

Title: Actions at port are essential for ending illegal, unreported and unregulated fishing

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Abstract

The Port State Measures Agreement (PSMA) provides a legally-binding mechanism to deter illegal, unreported and unregulated (IUU) fishing by foreign vessels through standardized reporting, inspections, information sharing, and port denial. To be more effective, region-wide adoption and consistent implementation of PSMA are essential for ensuring IUU fishing vessels cannot easily land catches with identities that will receive less scrutiny or in locations with weaker governance. The PSMA also recognizes the centrality of tackling IUU fishing in domestic fleets, which account for more than 90% of port visits. Port State measures aligned with PSMA need to be applied to these fleets to prevent the flag-switching that allows vessels to dodge oversight. Accelerating adoption and implementation of PSMA as well as extending port State measures to domestic fleets is crucial for reducing opportunities to hide illegal catches and maximize the potential of actions at port to address IUU fishing.

One-Sentence Summary: Reducing IUU fishing risks will depend on consistent, regional implementation of effective port State measures across both foreign and domestic fleets.

Keywords: Fisheries, Food Systems, Illegal Fishing, Policy, Ports, Seafood, Sustainability

Main Text:

Illegal, unreported and unregulated (IUU) fishing is a global threat to the environmental sustainability of fisheries (1), jeopardizing the health, livelihoods and economies of coastal communities and nations (2) by diverting nutrients and revenues (3) away from places where they are most needed. In West Africa alone, IUU catches result in \$2.3 – 9.4 billion annually in economic losses (4, 5). IUU fishing can also trigger and aggravate international conflicts (2, 6), a major barrier to creating durable, effective management. On paper, eliminating IUU fishing is a clear priority, codified by the United Nations' Sustainable Development Goals (Target 14.4), embraced by industry actors in multiple voluntary commitments (7-9), and pursued by diverse civil society actors (10). However, progress on reducing IUU fishing has remained elusive partly because of the complexity of monitoring fishing activities across fragmented jurisdictions at sea. Ports are places where monitoring and enforcement, including seizure of IUU catches, are logistically easier and more cost-effective. Jurisdiction within ports is also simpler, so legal and policy frameworks can provide greater accountability (11).

Consequently, achieving commitments to end IUU fishing will largely depend on transforming ports associated with IUU fishing into hubs of effective governance. A key tool for achieving this goal is the United Nations Food and Agriculture Organization's Agreement on Port State Measures to Prevent, Deter and Eliminate IUU Fishing, or the Port State Measures Agreement (PSMA). The PSMA entered into force in 2016 (12) and has provisions largely focused on foreign vessels. Although more than 70 States and the European Union have adopted and become Parties to PSMA, several important fishing and port States have not. In addition, some States have existing regulations aligned with PSMA and others have implemented port State measures designed to be as effective as PSMA because of their inability to join international agreements. Without region-wide effective implementation of PSMA or these aligned port State measures, vessels with higher IUU fishing risks can more easily shift to landing their catches at ports not subject to PSMA, facilitating continued IUU fishing.

At the same time, governments need to extend measures like those specified in PSMA to domestic vessels (13). Within the PSMA, Article 20 paragraph 6 specifies that Parties should control IUU fishing by their domestic vessels using measures that are at least as effective as those for foreign vessels, although there is no specification that the approaches must be the same (14). An initial focus on PSMA adoption and implementation has resulted in overlooking controls for domestic fleets. Yet, they are paramount to PSMA's long-term success. Port State measures for domestic fleets are logistically easier, more cost-effective than enforcement at sea (15), and would dovetail with current efforts to establish traceability in supply chains (7, 8). Applying measures like those specified in PSMA to domestic fleets will also deter vessels from using domestic flags to avoid robust port controls. By implementing PSMA across regions and fleets, governments can ensure that there are no easy places to land IUU fishing catches.

Ensure regional adoption of PSMA

The PSMA provides legal mechanisms to move towards practices that support more sustainable fishing by obligating Parties to deny foreign fishing vessels and support vessels (i.e., transshipment vessels and fueling or bunker vessels) entry to their ports if they are engaged in or supporting IUU fishing (12). The PSMA also requires Parties to designate ports for foreign

vessel visits, implement standardized entry requirements and inspections, and then deny port access if they find the vessel is linked to IUU fishing. (12). It further stipulates that Parties cooperate and exchange information with each other and relevant governance bodies.

The effectiveness of PSMA will depend on which States have adopted, how well they have implemented it, and where they are geographically located relative to each other (Fig. 1) (16). For the initial 29 Parties¹, landings from foreign vessels had a smaller proportion of those States' total landings than States who had not adopted PSMA², which means they would have had fewer vessels subject to PSMA in 2016. States with substantial foreign vessel landings (Fig. 1) will need to adopt and effectively implement PSMA for it to have the greatest impact on reducing IUU fishing risks from foreign vessels. As more States adopt and become Parties to PSMA, they can accelerate impact by making it harder for vessels to reach non-PSMA ports where they may face less scrutiny (Fig. 1).

Region-wide adoption and consistent implementation of PSMA is needed to address rather than displace IUU fishing vessels, particularly to less well-resourced States. If vessels can easily land catches at other ports, they not only undermine PSMA, but also perpetuate IUU fishing risks (17). Previous research has shown that vessels with greater risks of IUU fishing made fewer port visits to PSMA Parties after adoption, compared to visits to non-PSMA Parties (18).³ In other words, higher risk vessels perceive PSMA to be effective. Similarly, we found the fraction of fishing effort (i.e., number of landed fishing hours per port visit by vessels flagged to non-PSMA States visiting PSMA ports dropped steadily from 43.6% in 2016 to 28.0% in 2021 while the fraction of fishing effort by vessels flagged to PSMA Parties visiting PSMA ports remained practically unchanged, despite an increase in PSMA Parties (Supplementary Materials; fig. S1). Vessels flagged to non-PSMA States are not necessarily more likely to be engaged in IUU fishing, but an increased use of non-PSMA ports may mean less rigorous port State measures.

These findings highlight the potential of PSMA to deter landing IUU catches, and the importance of region-wide adoption and implementation. States that rigorously implement PSMA have a responsibility and vested interest in ensuring its effective implementation by their neighbors so that IUU fishing activities are not simply moved elsewhere. In addition, losing port visit revenues after having invested resources in PSMA may undermine future financial and social viability for similar efforts.

Implement port State measures for domestic fleets

IUU fishing is not solely a foreign vessel problem. The PSMA's Article 20 also recognizes the importance of addressing IUU fishing by domestic fleets. Implementing effective port State measures for domestic fleets are a promising way to fulfill the ambitions of PSMA to eliminate IUU fishing because domestic vessels account for the vast majority of port visits (Fig. 2). A focus on domestic vessels is also exigent because many vessels operate within domestic

¹ The European Union approved as a single signature on behalf of its Member States.

² In 2016, landings, binomial GLM, $z=-102.362$, $p < 0.001$.

³ Higher risk vessels include those flagged to particular States associated with poor control of corruption, intermediate levels of ownership by States other than the flag State, and low fidelity to the flag State's EEZ (18, 19).

‘closed loops’, some States extend ‘domestic’ status to their territories even when they use different flags, and foreign vessels can shift to the flag of the port State when landing catches (Fig. 2) (19).

Based on Automatic Identification System (AIS) vessel position data, 98% of port visits by fishing vessels and 49% of visits by support vessels in 2021 were by domestic fleets (Fig. 2; Supplementary Materials; table S1). These numbers are likely underestimated, given AIS is used primarily by large commercial vessels that are more likely to operate beyond national waters (20), so do not include many commercial or small-scale fishing vessels.

The relative magnitude of domestic fleet port visits and domestic ‘closed loops’, where the flag State of the fishing vessel is the same as the port State where they land those catches, sometimes enabled by moving catches to transshipment vessels with the same flag (Fig. 2), underscore the need for effective port State measures for domestic fleets. For example, in 2021, the Russian fleet had 969 fishing and 151 transshipment vessels, which used Russian ports for 83% of their total visits, a consistent increase from 2015 when 58% of visits were to Russian ports (Supplementary Materials). Closed loops may be beneficial where governance is strong, but they can facilitate concealment of IUU fishing activities where governance is weak by providing less opportunity for transparency or due diligence.

In parallel, some Parties to PSMA treat ships flagged to their overseas territories as if they were domestic vessels (Fig. 2). For example, in the UK, the Red Ensign Group collectively grants the Crown Dependencies and the UK Overseas Territories reciprocal privileges when entering each other’s ports (Supplementary Materials). In 2021, 14% of fishing vessels that used AIS transmitters had sovereign-territory relationships (Supplementary Materials). Vessels flagged to some of these territories are associated with higher IUU fishing or transshipment risks (18), so it is important that States ensure consistent port State measures across these networks.

Finally, switching to the flag of the port State for landing, a practice known as flag ‘domestication’, can allow foreign vessels to bypass PSMA standards (Fig. 2). Re-flagging can be a positive strategy where the port State has strong governance in place, but it may also be problematic where monitoring of the domestic fleet is not rigorous. An increase in flag domestication is evident in select PSMA Parties, including Namibia, Chile, New Zealand, and Senegal, although the specific drivers and impacts of these shifts may vary (Supplementary Materials; fig. S2). For these States, more than 80% of foreign vessels have re-flagged to the port State since 2016 (fig. S2). These vessels are likely no longer subject to PSMA standards, unless similar or more stringent standards are applied to domestic vessels. Applying port State measures to domestic vessels could disincentivize opportunistic flag switching. Together, these scenarios highlight the importance of harmonizing port State measures across domestic and foreign fleets.

Foster a shared responsibility

Recent calls for action on IUU fishing have focused on safeguarding the ocean for food security and the livelihoods of millions of fisheries-dependent people. The PSMA is an important tool for eliminating the IUU fishing that imperils those benefits, but success will depend on States cooperating to ensure robust, consistent implementation and extending similar port State Measures to their domestic fleets. Gaps in effective implementation allow IUU fishing vessels to

move to the least well-regulated fisheries, ports or coastal States, exacerbating underlying equity disparities. Creating a minimum standard across all vessels will also deter flag behavior that undermines PSMA. For States committed to effectively managing their domestic fleets, the pay-off can be less IUU fishing pressure on their stocks, which together with effective fisheries management and good governance, can contribute to nutritional and economic benefits to their coastal populations.

Information sharing is also an essential component of ensuring that all Parties have the knowledge they need to deny port access to vessels engaged in IUU fishing. As of spring 2023, only 60% of the current Parties have uploaded designated ports in the online application designed for sharing them⁴. Addressing gaps in resourcing and barriers to information sharing will be critical for making PSMA effective (13).

Governments are responsible for the implementation of PSMA, but complementary measures by regional bodies and private sector actors can help to reinforce these efforts. Seafood companies can create traceability practices to promote transparency and work with government actors to ensure ports that are important to their business have robust port State measures. Fishing has always been dynamic and responsive to changes in weather, stocks, and trade. Actions to reduce IUU fishing will need to be similarly nimble and anticipate the challenges that are already emerging, to truly ‘close the net’ on IUU fishing.

⁴ [Operational Resources | Agreement on Port State Measures \(PSMA\) | Food and Agriculture Organization of the United Nations \(fao.org\).](#)

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Figure 1. Importance of regional adoption of the Port States Measures Agreement (PSMA) by States with a high percentage of foreign vessel visits. The number and spatial configuration of current PSMA Parties as of March 15, 2023 (upper panel) affects how easy it may be to land

at ports not governed by PSMA in some parts of the world. Regional coordination on implementation will be particularly important to avoid vessels shifting to potentially more weakly governed ports in PSMA Parties or non-PSMA States. Adoption and effective implementation is particularly important for States with substantial foreign vessel visits (lower panel). Only States with more than 50 foreign vessel visits are shown. China and Chinese Taipei are not counted as foreign vessel visits to each other's ports. Port visits by vessels with unknown flag identities are excluded (Supplementary Materials).

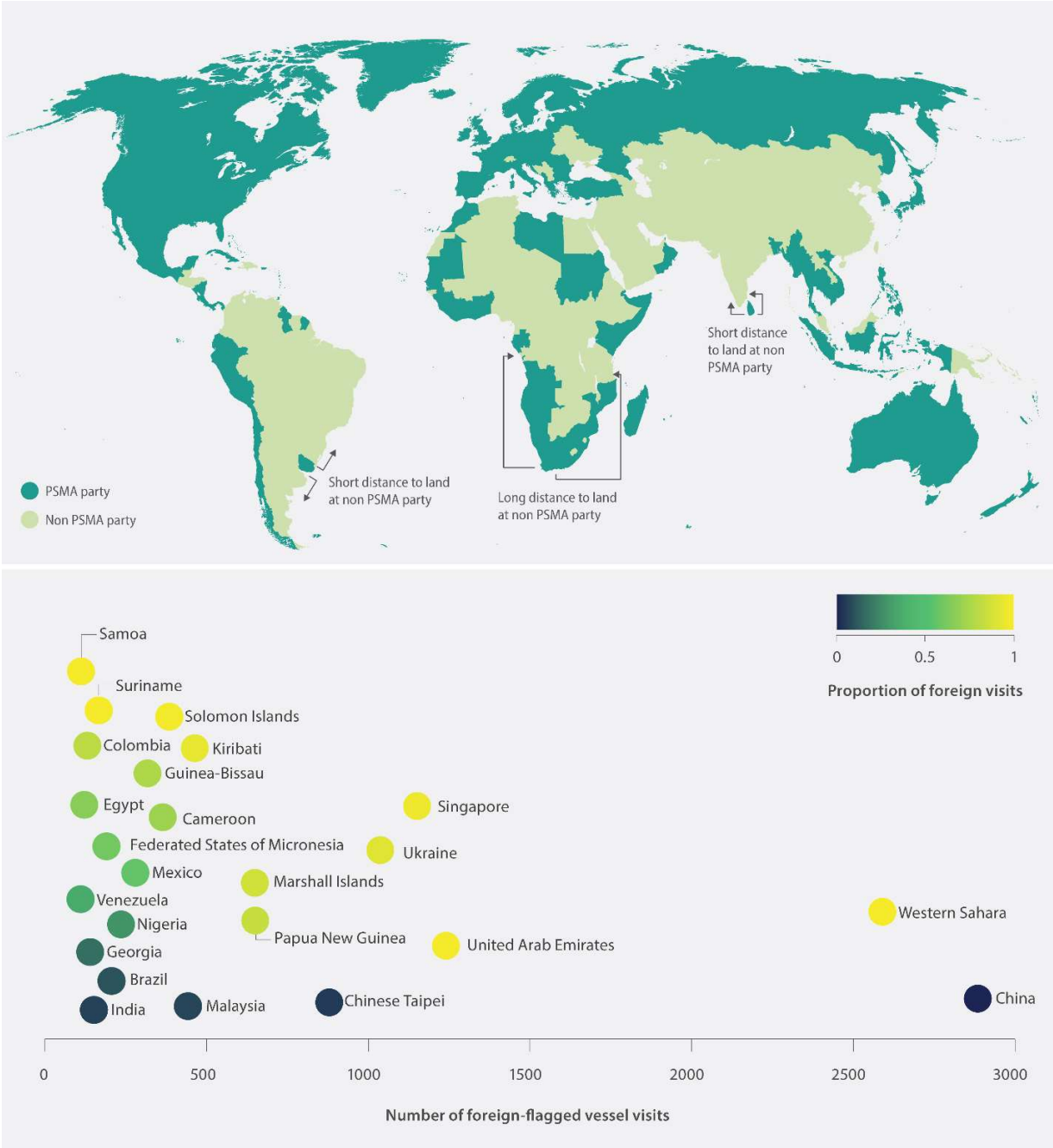
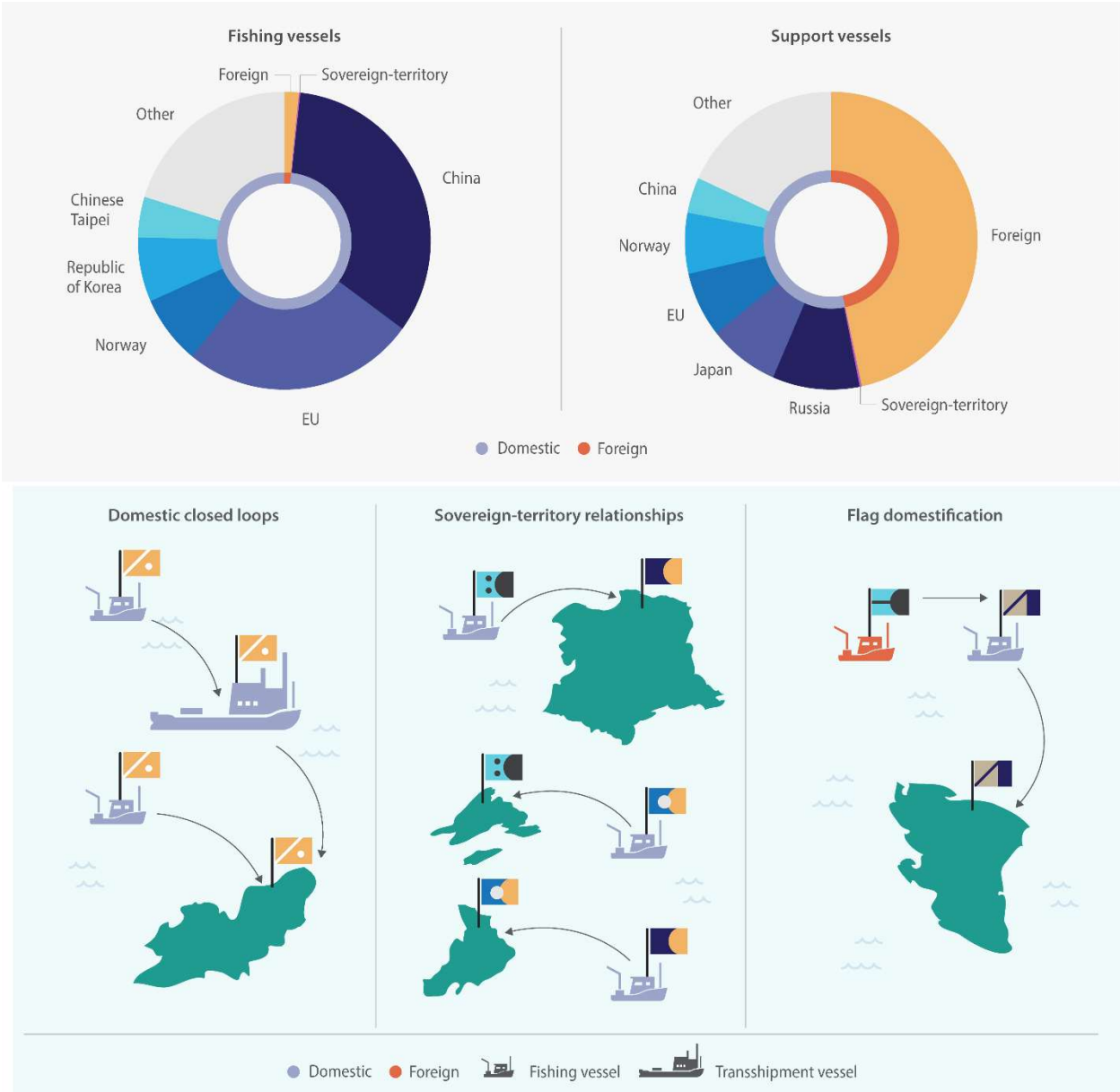


Figure 2. Importance of creating consistent port State measures across foreign and domestic fleets.

Port State measures for domestic fleets need to be at least as stringent as those applied to foreign vessels because of the high proportion of port visits by domestic vessels compared to foreign fishing and support vessels (upper panels) . We consider ‘foreign’ to represent vessels that fly a different flag from the port State. Vessels can also use domestic flags to avoid potential port State measures through three pathways (lower panels): domestic closed loops, where the flag of the fishing vessel and transshipment vessels, if used, are the same as the flag of the port State where catches are landed; sovereign-territory relationships where territorial-flagged vessels are treated as domestic vessels; and flag domestication, where foreign vessels shift to the flag of the port State where they are landing catches.



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Supplementary Materials

Supplementary Text

Figs. S1 – S3

Tables S1 – S2

5 References (21 - 28)

Supplementary Text

AIS data

To analyze fishing and fishing support vessels' behavior, including fishing activities, port visits, transshipment, and changes of vessel identity (such as name, flag, and international radio call sign), we used automatic identification system (AIS) data from Global Fishing Watch (GFW), a non-profit organization that curates AIS data for vessel movement along with relevant satellite imagery data. AIS is a radio trans-receiver system originally designed for ship-to-ship communication using terrestrial receivers and satellite receivers, but its positional data has been increasingly used to monitor human activities at sea, including fishing (21-23). AIS has two main limitations - limited use across fleets and susceptibility to tampering. Only a small fraction of the world's fishing vessels are mandated to use AIS, generally only those over 300 gross tons, although some regions like the European Union mandate its use for all vessels over 15 meters (21). Most vessels operating within a State's Exclusive Economic Zone (within 200 nautical miles of the coastline) use vessel monitoring systems (VMS), which are typically only accessible by government bodies. AIS is much more publicly available through various platforms compared to VMS and it provides frequent positional messages, allowing for a high resolution view of vessels' activity. GFW has processed available AIS data to create the largest existing database of fishing activity in the world's oceans, which has been used to investigate patterns of fishing and fishing-associated activities at broad scales (18, 24-27). Data used in all analyses reported in this study were extracted from GFW databases in November 2022, and reflect updates up to that date. The AIS analyses that underpin this study span the years 2016 to 2021.

Vessel visits to port

We used AIS data to identify vessel visits to specific ports. To ascertain that a vessel is in port, we used an algorithm that identifies a vessel's port visit based on two different distance thresholds: 1) a vessel is considered to be at anchorage when it comes within three kilometers of an anchorage point; and 2) a vessel is considered to exit an anchorage when it is more than four kilometers off the anchorage point. The four kilometer threshold helps to distinguish between vessel navigating along the 3-km circumference of an anchorage point and those actually moving to anchor. This set of two thresholds allows us to avoid situations where a vessel continuously enters and exits an anchorage (e.g., a vessel traveling along coastlines and repeatedly coming within close proximity of several anchorages). To distinguish actual visits from coastal transits, we further refined our approach to identify when a vessel is considered to be stopping near an anchorage. A vessel is considered to have "stopped" at an anchorage when its speed drops below 0.2 knots, and the vessel is considered to be exiting a given anchorage when its speed rises above 0.5 knots. AIS is often switched off when a vessel enters an anchorage and turned back on when it leaves. As a result, the model also tracks anchorage "gaps," where a vessel that has entered an anchorage and does not broadcast on AIS for at least four hours. We consider *port visits* to be all instances where a vessel is in port and has either a port stop, as described above, or a port gap event. While visits occur at the level of an anchorage, we cluster the individual anchorage points into an associated port using existing port databases and manual review (18). Data from this model were used to identify patterns in foreign vessel visits to PSMA Parties and those that have not adopted PSMA (Fig. 1).

Quantifying patterns of fishing vessels' port visits

Vessel flag identities used in our analyses were extracted from the GFW database. The flag information was compiled and cross-checked through AIS data, registry information, and expert reviews (28). We then tracked the change in the fraction of fishing vessels visiting ports within Parties to PSMA (hereafter referred to as PSMA ports or PSMA Parties).

We used *landed fishing hours* as a metric for a port visit, instead of *number of visits*, to better reflect the magnitude of importance per visit, as previously used in Boerder *et al.* (25). The *fishing hours* are calculated based on GFW's neural network model (20) of fishing effort by fishing vessels measured in hours. *Landed fishing hours* are the sum of fishing hours by a fishing vessel between its previous point of landing (or transshipment) and its current landing port. We make two assumptions for this analysis. When a fishing vessel visits a port, we consider that vessel to land all fishing effort between its previous landing port and the current landing port. In addition, when a fishing vessel meets a transshipment vessel at sea after leaving its previous port and before arriving at the current port, it transfers all of its fishing effort to the transshipment vessel, and that transshipment vessel then lands all received fishing effort to the next port the transshipment vessel visits. In other words, the metric of landed fishing hours represents a proxy for how much fishing has been done before arriving at port and a general indication for catch volume, although catch volume may not be necessarily proportionate to unit effort (hour) and may depend on many factors including fishing gear types.

We excluded port visits by vessels fishing mostly in domestic waters (i.e., >95% of a vessel's fishing hours) from the analysis. These domestic vessels can represent a large proportion of the fleet in a given State, but AIS is inconsistent in its coverage of domestic fleets. Excluding the domestic-only vessels corrects potential biases in our analysis (28). We focused analyses on foreign fishing vessels and domestic vessels that fish outside domestic waters, which will more uniformly use AIS, to ensure comparability of results across States. By restricting the analysis to foreign fishing vessels and domestic vessels that fish outside domestic waters, our results more clearly reflect how PSMA adoption has affected their vessel (landing) behavior.

When we analyzed the ratio of landed fishing hours by vessels flagged to PSMA vs. non-PSMA States between 2016 and 2021, we found a doubling in domestic landing (i.e., the vessel flag and the port State where catches are landed are the same) for all vessels flagged to non-PSMA States combined (fig. S1). This trend is mostly driven by China. The proportion of domestic landings increased by 2.4 times for China, compared to 1.7 times by other non-PSMA States. Conversely, in aggregate, vessels flagged to Parties to the PSMA show no significant change over the same time period. Among PSMA Parties, the Republic of Korea had a distinct pattern with its domestic landing fraction dropping from 75% in 2016 to 41% in 2021.

Magnitude of foreign and domestic vessel visits

To understand the magnitude of port visits by domestic vessels, we calculated the proportion of port visits by vessels using port State flags relative to the number port visits by any vessel in 2021. We used the port visit data from the GFW database (retrieved on November 14, 2022). For support vessels, we included transshipment vessels like reefers and specialized reefers as well as bunker vessels, as defined by GFW. In the analysis, we exclude port visits less than 3 hours or in the Panama Canal because of the time it takes to clear the Canal. Because these

patterns could be influenced either by Covid or by the dominance of the Chinese fleet in the dataset, we also examined results in 2019 and without the Chinese fleet (tables S1 and S2). Results were comparable across years and with the exclusion of the Chinese fleet.

5 ***Relationships between sovereign and territorial States***

Relationships between sovereign and territorial States were defined according to data from Marine Regions (<https://www.marineregions.org/>). Combining this dataset with AIS data, we categorized and analyzed the behavior of territorial- and sovereign-flagged vessels that are Parties to PSMA, either independently or through adoption by the sovereign State. Most territorial flags identified in this analysis are associated with sovereign States including Denmark, France, and the United Kingdom. Both France and the United Kingdom have more than 10 associated territorial flags. For the Red Ensign group in the United Kingdom, we included the Crown Dependencies (Isle of Man, Guernsey and Jersey) and the UK Overseas Territories (Anguilla, Bermuda, British Virgin Islands, Cayman Islands, Falkland Islands, Gibraltar, Montserrat, St Helena and the Turks & Caicos Islands), and the Pitcairn Islands. We found that territorial-flagged vessels visit ports in sovereign States less often than sovereign-flagged vessels visit ports in territorial States. The number of vessels flying these flags in our data increased by 30-50% between 2016 and 2021. More than 250 vessels fly the flags of Faroe Islands and Greenland, both of which are part of the Kingdom of Denmark. We excluded China and Chinese Taipei, Hong Kong, and Macau from this analysis because the size of the Chinese fleet dominates the AIS dataset and would bias the results. In addition, most Chinese-flagged vessels return to ports in mainland China.

Territorial flagged-vessels could enjoy the same rights as domestic vessels and be exempt from inspection for foreign vessels according to the PSMA. National regulations will determine how sovereign and territorial fleets are treated when landing at each others' ports. Nevertheless, our analysis suggests that greater attention may be warranted to ensure that those regulations are in place. In 2021, about 110 port visits with up to 7,000 fishing hours were landed by territorial-flagged vessels to sovereign ports. While it represents roughly only 1% of total port visits and fishing hours landed in the same ports, these numbers have gradually increased since 2017. Most of these port visits were conducted by vessels flying the flags of Faroe Islands or Greenland visiting Danish ports. Results underscore the importance of ensuring a clear understanding of how sovereign and territorial flags are treated, to ensure consistent and comprehensive application of port State measures.

35 ***Reflagging***

We obtained information about patterns in reflagging using the dataset developed by Park *et al.* (28) and then analyzed relationships between reflagging and PSMA adoption. To complement the set of vessels that may not match to AIS data due to lack of registry information, we added data on vessel flag changes based on AIS Maritime Mobile Service Identity (MMSI) flag code (a 9-digit code that identifies a vessel with the first three digits of the MMSI identifier indicating a vessel flag). We then analyzed reflagging instances over time by combining them with port visit data and categorizing them into 1) vessels flying the flag of the port State where they are landing their catches, and 2) vessels flying a foreign flag (i.e., one different from the

port State). Although there is no clear global pattern across all PSMA Parties, several Parties demonstrate a distinguishable trend of domestication of vessel flags.

Namibia, Senegal, New Zealand, and Chile (fig. S2) all had a strong trend of previously foreign vessels reflagging to the flag of the port State, thereby becoming ‘domestic’ vessels. The ratio of domestication in these States to their respective total reflagging events is above 80%, with only a limited number of vessels that flagged out to other States since 2016. The majority of domestic re-flagging events in New Zealand and Namibia took place 1.5 years before and after their PSMA ratification. For Namibia, Senegal and Chile, the number of vessels re-flagging to the domestic flag represents roughly about 40-50% of the total numbers of domestic flagged vessels visiting their ports. For New Zealand, this number was only about 10%. It is possible that some of these domestic vessels (not those re-flagged ones) actually flew a foreign flag in the past, but our data is missing their historical foreign flag information. If that is the case, the suggested ratio (40-50% or 10% above) would be greater, meaning our estimates are conservative and domestication could be an even greater factor in these fleets. In other words, these percentages reflect the minimum level of domestication. With more complete reflagging data, they may be higher.

Our re-flagging data do not include vessels that change flags, but do not broadcast an AIS signal. In some cases, even though vessels that change flags do broadcast an AIS signal, lack of information in the database means that we (erroneously) consider a vessel to have undergone an identity change (i.e., reflagged) as two separate vessels. In addition, the dataset does not include most small vessels under 15 meters (and those that are under 24 meters outside Europe and the USA) because there are no national mandates to broadcast AIS. However, these vessels mostly operate within domestic waters, are less likely to change their flags (28) over their lifespan, and we excluded vessels fishing >95% of their fishing hours in domestic waters from our analysis. In other words, most vessels embarking on international voyages are likely to broadcast AIS signals according to the recommendations of the Safety of Life at Sea or other international or national regulations. As a result, missing these vessels not broadcasting on AIS in the dataset is unlikely to affect our analysis significantly.

Closed loops

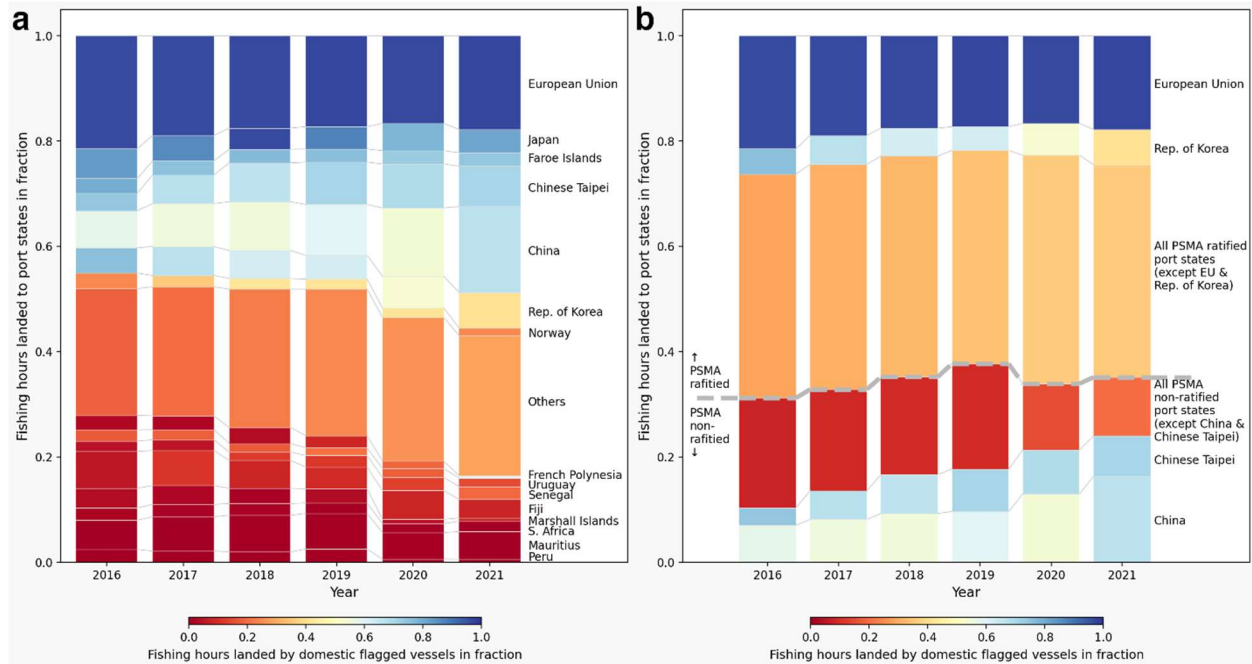
To identify cases where the fishing vessel flag and transshipment vessel flag are the same as the flag of the port State where catches are landed, referred to here as *closed loops*, we used GFW AIS data on encounters between a fishing vessel and a transshipment vessel (including reefer and specialized reefer) (<https://globalfishingwatch.org/datasets-and-code-transshipment/>). Here, an encounter is defined as an event occurring between a fishing vessel and a transshipment vessel that are continuously within 500 meters from one another for at least two hours and traveling at less than two knots, while at least 10 kilometers from an anchorage (26). We assume that an encounter between a fishing vessel and a transshipment vessel entails a total transfer of fish catch from the fishing vessel to the transshipment vessel as there is no detailed information about the amount of fish transferred during an encounter. While an encounter might involve the transfer of workers, supplies, and food, in addition to fish, we apply the above thresholds to reduce the possibility of non-fish transshipment being included in our analyses.

Results show China represents the majority of all closed-loop cases, because the proportion of Chinese fishing vessels directly landing at Chinese ports (i.e., not using

transshipment vessels to land fish) is greater than all other top fishing nations. Therefore, we include only closed-loop cases that involve transshipment vessels in our analysis (i.e., fishing-transshipment-port closed loops). Russia accounts for 60% of all closed loops with transshipment vessels. Approximately 90% of Russian port visits between 2016 and 2021 were closed loop cases, meaning very few landings were made by non-Russian flagged vessels. Although Indonesia, the United States, Canada, and Chile also had high percentages of these closed loops, Russia is notable for the number of port visits involved (fig. S3).

Given their total port visit size, Russia and China account for relatively high closed loop ratios (fig. S3). While about 30% of port visits at Chinese ports (out of 8,000 instances) are closed loop instances (i.e., involving Chinese-flagged fishing and transshipment vessels), roughly 75% of all port visits by Chinese transshipment vessels around the world (out of 3,000 instances) are closed loops. In comparison, <5% of all port visits at Panamanian ports are closed loops by Panamanian-flagged fishing and transshipment vessels, and only <0.1% of all port visits by Panamanian transshipment vessels around the world are closed loops. In other words, almost none of the landings involving Panamanian flags (i.e., fished by and transshipped to Panamanian vessels) take place at Panamanian ports. Panamanian ports represent a small proportion of total landings by Panamanian transshipment vessels, and also almost none of the landings that take place at Panamanian ports are made by Panamanian-flagged vessels. In contrast, almost all landings involving Russian flags (i.e., fished by and transshipped to Russian vessels) take place at Russian ports, and almost all landings that take place at Russian ports are made by Russian-flagged vessels. This stark contrast between flag States means that PSMA effectiveness may also depend on the strength of monitoring of domestic fleets due to the high prevalence of such closed loop networks in particular PSMA Parties.

Supplementary Figures



5 **Figure S1. Fishing effort by flag State and by PSMA status as a fraction of landed fishing**
hours between 2016 and 2021. For (a) fishing effort by flag state, the color associated with
each flag State indicates the fraction of landed fishing hours by vessels flagged to the port State
where catches were landed, i.e., the domestic flag (with 0 meaning that all fishing hours landed
are done by foreign vessels while 1 represents the opposite). For (b) flags are grouped by PSMA
Parties vs. non-PSMA States. The top 2 flag States/blocks of each group (the EU and Rep. of
Korea for PSMA Parties, China and Chinese Taipei for non-PSMA States) are separated from
each group to show general trends without the influence of those top States/blocks.

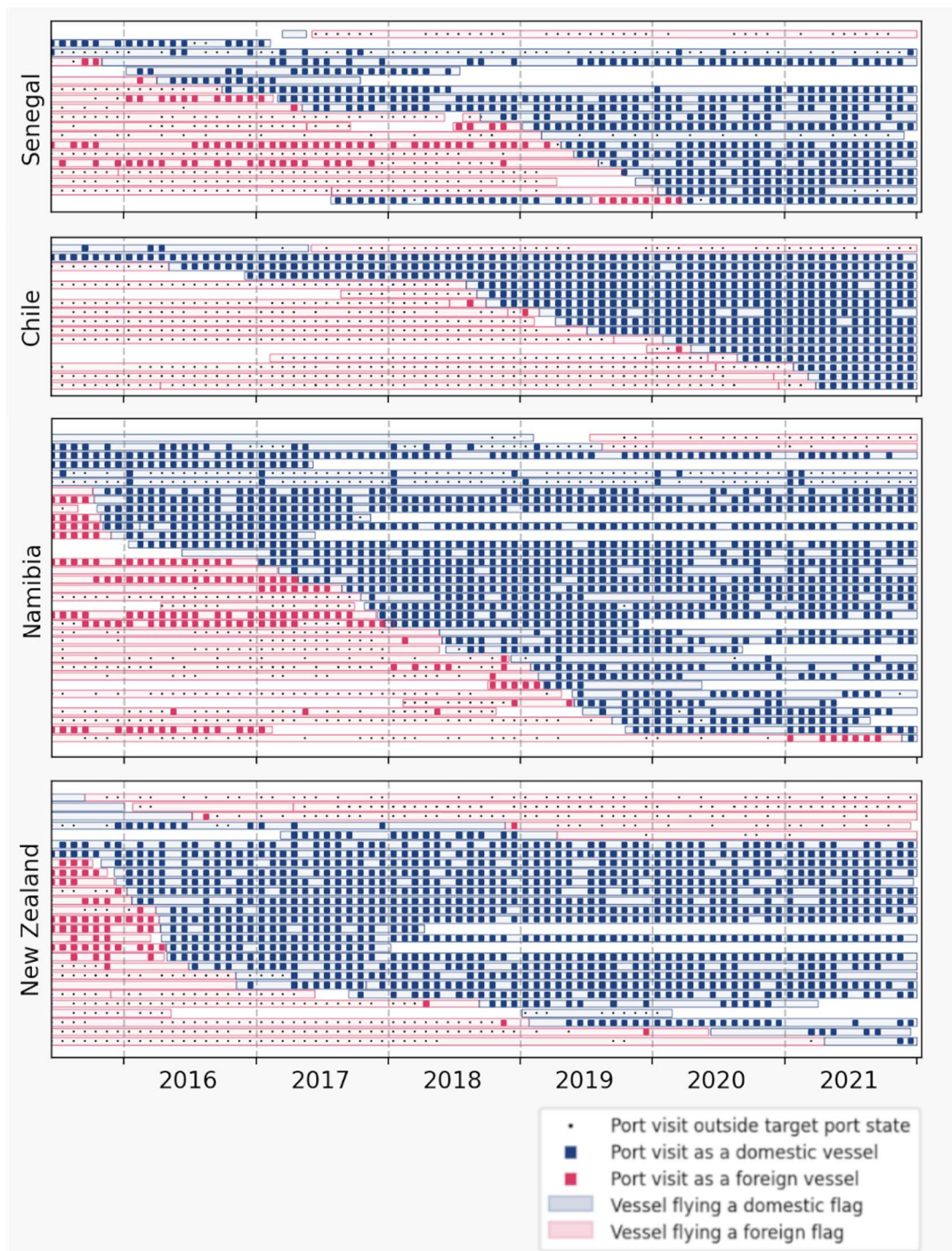


Figure S2. Monthly port visit summary for vessels that reflagged to or from four PSMA Parties (Namibia, Senegal, Chile, and New Zealand) from 2016 to 2021. Each horizontal line represents a vessel. The time range over which a vessel has a foreign flag (with respect to the target port State) is depicted as a horizontal bar in red, while the time range over which a vessel would be considered flying a domestic flag is depicted in blue. Where these two bars meet indicates a flag change. Filled squares represent visits of a given vessel to the target port State (with a foreign flag with regard to the port depicted in red, and a domestic flag in blue). Black dots indicate port visits outside the target port State.

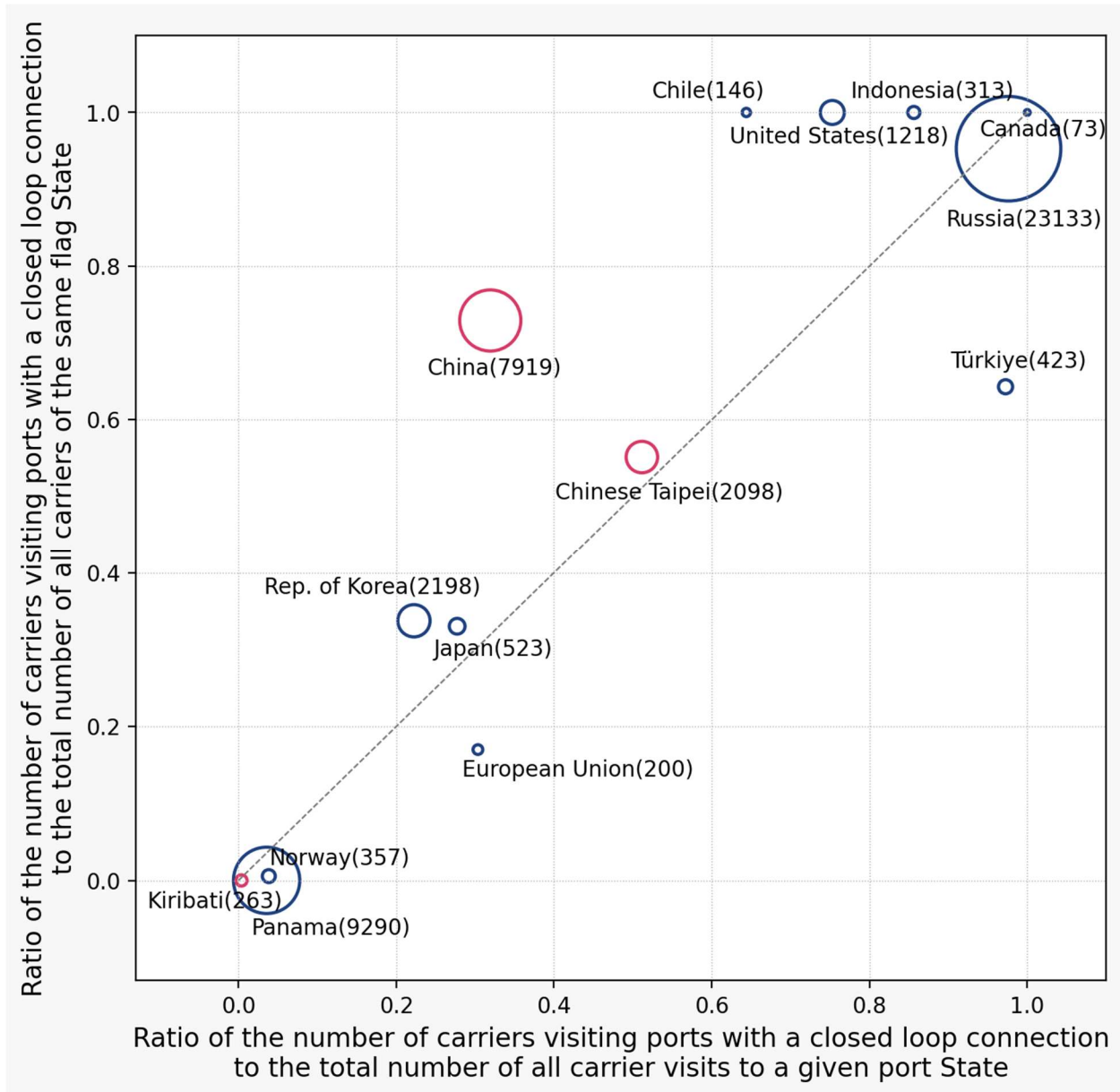


Figure S3. Proportion of carrier (transshipment) vessels in a closed loop by port States and flag States. Values on the x-axis show a proportion of the number of visits to a given port State by carrier vessels in a closed loop over the number of visits to that port State by all carrier vessels. Values on the y-axis show a proportion of the number of port visits by closed-loop carrier vessels flying a given flag over the number of global port visits by carrier vessels flying that flag between 2016-2021. The size of the circle and number in parentheses indicate the total number of port visits, and the color represents whether an individual State adopted PSMA (blue for those that have adopted PSMA, red for all others).

Table S1. Number and proportion of port visits (2021) by domestic and foreign fishing vessels. Due to rounding, totals do not necessarily equal 100%.

	Percent of total port visits (2021)	Percent of total port visits (2019)	Percent of total port visits excluding Chinese-flagged vessels (2021)	Percent of total port visits excluding Chinese-flagged vessels (2019)
Domestic vessels	98.2	98.4	97.7	97.5
Foreign vessels	1.6	1.4	2.0	2.2
Other (including sovereign-territory relationships)	0.1	0.1	0.2	0.2

- 5 **Table S2. Number and proportion of port visits (2021) by domestic and foreign support vessels (i.e., reefer, specialized reefer and bunker vessels as defined by GFW).** Due to rounding, totals do not necessarily equal 100%.

	Percent of total port visits (2021)	Percent of total port visits (2019)	Percent of total port visits excluding Chinese-flagged vessels (2021)	Percent of total port visits excluding Chinese-flagged vessels (2019)
Domestic vessels	53.1	47.3	52.0	44.4
Foreign vessels	46.7	52.3	47.8	55.2
Other (including sovereign-territory relationships)	0.2	0.4	0.2	0.4