11–2022 Ecuador Statement made after SPRFMO COMM10 (2022).
89. CALAMASUR, G12-2022 CALAMASUR Statement made after SPRFMO COMM10.pdf (2022).
90. J. Goodman, South America squid left exposed amid surge in China fishing. *Associate Press*, 2022; https://apnews.com/article/business-china-south-america-squid-f4092351b2c070d515e87fb408c7d01d.
91. K. P. Andersson, E. Ostrom, Analyzing decentralized resource regimes from a polycentric perspective. *Policy Sci.* **41**, 71–93 (2008).
92. E. Ostrom, Beyond markets and states: Polycentric governance of complex economic systems. *Am. Econ. Rev.* **100**, 641–672 (2010).
93. K. Carlisle, R. L. Gruby, Polycentric systems of governance: A theoretical model for the commons. *Policy Stud. J.* **47**, 927–952 (2019).
94. F. Berkes, ECOLOGY: Globalization, roving bandits, and marine resources. *Science* **311**, 1557–1558 (2006).
95. T. Appelhans, F. Detsch, C. Reudenbach, S. Woellauer, mapview: Interactive viewing of spatial data in R (2021); https://CRAN.R-project.org/package=mapview.
96. T. Appelhans, K. Russell, L. Busetto, J. O'Brien, J. Gutschlhofer, mapedit: Interactive editing of spatial data in R (2020); https://cran.r-project.org/web/packages/mapedit/index.html.
97. R Core Team, *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, 2022); https://www.R-project.org/.
98. Flanders Marine Institute, Marine Regions v. 11 (2022); www.marineregions.org.
99. 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).
100. Stop Illegal Fishing, Trygg Mat Tracking, NFDS, "Squid capture in the Northwest Indian Ocean: Unregulated fishing on the high seas" (Gaborone, Botswana, 2017).
101. C. Kilgour, D. Copeland, "Illegal fishing hotspot identified in Northwest Indian Ocean" (2020); https://globalfishingwatch.org/impacts/illegal-fishing-northwest-indian-ocean/.
102. F. C. Hsu, C. D. Elvidge, K. Baugh, M. Zhizhin, T. Ghosh, D. Kroodsma, A. Susanto, W. Budy, M. Riyanto, R. Nurzeha, Y. Sudarja, Cross-matching VIIRS boat detections with vessel monitoring system tracks in Indonesia. *Remote Sens. (Basel)* **11**, 995 (2019).
103. J. Li, P. Zhang, Y. Cai, Q. Zhang, K. Zhang, Z. Jing, Q. Wu, Y. Qiu, S. Ma, Z. Chen, Performance of VMS and nightly satellite in monitoring light fishing vessels in the open South China Sea. *Fish. Res.* **243**, 106100 (2021).
104. J. Ruiz, I. Caballero, G. Navarro, Sensing the same fishing fleet with AIS and VIIRS: A seven-year assessment of squid jiggers in FAO major fishing area 41. *Remote Sens. (Basel)* **12**, 32 (2020).
105. R. K. Sarangi, S. N. N. Jaiganesh, VIIRS boat detection (VBD) product-based night time fishing vessels observation in the Arabian Sea and Bay of Bengal Sub-regions. *Geocarto Int.* **37**, 3504–3519 (2021).
106. R. C. Geronimo, E. C. Franklin, R. E. Brainard, C. D. Elvidge, M. D. Santos, R. Venegas, C. Mora, Mapping fishing activities and suitable fishing grounds using nighttime satellite images and maximum entropy modelling. *Remote Sens. (Basel)* **10**, 1604 (2018).
107. C. Elvidge, M. Zhizhin, K. Baugh, F.-C. Hsu, Automatic boat identification system for VIIRS low light imaging data. *Remote Sens. (Basel)* **7**, 3020–3036 (2015).
108. F. J. Pavón-Carrasco, A. D. Santis, The South Atlantic anomaly: The key for a possible geomagnetic reversal. *Front. Earth Sci.* **4**, (2016).
109. D. Kroodsma, T. Hochberg, P. Davis, F. Paolo, R. Joo, B. Wong, Revealing the global longline fleet with satellite radar. *Sci. Rep.* **12**, 21004 (2022).

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