Science Advances
AAAS

advances.sciencemag.org/cgi/content/full/6/30/eabb1197/DC1

Supplementary Materials for

Illuminating Dark Fishing Fleets in North Korea

Jaeyoon Park*, Jungsam Lee, Katherine Seto, Timothy Hochberg, Brian A. Wong, Nathan A. Miller, Kenji Takasaki, Hiroshi Kubota, Yoshioki Oozeki, Sejal Doshi, Maya Midzik, Quentin Hanich, Brian Sullivan, Paul Woods, David A. Kroodsma

*Corresponding author. Email: jaeyoon@globalfishingwatch.org

Published 22 July 2020, *Sci. Adv.* **6**, eabb1197 (2020)
DOI: 10.1126/sciadv.abb1197

This PDF file includes:

Supplementary Materials and Methods
Sections S1 to S9
Figs. S1 to S27
Tables S1 to S6
Legends for movies S1 to S3
References

Other Supplementary Materials for this manuscript include the following:

(available at advances.sciencemag.org/cgi/content/full/6/30/eabb1197/DC1)

Movies S1 to S3

(This is a version of the Supplementary Materials with page numbers.)

Materials and Methods

Introduction

The following provides details on the methods used in “Illuminating dark fishing fleets in North Korea.” To identify the fishing activity and identity of vessels fishing in North Korea, we synthesized data from four satellite sources and from various sources, such as the South Korea Coast Guard and media reports. The sections of this supplement are presented in the order that they are referenced in the main paper. Below is a short summary of each section. Also note that for brevity, throughout the supplementary materials, the vessels originating from China are referred to “Chinese vessels,” although the exact flag and registration of them cannot be confirmed through this study.

1. Boundaries and access agreements. This section defines our study area based on the claimed North Korean waters and nearby areas where Chinese vessels may operate. It also provides an overview of fishing access agreements in North Korean waters and in Russian waters and how many foreign fishing vessels are allowed to operate as a basis for our subsequent analyses.

2. Daytime optical imagery (Planet imagery). This section describes how three-meter imagery from the satellite company Planet was used to automatically detect the presence and activity of pair trawlers. In addition, we obtained 0.72-meter resolution imagery of pair trawlers and lighting vessels, verifying that these vessels appear exactly like the Chinese vessels crossing into North Korean waters observed by the South Korea Coast Guard. We also note how we matched observations of pair trawlers to Automatic Identification System (AIS) data, confirming the identity of the vessels that were broadcasting AIS.

3. Synthetic Aperture Radar (SAR). Across the fishing seasons of 2017-2018, we obtained satellite radar imagery from three sources that covers portions of the study area. Using the SAR imagery, we explain how we identify Chinese pair trawlers and distinguish different fleets of lighting vessels by overlaying the imagery with nighttime light detection described in section S5.

4. Automatic Identification System (AIS). This section describes how we analyze AIS data to track a fraction of the vessels fishing in North Korea and confirm that they are of Chinese origin.

5. Nighttime optical imagery—Visible Infrared Imaging Radiometer Suite (VIIRS). This section explains how we combine satellite detections of night lights with fishing access agreements to distinguish Chinese lighting vessels fishing in North Korean waters, and North Korean lighting vessels fishing in Russian waters. We estimate the number of vessels in the two fleets each year and their total fishing days.

6. Observation on the water. This section provides information about Chinese vessels crossing into and out of North Korean waters through South Korean waters. We used the vessel count of the South Korea Coast Guard and its observation data to validate our estimate made by satellite observation in section S2 through S5.

7. Legal analysis of Chinese fishing in North Korea. We collected written evidence from China of Chinese fishing in North Korea in 2017-2018, and how it constitutes a violation of Chinese domestic regulations in addition to international laws.

8. Estimated number of Chinese vessels and days of fishing in North Korea. This section presents how we calculate the estimated number of Chinese vessels fishing in North Korea and their total fishing days each year, resulting in an estimated catch and its landing value in monetary terms.

9. Data availability and cost. This section documents the cost and availability of the satellite data used in this study.

Section S1. Boundaries and access agreements

In this section, we define and justify the study area for identifying Chinese fishing within North Korea. We then outline various fisheries access agreements, and which fleets are known to fish where in the region. This information is critical for verifying and calibrating some of our methods for identifying fishing activity as described in later sections.

1.1. Boundaries

Boundaries claimed by North Korea

Although North Korea has not formally agreed on maritime delimitations with South Korea and Japan, it officially claimed an exclusive economic zone (EEZ) in 1977, which has been cited in multiple publications (*31-33*). In this proclamation, North Korea also set a 50-mile wide military boundary zone (hereafter referred to as the military zone) where no foreign vessels are allowed to enter unless authorized. Evidence suggests that North Korea defines this 50-mile boundary (which has not been internationally recognized) by connecting a straight line between points 50 miles from the coast at the north and southern boundary of the EEZ (*31*). The exact coordinates to its military zone and EEZ claimed in 1977 have not been published by North Korea, but they are reported on in the literature based on meetings with North Korean officials (*33, 34*). The coordinates of this claimed area, minus the claimed military zone where no foreign fishing is allowed and the claimed internal waters (between the shore and the military zone), are shown in fig. S1 by the points A-B-C-D. Since this 1977 proclamation, North Korea has negotiated a slightly different northern boundary with the former Soviet Union (see below).

Boundary between North Korea and Russia

The demarcation line on the sea between North Korea and the former Soviet Union was formally agreed to in 1986 and no change has been reported since the breakup of the Soviet Union (*35*, *36*). The Federation Agency of Fisheries of Russia (Росрыболовство) continues to use this demarcation line as the limit of its fishing grounds (*37*). We, therefore, use this demarcation line between the two nations to define the edge of the claimed North Korean EEZ for our study. The adjusted area of interest where foreign vessels can be present within the claimed North Korean EEZ is thus the EEZ claimed by North Korea since 1977 excluding the claimed military zone, with a slight adjustment based on the agreement with the former Soviet Union in 1986. This area is shown in fig. S1 by points A-B-E-F-G.

Boundaries between North Korea and South Korea/Japan

South Korea and Japan have disputed boundaries in the region, but they have also developed an area of joint fisheries management (*38*, *39*), which does not include any of the EEZ claimed by North Korea. Between North and South Korea, the northern limit line of fishing for South Korean vessels is the seaward extension on latitude 38° 33’ 09.83” N from the eastern shore to longitude 132° 34’ 07.58” E, and is not included in the EEZ claimed by North Korea (*40*). Therefore, our area of interest, as defined above, represents the region where no foreign fishing vessels may operate without official authorization from the North Korean authorities.

In the southeastern part of the claimed North Korean EEZ, Chinese fishing fleets are often seen operating to the east of the boundary line (line B-E in fig. S1), whereas South Korean and Japanese fishing boats are rarely present in this area. South Korean fishing boats are restricted from traveling near this area by the Republic of Korea (South Korea) Ministry of Oceans and Fisheries. The Ministry also requires all fishing boats approaching the area to report their locations multiple times a day, and monitors them closely to avoid undesired conflict with the North Korean authorities, such as the recent abduction of a fishing vessel from South Korea (*40*). In the past five years, the average daily number of South Korean squid jiggers entering into this area is below one (*41*).

Study area

Based on the boundaries and area of interest described above, we define our study area for the analysis of foreign fishing activities to be the claimed North Korean EEZ beyond the military zone in the eastern part of the Korean peninsula (blue area in fig. S1). However, during initial data explorations, we occasionally observed fishing activities by likely Chinese vessels a few kilometers to the east of the lines B-E-F-G on fig. S1. We, therefore, extend our study area 100 km to the east of these lines, and then exclude the South Korea-Japan joint fisheries management area, which is to the east of line J-K in fig. S1. The resulting study area for fishing activities by foreign fishing vessels is shown as a red polygon in fig. S1.

1.2. Fishing access agreements

In North Korean waters

Chinese fleets

Chinese fleets have officially fished on the eastern side of North Korea since 2004. The *China Fisheries Yearbook* states that the number of fishing vessels sent to operate in North Korean waters often exceeded 600 between 2011 and 2014 (see section S7. Legal analysis of Chinese fishing in North Korea). Since 2014, the yearbook has not specified the total number of fishing vessels sent to North Korea. The South Korea Coast Guard and the East Sea Fisheries Management Service of South Korea monitor Chinese fishing fleets entering into North Korean waters from South Korean waters (see section S6. Observation on the water). Some written evidence, including individual fishing certificates, also suggests that some forms of fishing access agreement exist between China and North Korea (see section S7. Legal analysis of Chinese fishing in North Korea).

Russian fleets

North Korea has had a bilateral agreement on fisheries cooperation with Russia, and previously the Soviet Union, since 1987 (*42*). During 2014, 2015, and 2016, however, the Russian fleets did not enter North Korean waters to fish (*43*, *44*). In 2017, no agreement was made due to illegal fishing activities by North Korea in the previous years and lack of cooperation from North Korea to settle the issue (*45*). An agreement was reached in 2018, but Russia did not request any quota for Russian vessels in North Korean waters.

South Korean and Japanese fleets

South Korea and Japan have no diplomatic relations established with North Korea to manage fisheries. In the past, South Korean vessels that fished in the claimed North Korean EEZ have been arrested by North Korean authorities. Releasing captured fishermen has required difficult negotiations, such as those that took place after the capture of the South Korean boat, *391 Hungjin* in 2017 (*41*). As a result, South Korean fishermen stay clear of North Korea's claimed areas. The same applies to Japanese fishermen.

In Russian waters

Russia allows foreign vessels to fish within its EEZ through bilateral access agreements. The agreements define the number of foreign vessels authorized to enter the Russian EEZ for the purpose of commercial fishing and their allowed catch quota. Russian fishing vessels rarely target *Todarodes pacificus* (called Japanese Flying Squid or Pacific Squid) (*46*), and Russian vessels caught no more than 500 metric tons per year for the past few years in the Primorye subzone below 47° 20' N (*47-49*). Russia reportedly has only one squid jigger operating in the same subzone (*50*).

North Korean fleets

North Korea officially obtained permission for 76 vessels to catch 9,000 metric tons of squid in Russian waters in 2016. This represents a slight increase from the 65 vessels authorized from the previous year (*44*). In 2017, the Russian-DPRK Commission on Cooperation in the Field of Fisheries was not held due to issues arising from North

Korea's illegal fishing in the Russian EEZ in previous years, and no fishing permission was granted for North Korean vessels to fish in Russian waters (*45*). An agreement was subsequently reached, with specific conditions including payment of fines for previous violations. These were settled in June 2018, and North Korea then obtained access for 88 vessels during 2018.

South Korean fleets

South Korea's National Federation of Fisheries Cooperatives is the authorized body handling the operation of the country's offshore fleets, and it also manages the operation of the South Korean squid jigger fleet authorized to fish in the Russian EEZ. The Federation records entry/exit time and the amount of catch of each vessel of the authorized fleet. In 2017, 48 South Korean squid vessels fished in the Russian EEZ (*51*). In 2015, 2016, and 2018, 84, 63 and 68 vessels respectively were permitted to enter the Russian EEZ (*43*, *44, 52*).

Japanese fleets

Japan and the former Soviet Union established a bilateral agreement on fisheries in 1977. Although, in recent years, Japan reached an agreement with Russia that would allow hundreds of Japanese squid jiggers to enter the Russian EEZ to fish, very few Japanese squid jiggers obtained authorization to enter the EEZ. Between 2015 and 2018, only one Japanese squid jigger operated in the Russian EEZ (*53*).

Chinese fleets

Through an agreement with the Federal Agency for Fisheries of the Russian Federation, China was entitled to have three fishing vessels in the Russian EEZ each year during 2015, 2016, and 2018 (*43*, *44*, *52*). Although data on the number of vessels by flag approved to fish in Russia during 2017 are not currently available, the total number of foreign vessels of any flag allowed to fish in the Russian EEZ is practically unchanged from the previous year (358 from 356) (*54*). As a result, we assume that the number of authorized Chinese fishing vessels remained at about three during 2017.

Section S2. Daytime optical imagery (Planet imagery)

Planet is an integrated aerospace and data analytics company that operates the world's largest fleet of Earth-imaging satellites. We used 3-meter imagery from Planet to count the number of days pair trawlers were active in the study area, and 0.72-meter imagery to confirm that the vessels were the same class of vessels observed by the South Korea Coast Guard to be crossing into North Korean waters (pair trawlers and large lighting vessels). Finally, we matched 140 vessels in AIS to images of pair trawlers, verifying that these vessels originated from Chinese ports. Planet provided imagery in kind for this study.

Planet also operates the PlanetScope and SkySat constellations of satellites. The PlanetScope constellation consists of over 100 active satellites, collecting visible and near-infrared imagery with a ground sampling distance of 3-4 m. These satellites are deployed into sun-synchronous orbit (~475 km orbit altitude) with a midmorning equatorial overpass time (9:30-11:30 am local solar time). The SkySat constellation consists of 15 active satellites collecting visible, near-infrared and Panchromatic imagery with a ground sampling distance of 0.72 m. They are deployed into a sun-synchronous orbit (~500 km orbit altitude) with overpass times at 10:30 am and 1:30 pm.

The PlanetScope constellation operates in "always-on" mode. That is, the constellation has been designed to programmatically capture worldwide daily imagery. SkySat, in contrast, operates under a tasking model. They need to be instructed to capture an individual image and each footprint (7 km × 40 km, or 280 km^2) is much smaller than our study area (about 90,000 km^2).

2.1. Using PlanetScope imagery to identify pair trawlers

<u>Detection of pair trawlers in images</u>

For much of 2017 and 2018, PlanetScope captured imagery of large portions of North Korean waters. We developed an object detection model using a convolutional neural network (CNN), a type of machine learning algorithm commonly used in modern image recognition and object detection. We trained the CNN to detect pair trawlers in this imagery and then used the model to count the number of vessels operating in the study area. We trained our model to identify pairs of trawlers instead of individual vessels. Single pair trawlers, which are about 30 meters in length, are only about 10 pixels long in a PlanetScope image (Fig. 1B). These individual trawlers are sometimes difficult to differentiate from waves and are not distinguishable from other small vessels; identifying pairs of trawlers is far easier and more reliable.

We use the pair trawler detection model in two ways: first, to identify the locations of pair trawler clusters, and second, to count the trawlers in these clusters. We count only pair trawlers in operation within and near these dense vessel clusters because, as revealed by both radar (see section S3. Synthetic Aperture Radar) and optical imagery, the pair trawlers almost always fish in relatively tight groups. Counting only vessels in the core fleets reduces the number of false positives because the density of false positives, while low, can still be significant when summed over the entire study area, particularly on days with poor imaging conditions.

<u>Modelling</u>

The CNN we developed is a one-stage object detector where both object presence and the bounding region are predicted at each output location. Unlike most object detection models, ours uses elliptical regions derived from the predicted location, length, and orientation, which helps accommodate the arbitrary orientation of the trawler pairs in each image.

Our CNN model is built in Tensorflow (see https://www.tensorflow.org/about/bib), one of the primary libraries for developing machine learning models. The CNN takes an $n_r \times n_c \times 3$ image as input and returns an $(n_r / 16) \times (n_c / 16) \times 5$ array – that is, the image is downsampled by a factor of 16 while being mapped to five parameters: an *is-ship* score and four parameters specifying the predicted position, length, and orientation of the vessel (fig. S2).

The model consists of four blocks, each consisting of two convolutional layers followed by a pooling layer that combines the output of max-pooling and stride-2 convolutional layers. After the fourth block, there are five parallel output blocks, each consisting of four convolutional layers, each predicting one of the values described above. The number of filters in each layer varies from 24 in the input layer to 384 in the final ship detection layer.

The model is trained using 3,440 image patches derived from 236 Planet scenes (24 km × 7 km per scene) to which runtime data augmentation is applied. Training data were generated by hand labeling these scenes. Training was run for 80,000 steps using Nesterov accelerated gradient descent with a momentum of 0.9, a batch size of 32, and an initial learning rate of 0.04, which is decayed every 20,000 steps by a factor of five. Cross entropy loss was used for the *is-ship* score, with L1 and L2 losses used for the other parameters. For full details of the model structure and the training regimen, see the code in https://github.com/GlobalFishingWatch/paper-dark-fishing-fleets-in-north-korea.

The output of the core model is post processed using thresholding followed by non-max suppression to produce a set of detections for each PlanetScope scene. The final output is a set of vessel detections consisting of latitude, longitude, angle of the trawler pair, and separation between the trawlers. These can be visualized as ellipses superimposed on the original image as shown in Fig. 1B.

<u>Evaluation</u>

We evaluated the effectiveness of the CNN model on an annotated test set of 587 scenes from seven days chosen from the study area. In these scenes, the annotators identified 2,566 trawler pairs, 936 single trawlers, and 603 other vessels. Note that these numbers are not adjusted for overlapping scenes as described below. The model had a precision of 0.93 and recall of 0.91 for predicting trawler pairs with an Intersection over Union of 50%. The total counts for each day are plotted vs. human-annotated counts in fig. S3.

When using the CNN model to count vessels, we have identified several sources of error:

1. Background false positives due to sea state, clouds, and image artifacts.
2. Classifying non-pair trawlers as pair trawlers. This effect is small relative to the other effects described here, in part because there were few non-pair trawlers in the scenes that were counted.
3. Classifying single pair trawlers as trawler pairs.
4. Not counting single pair trawlers. The model is not designed to detect single pair trawlers and they make up about 14% of the total annotated trawlers, although this varies by day. This undercounting is generally a larger effect than 3.
5. Incomplete satellite coverage.
6. Cloudy conditions.
7. Pair trawlers that are missed because they are away from any vessel clusters.

The primary cause of false positives is 1 above, particularly extensive whitecaps and patchy clouds. These background false positives can be controlled by keeping a relatively small area of interest, which results in the main source of error being undercounting due to 4-7. Given a conservative area of interest, in most situations the model will undercount, rather than overcount.

Calculating the false positive density

We estimated the background false positive density in the scenes without pair trawlers by choosing 100 random scenes that had not been previously used during training or evaluation, and then annotated them by hand. Any scenes that had single or paired trawlers were then excluded from the calculation since we were interested in the background rate. In the remaining 96 scenes, the average false positive density was 1.4 / 1,000 km^2, primarily due to a combination of sea state and clouds.

Identifying vessel clusters

A key step in accurately counting the pair trawlers is to identify the primary clusters of vessels on each date. We then count the number of detections in these primary clusters, and not across the entire study area. We count only vessels in the clusters because the average of 1.4 false positives / 1,000 km^2, while relatively low, would still result in about 120 false positives over the 90,000 km^2 of the study area. The number of false positives also varies considerably due to weather conditions, with areas containing large numbers of whitecaps or patchy clouds contributing to larger false positive densities. Thus, the number of false positives would be considerably higher on days with poor conditions. For this reason, we establish an area of interest around the primary vessel clusters on each day, and count vessels only within these areas. These areas of interest average roughly 9,300 km^2, thus reducing the number of expected false positives to about 13, which is small relative to the typical total counts.

We establish these areas of interest by first spot checking each apparent vessel cluster to verify that the detections are due to vessels and not whitecaps or clouds. There is typically a single primary cluster containing the trawler fleet (fig. S4). Although the fleet is occasionally split into two clusters, more typically, what appears to be a secondary cluster is a region of poor detection conditions, such as whitecaps or patchy clouds. Boundaries are then established around each of the vessel clusters so as to include the high-density core (five or more detections per scene) as well as any nearby medium density scenes (three or more detections per scene). When the region surrounding the fleet has areas with adverse detection conditions, the borders of the areas of interest are chosen so as to avoid the problematic areas and minimize false positives. When the region surrounding the fleet has good detection conditions, the exact shape of the area of interest is not critical and is typically chosen to be rectangular for simplicity. This method likely leads to a conservative estimate of the number of vessels, as it will not count any pair trawlers operating away from the main fleet.

Counting the fleet

We estimate the fleet size by counting all detections that fall inside the area of interest for a given day, and then compensate for overlapping scenes. Double counting due to scene overlap is dealt with by scaling detections by 1 / N_s, where N_s is the number of scenes which overlap the detection. For example, a detection that overlaps one scene is counted as 1.0, while a detection that overlaps two scenes is counted as 0.5.

To cover the squid fishing season, which runs from roughly mid-May to mid-December, we chose a set of 22 days on which to count vessels so as, with 1-2 days per month. It was not possible to regularly count a meaningful fraction of the fleet with a higher frequency than this because days with both good satellite coverage over the study area and relatively clear skies were not consistently available. In general, we chose days with the best combination of satellite coverage, clear skies, and sea state. Also, given the choice between multiple, nearby days with similar coverage, we chose the day where the coverage overlapped most with the fleet. On each day, we processed all images with less than 50% cloud coverage. The detections, areas of interest, and counts for 2017 and 2018 are shown in fig. S3 and S4.

2.2 Using SkySat imagery to identify pair trawlers and lighting vessels

Pair trawlers in SkySat

In near-real time, PlanetScope and the CNN could detect pair trawlers, which allowed Global Fishing Watch and Planet to use a “tip-and-cue” approach to acquire high-resolution (0.72 m) SkySat imagery of pair trawlers in operation. That is, we first used PlanetScope to identify the location of the pair trawler fleet, and then we tasked SkySat to take higher-resolution images of this area (Fig. 1C) to confirm the identity of these trawlers. SkySat’s high image resolution shows the vessels with considerably more detail (Fig. 1C). This imagery allows more accurate characterization of the vessel length, typically 30-35 m, and separation, typically 300-500 m. Fig. 1C was acquired on 17 September 2018 near the location (39.69° N, 132.60° E) where a cluster of pair trawlers had been detected by PlanetScope a few days previously.

Lighting vessels in SkySat

To identify the location of the lighting fishing fleet, we used the Visible Infrared Imaging Radiometer Suite (VIIRS) (see section S5. Nighttime optical imagery) to find the approximate location of the fleet. Using these VIIRS vessel detections, we identified the core location of the lighting fleet and then tasked SkySat to acquire images of the identified location. The vessel captured by SkySat on 22 September 2018 in the vicinity of 39.77° N, 132.87° E is about 58 meters long and has four long arms projecting out diagonally and two tall structures at the stern and bow (Fig. 3B). Close inspection of Fig. 3B reveals wires that hold the cantilever crane arms. This observation is consistent with the pictures and video recorded in the study area (fig. S26 and movie S3).

2.3 Matching AIS to imagery

We matched 140 unique maritime mobile service identity (MMSI) numbers to detections in Planet imagery by identifying the most likely position of the vessel at the time of each image. We estimated this position using the speed and course of each vessel from the Automatic Identification System (AIS) position that was closest in time to the image (fig. S5). This method works only when there are positions from AIS that are relatively close in time to the image, and for many scenes, because of poor AIS reception or vessels not broadcasting, such matching was not possible. The vessels identified in fig. S5 were subsequently tracked returning to ports in China using AIS. All of the vessels that were matched to AIS in this way originated from Chinese ports (See section S4. Automatic Identification System)

Section S3. Synthetic Aperture Radar (SAR)

To detect vessels, including those potentially not broadcasting AIS, we analyzed satellite Synthetic Aperture Radar (SAR) data. Due to its focus on land observation, only a limited number of SAR data sets are available over the ocean. To best cover our study area, we obtained all SAR data that we could freely access. This included all imagery from the European Space Agency's Sentinel-1 mission. In addition, the satellite company Kongsberg Satellite Services contributed, in kind, RADARSAT-2 imagery, and the Japanese Aerospace Exploration Agency provided imagery from PALSAR-2. This satellite radar allowed us to identify all large, metal vessels operating on the ocean, and also estimate the number of pair trawlers operating at a given time.

SAR vessel detection methods are well established and are typically parameterized according to sensor characteristics such as polarization combination (e.g. HH, HV, VV, VH), resolution, and frequency band (X-band, C-band, and L-band). All imagery was processed using variations of the Constant False Alarm Rate (CFAR) algorithm (*55*). Numerous versions of CFAR exist, all of which employ localized peak detections by determining an adaptive threshold within a defined moving window that includes a guarded area between the target cells and its outermost bounds (*56, 57*). A K-distribution is expected in a vessel detection whereas a Gaussian distribution is expected otherwise (*58*).

Because each satellite source was processed by a different group (PALSAR-2 by the Japan Fisheries Research and Education Agency; RADARSAT-2 by the satellite company Kongsberg Satellite Services; and Sentinel-1 by Global Fishing Watch), and because each sensor has slightly different characteristics, the details of each model vary slightly and are described below.

3.1. Vessel detection with PALSAR-2

Data source

The PALSAR-2 sensor aboard the ALOS-2 satellite of the Japanese Aerospace Exploration Agency transmits L-band microwave signals and receives the reflection from the ground to acquire information to rapidly monitor disasters. We acquired data sets for 27 September 2017, 2 October 2017, and 24 October 2017 (table S2). The original image resolution is 25 meters in the UTM projection.

Boat detection algorithm for PALSAR-2 data sets

To avoid false detections, we first excluded land-based and human-made structures. The National Oceanic and Atmospheric Administration's shoreline data (https://www.ngdc.noaa.gov/mgg/shorelines/) were used to create a mask that excluded land and islands within 1 km off from shoreline. Furthermore, we manually checked the mask in comparison with SAR images to make sure that all fixed structures were accurately removed. After the masking process, a maximum filter with a 3 × 3 pixel window was applied to eliminate pixel discontinuities, thus avoiding duplicate ship detections.

To detect vessels in PALSAR-2, all pixels from the masked image were compared with the average value of pixels within a 10-pixel radius (most of which correspond to sea surface) of the target pixel. The target pixel was marked as a candidate pixel for boat detection if the value of the pixel was greater than twice the average value over the surrounding region. A single boat detection consisted of a cluster of adjacent marked pixels surrounded by unmarked pixels. The representative point of a detected boat was calculated as the centroid of the group of marked pixels.

The detection results were all manually reviewed to reduce the remaining noise created by overlapping images, and to add, by hand, apparent ships that were missed by the automated process. To validate the accuracy of detection, we used PALSAR-2 images acquired in the North Pacific areas and compared vessel detections to AIS positions. We used this region because the reception of AIS signal is much better in the North Pacific than it is near North Korea. We compared 211 PALSAR-2 vessel detections to AIS data set by interpolating the locations of the two closest AIS messages in time before and after the PALSAR-2 acquisition time, using a method similar to the one explained in the section on matching AIS to Planet imagery.

Of the interpolated AIS positions, 91%, matched to PALSAR-2 detections. Unmatched detections were primarily attributed to the cases where only one AIS position was available with a large time gap (> 5 minutes) or the AIS-derived estimated position was slightly farther than 1 km from the PALSAR-2 detection position.

Because not all vessels broadcast AIS, it is difficult to definitively determine whether a given detection by PALSAR-2 is a false positive. However, the false discovery rate of PALSAR-2 has been estimated in the literature to be between 0 and 20% (*59-61*). We confirm that our observations are consistent with these rates by comparing the number of pair trawlers detected on 24 October 2017 using PALSAR-2 with the number detected using Planet imagery on the same date. We examined the PALSAR-2 detections that appear to be pair trawlers based on the filtering algorithm described below and by restricting the area to a box bounding containing the two pair trawler clusters in the SAR data that correspond to the cluster seen in the Planet imagery. The number of vessels seen by PALSAR-2 in this region is 758 as compared to the 723 observed in the Planet imagery, a difference of 5%, which is consistent with the reported false discovery rates for PALSAR-2.

3.2. Vessel detection with Sentinel-1

Data source

The Sentinel-1 mission of the European Space Agency's Copernicus Programme has open sourced C-band SAR imagery through multiple avenues. In particular, S1 Level-1 Ground Range Detected products are intermittently batch ingested into Google Earth Engine for public consumption. These data are pre-processed according to the agency's Sentinel-1 Toolbox specifications, which applies standardized SAR imagery pre-processing steps that include border noise removal, thermal noise removal, radiometric calibration, and orthorectification. Although Sentinel-1 is primarily a terrestrial observation satellite, a significant portion of North Korean waters is consistently captured every twelfth day through four sequential scenes with a 250-km wide swath covering 43% of our study area (fig. S9). Here, to estimate vessel counts over time, we processed 230 images from Sentinel-1 that intersected the claimed North Korean EEZ in 2017-2018. All images were in Sentinel-1's interferometric wide swath mode

Pre-processing SAR: Incidence angle normalization and natural units transformation

Several common radar pre-processing steps were applied before vessel detection was executed. These included incidence angle normalization and transformations to backscatter coefficients. The former adjusts for Sentinel-1's off-nadir signal transmissions and receptions in a manner specific to ocean-based regions (*62*). The latter procedure transforms pixel units from decibels to backscatter coefficient (*63*). The dual polarization VH-band was used in favor of the single polarization VV-band due to relatively lower background ocean noise within the VH-band. The backscatter coefficients in the VH-band are the ratio of horizontal polarization signals returned to the satellite relative to vertical polarization signals sent. These pre-processed outputs are then masked to exclude all land masses plus a 1-km buffer.

Difference of Gaussian filter

The majority of SAR-derived vessel detections use some form of the CFAR algorithm to identify peaks within a localized region. Specifically, the K-distribution of a cell containing a vessel is expected to produce a significantly stronger return signal than the background ocean, which should produce only Gaussian distributions. An analogous way to extract the same information without calculating a probability density function is to isolate pixels that are significantly greater than their neighborhood. Here, a Difference of Gaussian filter was used to achieve this goal and improve feature extraction (*64*). First, an image was created where each pixel had the median value of all the pixels that were within a 250-meter radius from that pixel in the original image. This temporary image was subtracted from the pre-processed SAR scene to create this Difference of Gaussian image. This subtraction normalized the ocean background and created the CFAR-like "guarded area" between target pixels and the ocean background by producing a moat-like ring of negative-valued pixels around each vessel.

Dynamic thresholding

Next, image thresholding was applied to select candidate vessel pixels (*65*). Difference of Gaussian image pixels greater than six times the value of the smoothed image described above were classified as candidate vessel pixels for imagery acquired before 13 March 2018. Because Google Earth Engine experienced some pre-processing issues in its Sentinel-1 collection after the European Space Agency implemented file format changes on 13 March 2018, the threshold for scenes after this date was adjusted to produce results similar to the pre-13 March 2018 collection. For Sentinel-1 scenes after this date, a threshold of 15 times the calculated neighborhood median filtered image was used to classify pixels as candidate vessel pixels.

Binary image post-processing: Sieve, erosion, and dilation

To minimize false positives, further image morphological techniques were used to remove speckling in the candidate vessel pixels (*66*). First, a sieve was used to filter out any single isolated pixels from the candidate vessel pixel class. Next, an erosion was applied where each cluster of connected candidate pixels was eroded by 10 meters on all sides. This was followed by a dilation that expanded the connected candidate clusters outward by 70 meters.

Vectorize to centroid

The last step vectorized the remaining pixels for the model output. Each connected cluster of pixels was considered to belong to one vessel. To further minimize false positives, pixels that were adjacent diagonally, horizontally, or vertically were considered connected in order. Vectorization retrieved the centroid for each cluster, reducing each cluster of connected pixels to a single point of longitude and latitude. These centroids are the final detection output for each vessel.

Validation

Our methods to detect vessels with Sentinel-1 were validated against human-labeled observations (*67*). To produce a ground truth vessel dataset, Four Sentinel-1 scenes from 1 June 2017, 23 October 2017, 15 May 2018, and 23 November 2018 were annotated, which included 1,936 vessel detections. The selected scenes were spread over both analysis years on days with relatively high vessel counts in North Korean waters. Each validated Sentinel-1 scene captured approximately 42,500 km^2 (250 km range × 170 km azimuth) and a 5-km land mask was used to remove land. Vessels detected from Sentinel-1 were considered a true positive if the detection was within 100 meters of the ground truth location. The short distance was used to ensure individual detections from pair trawlers were not confounded with each other. Table S3 demonstrates full performance metrics for each scene individually. The aggregate precision and recall for Sentinel-1 detections were 0.96 and 0.92, respectively.

3.3. Vessel detection with RADARSAT-2

Images from the Canadian Space Agency's RADARSAT-2 taken between May and November 2018 were processed by Kongsberg Satellite Services (table S2). Ship detection mode (ship detection mode, known as "Detection of Vessels Wide Far" or DVWF) of RADARSAT-2 was used to acquire images with 20-m pixel spacing and single polarization (HH). The vessel detection was carried out using the CFAR algorithm and K-distribution method described in the previous section, on the basis of the report published by the Norwegian Defense Research Establishment (*68*). For vessels larger than 30 meters, the detection rate for ship detection mode of RADARSAT-2 is over 85%. We then applied the model described above to filter for pair trawlers and further suppress noise.

3.4 Filtering and identifying pair trawlers

The detection algorithms employed here do not distinguish between different vessel types. To select only likely Chinese pair trawlers, we rely on the fact that unlike other vessels, pair trawlers operate extremely close to each other. Based on a review of the pair trawlers in Planet images (see section S2. Daytime optical imagery), these vessels usually operate within 500 meters of each while fishing. For each vessel, we calculated the distance to the nearest vessel and used the receiver operating characteristic curve to measure the performance of various distance thresholds. Fig. S7 shows the true positive rate plotted versus the false positive rate for various thresholds (distances to the nearest vessel). With a threshold distance of around 535 meters, the true positive rate is over 0.9 while the false positive rate is under 0.1. The F1 score when using this threshold is 0.95.

In addition, this pair trawler filter suppresses some of the remaining noise in SAR detections because it filters out single false positive detections. Although the filter results in an underestimated count of pair trawlers because they may be more than half a kilometer apart when not trawling, the filter limits overestimating pair trawlers due to false detections by SAR.

We can compare the performance of this model to observations by Planet on 24 October 2017, when Planet captured a relatively cloud-free image of the entire study area, and by PALSAR-2, which also obtained an image of the study area. The number of pair trawlers estimated by PALSAR-2 (796) compares favorably with that estimated by Planet imagery (723 or 8% fewer in Planet images). As explained in section S2 (Daytime optical imagery), we expect the count from Planet to underestimate the number of vessels for several reasons, e.g. our method counts only pair trawlers fishing in the main cluster and the Planet imagery does not always cover the entire study area.

3.5 Results of SAR vessel detections

<u>PALSAR-2 vessel detections</u>

We analyzed the three PALSAR-2 data sets from the three dates in table S2. Each date covers a different subarea of the region, making it difficult to directly compare results, but comparing each of them with vessel detection using VIIRS (see section S5. Nighttime optical imagery) allows us to separate fleets with different characteristics—notably, the ones detected both by SAR and VIIRS, the ones detected by VIIRS but not by SAR, and the rest not detected by VIIRS but detected by SAR. Fig. S8 (A, C, and E) shows this comparison on those three different dates with 2-9.5 hours of difference in acquisition time between SAR and VIIRS.

The cluster of vessels detected by both PALSAR-2 and VIIRS corresponds mostly to Chinese lighting vessels with bright light (>500 $nW/cm^2/sr$). Chinese ships entering

North Korean waters are observed to be large (>30 m) and made of steel or fibre-reinforced plastic, both of which are easily detected by SAR unlike small, wooden boats (*69*).

In contrast, the cluster of vessels with low intensity (<50 nW/cm^2/sr) in the Russian EEZ is mainly detected only by VIIRS and not by PALSAR-2, indicating that they are likely small and/or wooden boats. Such small (<20 m), wooden boats, are the vast majority of boats anchored in all major ports in North Korea imaged during off-season, as in images of two main anchorages in Chongjin, North Korea's largest port for fishing boats (fig. S6). Eyewitness accounts further confirm their operation in the Russian EEZ (movies S1 and S2). North Korea has a bilateral fishing agreement with Russia and squid is not a common target for Russia in this region (see section S1. Boundary and Access Agreements). We conclude from these observations that the large group of boats detected by VIIRS but not by PALSAR-2 are very likely North Korean boats, as we find no other plausible explanation for hundreds of dimly lit vessels that are not detectable by PALSAR-2 (see also section S5. Nighttime optical imagery).

A significant portion of the vessels that are mostly detected by PALSAR-2 but not by VIIRS are found to be in pairs operating close to each other, exactly as shown in the Planet images of pair trawlers. By using the pair trawler filter described above, we detected likely pair trawlers in those clusters (fig. S8, B, D, and E).

<u>Sentinel-1 vessel detections</u>

When using Sentinel-1 vessel detections to estimate the number of pair trawlers in our study area, we used the same filter based on distance to the nearest neighbor described in the previous section. Because Sentinel-1 does not cover the entire study area, the number of vessel detections fluctuates significantly depending on whether the fleet is in the area captured by Sentinel-1. Also, the Sentinel-1 imagery generally does not include the areas where the Chinese or North Korean lighting vessels are active, thus limiting comparison with VIIRS data.

Comparing the result of 23 October 2017 (21:20 UTC) to Planet's pair trawler detections on 24 October 2017 (1:58 UTC; see section S2. Daytime optical imagery), Sentinel-1 estimates 348 pair trawlers while Planet detects 723. When Planet imagery is clipped so that it includes only the area that was also covered by Sentinel-1, only 303 vessels are observed. The difference (303 versus 348) could be because the fleet is located at the edge of the Sentinel-1 footprint and the fleet can move across it between satellite acquisition times. Fig. S10 demonstrates a few selected cases (A-F) where the core fleet is detected away from the Sentinel-1 detection border, as well as a few examples of cases where the fleet is found at the edge of the border or across the boundary of the study area (G-I).

<u>RADARSAT-2 vessel detections</u>

Each of the seven RADARSAT-2 images that were used to detect vessels has a different footprint. However, each covers over 60% of our study area including the core fishing grounds at the southeastern corner of the claimed North Korean EEZ. Fig. S11 shows the detection of likely pair trawlers selected from the full set of detections, using the distance-based filter described earlier. Due to differences in acquisition time and coverage, it is difficult to directly compare the number of detected pair trawlers by RADARSAT-2 and Planet images, but the locations of the clustered fleets correspond well to one another.

Section S4. Automatic Identification System (AIS)

The Automatic Identification System (AIS), designed for ship collision avoidance, can also be used to track movements of fishing vessels. AIS messages contain, among other information, vessel location, time of transmission, and a nominally unique maritime mobile service identity (MMSI) number assigned to each vessel. For a description of AIS data processing and requirements globally, see *Kroodsma et al*. (*16*).

A subset of the fishing vessels operating in our study area were broadcasting AIS, and we tracked these vessels and revealed that they appear to originate from Chinese ports. Even the vessels that use AIS, however, appear to use it for only a portion of the fishing season. Challenges with satellite reception in the region also limit the ability to track vessels solely with AIS.

4.1 Identifying fishing vessels in North Korean waters

We analyzed all AIS-broadcasting vessels with AIS that traveled through North Korean waters from the beginning of 2017 through October 2018. Of the 2,692 unique MMSIs that transited through the claimed North Korean EEZ, 204 were identified as fishing vessels by Global Fishing Watch's vessel classifier algorithms. The first three digits of each MMSI should correspond to the flag state of the vessel, and of the fishing vessels we identified, 89 had prefixes associated with Chinese vessels (412, 413, 414) in their MMSI numbers, 51 with Russia (273), three with Belize (312), and two with South Korea (440, 441). An additional 59 MMSIs were assigned to China based on the categorization described in *(16)*. For example, prefixes such as 100, 150, 200, 800, 900, etc. are used, but do not pertain to any particular country; as shown in *(16)*, a significant number of Chinese vessels use these so called "invalid MMSI numbers." Upon closer inspection, the vessels from Belize and South Korea appear to be cargo vessels or other non-fishing vessels misclassified by the Global Fishing Watch vessel classification algorithm, with the exception of one South Korean fishing vessel that transited through the area without fishing. Of the 2,049 MMSI numbers classified as non-fishing vessels, over 90% are cargo vessels or tankers, with Panama, Russia, and Hong Kong as the top three countries to which they are flagged. Fig. S14 shows the AIS positions of fishing vessels that are not Chinese and the positions of vessels that are not fishing vessels. These vessels only transit through North Korean waters.

There were 220 MMSI that we were unable to classify by vessel type, but which appeared to fish more than five hours within North Korean waters. The majority of these vessels (87%) had fewer than 1,000 positions over the entire time period, which is below the number needed for the Global Fishing Watch vessel classification model to classify the vessel type. Based on their MMSI prefixes, 84 of these vessels are presumed to be Chinese. Careful mapping of the remainder clearly demonstrated that the behavior, transit, and anchorage patterns of the majority of them were quite similar to previously identified Chinese vessels detected within North Korean waters, with the exception of four vessels that were not fishing vessels but were transiting through the claimed EEZ. We concluded that these 216 MMSI represent additional members of the Chinese fleet.

Although MMSI numbers are not supposed to be shared by different vessels, a number of these fishing vessels appear to share MMSI numbers with vessels operating in other places in the world ("sharing" is defined as the same MMSI operated by more than one vessel for >1% of the time that MMSI is observed). In 2017 and 2018, 11% and 10% of the likely Chinese fishing vessel MMSIs were shared, which is higher than the global rate of about 2% of fishing MMSI numbers (*16)*.

4.2 AIS reception quality

AIS satellite reception quality is relatively low in the claimed North Korean EEZ, largely due to radio-frequency congestion caused by the high number of vessels that broadcast AIS in East Asia; this congestion of radio signals is much worse farther south and closer to China (fig. S12). As a result, AIS reception is intermittent for many vessels and large gaps occur in the tracks of vessels when they transit from Chinese ports to North Korean waters—many vessels, while broadcasting AIS, may have only one position recorded in a given day.

To determine whether the low number of vessels detected by AIS (only a few hundred out of 900 total operating identified in this study) could be attributed to the low AIS reception quality, we analyzed AIS data near Busan, which is located at the southeastern corner of the Korean peninsula and on the route from China to North Korean waters. Though the reception quality near Busan is better due to terrestrial antennae, we did not identify more Chinese fishing vessels than we saw operating in our study area. This finding indicates that these hundreds of vessels were also likely not transmitting AIS en route to North Korea.

4.3 Spatial distribution of AIS positions of fishing vessels operating in North Korean waters

Most vessels fishing in North Korean waters also fished in Chinese waters (fig. S13). In the Chinese EEZ, their positions, both fishing and non-fishing positions of vessels, mostly appear near Shandong, Liaoning, Zhejiang, and Fujian provinces. Among the likely Chinese fishing vessels that we identified, fewer than five each year appeared to have also fished in the Pacific east of Japan. Within North Korean waters, the fleet appears to have fished in a different location in 2017 than in 2018. The area in 2017 is closer to the border between Russia and North Korea whereas in 2018 fishing positions appear more in the southern part of the EEZ.

4.4 Estimated number of Chinese vessels in operation

The number of unique MMSI received each day that are likely associated with Chinese fishing vessels fluctuates, likely due to both changes in how many vessels are broadcasting and the reception quality in the region. Fig. S15 shows the number of unique MMSI detected each day during 2017 and 2018. In both years, the first significant group of vessels appears in May, the number of vessels peaks within the first two months (May or June), and then decreases toward the end of the year. The number exceeded 100 in June 2017 and reached nearly 200 in June 2018. Almost no AIS signals are observed between mid-December and the beginning of May, which corresponds to the period when no Chinese vessels are observed on the water by the South Korea Coast Guard (see section S6. Observation on the water).

It is possible that some of the spikes in the number of vessels observed may have to do with changes in AIS reception, and that many of these vessels may have been broadcasting for many more days than were recorded in our database. On the days with the most vessels observed, the messages were received by terrestrial receivers instead of satellite. Poor reception, however, cannot explain why only about 200 MMSI were observed instead of more than 900; the majority of vessels did not broadcast AIS.

Compared to the SAR and VIIRS analyses (see section S3. Synthetic Aperture Radar and section S5. Nighttime optical imagery), the number of vessels in the AIS analysis is skewed towards the beginning of the fishing season. Manipulation of AIS devices can alter observations in several ways (*16*), which would not influence VIIRS and SAR detections. One possible explanation is that many actively broadcasting vessels turned AIS devices off once they arrived in North Korean waters.

Counting only the AIS-detected vessels in North Korean waters yields an estimate of 4,200 fishing days during 2017 and 2018 (fig. S15), which is only about 2% of the total fishing days estimated in this paper (see section S8. Estimated number of Chinese vessels and days of fishing in North Korea).

4.5 Tracks of individual fishing vessels

We investigated the tracks of each likely Chinese fishing vessel identified above. Their movements show departures from Chinese ports before arriving in North Korean waters, and a few individual tracks of likely Chinese fishing vessels during 2018 are illustrated in fig. S16. (The signals of some vessels were lost in North Korea, and a few vessels headed to the Pacific before returning to Chinese ports). By analyzing their position messages in North Korean waters and near Busan, South Korea, we can estimate their origin/destination port, their approximate period of fishing activities, and the number of entries into North Korean waters during the year. The number of entries is also used to refine our estimate of the total number of Chinese fishing vessels derived from the number of entries counted by the South Korea Coast Guard (see section S8. Estimated number of Chinese vessels and days of fishing in North Korea). Fig. S17 shows an instance of two trawlers in a pair in North Korean waters broadcasting a relatively high number of AIS signals for more than 12 hours, and demonstrates an operation cycle of transiting to fishing ground (>10 knots), trawling in a pair (between 3 and 6 knots), and likely hauling (<1 knot).

Section S5. Nighttime optical imagery—Visible Infrared Imaging Radiometer Suite (VIIRS)

The Visible Infrared Imaging Radiometer Suite (VIIRS) is a sensor on board the Suomi National Polar-orbiting Partnership satellite jointly operated by the National Oceanographic and Atmospheric Administration and the National Aeronautics and Space Administration. The sensor can detect nocturnal surface-sourced light, and *Elvidge et al*. (*18*) developed a method to use this sensor's imagery to identify vessels that use lights. *Elvidge et al*. have produced a database, freely available, of these daily vessel detections and the radiance of each vessel, measured in nW/cm^2/sr.

In this section, to establish our methods and demonstrate how different fleets can be differentiated by brightness, we analyze the activities in five different regions in the waters between Japan, Russia, and the Koreas. In each region different fleets using different lighting power are active. These areas are:

1. A portion of the Russian EEZ where one Japanese and 48 South Korean squid jiggers operated in August and September of 2017, and where few other vessels operated.
2. Russian territorial waters (the coast to 12 nautical miles to sea, with some variation). In these territorial waters there is little if any squid jigging, and only Russian vessels are permitted to operate.
3. Russian EEZ outside the territorial waters (from 12 nautical miles to the EEZ boundary), where the North Korean fishing fleet operated. We used the eastern EEZ boundary of this region for Russia from MarineRegions (http://www.marineregions.org) and adjusted the western and southwestern boundary with North Korea as explained in section S1 (Boundaries and access agreements).
4. North Korean military zone and the claimed internal waters (North Korea's coast to about 50 nautical miles—see section S1. Boundaries and access agreements). In this region, no foreign vessels operate.
5. Our study area, which is the claimed North Korean EEZ outside the military zone, plus some areas to the east in the Russian EEZ and in disputed waters between nations in the region (see section S1. Boundaries and access agreements). In this area, the Chinese fleet and some likely North Korean vessels were present.

Combining the analyses of these regions with information on the water about the different fleets and their lighting power, we find:

- Chinese vessels are extremely bright, and can be differentiated from North Korean vessels by only counting vessel detections with a radiance over 500 nW/cm^2/sr.
- North Korean vessels in Russian waters are comparatively dim, and can be differentiated from other fleets in the region using lights (Japanese, South Korean, and Chinese) by counting the number of detections under 50 nW/cm^2/sr on clear nights.
- Counting vessels with detections under 50 nW/cm^2/sr on clear nights may count some vessels that do not use light to fish (such as cargo vessels or trawlers). We demonstrate that the number of these detections in Russian waters should be sufficiently low so as not to affect our estimate of the North Korean vessels present.
- To analyze data from the clearest night, we identified the night in each half month period in each region that had the most detections using our radiance thresholds. Based on nearby weather stations, we should have one clear night every 15 days. We tested this method on the South Korean and Japanese fleets, and found the resulting estimates agreed reasonably well with the known number of vessels active and the days they fished.

5.1. VIIRS vessel detections, radiance, and false detections

Vessel detections

We use the VIIRS vessel detection data downloadable from the Colorado School of Mines (https://eogdata.mines.edu/vbd/), described in (*18*). We selected only detections categorized as boat (QF=1) or weak detection (QF=2). VIIRS has global coverage and, because satellite paths overlap slightly, sometimes provides two data sets per night for a given region with about a 2-hour gap between acquisitions. In this case, we avoid double counting and use the dataset that has the higher number of boat detections to represent the night, except when the average satellite zenith angle is above 60°; we then choose the dataset that has lower average zenith to better standardize detections. VIIRS is also relatively low resolution, with each pixel 750 m wide, meaning that vessels using lights and operating closer together than this distance will not be resolved into different vessels.

Vessel radiance and angle

Each vessel detection has an associated brightness, measured in units of radiance (nW/cm^2/sr). Elvidge's team performed an experiment with a 1-kw tungsten bulb in a region of Colorado with no nearby lights, and this bulb was detected by the satellite with a radiance under 10 nW/cm^2/sr when the satellite was directly overhead, with a zenith angle of 0. The number of 1-kW tungsten bulbs on squid fishing vessels in this study range from just a few for North Korean vessels to as many as 700 for some Chinese vessels. As such, it should be possible to differentiate the vessels based on brightness.

In addition to clouds, which can reduce the brightness of vessel detection, a key issue is that the detected brightness is affected by the zenith angle to the satellite. Because the VIIRS sensor is at an altitude of about 800 km and captures an image swath about 3,000 km wide, pixels at the edge of the image have a very different zenith angle than those overhead.

Detections at a high zenith angle appear much brighter, likely due to the geometry of the bulbs and the reflection properties of water. Elvidge reports that, in their tests with bulbs, they observe brighter detections at higher angles on land, and believe that might have to do with the geometry of the lights: The filaments often hang vertically, and radiate more light to the sides that straight up. For higher angles, especially above 60°, properties of water exacerbate this effect. Because of the index of refraction of water, water reflects very little light at 0° (straight down), but almost all light at a zenith angle of 80°. As such, the light viewed from the horizon will be doubled due to reflections from the ocean, while light viewed from overhead will not be.

An analysis of the radiance of vessels in the waters between Japan, the Koreas, and Russia shows that the median radiance per vessel detection is about six times higher at a zenith angle of 60° than 0°, and almost 10 times higher at 70°. For this reason, we eliminated detections at angles greater than 60°. Fortunately, because the difference in brightness between North Korean lighting vessels and Chinese lighting vessels is much larger than a factor of 10, it is still possible to differentiate the vessels.

False detections

Potential sources of false detections include moon glint, cosmic rays, airplanes, sunlight hitting the satellite, the aurora borealis or aurora australis, and the South Atlantic Anomaly (where the Earth's inner Van Allen radiation belt comes closest to earth, mostly only an issue near South America and in the southern Atlantic). *Elvidge et al*. (*18*) do not report the rate of false detections for the vessel detection algorithm. To estimate the potential number of false detections per unit area per night, we analyzed other patches of ocean at similar latitudes where we knew very few vessels to be operating based on Global Fishing Watch's global feed of AIS data (which includes both fishing and non-fishing vessels).

At a latitude similar to that of North Korea (we reviewed 38° N to 43° N), the region of the ocean with the lowest traffic was between 160° W and 170° W, which is a patch of the Pacific about halfway between Hawaii and the Alaskan Aleutian Islands. In this 5° by 10° box during 2017, we detected an average of about three vessels of any kind broadcasting AIS per day. In the VIIRS data for this region, we observed only 346 vessel detections in 2017, an average of one per day, or about 2.5 detections per million km^2 per day.

Even fewer vessels were detected in an analysis of a region in the southern Indian Ocean, potentially because of the lower vessel traffic. We choose a similar latitude (38° S to 43° S) so as to mimic potential latitudinal effects such as sun glint or the aurora (although sun glint and the aurora would be at different times of the year than in the northern hemisphere, the effect should be similar across an entire year). Between 70° E and 115° E at this latitude, we observed just under three vessels broadcasting AIS per million km^2 per day. The number of vessel detections here, during 2017, was 1.2 per million km^2 per day. The majority of these detections (>85%) have a radiance under 5 $nW/cm^2/sr$.

If all of these detections are false detections, and not real vessels, then the rate of false detections is around one to two detections per million km^2 per day. Our study area is about 90,000 km^2, and the area in Russian waters where North Korean vessels fished was about 100,000 km^2. Given these numbers, we expect, on average, less than one false positive per day in our study area, and only about three false detections with a radiance over 5 $nW/cm^2/sr$ per year.

Another source of false detections is when light from a vessel is picked up by two adjacent pixels in imagery. In such cases, Elvidge's team filters out pixels with the weaker radiance to assure that only one vessel detection is reported. This filter examines cross-neighboring pixels (one pixel away from the target pixel either horizontally or vertically) to determine the local maximum around a target pixel and remove neighboring detections that are weaker than the local maximum. It is difficult to measure how many neighboring detections sourced from the real vessels the filter removes; however, it effectively suppresses false detections. The filter, however, disregards the pixels that are diagonally adjacent (one pixel away both horizontally and vertically) to a target pixel. It may result in a pair of detections in diagonal for a single source of light whereas it is equally possible that the two detections are legitimate detections of vessels that are diagonally adjacent in pixel. For small vessels with low radiance, it is unlikely that it could result in overcounting because multiple vessels could be detected in a single pixel (thus one single detection) particularly when areas are crowded. For larger vessels with higher radiance, they could keep a longer distance to each other and radiate light much farther to be detected in a neighboring pixel. In the study area where we identify bright Chinese lighting vessels with a cutoff of >500 $nW/cm^2/sr$ (see below), fewer than an average of 1.5 detections per day are detected diagonally adjacent to another detection of >500 $nW/cm^2/sr$ during the squid fishing season, counting only days with the most detections in each half-month period.

5.2 Method validation with South Korean and Japanese squid jiggers

As described in section S1 (Boundaries and access agreements), in 2017, one Japanese and 48 South Korean squid jiggers operated, with permission, in the Primorye subzone of Russian waters, which is to the northeast of our study area. Because we know the approximate size of these vessels and the days they operated, and because there were few, if any, other lighting boats operating nearby, we can use this fleet to calibrate our methods for 1) differentiating fleets based on vessel brightness, 2) counting the number of vessels active in a region, and 3) estimating the number of vessel days over a season.

Operation of South Korean and Japanese lighting vessels

For 2017, we have details on the daily activity of the 48 South Korean and one Japanese squid jigger in Russian waters (*51, 53*). These vessels operated in a part of the Russian EEZ where, according to the captains of these vessels, no other vessels fished with lights. This region is the northern part of the EEZ, between 42° 40' N and 45° N in the Primorye subzone. The North Korean squid boats operating in Russian waters in 2017 appear to have fished mostly in the southern part of the EEZ, near North Korean waters (below 42° 40' N in the Primorye subzone). The South Korean fleet also observed no Chinese vessel in their operating area over the past three years. It is believed that the three Chinese vessels that were authorized to fish in Russian waters (see section S1. Boundaries and access agreements) fished farther east in either the Sea of Okhotsk or the Bering Sea.

It is possible that other vessels, such as fishing vessels not using light (e.g., trawlers) or non-fishing vessels (e.g., tankers) were present in these waters. These vessels can sometimes appear as vessel detections by VIIRS, although usually with lower radiance levels (see below on detections within the Russian territorial waters). It is also possible that some North Korean squid fishing vessels were fishing in the same area, but were not reported by the South Korean and Japanese vessels.

Japanese and South Korean squid jigging boats are restricted by law to use no more than 250 and 141 kW respectively (*70, 71*). Based on co-authors' discussions with fishing captains, the vessels use as much light as possible, so this upper limit should approximate their lighting power. By comparison, North Korean vessels usually use about 5-20 tungsten bulbs, each 1-2 kW (see below), and should be about an order of magnitude dimmer.

<u>Radiance and counts of South Korean and Japanese lighting vessels during 2017</u>

Fig. S18A shows the number of vessels one would count with different brightness thresholds. There is a sharp distinction between these lighting vessels and the non-squid jiggers in the area, which have a brightness well under 10 nW/cm^2/sr, as seen in jump in detections at the far left of the figure. The number of vessels detected is relatively flat at thresholds between 4 and 258 nW/cm^2/sr and thresholds between 140 and 258 nW/cm^2/sr predicts the correct maximum number of vessels present (47 was the maximum present at any given time, although there were in total 49 in operation). Based on this we chose a threshold of 140 nW/cm^2/sr for examining the South Korean and Japanese lighting vessels.

Fig. S19 shows the daily counts of vessels detected in this region for the 30 days between August and September 2017 with radiances above 140 nW/cm^2/sr. As shown in fig. S20, this filters out nearly all North Korean lighting vessels, as well as non-light fishing vessels, leaving South Korean and Japanese vessels (see below). The peaks in the number of detections in fig. S19 fall near the number of North Korean and Japanese lighting vessels known to be in the area. However, on most days, the number of vessels detected at above 140 nW/cm^2/sr is considerably lower, likely due to a combination of weather (particularly clouds), zenith angle of the observation and the brightness and orientation of the moon. On two days we see a few more detections than expected in the region, these are likely the result of either unaccounted for vessels in the area, or false detections as described in section S5.1.

To estimate the number of fishing days, which we approximate as the number of days vessels are present, we take the maximum number of vessels above a given radiance for a given half-month period. This method assumes that the number of vessels does not vary much on a time period shorter than half a month, or 15 days. We chose this period because, according to weather data from the Korea Meteorological Administration weather for Ulleung-do, the nearest island to the core fishing ground (see section S6. Observation on the water), there is a high likelihood of at least one cloud-free day every 15 days. Fig. S18B shows the number of vessel days estimated by counting the maximum number of vessels present over each half month period. At the chosen threshold of 140 $nW/cm^2/sr$, this slightly undercounts vessel days.

Taking the maximum over half-month periods would tend to bias a measurement upward. However, examining fig. S19 shows that there are only a few good observation days each month, so this effect is minimal. When combined with the factors biasing this estimate downward, we still expect the estimate to be conservative. For evidence of this underestimation, note that fig. S18B shows a slight underprediction of vessel days.

5.3 Vessels not fishing with lights

Vessels that do not use light to fish, which includes both non-light fishing vessels such as trawlers and non-fishing vessels such as cargo ships or passenger ships, sometimes appear in the VIIRS data because of deck lights, although their radiance levels are much lower than those of vessels using light to fish. To eliminate these vessels from our analysis, we examined 1) the range of radiances observed in the Russian territorial waters where no foreign nations are allowed to fish, and where very few fishing vessels using light to fish are known to operate, and 2) the Russian EEZ outside of the territorial waters during non-squid fishing season.

Few vessels are detected by VIIRS within the Russian territorial waters in this region, and most are very dim. Fig. S20 shows the distribution of radiances of boats detected with light in the Russian territorial waters during 2017, from the North Korean border to 46° N (we use only the day with the highest number of detections in each half month). In these 24 days (one for each half month of the year), we saw just 139 detections, or about 6 per day; only 12 were brighter than 10 $nW/cm^2/sr$, and none were over 20 $nW/cm^2/sr$. About 40% of these detections have a radiance below 2 $nW/cm^2/sr$. Given the small area of the territorial waters in this region (~17,000 km^2), we expect very few false detections.

To determine if we could see the Chinese Pair trawler fleet in VIIRS data, we also analyzed a few nights of VIIRS imagery that coincided with days when we had satellite radar or Planet imagery. During 2017, within the areas of interest shown in fig. S8A, the number of VIIRS detections was less than 10% of the number of pair trawlers. While it is possible these detections were other vessels, the data suggest that we might be able to see as much as 10% of the pair trawler fleet, as weak detections, in the VIIRS data. That means that when the pair trawling fleet is active, with hundreds of vessels, we might see, at most, tens of low-radiance detections in the VIIRS data.

We also analyzed the Russian EEZ outside the territorial waters during non-squid season, from mid-December to mid-May (fig. S24). During that time we observed almost no detections in this region, which spans about 100,000 km^2; the most active day of every half month had under 10 detections per day during 2017. In contrast, during the squid season hundreds and sometimes thousands of vessels were detected. The detections during the non-squid season were generally quite weak, with over 40% having a radiance under 2 $nW/cm^2/sr$ and 90% under 5 $nW/cm^2/sr$.

The Global Fishing Watch website also allows one to compare the number of detections during and outside the squid season. Here is a link to an interactive map with all detections that have a radiance under 100 $nW/cm^2/sr$ over the first four months of 2017: https://bit.ly/2lYVOoM. And here is a link to an interactive map with all detections that have a radiance under 100 $nW/cm^2/sr$ between July and October, 2017: https://bit.ly/2lYW72U.

From this analysis, we conclude that:

- Vessels not using light to fish can be observed in VIIRS data, but most likely only a small fraction are observed (likely no more than 10%).
- Vessels not using light to fish are likely to be detected with very low radiances, with 90% under 5 $nW/cm^2/sr$.
- During the non-squid season, few vessels are observed in the Russian EEZ outside the territorial waters.

5.4 North Korean vessels in the military zone and the claimed internal waters

Within the North Korean claimed EEZ, a key challenge is to be sure that we are identifying Chinese lighting vessels and not North Korean fishing vessels. To estimate the potential brightness of North Korean vessels, we analyze the lights produced in North Korean waters within the military zone and the claimed internal waters, where, in theory, only North Korean vessels are allowed to operate (see section S1. Boundaries and access agreements).

Many more lights are found in North Korean waters than in the Russian territorial waters, reflecting the fact that North Korea fishes with light extensively and Russia mostly does not (see section S1. Boundaries and access agreements). Using a filter that selects the day with the most detections in each half month, we observed during 2017 a mean of about 250 detections per half month, with a peak of over 700 detections at the height of the squid season in October. Of these detections, as shown in fig. S20, 99% of them had a brightness under 300 $nW/cm^2/sr$, only one was over 500 $nW/cm^2/sr$, and the detections peaked under 5 $nW/cm^2/sr$. From this analysis, we conclude that North Korean vessels are unlikely to produce detections brighter than 300 $nW/cm^2/sr$, and detections brighter than 500 $nW/cm^2/sr$ are extremely rare.

5.5 North Korean fishing vessels in Russian waters

The evidence we have that wooden North Korean vessels are fishing in Russian waters includes the following:

- Eyewitness accounts from fishing captains, including pictures (fig. S27) and videos (Movie S1 and S2).
- Media reports (see section S6. Observations on the Water).
- North Korean vessels shipwrecking on the shores of Russia and Japan (see section S6. Observations on the Water) in areas consistent with North Korean vessels fishing in Russian waters.
- Planet's optical images over Chongjin, North Korea's largest fishing port between a day in non-squid fishing season and the one in peak fishing season (fig. S6), showing that thousands of small, wooden vessels were missing during the fishing season. We do not see that many vessel detections in the claimed North Korean EEZ, suggesting that the vessels are elsewhere.
- VIIRS documenting numerous vessels in Russian waters during the squid season, with most detections below 50 $nW/cm^2/sr$, consistent with the 5 to 20 bulbs found on North Korean vessels (see more below)
- The SAR acquisitions for this study that overlap with the Russian EEZ showing almost no detections where the VIIRS vessel detections are found (see fig. S8), indicating that these are small, wooden vessels.
- Russian claims that illegal fishing by North Korean vessels in their waters was the reason for not issuing permits to North Korea for 2017;

From this information, we are confident that the small North Korean wooden vessels are fishing for squid inside the Russian EEZ. The key questions are how many vessels, and how confidently can we infer this number from the VIIRS data.

Within the Russian EEZ, we observe hundreds, and sometimes thousands, of vessel detections per day over the course of the squid season, and during the non-squid season only about 10 detections per day on average (selecting the day of each half month with the most detections). The rate of false positives for VIIRS vessel detections, assuming it is similar to other parts of the ocean, should be much less than one per day, meaning that almost all of these detections are vessels.

Among these thousands of detections, 85% have a radiance under 15 $nW/cm^2/sr$, 97% under 50 $nW/cm^2/sr$, and 98% under 100 $nW/cm^2/sr$ (fig. S20). Interestingly, these vessels appear to have weaker lights than many of the vessels operating in the North Korean military zone and the claimed internal waters. While only 2% of the detections in the Russian EEZ are above 100 $nW/cm^2/sr$, over 10% of the detections are brighter than this threshold in the North Korean military zone and the claimed internal waters.

The Japanese and South Korean fleets, and possibly some Chinese vessels, also operate in the Russian EEZ. All of those squid jiggers use much more powerful lights. Based on our analysis of the South Korean and Japanese fleet (fig. S18, S19), a threshold of about 50 $nW/cm^2/sr$ on clear nights would be sufficient to distinguish the far brighter Japanese, South Korean and Chinese vessels from the dimmer North Korean vessels.

Such a threshold would attribute a few (<5% of total vessels) of the brightest North Korean vessels to other countries.

A key question is whether the numerous low-radiance detections in Russian waters could be anything other than the North Korean fleet. Careful examination suggests that the North Korean fleet is the only plausible answer for the vast majority of these detections, as other possible explanations account for only a few tens of detections per day, far fewer than the peak of over 3,000 detections observed in 2018. The AIS data shows very few vessels active here: In this part of the Russian EEZ, about 30 vessels broadcast AIS, on average, per day, and this number does not increase during the squid season (the majority is AIS traffic from cargo or tanker vessels). In the radar data, very few objects are detected in the Russian EEZ, making numerous larger vessels unlikely (fig. S8), and making it more likely that these detections are wooden vessels. It is possible that some Chinese pair trawlers sometimes fish over the line in Russian waters (we observed it on one day, see fig. S8), but this event happens rarely and we should observe only about 10% of this fleet in the VIIRS data at most (see previous section on vessels not using lights to fish). Given the low rate of false detections (estimated at less than one per day for this region), we are confident the vast majority of these detections are real vessels. If a significant portion of these detections are not North Korean, they would have to be an unaccounted for fleet of small, wooden vessels fishing with lights in these waters.

Given that the majority of these detections are likely North Korean vessels, we count all detections in these waters with an intensity under 50 $nW/cm^2/sr$ as North Korean fishing vessels. This threshold removes detections likely due to South Korean, Japanese, or Chinese vessels fishing with light in the region. For several reasons we believe this count of North Korean vessels is an underestimate. First, these vessels are much smaller than the Chinese, South Korean, or Japanese vessels, and thus are more likely to fish within 750 meters of one another, occupying the same, or horizontally or vertically adjacent, VIIRS pixel and resulting in only one vessel detection for several vessels. Second, we observe that the North Korean fleet sometimes fishes over the line in Japanese waters and in the Russian territorial waters, and we have counted only the vessels within the Russian EEZ (based on the EEZ provided by MarineRegion slightly modified for the border between Russian and North Korea) but outside the territorial waters. As such, it is likely that the total number of vessels that fished in Russia is higher, as some of these vessels likely moved back and forth across this line. Third, it seems likely that not all vessels will have their lights operating at the moment of the satellite overpass. Fig. S21B shows the day with the maximum number of vessels operating in this area, which was on 13 October 2018.

For the time period 2015 to 2018, fig. S22 shows the sensitivity of our counts of the number of vessels and the number of vessel days to the radiance threshold. Both charts show that the maximum number of vessels and the total vessel days are relatively insensitive to the upper limit chosen once above 20 $nW/cm^2/sr$.

5.6 Chinese lighting vessels

The lighting power of Chinese lighting vessels is well described by several papers (*72-76*), where they are referred to as "light falling-net" vessels. In those papers, however, the vessels are smaller in size (32-42 m) and use fewer light bulbs (180-460, 1-2 kW/bulb) than do the Chinese lighting vessels likely engaged in fishing in North Korea. The Chinese vessels observed by the South Korean authorities are typically 55-60 meters long and have up to 700 bulbs (fig. S26 shows an image of one of these vessels with about this many lights), so they should radiate far more light than do the light falling-netters described in these papers. We thus expect the Chinese lighting vessels to have between 180 and 700 of 1-2 kW bulbs. The vessels with 700 bulbs likely produce at least 1,050 lux of light, assuming at least 1 kW per bulb ($1 \text{ kW} \times 700 \text{ bulbs} \times 15 \text{ lm}\cdot\text{W}^{-1} \times 10{,}000 \text{ m}^2 = 1{,}050 \text{ lux}$, ignoring light loss), which is similar in magnitude to the illuminance level required for lower level competition matches in European football stadiums (*77*).

To estimate the radiance levels of these vessels, we can compare them to the radiance values of the Japanese and South Korean squid jigging boats (with regulated limits of 250 and 141 kW respectively), which we observed clearly in Russian waters (see previous section). Given the Chinese vessels have at least 180 bulbs, and most have many more, and each light is usually at least 1 kW, these vessels should all be brighter than the South Korean fleet, and likely much more so. They should also be about as bright or brighter than the Japanese vessels.

To count all the South Korean and Japanese vessels, we chose a threshold of 140 nW/cm^2/sr on the day with the maximum number of observations and obtained an accurate count of vessels operating and a slight underestimate of fishing days. Because the Chinese vessels are brighter, it should be possible to have a higher threshold for the Chinese vessels. The key challenge, though, is to differentiate these vessels from potential North Korean vessels fishing in the claimed North Korean EEZ.

Our analysis of the North Korean military zone and the claimed internal waters suggested that 99% of North Korean vessel detections are under 300 nW/cm^2/sr, and only one detection was above 500 nW/cm^2/sr in 2017. We used a threshold of 500 nW/cm^2/sr and counted all vessels above this brightness as Chinese, because almost no North Korean vessels should be this bright. This value gives us at least 108 unique Chinese lighting vessels in 2017 and 130 in 2018. Using a threshold 20% higher or lower (400 or 600 nW/cm^2/sr) adjusts this estimated number of vessels by 7% (fig. S23A, B). With a threshold of 500 nW/cm^2/sr, counting the maximum number of detections over this value in a given half-month period, we estimate 15,000 fishing days in North Korea by Chinese lighting vessels in 2017-2018. Adjusting the threshold up or down 20% (to 400 or 600 nW/cm^2/sr) increases or decreases the fishing days by 7% (fig. S23C). We believe this number is conservative, and the actual number of Chinese vessels is likely, although not definitely, higher. Fig. S21A shows the day with the maximum number of Chinese vessels observed, 3 October, 2018.

In summary, counting the number of vessels brighter than 500 nW/cm^2/sr in our study area should count only Chinese vessels, and provide a conservative estimate of the number and activity of these vessels.

Section S6. Observation on the water

This section provides information about Chinese vessels entering and leaving North Korea by way of South Korean waters. We used the vessel count of the South Korea Coast Guard and its observation data to validate our estimate by satellite observation in sections S2 through S5. We also include observations of North Korean vessels operating in Russian waters.

6.1. Observations in South Korean waters

South Korea Coast Guard and the East Sea Fisheries Management Service

The South Korea Coast Guard, in collaboration with the East Sea Fisheries Management Service, monitors vessels that transit through the South Korean EEZ to North Korean waters. This route is the most direct path from China to the eastern part of North Korea, the alternative being a long detour through the Japanese EEZ. The coast guard closely monitors all vessels entering and exiting North Korean waters through the Northern Limit Line between the Koreas, except for non-fishing vessels broadcasting AIS (such as cargo vessels, tankers, etc.), as these vessels are relatively easily identified from AIS alone. The two organizations then inspect about one third of these vessels either by onboard inspection or by radio communication. Because many Chinese fleets pass by in groups of multiple vessels, and some are obviously transiting from Chinese waters, the organizations inspect only a few from each group and assume the rest of the group is also Chinese. In 2017, the South Korean authorities inspected 1,074 out of the total 3,165 vessels believed to be Chinese transiting through South Korean waters (tables S4 and S5). According to the coast guard, no fishing vessels from Taiwan or other Southeast Asian countries were observed.

Table S4 and S5 provide information about Chinese vessels monitored and inspected by the South Korean authorities for 2017 and 2018 (*78*). The monthly count of likely Chinese vessels is used to estimate the number of Chinese fishing vessels that remain in North Korean waters at a given time (see section S8. Estimated number of Chinese vessels and days of fishing in North Korea), as only a small fraction leaves North Korean waters and heads out to the Pacific before returning to China.

Ulleung-gun county office

Ulleung-do is an island in the county of Ulleung-gun, South Korea. It is 120 km east of the Korean peninsula, about 120 km south of North Korean waters, and is the nearest island to the border between South and North Korea. The island is about 200-300 km away from the primary fishing grounds for the Chinese fleets, while the nearest North

Korean port is 300-350 km away. Ulleung-do is known as an anchorage where Chinese fleets shelter from typhoons when fishing in North Korean waters.

The Ulleung-gun county office has taken photographs of Chinese vessels when they came to the port fleeing typhoons. Fig. S25 shows an overview of the fleets (mainly Chinese pair trawlers) anchored near the port in 2016-2017, and fig. S26 gives closer views of Chinese lighting vessels from 2016-2018; the lighting vessels are larger and have four foldable structures that are stretched out to hang nets when in operation. These photos can be compared with the satellite images from SkySat to reveal that they are very similar to, if not the same, as vessels that are seen operating in North Korean waters.

6.2. North Korean fishing boats

Media coverage of North Korean ghost boats

Some North Korean squid boats have been covered by the media in neighboring countries—South Korea, Japan and Russia—and by some international media. Some photographs and videos accompanying these articles provide views of North Korean fishing boats that are often observed on the sea in this region. In recent years, up to a hundred North Korean boats a year have washed ashore on Japanese or Russian shores, often shipwrecked and with bodies found aboard; between 2014 and 2018, the media documented a total of 505 of these so-called ghost boats, including a record 225 during 2018. Many of these cases occurred in autumn and winter when sea conditions are rough. According to reports, these boats are usually not equipped with GPS and are unfit for long-distance fishing on the sea (see a few selected media articles below).

Media	Link
Nikkei	https://www.nikkei.com/article/DGXMZO38505560U8A201C1CC0000/
Yomiuri	https://www.yomiuri.co.jp/local/shimane/feature/CO029071/20190115-OYTAT50068/
KBS	http://mn.kbs.co.kr/news/view.do?ncd=3318795
New York Times	https://www.nytimes.com/2017/12/07/world/asia/japan-north-korea-ghost-ships.html
BBC	https://www.bbc.com/news/world-asia-34981195
RFE/RL	https://www.rferl.org/a/north-korean-ghost-ships-deliver-grim-cargo-to-russian-coast/29463803.html

In addition to the media coverage, movies S1 to S3 provide edited footage of North Korean boats operating in the Russian EEZ. These videos were recorded by the captain of a South Korean fishing vessel entering Russian waters. A few Chinese lighting vessels at the edge of the claimed North Korean EEZ are also captured in these videos. A few selected images from the footage are shown in fig. S27.

In these direct observations, North Korean boats are usually 10-20 meters long, constructed from wood, and carry up to 10 crew members. To attract squid at night, they are equipped with 5-20 lighting bulbs on the deck and they are often observed with squid being dried on the deck, suggesting that these boats are not equipped with proper refrigeration systems. The intensity of their lighting can be estimated by the number of light bulbs, usually assuming 1-2 kW per bulb, which results in an estimated 5-40 kW of lighting. In comparison, Japanese and South Korean squid jiggers use up to 250 kW and 141 kW, respectively, while Chinese lighting vessels appear to carry hundreds of bulbs and are far brighter (see section S5. Nighttime optical imagery).

Section S7. Legal analysis on Chinese fishing in North Korea

This section provides a legal analysis on Chinese fishing in North Korean waters based on international laws and domestic regulations. It also presents written evidence of Chinese fishing in North Korea, sourced from official Chinese government communication platforms (provincial or municipal) and major information networks about fisheries. This section further discusses the number of Chinese vessels that entered North Korean waters and the reported amount of fish caught based on the combination of Chinese official fisheries yearbooks and communications through the government's official gazette.

7.1. Fishing rights

It is widely known that China has traded for the right to fish in North Korean waters since 2004 (*79*). During 2017-2018, following sanctions by the United Nations, the South Korean authorities continued to discover North Korean fishing permits on Chinese vessels during inspections. These permits describe the details of the permitted fishing, including amount and type of allowed catch, authorized period, designated areas, and allowed fishing gear.

<u>United Nations resolutions prohibiting fishing in North Korea</u>

In August 2017, the UN Security Council tightened sanctions on North Korea, unanimously adopting Resolution 2371, condemning the launch of ballistic missiles and the country's continuous attempts to develop nuclear weapons. This resolution, adopted by the UN Security Council, including China, which is a permanent member holding veto capability, states that the "*[UN] decides that [...] all States shall prohibit the procurement of [seafood] from the DPRK by their nationals, or using their flag vessels or aircraft, whether or not originating in the territory of the DPRK*" (*80*). The measure was adopted on 5 August 2017, and included a 30-day notice period, meaning that it would take effect on 5 September 2017. Any fishing in North Korean waters after this date is a breach of Resolution 2371.

Moreover, Resolution 2375, also unanimously adopted in September 2017, further clarifies that all joint ventures and cooperative entities are prohibited and all existing ones, unless approved by the Council, must be terminated by the beginning of January

2018 (*81*). This forecloses the possibility of legal commercial fishing conducted by North Korean individuals or entities for Chinese beneficiaries.

In December 2017, Resolution 2397 clarified that the UN Security Council "*prohibits [North Korea] from selling or transferring, directly or indirectly, fishing rights*" (*82*). Despite this series of sanctions, analyses from section S2 to section S6 indicate that Chinese fishing operations have continued through 2018. This suggests that there is a high possibility that the trade of fishing rights, either officially or unofficially, between North Korea and China still occurs.

All three UN Resolutions were declared under Chapter VII of the UN Charter, taking measures under Article 41, and are, therefore, mandatory and binding. As such, the sanctions are considered an integral part of States' substantive obligations under international law. Non-respect of these sanctions could consequently trigger State responsibility (*14, 83, 84*). Fishing in North Korean waters by foreign nations, therefore, constitutes a violation of international law.

<u>China's implementation of the resolutions</u>

The Chinese government has consistently confirmed its fulfillment of international obligations and implementation of the Security Council resolutions. Beginning in November 2017, the Permanent Mission of China to the United Nations has submitted regular implementation reports, informing the Sanction Committee for North Korea about the implementation of each of these resolutions, e.g. Resolution 2371 (*85-87*).

> *"China [...] has put in place a series of effective operational mechanisms and practices. Following the adoption of resolution 2371 (2017), the Ministry of Foreign Affairs of the People's Republic of China, with the authorization of the State Council, issued a circular requiring implementation of the resolution by all Chinese Government ministries and commissions, provinces, autonomous regions, and province-level municipalities [...]."*

In addition to these implementation reports, in the official response to the Expert Panel on the UN Sanction Committee for North Korea in March 2019 (*88*), China emphasized that,

> *"[...] the Chinese competent authorities immediately published an announcement to prohibit procuring fishing rights from the DPRK, and the Chinese entities have stopped procuring fishing rights from the DPRK in accordance with the announcement. If any Chinese national or vessel is confirmed to illegally procure fishing rights from the DPRK or illegally go fishing in the DPRK sea areas without permission, China will deal with relevant issues in accordance with laws and regulations."*

Additionally, South Korean and Japanese governments have confirmed that at their respective bilateral fisheries commissions, Chinese representatives consistently assert that

China has authorized no nationals or fishing vessels flying their flag to operate in North Korean waters after the sanctions took effect.

Chinese regulation on distant water fleet in North Korea

China's distant water fisheries management regulations (远洋渔业管理规定) stipulate that fishing vessels and companies that operate in other countries' EEZ must be approved by the Ministry of Agriculture and Rural Affairs of China (*15*). In 2016, the Ministry announced the strengthened management regulation for vessels fishing in North Korean waters in accordance with the relevant national laws and regulations (*89*). It reiterated that all enterprises and fishing vessels that intend to fish in North Korea must be approved by the Ministry and emphasized that pair trawling is not authorized in North Korean waters (*89*), which has not been complied with given the evidence of pair trawling operation presented in the previous sections.

Illegality of fishing in North Korea

Since the first resolution took effect on 5 September 2017, three scenarios were possible for Chinese fishing in North Korea.

1. If China (the state) authorized Chinese vessels fishing in North Korean waters despite UN Resolutions, China (the state) was in violation of international law, under Chapter VII Article 41 of the UN Charter. In the previous section, however, we presented evidence that the Chinese government consistently confirms the prohibition of fishing in North Korea as per the UN resolutions.
2. If China (the state) did not authorize Chinese vessels fishing in North Korean waters, but a lower level of government did, then it is likely a violation of China's distant water fisheries management regulations.
3. If China (the state) did not authorize Chinese vessels fishing in North Korean waters, and permission was not obtained by any other level of government in China, the Chinese fishing entities/fishermen violated Chinese domestic regulations.

Additionally, if North Korea traded the right to fish with Chinese fishing entities or allowed them to procure seafood from its waters, North Korea is in violation of international law under Chapter VII Article 41 of the UN Charter. If North Korea is not behind Chinese fleets fishing in North Korea, Chinese vessels fishing in North Korea are in violation of the United Nations Convention on the Law of the Sea, which grants sovereign rights for managing living resources to the coastal state. Regardless of the scenario, Chinese vessels fishing in North Korea constitutes a violation of China's domestic regulations, international laws, or both. Additionally, North Korean fishing in Russia represents illegal fishing by a large number of unauthorized vessels.

7.2. Written evidence of fishing between 2017 and 2018

<u>Fujian province (福建省)</u>

Jinjiang Municipal Ocean and Fisheries Bureau (晋江市海洋与渔业局)

Excerpt from *2017 Work Summary And 2018 Work Plan (2017年工作总结及2018年工作计划)* —under "Urge the Development of Distant Water Fishing" section (力促远洋渔业发展), published in December 2017 (*90*). The summary of Jinjiang city's distant water fleet shows that 20 vessels operated in North Korean waters in 2017 and they were authorized by the Ministry of Agriculture of China (currently the Ministry of Agriculture and Rural Affairs). It does not however specify whether the operation was before September 2017 (after the Resolution 2371 came into effect) or later.

> "2.力促远洋渔业发展。支持和推动中际远洋渔业公司收购连江县远洋渔业公司旗下13艘二手远洋渔船，目前该公司已取得农业部远洋渔船船网工具指标，**福建海顺渔业有限公司旗下20艘远洋渔船获得农业部审批，准予在朝鲜以东海域作业，成为福建省首家在朝鲜东部海域生产作业的远洋渔船。**1-12月，我市远洋捕捞总产量达1.3万吨，同比增长29.2%。"
>
> (Rough translation of the part in bold) The 20 distant water fishing vessels of Fujian Haishun Fishery Co., Ltd. were approved by the Ministry of Agriculture to operate in the eastern waters of North Korea, becoming the first distant water fishing vessels in Fujian Province to produce in the eastern part of North Korea.

Quanzhou Municipal Ocean and Fisheries Bureau (泉州市海洋与渔业局)

Excerpt from *2017 Work Summary And 2018 Work Plan (2017年工作总结及2018年工作计划)*—under the section entitled "Promote the Development of Distant Water Fisheries" (推进远洋渔业发展), published in February 2018 (*91*). The Quanzhou municipal government, in the same Fujian Province, also announced that it sent 20 distant water fleet trawlers to North Korean waters. Moreover, the announcement specifies that the period of the operation was after the end of September 2017, which corresponds to the period that Resolution 2371 was in effect.

> "1.推进远洋渔业发展。紧抓远洋渔业发展战略机遇期，新增远洋渔船13艘，累计投产远洋渔船57艘，总投资近15亿元。**积极推动远洋渔船转场作业，海顺远洋渔业公司20艘远洋拖网渔船9月底转场朝鲜北部湾海域开展对外渔业合作**，港顺远洋渔业公司10艘灯光围网渔船由北太平洋转场东印度洋开展公海作业。全市远洋渔业捕捞产量预计**达**7.89万**吨**，比增28.17%。"
>
> (Rough translation of the part in bold) Actively promoting the transfer of Distant water fishing vessels. 20 ocean-going trawlers of Haishun Ocean Fishing Co., Ltd. transfers to North Korean waters at the end of September to carry out distant water fishing operation.

Jinjiang News Network (晋江新闻网)

Excerpt from Jinjiang News Network, published on 8 September 2017. Jinjiang News Network is under the responsibility of Jinjiang Municipal People's Govern. It provides more detailed information about the 20 distant water fleet vessels that operated in North Korea in 2017, although it does not specify which municipality they are registered to (*92*). It reveals the names of the vessels as well as when these vessels planned to leave port for operation in North Korea.

> "**日前，晋江市福建海顺渔业有限公司旗下福远渔200、201、202、203、205、206、207、208、209、210、211、212、213、215、216、225、226、227、228、229等20艘远洋渔船获农业部远洋渔业项目审批，准予在朝鲜以东海域作业，主要捕捞品种为北朝鱿鱼**（日本海真鱿），成为福建省首家在朝鲜东部海域生产作业的远洋渔业企业。**其中福远渔226、227、228、229等4艘远洋渔船已于9月6日上午办好相关出境手续成功开赴朝鲜海域，剩余16艘远洋渔船将于未来半个月内陆续启航开赴朝鲜海域。**"
>
> (Rough translation) Recently, 20 distant water fishing vessels of Jinjiang Fujian Haishun Fisheries Co., Ltd., FUYUANYU 200, 201, 202, 203, 205, 206, 207, 208, 209, 210, 211, 212, 213, 215, 216, 225, 226, 227, 228, and 229 were approved by the Ministry of Agriculture's distant water fisheries project to operate in the eastern waters of North Korea. The main fish species are squid, … Among them, four distant water vessels such as FUYUANYU 226, 227, 228, and 229 have successfully completed the relevant exit procedures on the morning of 6 September and gone to North Korean waters. The remaining 16 vessels will sail to North Korea in the next half month.

Shandong province (山东省)

Weihai City People's Government (威海市人民政府)

Excerpt from official announcement via *Weihai City News (威海网·威海晚报)*, published on 17 April 2018. Weihai City of Shandong province is the region where most of the suspected Chinese vessels originated from before fishing in North Korea (See section S4. Automatic Identification System). The announcement gives information about the moratorium on fishing activities in Shandong waters (from May 2018). The announcement specifically informs the fleets that they should not fish in the Chinese EEZ when returning from North Korea because of the moratorium at this time of year (*93*). The moratorium is known to continue until the end of August 2018 and the first squid fishing season is between May and July. It advises that private fishing documents are not valid for operation in North Korea and vessels require official authorization from public agencies in order to fish in North Korean waters.

> "在远洋渔船监管方面，我市在朝鲜东部海域作业的远洋渔船在项目结束后要立即返回船籍港所在地停港休渔，严禁返港期间在国内近海海域捕捞作业，民间办理到朝鲜东、西海岸作业的证件一律无效。"
>
> (Rough translation) In terms of the regulation of distant water fishing vessels, distant water fishing vessels operating in the eastern part of North Korea should immediately

return to the port of registry to stop fishing after the completion of the project. It is strictly forbidden to fish in the offshore waters of China during the returning period, and documents handled privately to operate in the eastern and western coasts of North Korea are invalid.

Weihai City Wendeng District Government (威海市文登区人民政府)

Excerpt from an official announcement of Wendeng District Government (文登区政府), published on 19 April 2018. It is the same announcement from Weihai City government as above, but re-announced by the Wendeng district authorities two days later to emphasize that this is an official directive that matters to the fishers in the city (*94*).

Rongcheng City Government (荣成市人民政府)

Excerpt from an official announcement of *Rongcheng Municipal News* (荣成市新闻中心), published on 8 November 2018. In this announcement, the operation of 35 fishing vessels in North Korean waters in July was mentioned (*95*).

> **今年7月，按照上级要求，我市在朝鲜东部海域作业的35艘作渔船完成撤离，顺利返回国内。为了保证远洋渔业项目平稳过渡，减少因项目停产带来的经济损失，市海洋与渔业局积极协调有关部门，协助企业开发新的后备作业渔场。**
>
> (Rough translation) In July this year, according to the requirements of the higher authorities, 35 fishing vessels operating in the eastern part of North Korean waters completed evacuation and returned to the country. In order to ensure a smooth transition of distant water fishery projects and reduce economic losses caused by project shutdowns, the Municipal Ocean and Fisheries Bureau actively coordinated relevant departments to assist enterprises in the development of new reserve fisheries.

7.3. Chinese official records

Records from Chinese governments

Written records of the Chinese fleets' operation in North Korean waters are found in table S6. The figures there are drawn mainly from the *China Fisheries Yearbook* published by the Ministry of Agriculture of China, but some are found in the Ministry's public notices or reports from government-related institutions. Note that the *China Fisheries Yearbook* has not provided information about fishing in North Korean waters since 2016.

This historic information allows us to estimate the catch by the vessels that we identified in the paper. Between 2011 and 2014, the number of vessels that fished each year in North Korean waters was over 600, while in 2015 far fewer were reported to have fished there. Interestingly, with fewer vessels, the catch per vessel is the highest in 2015. Among the years with available data, the minimum catch per vessel was 114 metric tons in 2012. The total catch value and value per vessel have steadily decreased, with the latest figure being about $200,000 worth of catch per vessel.

Section S8. Estimated number of Chinese vessels and days of fishing in North Korea

For 2017 and 2018, we estimate the number of Chinese fishing vessels operating in North Korean waters by combining three analyses: those based on 1) various satellite technologies presented in section S2 to section S5, 2) the observations on the water by the South Korea Coast Guard presented in section S6, and 3) historical catch data. These estimated numbers are used to demonstrate the extent of fishing by Chinese vessels in North Korean waters, and to estimate the total catch by these vessels as well as its value.

8.1. Number of Chinese vessels per year

The number of distinct fishing vessels that fished in North Korean waters is estimated in two ways. One method starts by examining the entire fishing season and identifying the maximum number of trawlers detected on a single date and the maximum number of lighting boats detected on a single, possibly different, date. Because the two groups of fishing vessels are detected separately, their counts can be computed independently. Due to bad weather (clouds or choppy seas which hinder detection) and incomplete coverage of North Korean waters (Planet imagery and SAR rarely cover the entire area of interest), the count of vessels on any single date is an approximate lower bound on the true number of distinct vessels present. To obtain the maximum, most accurate estimate of the number of vessels present across the fishing season, we use the count on the day with the most favorable weather and coverage. These counts of the two vessel types are then added to give an estimate of the number of distinct Chinese vessels present during the fishing season.

The second source of vessel counts is observation data from the South Korea Coast Guard. The coast guard counted every likely Chinese vessel that entered into North Korean waters by passing through South Korean waters, and every vessel that left via the same route. These are not unique counts, however, as the same vessel could leave and enter again, which results in double counting for a given year.

Because of the geography of the waters, it is unlikely that many Chinese vessels are merely passing through North Korean waters on their way to other fishing grounds; it is most likely that their destination lies in North Korean waters. It is possible that vessels leave or enter North Korean waters from Russia and Japan, although the most direct path from China to North Korean waters is via South Korean waters. Vessels might take the indirect route if they are continuing on to fish elsewhere, such as in the Pacific, although we observe only a few vessels (8 out of 403) appearing to do so in our AIS analysis. Overall our analysis suggests that it is uncommon for vessels to enter North Korean waters from areas other than South Korea, and we are able to use AIS data to help correct for double counting in the estimates from the coast guard.

Satellite observation

In 2017

To estimate the total number of Chinese fishing vessels that operated within North Korean waters, we add the number of lighting vessels and pair trawlers as discussed above. Using VIIRS (see section S5. Nighttime optical imagery), we detected a maximum of 108 lighting vessels on 27 October 2017. To estimate the maximum number of pair trawlers, we used images from 24 October 2017, a date for which we have multiple images (Planet imagery and PALSAR-2 radar imagery) with nearly complete coverage and clear weather. We estimate 796 pair trawlers using PALSAR-2 (see section S3. Synthetic Aperture Radar) and 733 using automated counting on Planet imagery (see section S2. Daytime optical imagery). In addition, on this date we hand counted 798 pair trawlers which includes both paired trawlers actively fishing and inactive or transiting unpaired pair trawlers. By summing the intermediate PALSAR-2 estimate of pair trawlers and the estimated number of lighting vessels, we estimate that there were at least 904 distinct, likely Chinese, fishing vessels in North Korean waters in 2017. As this estimate applies only to a single day, it is likely an underestimate of the total number of distinct fishing vessels operating in North Korean waters over the course of 2017.

In 2018

We used the same methodology as above for 2018. Using VIIRS, we observed a maximum of 130 lighting vessels on 3 October 2018 (see section S5. Nighttime Optical Imagery). We detected a maximum of 588 pair trawlers on 26 May 2018 using RADARSAT-2, a maximum of 512 using Planet imagery on 2 June 2018, and a maximum of 504 using Sentinel-1 on 15 May 2018. Combining the number of lighting vessels and the maximum number of pair trawlers (588 from RADARSAT-2), we estimate that there were at least 718 distinct, likely Chinese, fishing vessels operating in 2018. Again, this estimate, based on maximum counts for single days, is likely fewer than the true number of distinct fishing vessels that operated in North Korean waters in 2018.

Observation on the water

In 2017

We used the vessel count by the South Korea Coast Guard (see section S6. Observation on the water) and AIS data (see section S4. Automatic Identification System) to estimate the number of unique vessels that fished during a given year. In 2017, the coast guard counted 1,711 entries into North Korean waters by vessels that were not readily identified as a cargo vessel (table S3, and see section S6. Observation on the water). Of these, they inspected 788, and found 739 (94%), to be fishing vessels (table S4). Assuming the set of vessels not inspected is similar to the inspected set, these data suggest that fishing vessels made about 1,604 entries into North Korean waters.

We then analyzed the AIS tracks of 179 likely Chinese fishing vessels (see section S4. Automatic Identification System). About 25% (60 out of 239 total) of the entries analyzed were made by fishing vessels that had already visited North Korean waters at least once in that year. If the vessels without AIS entered and exited as frequently as those with AIS, then about 1,203 unique Chinese fishing vessels entered North Korean waters. Because many vessels with AIS broadcast only intermittently, however, some vessels with AIS could have entered and exited without broadcasting, which would lower this estimate.

In 2018

We applied the same approach as above to the data for 2018. Based on our analysis of AIS during 2018, 224 likely Chinese fishing vessels broadcasting AIS in 2018 made 427 entries to North Korean waters; about 48% (203 out of 427) of the entries were made by vessels that had already entered North Korean waters at least once. Using this estimate of entries per MMSI and the coast guard's count of total vessels traveling into North Korean waters in 2018, we estimated that 1,056 unique fishing vessels entered North Korean waters in 2018.

Comparison of estimates

Combining estimates derived from satellite and on-the-water observations, the total number of unique Chinese fishing vessels in 2017 is estimated to be between 904 and 1,203. As the reception of AIS signal in this region is poor, and because the vessels broadcasting AIS may not be representative of all the vessels, the AIS track samples we used may be biased. Because our estimate of vessels from the coast guard relies on estimating the number of entries and exits by vessel, we are less certain about this number (1,203). However, we have multiple, independent estimates of the maximum number of vessels fishing on a single day, so we are confident that at least 900 unique vessels fished in North Korean waters during 2017. For 2018, based on the approaches used above, the total number of unique Chinese fishing vessels is estimated between 718 and 1,056. Given multiple satellite-based estimates, we are confident that at least 700 unique vessels fished in North Korea in 2018.

8.2. Number of fishing days by Chinese vessels

Using satellite vessel detection and on-the-water observation, we estimated the number of Chinese fishing vessels present in our study area at semi-monthly intervals over the period of 2017 and 2018.

To estimate the number of lighting vessels, we use VIIRS and count the maximum number of lighting vessels every half month, which makes it likely that at least one clear night is included in each period (see section S5. Nighttime optical imagery). For the numbers of pair trawlers, we use the combination of Planet imagery (see section S2. Daytime optical imagery), Sentinel-1 (see section S3. Synthetic Aperture Radar), PALSAR-2 (see section S3. Synthetic Aperture Radar), and RADARSAT-2 (see section S3. Synthetic Aperture Radar). As pair trawler detections rarely have perfect conditions (clear weather, full coverage, and all trawlers active at the time of image acquisition), we estimate the likely number of active pair trawlers in each period by counting the maximum number every half month in the same manner as done for lighting vessels.

Variations in the number of daily detections are due primarily to weather and coverage, but some variation also occurs due to changes in the underlying number of vessels across the fishing season. We address the issues of weather and coverage by approximating the vessel count in each half month period as the largest single-day value observed over that period. The variations in the underlying vessel count could introduce an upward bias to the estimate. Analysis of individual AIS tracks, however, demonstrates that vessels usually remain in North Korean waters for at least two weeks, so that the daily number of vessels should not vary significantly (see section S4. Automatic Identification System), except for a few dates each season, such as the start and end of the season, when a large portion of the fleet enters or leaves the fishing grounds. The resulting small upward bias is offset by the fact that there are essentially no dates when there is perfect weather and coverage which biases the results downward. Overall, we believe that the net effect of these two biases is that we undercount the number of vessels.

Second, the vessel count by the coast guard is used to indirectly estimate the total number of Chinese fishing vessels in North Korean waters each month. Based on the monthly aggregated data of entry into and exit from North Korean waters, we derive an estimated number of Chinese fishing vessels operating in North Korea during a given month (see section S6. Observation on the water). Because some vessels can head east to Russian or Japanese waters after fishing in North Korean waters, the count of entries into North Korean waters can be higher than the exit counts. As the coast guard observed no Chinese vessels entering or exiting after mid-December, and the squid fishing season in North Korean waters is closed at the end of the year, no Chinese vessels are believed to be present in North Korean waters after mid-December. The number of vessels in North Korean waters each month is likely between two extreme scenarios relating to these vessels that likely continued into the Pacific: 1) they might have all left at the earliest moment (May) or 2) at the latest moment (December). We use the average values of each month based on these two scenarios to give an estimate of the likely number of Chinese fishing vessels in North Korean waters during a given month.

<u>Estimate by the coast guard's counts</u>

Using the estimated number of fishing vessels in North Korean waters based on the coast guard's monthly count and linearly interpolating between the days on which the monthly counts were taken, we estimate the number of fishing days as the area under the resulting curve. By this method, the number of fishing days of Chinese vessels is estimated at 130,500 days in 2017 and 74,300 in 2018. Estimating the fishing days by using only monthly counts, however, does not reflect possible daily fluctuation in the number of vessels. The underlying daily numbers between monthly counts could be greater or less than the monthly counts, thus introducing uncertainty on our estimate. Nonetheless, our AIS analysis revealed that vessels stayed at least two weeks in North Korean waters for each trip, which prevents the daily number from changing significantly. Vessels present in North Korean waters may occasionally not fish due to extreme weather events or technical problems on board, which could introduce an upward bias to our estimate of fishing days from the coast guard.

Estimate by satellite observation

Using our satellite observations, we estimated the total number of fishing days by all Chinese fishing vessels as the area of the bars in Fig. 4A-C, which represent days of fishing by likely active vessels in each half-month period. The estimated total fishing days is 91,400 for 2017 and 67,300 for 2018. Even using the maximum value for each half month, we rarely have days with perfect coverage, which introduces a negative bias into our results. However, the fishing vessels cannot operate for a few days due to typhoons (usually 2-3 affect the region each year) or technical problems on board, and this introduces a small positive bias. These estimates based on the combined satellite observations are about 70% and 91% of the fishing days estimated by the coast guard counts, in 2017 and 2018 respectively, indicating that the net effect may be to somewhat undercount total fishing days.

8.3. Estimated total catch and value

Based on the number of total fishing days by these two types of Chinese fishing vessels, their collective catch and its value can be estimated using two approaches. The first approach uses the catch per unit effort (CPUE) of similar types of fishing vessel in the same area to estimate catch and value. The second approach uses historic data of catch per vessel derived from the *Chinese Fisheries Yearbook* to estimate the total catch based on the total number of unique Chinese vessels. For the catch calculation, we use the total fishing days estimated from the coast guard's counts and satellite vessel detections above.

CPUE approach

Because no recent data are available on the CPUE of Chinese fishing vessels fishing in North Korean waters, we use CPUE values of similar vessels in the region to estimate the total catch of the Chinese vessels. Because pair trawling is not practiced for the same squid stocks by the neighboring countries, we start with the CPUE of South Korean single trawlers that target the same stocks in the same sea but in South Korean waters, only 50-200 km from where the Chinese vessels are fishing and located on the stocks' main migration routes. According to a government report (*96, 97*), the average CPUE of a South Korean single trawler targeting squid was about 2.14 metric tons per day in 2017 and 1.79 in 2018. We adopt these values for a pair of Chinese trawlers (1.07 in 2017, 0.90 in 2018 per trawler) for the lower bound of our estimate. There is no comparable information about lighting vessel performance in the region, as the Chinese vessels are unique, so we scale the estimated trawler CPUE of 1.07 by the ratio of the production output of a lighting vessel to a trawler in the South China Sea, which is given as 1.38 by (*98*). This comparison results in an estimate of 1.47 metric tons per day as the CPUE for Chinese lighting vessel fishing in North Korea in 2017 and 1.24 in 2018.

We use the total fishing days derived above, 91,400 for 2017 and 67,300 for 2018, broken down into fishing days for pair trawlers (82,600 for 2017 and 60,700 for 2018) and lighting vessels (8,800 for 2017 and 6,600 for 2018). Using these numbers multiplied by the CPUEs above, we estimate 101,300 and 62,800 metric tons of catch in 2017 and

2018 respectively, by vessels observed by satellite sensors, for a total of 164,100 metric tons over 2017 and 2018.

There are a few caveats on the CPUE comparison, but the balance of evidence suggests this CPUE is conservative. The CPUE of South Korean trawlers may be higher than that of Chinese counterparts due to intense competition among Chinese. The fishing ground for South Korea is, however, located downstream from the Chinese fishing ground in North Korea, resulting in a smaller fraction of stock available. Perhaps most importantly, South Korean trawlers that target squid are almost half the size of the Chinese trawlers (60-120 vs. 100-200 gross tonnes). The net size of a pair of mid-water trawlers (with a distance of about 500 m between the pair) is, in general, larger than that of a single mid-water trawler (*99-101*). Also, in other areas, a pair of trawlers reportedly catches at least as much as a single trawler does (*102, 103*). Assuming that a pair of Chinese trawlers has the same CPUE as that of a single South Korean trawler may therefore lead to an underestimate of catch by Chinese trawlers, but it provides a conservative and likely lower bound for an estimate.

Finally, our satellite observations may result in lower vessel count estimates than those derived from the coast guard's count due to the limitations of satellite detection discussed earlier. It is, however, more reasonable to use the result from satellite observations as a conservative estimate of catch.

<u>Catch per vessel approach</u>

We have historical records of catch by Chinese fishing vessels that operated in North Korean waters until 2015 (see section S7. Legal analysis of Chinese fishing in North Korea). The catch per vessel varies from 114 to 288 metric tons per vessel between 2010 and 2015. Using the lower estimated number of unique Chinese fishing vessels for 2017 (904) and 2018 (718) and the range of historic catch per vessel estimates, we estimate the catch to be 103,000-260,000 metric tons in 2017 and 82,000-207,000 metric tons in 2018, for a total of 185,000-467,000 metric tons combined.

<u>Comparison of the catch</u>

For 2017, our two catch estimates differ by approximately 4%, whereas the 2018 estimates differ by about 25%, with the catch per vessel approach predicting more catch than the CPUE approach. This 25% difference is likely due to the drop in vessels between July and August 2018, perhaps explained by the following two factors. First, Northeast Asia (including the Koreas, Japan, and China) experienced a severe heat wave in the summer of 2018, preventing the squid population in the north from moving south due to warm sea water (the catch in South Korea was reduced by half in that 2018 period compared to 2017) (*104*). Second, the North Korea coal scandal broke out on 17 July 2018. This scandal, in which millions of dollars worth of North Korean coal was illegally shipped to South Korea in violation of UN Resolution 2371 (*105*), drew international attention, including that of the UN Security Council, to the waters of the region. As a result, the fishing vessels may have left North Korean waters.

The conservative estimate of catch above (101,300 metric tons in 2017 and 62,800 in 2018) represents both 68% of the total, legal, domestic squid catch of Japan and South

Korea in all surrounding seas (9, *10*), suggesting that the total catch by illegal fishers is comparable in magnitude to that by all legal fishers in the region combined (the catch of Russia is assumed to be negligible).

8.4 Estimated value of catch

Based on the estimated catch, we calculate the estimated total value in 2017 and 2018. The cost of medium size, raw *Todarodes Pacificus* in China as of 1 January 2018 is known to be 17,650 Chinese Yuan per metric ton (106). With 1 US dollar ≈ 6.50 Chinese Yuan as of 1 January 2018, the total value is estimated to be about \$275 million in 2017 and about \$171 million in 2018. As UN sanctions came into force from September 2017, the estimated portion of catch in violation of the sanctions is about 117,300 metric tons (54,500 Sep-Dec in 2017 + 62,800 in 2018), equivalent to about \$319 million.

Section S9. Data availability and cost

This section reviews the availability and cost of the various satellite technologies used to track vessels. A key argument made in the text is that increasing availability and decreasing costs means that widespread monitoring by satellite will be far easier. Here is the availability and trend of costs of the four satellite data sources we used.

9.1 Optical daytime imagery

This paper relies on imagery from Planet, which operates more than 150 earth observing satellites that image the entire world, every day, at 3-meter resolution, as well as a portion of the world's oceans. Before Planet launched its constellation in 2016, it was impossible to get a high revisit time across a wide area. The closest availability was RapidEye (later renamed to BlackBridge, and now owned by Planet), which, with five satellites, could capture 6.5 million km^2 per day (about ~3% of land surface or ~1% of the entire earth).

The cost of this imagery was generally listed at about \$1 to \$2 per square kilometer, meaning a single image of our 90,000 km^2 study area would have cost about \$100,000, and the total amount of Planet imagery used would have cost well over \$1 million. Planet does not publish its price list but it provided the imagery for free for this study. Planet also has a program specifically for supporting research projects.

There are several sources of free satellite imagery, although only some is at high enough resolution to observe vessels. The European Space Agency's Sentinel-2 satellite provides 10-meter resolution imagery of the entire terrestrial surface and a subset of the oceans (mostly the coastal oceans). While we did not analyze Sentinel-2 data for this study, we did look at some imagery of the area, and we were able to visually distinguish vessels in operation. Some companies are looking into using this data feed to identify all large vessels (https://www.vake.ai/).

9.2 Synthetic Aperture Radar

Synthetic Aperture Radar (SAR) has a notable advantage over optical imagery, in that it is not limited by clouds. Several commercial providers sell such imagery; the cost has decreased significantly over the past few years, and prices are often negotiated down from the list price. SkyTruth, a nonprofit where co-authors of this paper have worked at, has seen the negotiated price decrease by about 17% per year between 2013 and 2019.

More importantly, the European Space Agency's Sentinel-1 mission began providing global SAR data for free in 2014 (S1A) and doubled its acquisitions with a second satellite (S1B) in 2016. Although the open oceans are not covered, the entire world's coastlines are. A comparison of these data with Global Fishing Watch's fishing effort data shows that 82% of the fishing by vessels with AIS activity occurs within regions covered by Sentinel-1.

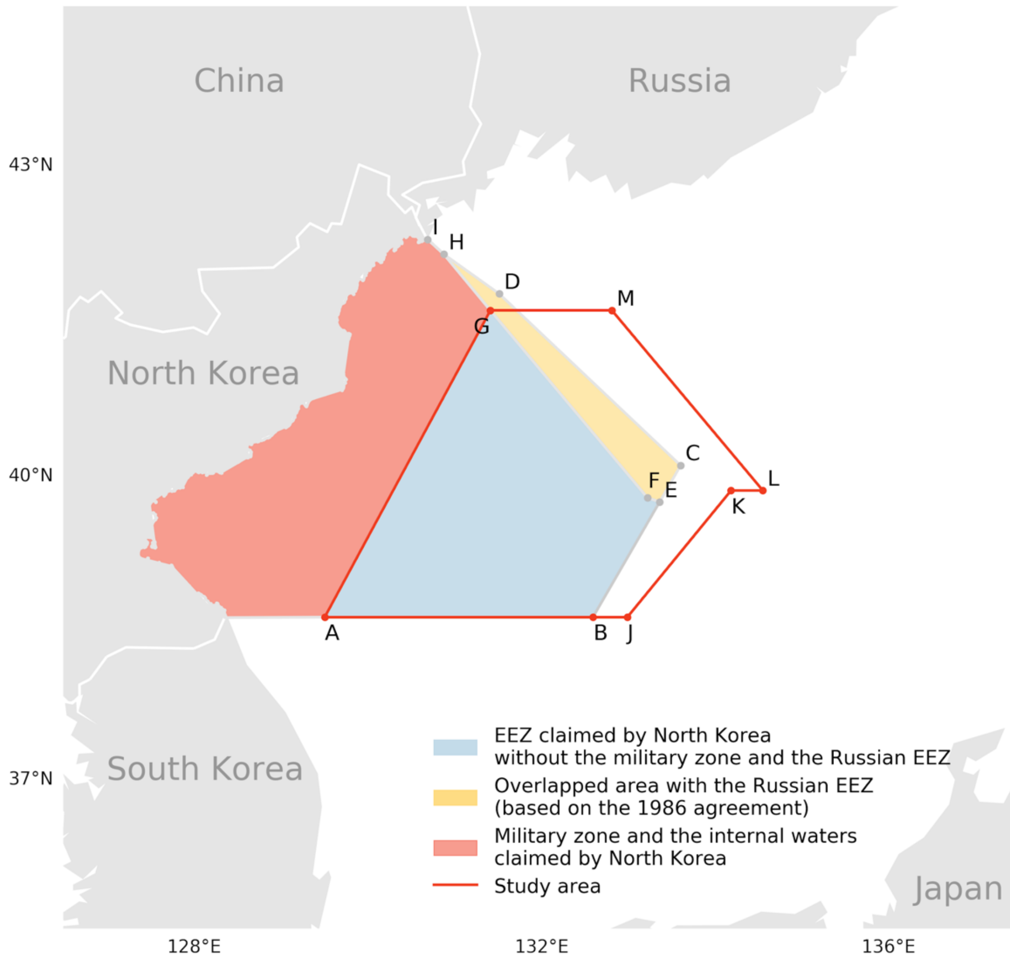
9.3 Automatic Identification System

AIS data are recorded by terrestrial receivers along the world's coastlines and by satellite companies, the major ones being ExactEarth, ORBCOMM, and Spire. As with companies selling optical imagery, the price of bulk AIS is usually negotiated based on the customer and the application. Since 2013, Global Fishing Watch has seen the cost per AIS message drop by 93%. At the same time, the data quality has increased substantially, as there are now more than 50 satellites recording AIS messages in orbit; in 2013, there were only a handful. Purchasing a single year of global AIS data is within the scope of most research grants (a few thousand dollars).

9.4 Visible Infrared Imaging Radiometer Suite

Visible Infrared Imaging Radiometer Suite (VIIRS) data is provided free from the U.S. Government, and vessel detections have been provided from the Colorado School of Mines since 2012. In 2017, the National Oceanic and Atmospheric Administration has launched a new satellite, Joint Polar Satellite System-1 (also known as NOAA-20), with the VIIRS sensor on board. It will double overpasses each night following the Suomi NPP satellite that we used in this paper with about a 1-hour gap. The data will continue to be provided publicly free of charge. An additional satellite Joint Polar Satellite System-2, with the same VIIRS sensor planned to be on board, is scheduled to be launched by 2022.

Supplementary Figures



A	38° 36' 48" N	129° 30' 30" E	H	42° 09' 00" N	130° 53' 00" E
B	38° 36' 46" N	132° 35' 52" E	I	42° 17' 33" N	130° 41' 49" E
C	40° 06' 27" N	133° 36' 38" E	J	38° 37' 00" N	132° 59' 48" E
D	42° 09' 00" N	130° 53' 00" E	K	39° 51' 45" N	134° 11' 30" E
E	39° 45' 05.3" N	133° 22' 09.5" E	L	39° 51' 45" N	134° 33' 28.4" E
F	39° 47' 30" N	133° 13' 42" E	M	41° 36' 39.6" N	132° 49' 09.5" E
G	41° 36' 39.6" N	131° 25' 09.5" E			

Fig. S1. Study area and boundaries around the EEZ claimed by North Korea.
The points A-B-C-D define the EEZ known to be claimed by North Korea excluding its claimed military zone (red area). However, North Korea and Russia (then the Soviet Union) also negotiated a boundary between their waters defined by I-G-F-E, rather than I-H-D-C as was initially claimed by North Korea. Our study area, within the red lines, includes the claimed EEZ lying beyond the military zone, the area within the boundary agreed to with Russia, as well as a buffer area to the east. This buffer, which was added to capture Chinese vessels which were seen fishing just outside the claimed North Korean EEZ, extends the study area roughly 100 km to the east but excludes the South Korean-Japanese joint fisheries management zone lying southeast of points J and K (not shown).

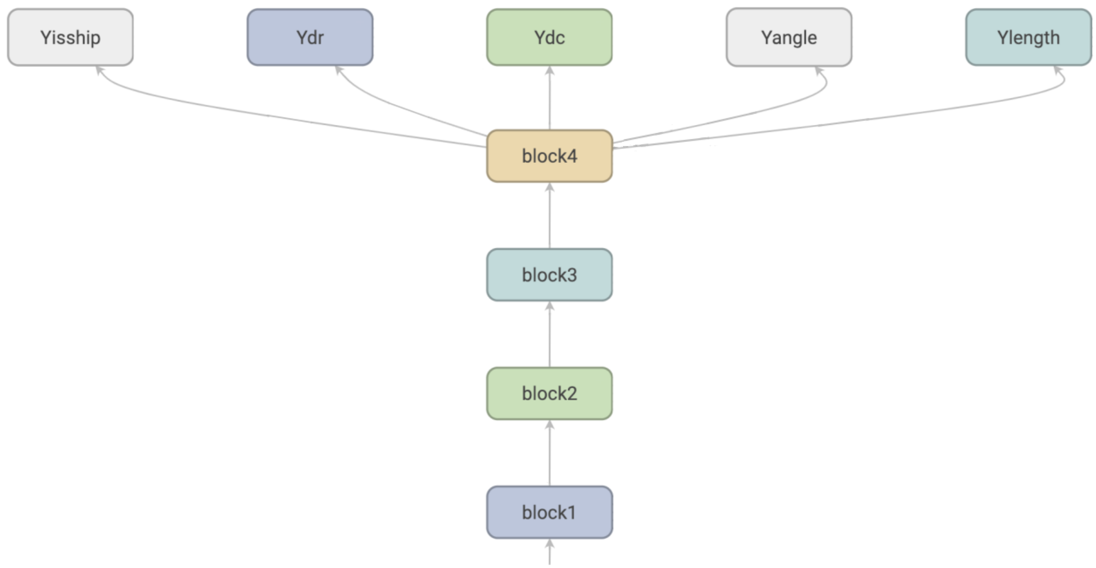
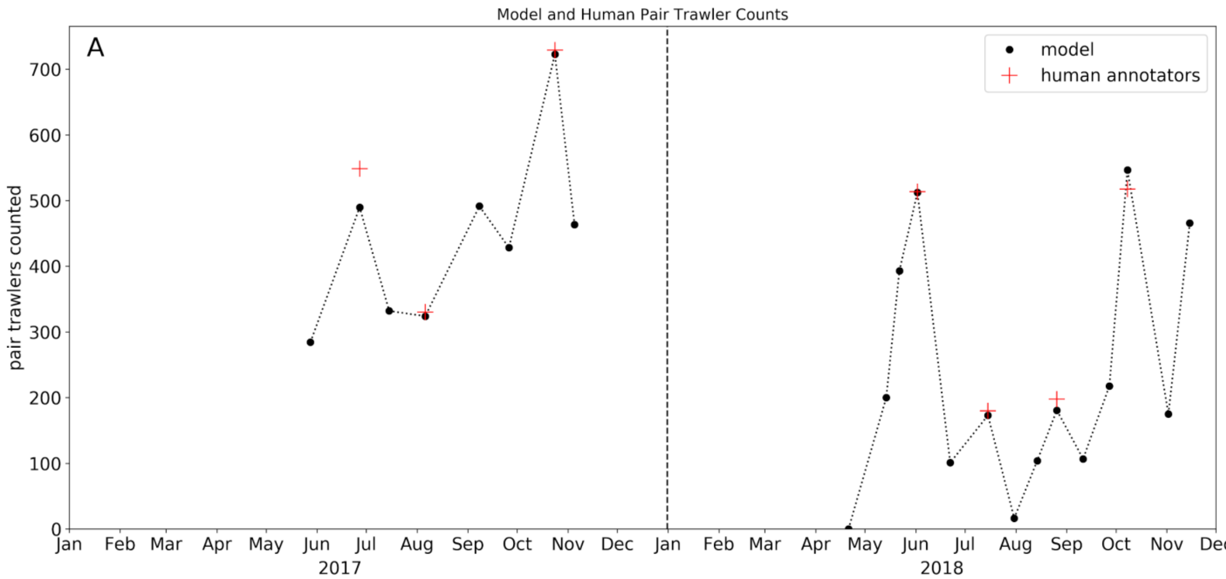


Fig. S2. Convolutional neural net architecture.

Our convolutional neural network (CNN) model is built in Tensorflow. The CNN takes an $n_r \times n_c \times 3$ image as input and returns an $n_r / 16 \times n_c / 16 \times 5$ array. That is, the CNN predicts five values: an is-ship score and four parameters specifying the predicted position, length, and orientation of the vessel, all on a grid with one-sixteenth the resolution of the original image. The values on this grid are then processed using thresholding, non-max suppression and reprojection into world coordinates to give the final vessel predictions. The model consists of four blocks, each consisting of two convolutional layers followed by a pooling layer which combines the output of max-pooling and stride-2 convolutional layers. After the fourth block there are five parallel output blocks, each consisting of four convolutional layers, predicting vessel presence, center, separation, and orientation. The number of filters in each layer varies from 24 in the input layer to 384 in the final ship detection layer.



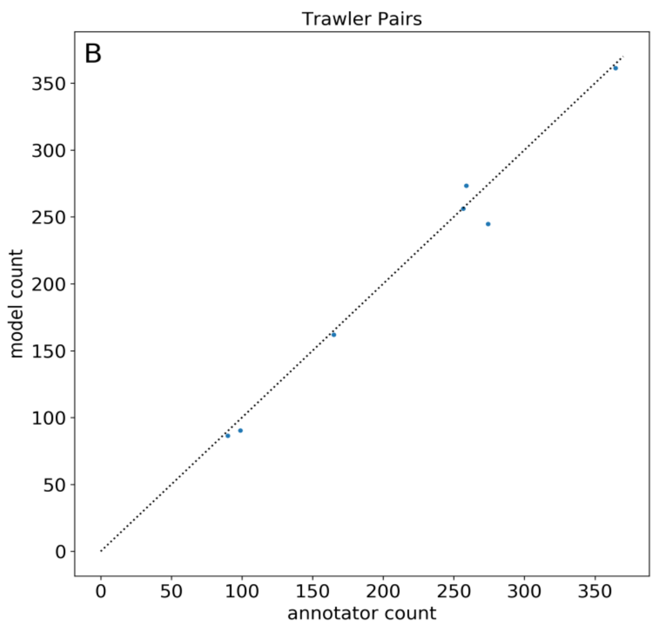


Fig. S3. Pair trawler counts for 2017 and 2018.

(A) The pair trawler counts by the CNN model and by human annotators for 2017 and 2018. (B) Agreement between the counts of vessels by the model and the annotators is good. Note that (A) and (B) show counts of paired, actively trawling vessels. Human annotators also counted the number of vessels that appeared to be trawlers but were not paired at the moment the image was acquired and these vessels add roughly 14% to the total trawler counts.

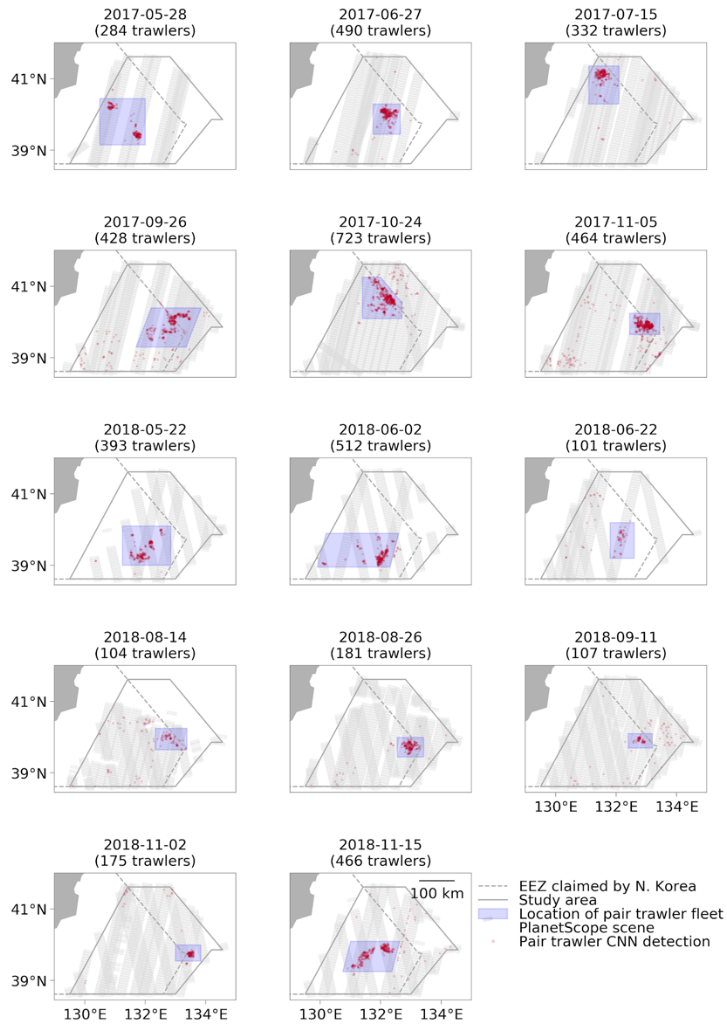


Fig. S4. Pair trawler detections for 2017 and 2018.

Shown is the claimed North Korean EEZ (dotted line), our study area (solid line), and detections of pair trawlers using a convolutional neural network (CNN) on PlanetScope imagery for 22 days in 2017 and 2018. Small grey rectangles show individual PlanetScope scenes (darker areas show where scenes overlap). Pair trawler detections by the CNN are in red. We use these detections to identify the location of the fleet, and then define an area surrounding the fleet in which to count the pair trawlers. For instance, on 26 August 2018 the location of the fleet is clear, but on 8 September 2017, manual inspection is required to determine whether the secondary clusters are caused by pair trawlers or areas with poor detection conditions. On some days (e.g., 28 May 2017) there are very few false positives due to weather conditions and the exact shape of this area is not critical, while on others (e.g, 27 September 2018) there are considerably more and constraining the count to the area of the core fleet is important to reduce the incidence of false positives. Note that no pair trawler fleet was found on 21 April 2018. An average of 67% of our study area was covered on these dates, with a low of 42% on 15 July 2018 and a high of 94% on 24 October 2017.

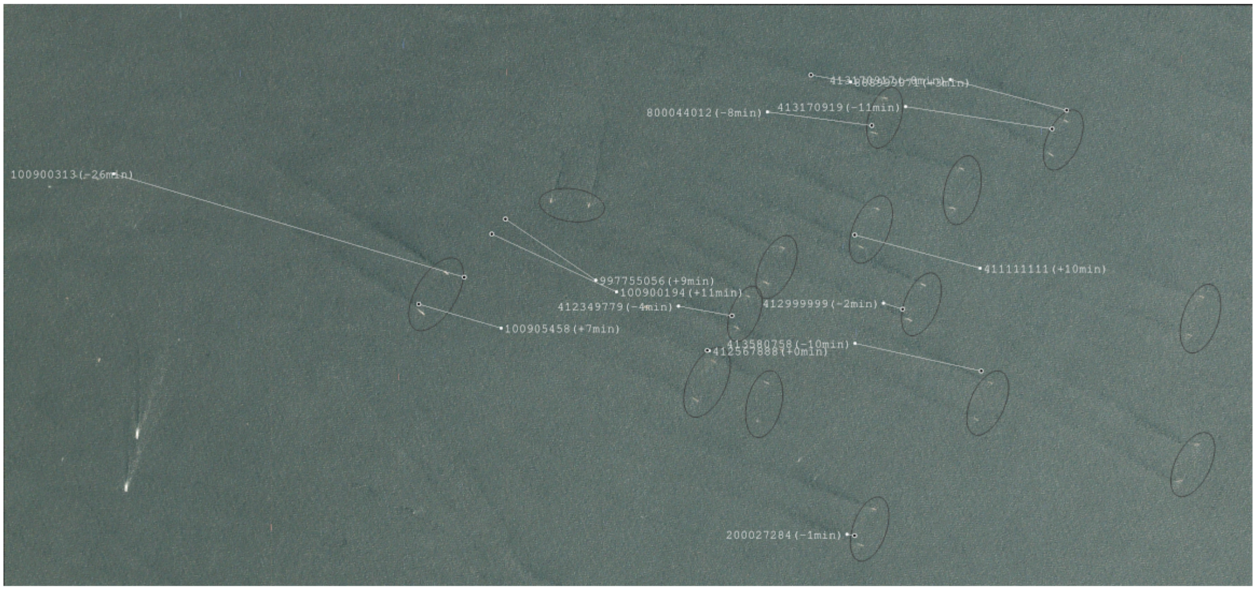


Fig. S5. Pair trawlers matched to AIS.

Twelve AIS messages are shown matched to detected pair trawlers (grey ovals) in a PlanetScope image captured on 2 June 2018 in North Korean waters. The solid white dots, with accompanying 9-digit MMSI numbers, indicate the AIS positions broadcast closest in time to image acquisition, while the hollow white dots are the estimated positions at acquisition time based on extrapolation of the vessels' speed and course.

Fig. S6. Major ports of North Korea in optical imagery.

(A, B) During the offseason for squid, fishing boats are abundant in Chongjin port, North Korea's largest port for fishing boats; both optical images were acquired on 17 March 2018, by Planet's high-resolution (0.72 m) SkySat. More than 3,000 boats are present, most of which are wooden and 10-20 meters long. (C, D) During the peak season for squid fishing (see section S5. Nighttime optical imagery), few vessels remain in port (Planet's PlanetScope images with a resolution of 3 meters, 14 October 2018). (E) Near the port of Wonsan, known as the registration port for fishing in North Korea, vessels of 30-35 meters in length are waiting for the 2018 fishing season to begin on 10 May and (F) heading to the fishing ground on 14 May as the season opens.

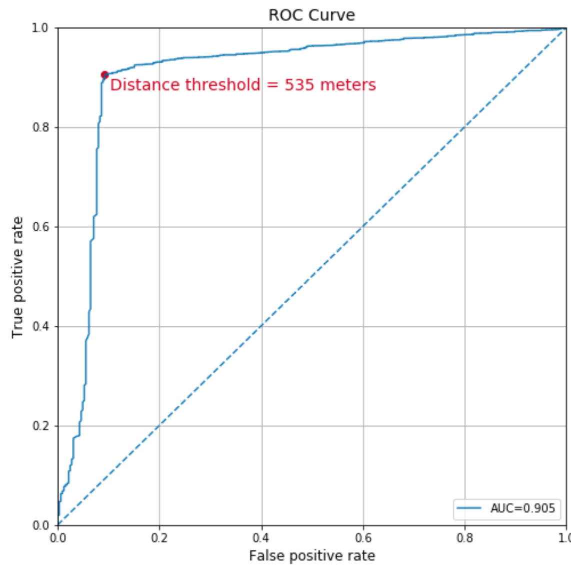


Fig. S7. ROC curve of the nearest distance model that determines pair trawlers. The receiver operating characteristic (ROC) curve shows the true positive rate plotted against the false positive rate as the distance threshold changes. The model classifies a vessel as a pair trawler if the distance to its nearest vessel is below a given threshold. The performance of the model for selecting likely pair trawlers as measured by the ROC area under the curve (AUC) was 0.905. The model was developed based on 4,800 vessel positions identified on Planet images. With a threshold of 535 meters, the probability of detection is over 0.9 while the false positive rate is below 0.1 (red point). Note that this model was developed using examples of paired, actively trawling vessels, and it may not detect pair trawlers when they are not trawling.

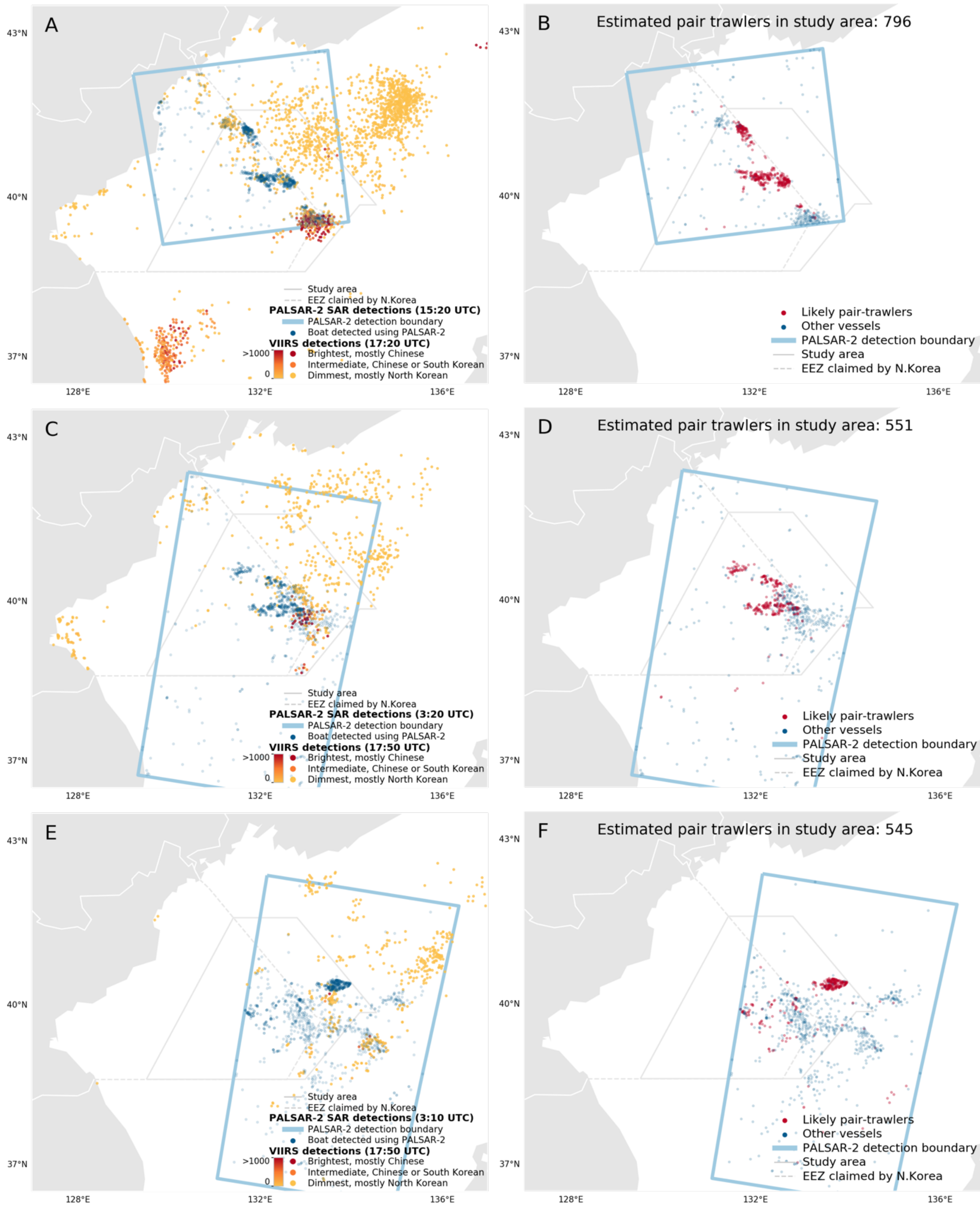


Fig. S8. PALSAR-2 boat detections overlapped with VIIRS night light detections. Superposition of detections from Synthetic Aperture Radar (SAR; via the satellite PALSAR-2) and VIIRS allows different types of vessels to be distinguished. We can identify 1) Chinese pair trawlers, which show up in SAR but infrequently in VIIRS, 2)

Chinese lighting vessels, which show up with high radiance in VIIRS and also appear in SAR, and 3) smaller, wooden North Korean lighting vessels, which show up in VIIRS with low radiance and do not appear in SAR.

(A) On 24 October 2017, images were acquired two hours apart, with PALSAR-2 at around 15:20 UTC and VIIRS at 17:20 UTC. The cluster at the southeastern corner of the claimed North Korean EEZ detected by both PALSAR-2 and VIIRS corresponds to Chinese lighting vessels. The large cluster of low intensity vessels outside the claimed EEZ, detected by VIIRS but not by PALSAR-2, is likely composed of small, North Korean wooden boats.

(B) In red are pair trawlers inferred for this date using the distance threshold model applied to the SAR data. The cluster of vessels that is mostly detected by PALSAR-2 but not by VIIRS in (A) corresponds to these likely pair trawlers.

(C) On 2 October 2017, images were acquired 9.5 hours apart, with PALSAR-2 at around 3:20 UTC and VIIRS at 17:50 UTC.

(D) In red, again, are the inferred pair trawlers on the same date.

(E, F) The same comparison is made for 27 September 2017 with about a 9.5-hour difference in detection times. On that night, the sky was cloudy near North Korean waters, making it difficult for VIIRS to distinguish fleets. Identification of pair trawlers using the distance threshold method

(F) is not affected by the clouds on this date because it uses SAR, not VIIRS. The large group of likely pair trawlers (over 300) in Russian waters raises the possibility that they fished in the Russian EEZ without authorization.

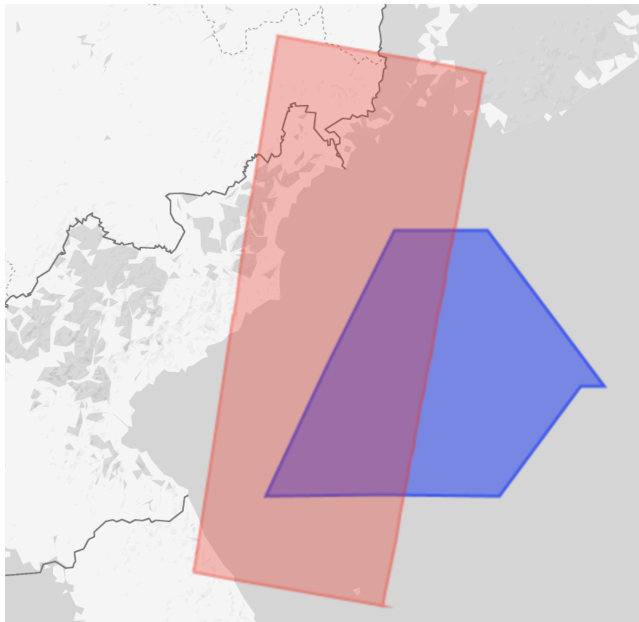


Fig. S9. Sentinel-1 SAR footprint used in this analysis.
Sentinel-1 SAR footprint (red-shaded region) imaged every twelfth day from January 2017 through December 2018 captures a 250-km wide swath covering 43% of the study area (blue-shaded region).

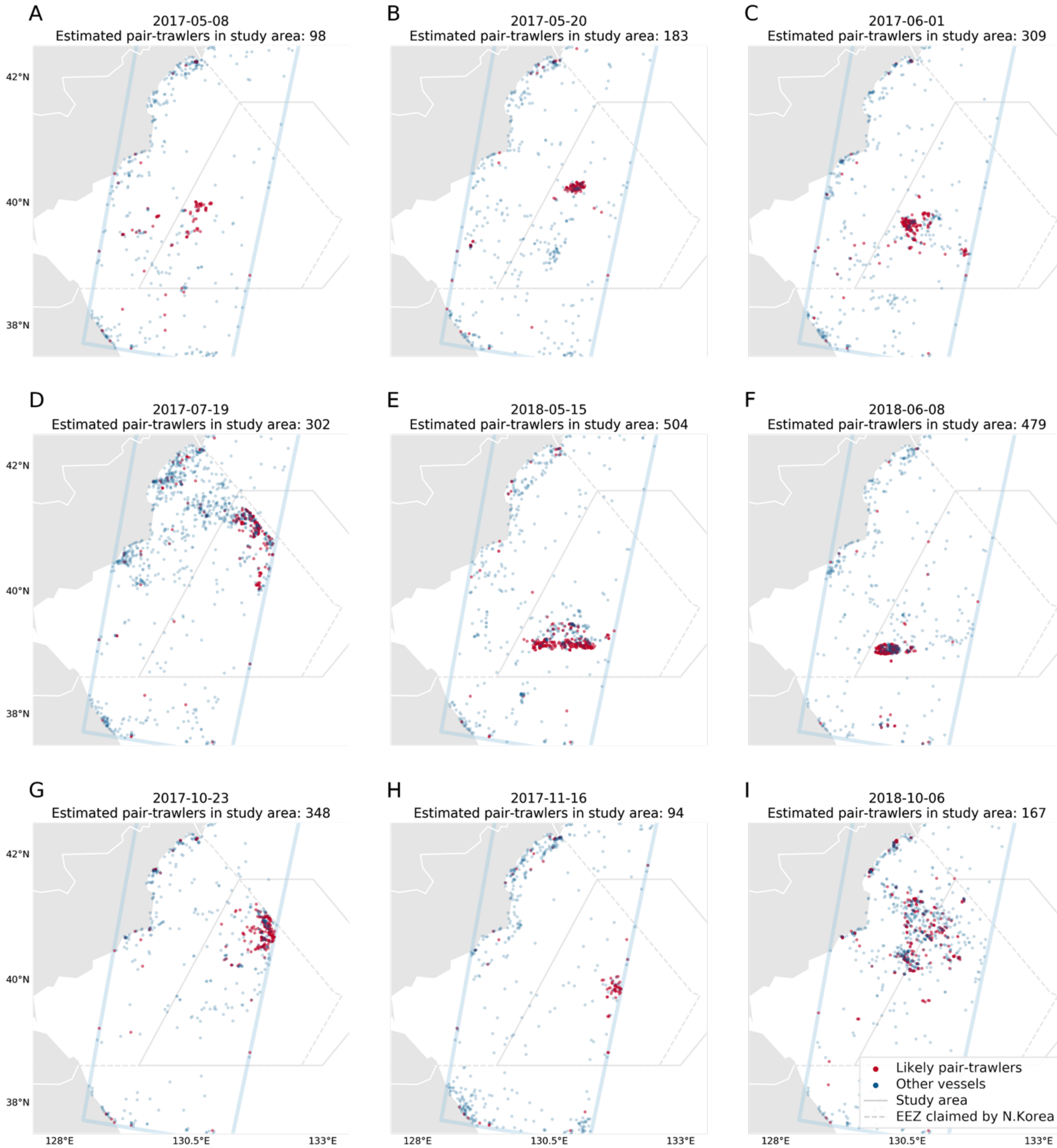


Fig. S10. Examples of Sentinel-1 detection maps.

(A-F) Detections of likely pair trawlers by Sentinel-1 with the pair trawler fleets relatively distant from the detection boundary (light blue box), and (G-I) fleets that might have been cut off by the Sentinel-1 image boundary or were not detected within our study area. Note that vessels that are in transit are usually not detected as pair trawlers because they are not paired up in their operational positions.

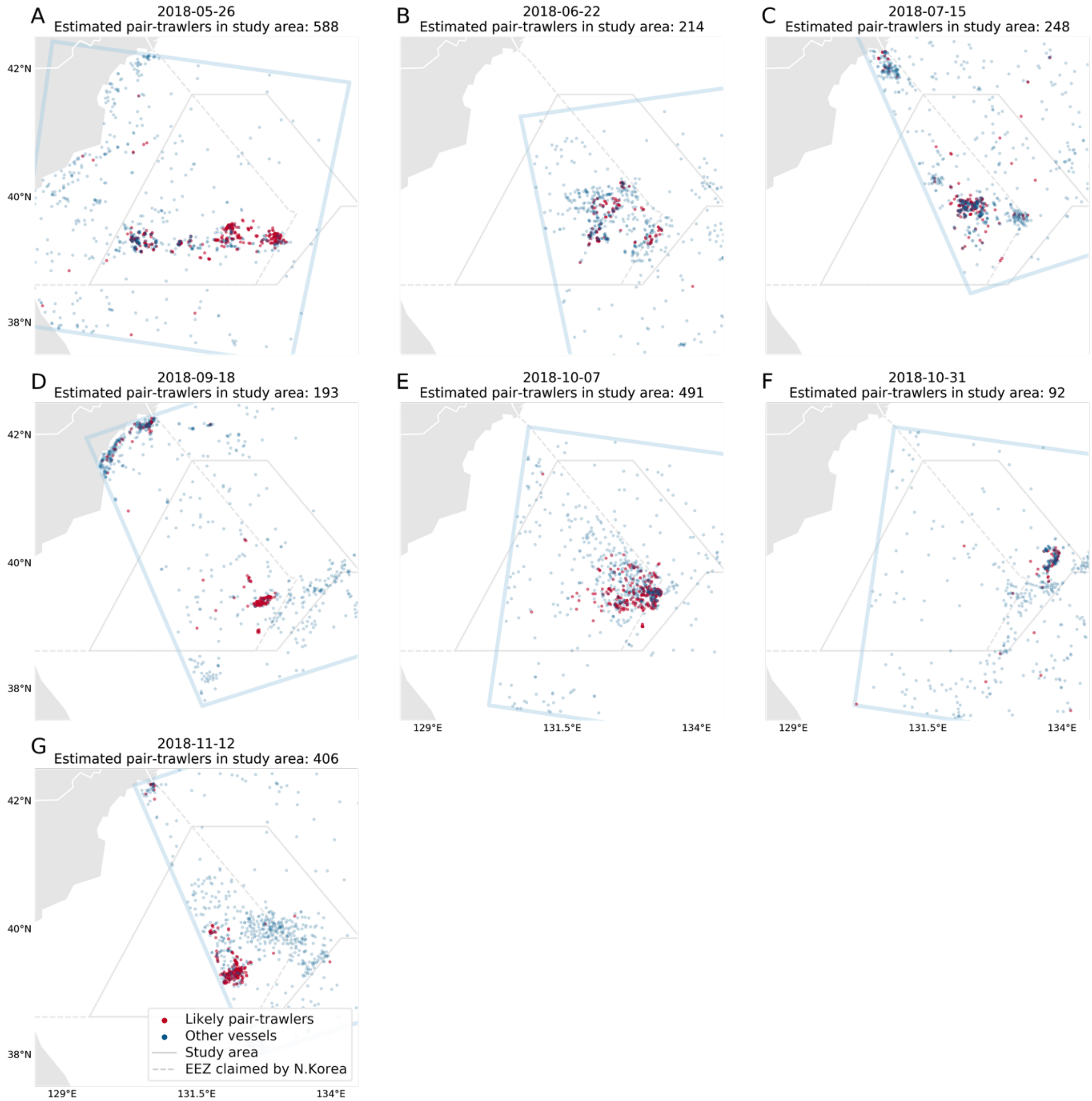


Fig. S11. Detection of likely pair trawlers by RADARSAT-2.

RADARSAT-2 detection maps and number of likely pair trawlers in seven radar images acquired between May and November of 2018. The footprint of RADARSAT-2 (light blue box) covers over 60% of the study area and includes the core squid fishing grounds (at the southeast part of the claimed North Korean EEZ). Vessels inferred to be pair trawlers by the distance threshold model are shown in red. The outline of the satellite footprint is shown by a thin blue line.

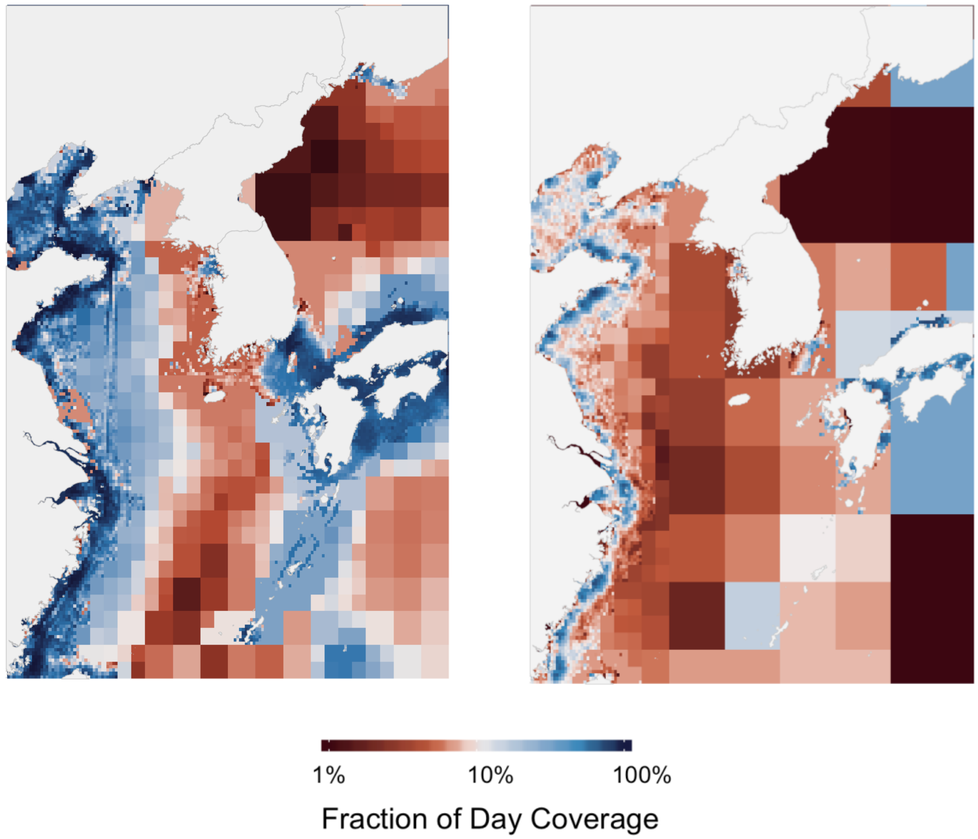


Fig. S12. AIS reception quality map.
AIS reception quality maps for Class A (left) and Class B (right) devices in 2017 show, for vessels in the Global Fishing Watch database, what fraction of a day that a message would be received from a continuously broadcasting vessel. The fraction is measured by dividing the day into five-minute intervals and counting the fraction of these intervals in which at least one signal is received. For both classes, the reception quality is extremely poor in North Korean waters. High-quality coverage near some coastlines is due to terrestrial reception of AIS, but not all coastal areas have terrestrial data available, notably much of the Korean peninsula.

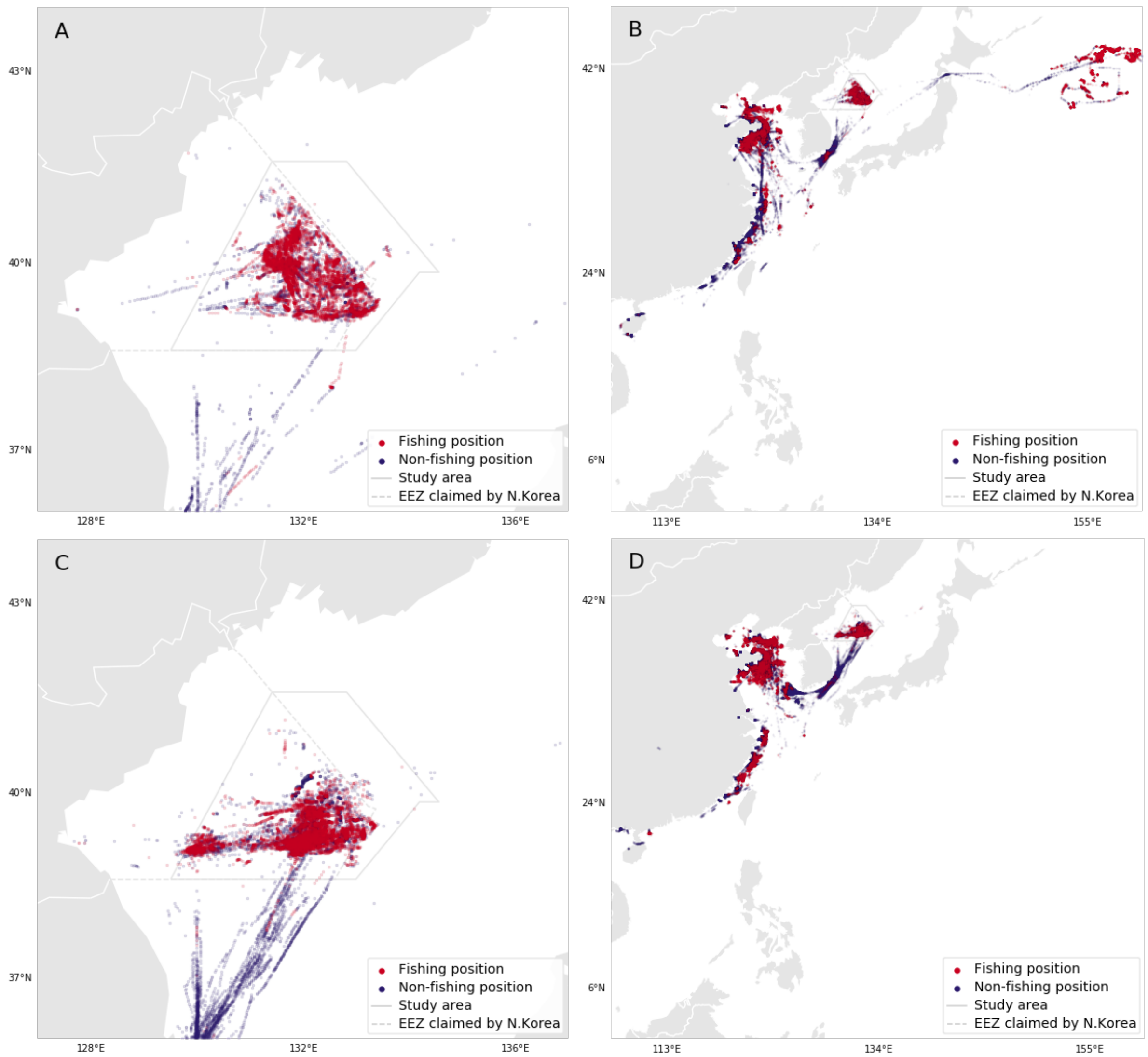


Fig. S13. AIS positions of likely Chinese fishing vessels.

(A) The figure depicts fishing and non-fishing AIS positions broadcast in 2017, with a focus on North Korean waters and (B) on Northeast Asia and part of Pacific region. (C, D) Similar patterns repeat in 2018. Fishing positions occur mostly within North Korean waters in A and C, but also appear in the disputed area beyond the southeast boundary of the EEZ as well as at the southwestern corner of the Russian EEZ. The figure shows that the vessels mostly enter and exit through the southern and eastern parts of the South Korean EEZ. C and D show that the vessels fishing in North Korea also fish in the Chinese EEZ. Note that some of these vessels share MMSI numbers with other Chinese vessels. We minimized the effect by selecting showing, in this figure, only MMSIs that are used by multiple vessels <1% of the time they were in operation.

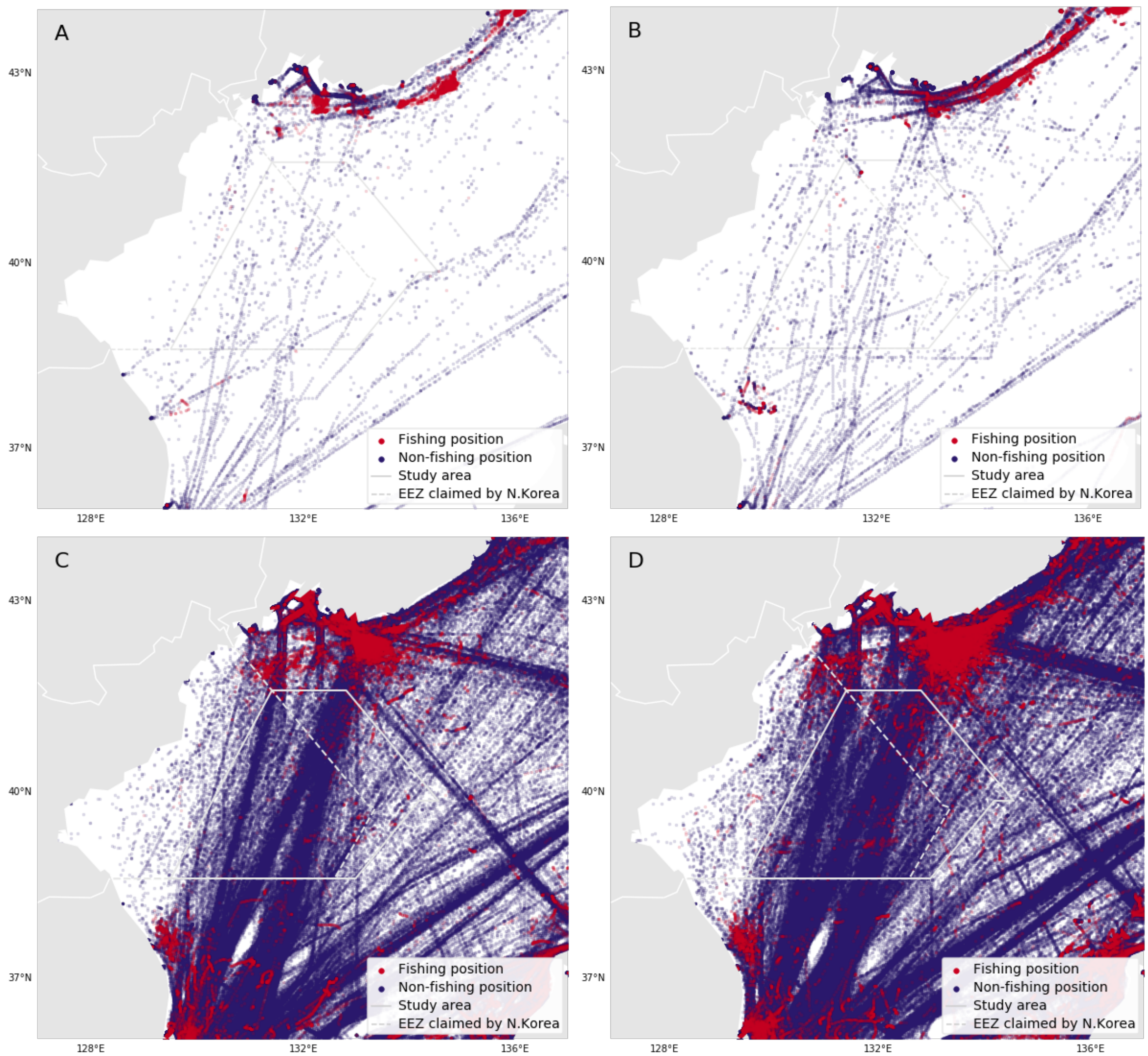


Fig. S14. AIS positions of vessels that are likely not Chinese fishing vessels.
(A) AIS positions of vessels that were present in the claimed North Korean EEZ that are likely to be fishing vessels from countries other than China (most are Russian) in 2017 and (B) in 2018, and (C) AIS positions of vessels classified as non-fishing vessels (mostly cargo vessels and tankers) regardless of their flag state in 2017 and (D) in 2018. Their behavior near shore is sometimes detected as "likely fishing" due to their slow movement near ports. The AIS positions, however, clearly show that they are mostly transiting through North Korean waters; that is, they proceed in a straight line through North Korean waters.

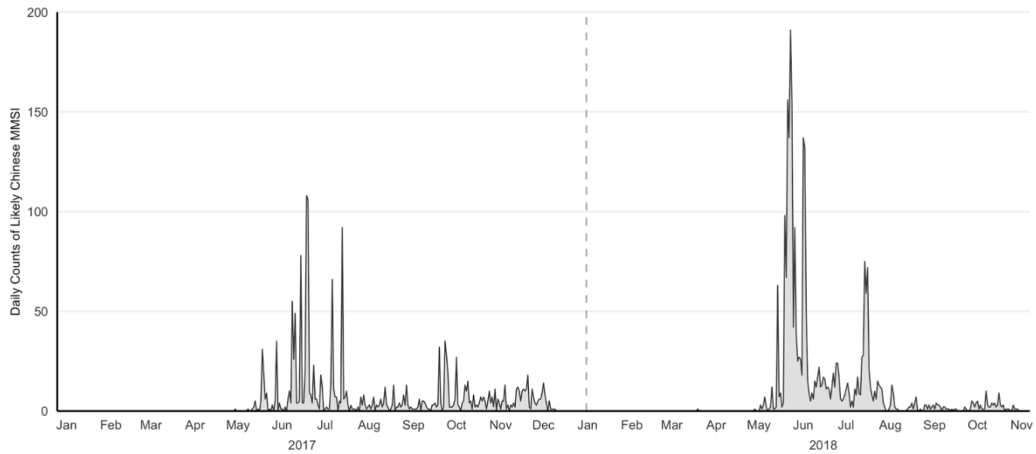


Fig. S15. Number of likely Chinese fishing vessels broadcasting AIS messages.
Daily number of likely Chinese fishing vessels operating in North Korean waters whose AIS messages were recorded, January 2017 through October 2018. Unlike the number of vessels revealed by VIIRS and SAR, the number of vessels broadcasting AIS is highest at the beginning of the fishing season (May-June). This pattern suggests that a significant portion of the vessels may have turned off their AIS devices shortly after arriving in the region. The peaks in vessels coincide to days when many vessels were detected by terrestrial receivers, and this better AIS reception may have been due to changes in weather.

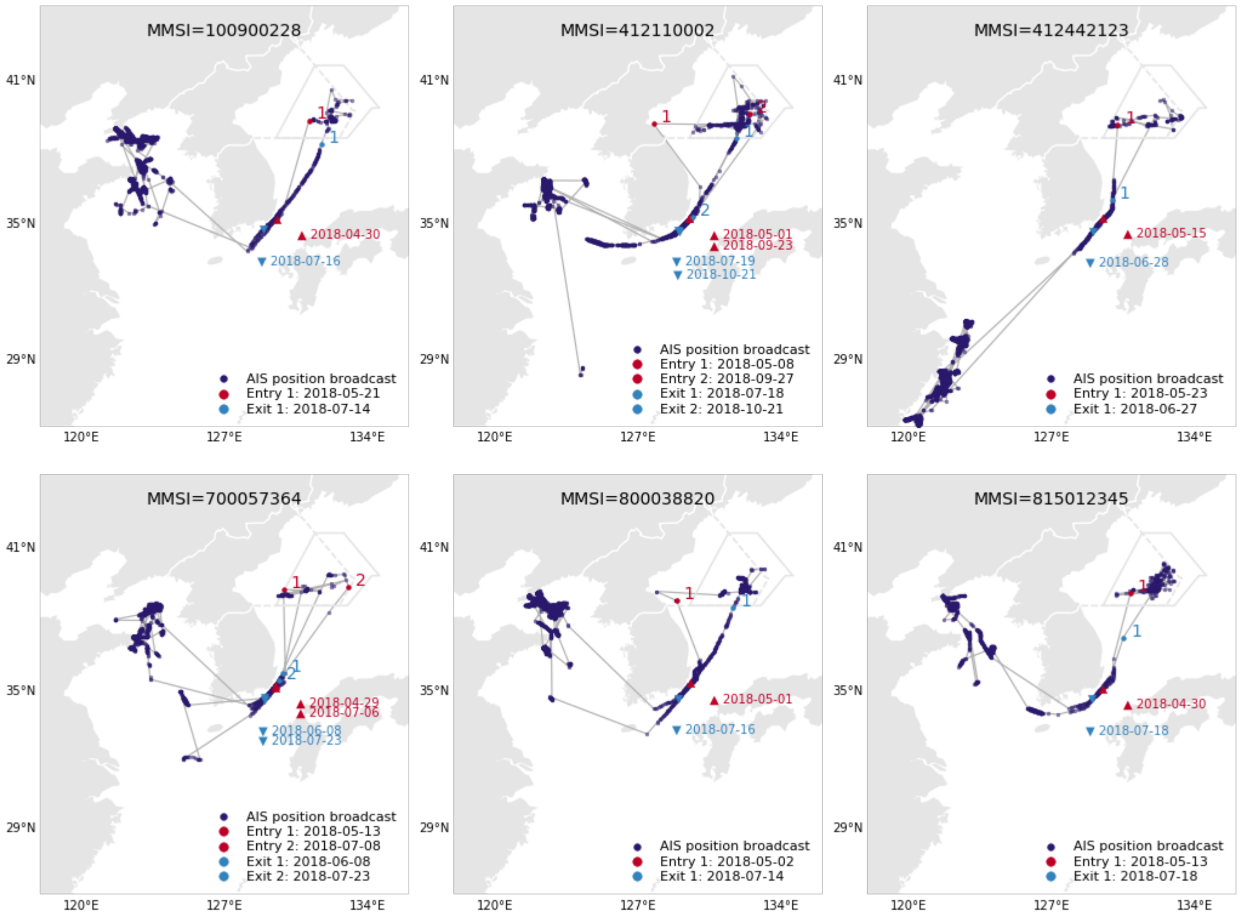


Fig. S16. AIS tracks of selected Chinese fishing vessels.

AIS positions of selected Chinese vessels that fished in North Korean waters during 2018. By mapping AIS position messages, we can estimate the duration of their fishing activities in North Korean waters and the number of times they entered North Korean waters. Note that if position messages are received infrequently, such as when a vessel is traveling through areas of very poor AIS reception, the path appears as an unrealistic, straight line.

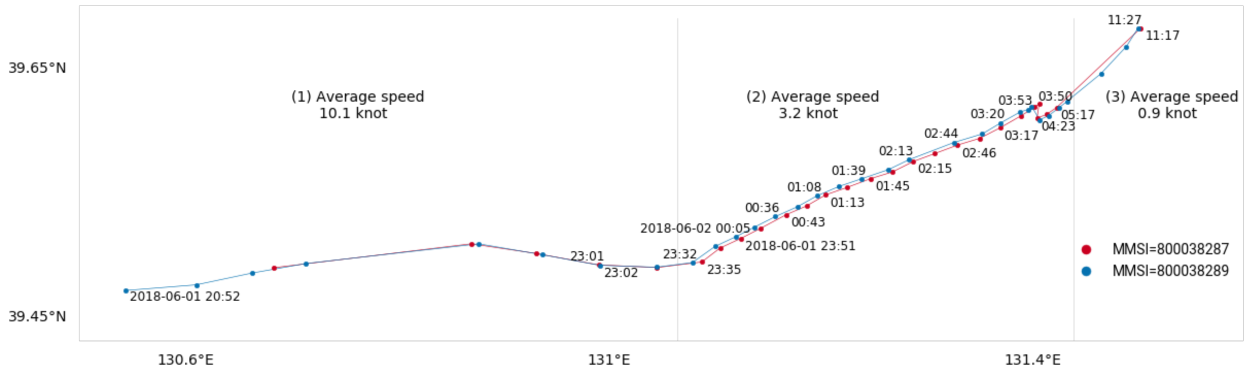


Fig. S17. AIS tracks of two pair trawlers in operation.

AIS signals demonstrate the pair trawling operation of two likely Chinese vessels in North Korean waters. The two vessels cruise together at high speed (>10 knots) for a few hours and then take up positions a few hundred meters apart from each other. They then move in parallel for the next six hours with a slower speed (3.2 knots) that generally corresponds to trawling, after which they become almost immobile (<1 knot). The displayed time is in UTC.

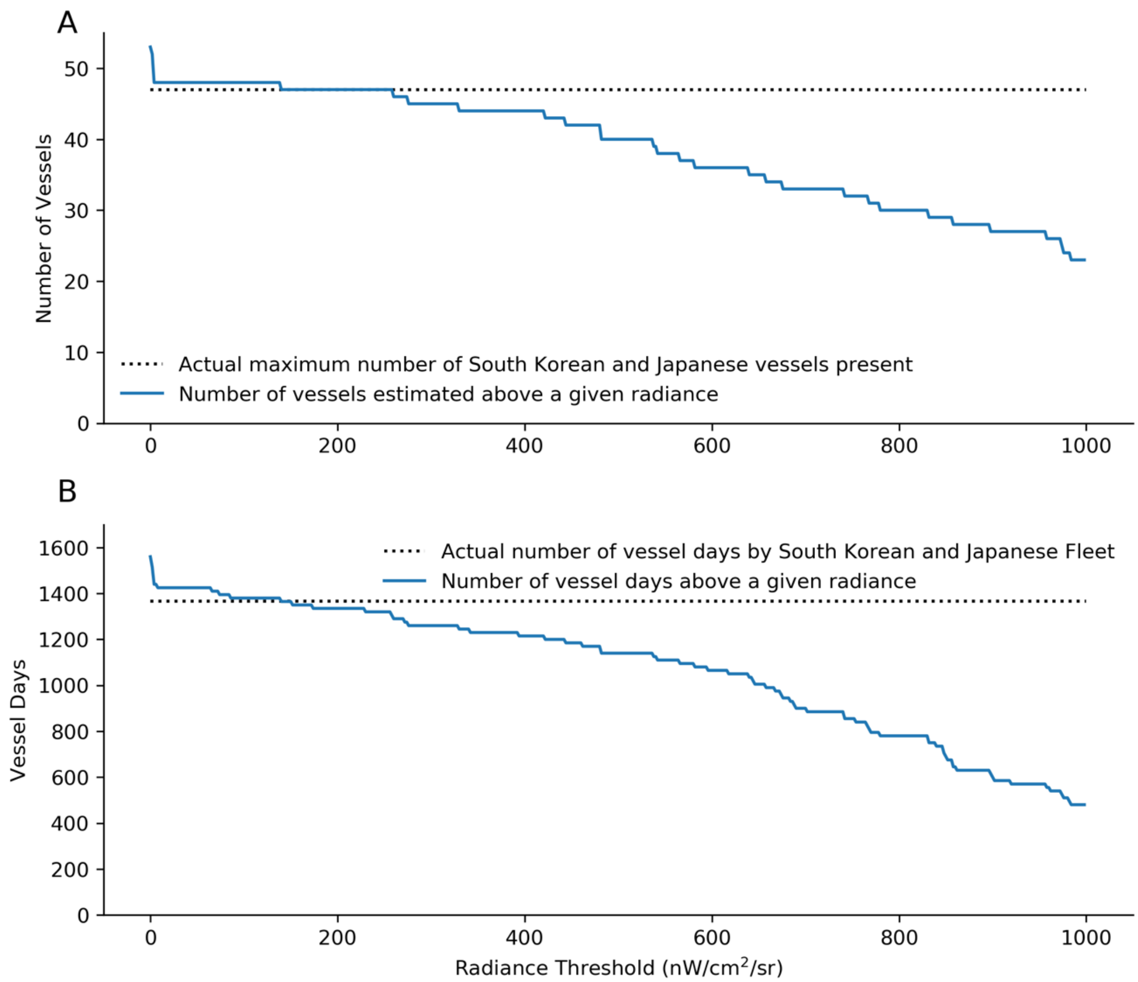


Fig. S18. Sensitivity of the estimated number of vessels and vessel days to radiance thresholds for the Japanese and South Korean fleets operating in the Russian EEZ, August and September 2017.

To count the number of vessels present, we selected a threshold and counted the number of vessels above that threshold on the day with the most detections. (A) As we increase the radiance threshold, the estimated number of vessels declines, increasingly falling below the known number of vessels operating (dotted line). For any threshold between 140 and 258 nW/cm^2/sr, this method counts the actual number of Japanese and South Korean vessels operating. Based on this, we chose a threshold of 140 nW/cm^2/sr. (B) To estimate the number of days vessels were active, we count the maximum number of detections above a given threshold for each half month period; as shown, increasing the radiance threshold yields increasingly lower estimates of vessel days for the South Korean and Japanese fleets. With a radiance of 73 nW/cm^2/sr, this method estimates the correct number of vessel days. At the chosen threshold of 140 nW/cm^2/sr, this slightly undercounts the number of vessel days for the Japanese and South Korean fleet.

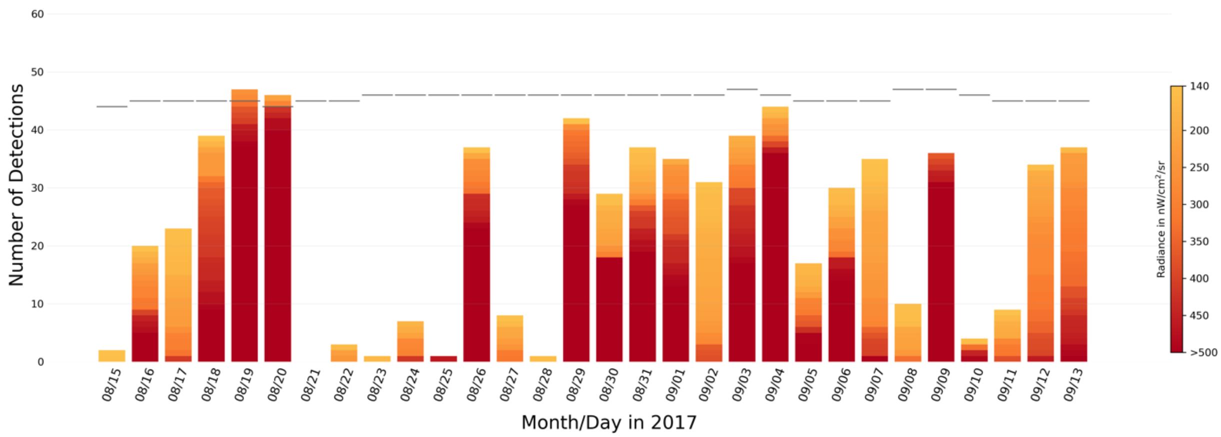


Fig. S19. Daily light detection in the northern part of the Russian EEZ.
The variation in the number of detections in each VIIRS brightness range in the northern part of the Russian EEZ (between 42° 40' N and 45° N latitude in Primorye subzone), but outside of Russia's territorial waters (the area within 12 nautical miles from shore) for 15 August to 13 September 2017. We exclude vessels with brightness below 140 nW/cm^2/sr to avoid counting North Korean vessels. The peaks in the number of detections closely approximate the number of South Korean and Japanese vessels known to be in the region on each day (gray line). However, the number of detected vessels as well as their brightness is often reduced significantly by a combination of factors including weather conditions, zenith angle and the location and brightness of the moon. To compensate for this, we approximate the number of vessels in each half month as the maximum counted during that period.

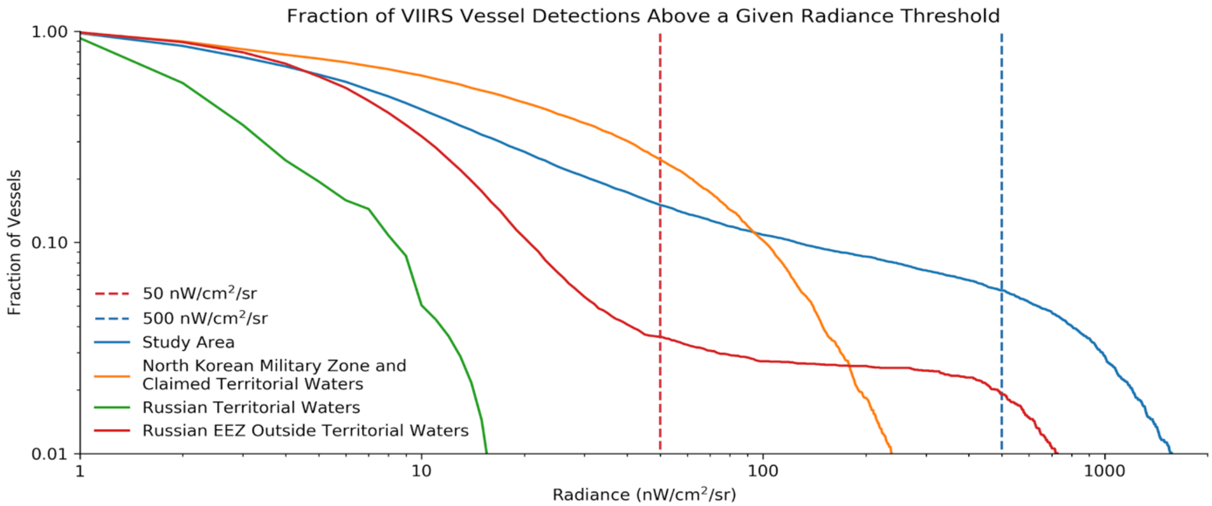


Fig. S20. Fraction of VIIRS vessel detections below a given threshold.
The distribution of vessel radiance varies by region depending on the underlying fleet. For this analysis, we plotted only the best day in each half month period so that we would be comparing only days with likely clear weather.

In the Russian territorial waters (green line; the coast to about 12 nautical miles to sea) south of 45° north, only Russian vessels are allowed to operate. Very few Russian vessels use lights, with 97% of detections have a radiance below 10 nW/cm^2/sr and almost all under 20 nW/cm^2/sr.

In the North Korean military zone and the claimed internal waters (orange line), which is the area from North Korea's coast to about 50 nautical miles to sea, only North Korean vessels are allowed to operate. Although 10% of these vessel detections can exceed 100 nW/cm^2/sr, 99% are below 250 nW/cm^2/sr, and almost none are above 500 nW/cm^2/sr

In the Russian EEZ outside the territorial waters and south of 45° N (red line), two fleets are active: a fleet of dim North Korean vessels, and a fleet of more powerful squid jiggers from Japan and South Korea. An analysis of the Japanese and South Korean fleet (fig. S18) suggests that on clear days these vessels should have radiances over 100 nW/cm^2/sr. Dimmer vessels are more likely to be North Korean. For this study, we counted vessels with a brightness under 50 nW/cm^2/sr in this region to be North Korean. Interestingly, it appears that the North Korean vessels that operate within the military zone the claimed internal waters are brighter than those that venture into Russian Waters.

In our study area (blue line), which includes the claimed North Korean EEZ outside of the military zone and some waters to the east, the brightest Chinese vessels are present, as well as some North Korean vessels. The shape is somewhat similar to the shape of the Russian EEZ, but extended to the right because of the brighter Chinese vessels. To ensure that we counted no North Korean vessels when estimating the Chinese vessels, we only counted all detections over 500 nW/cm^2/sr to be Chinese (blue dashed vertical line).

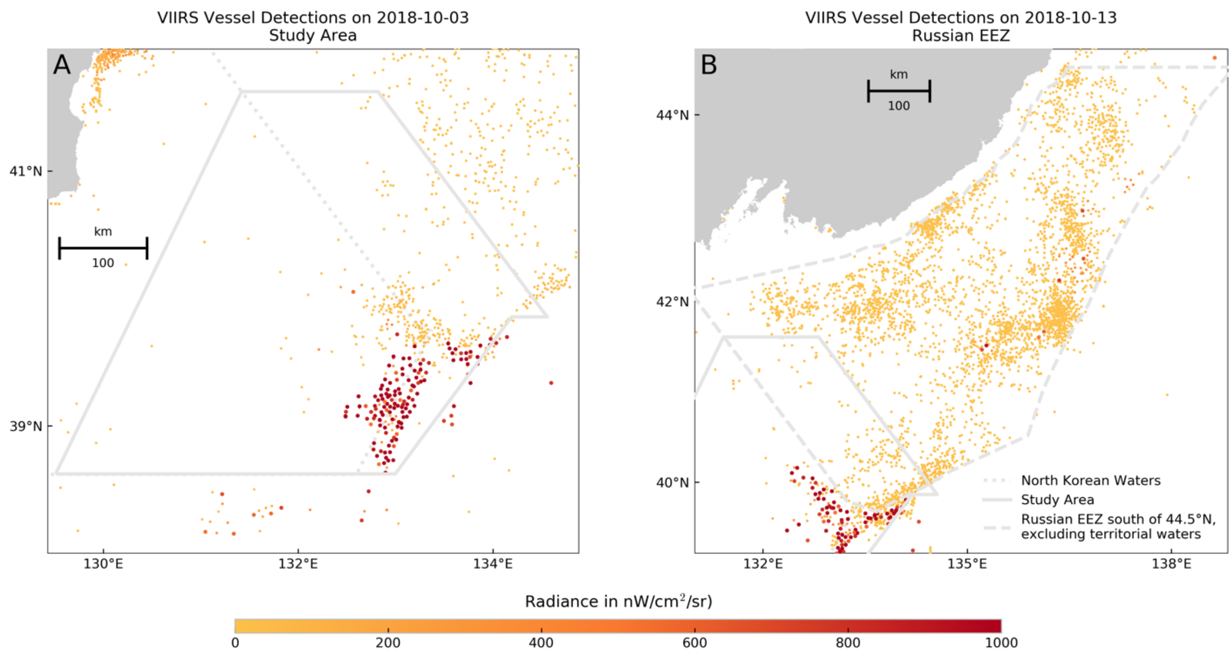


Fig. S21. Days with the maximum number of VIIRS vessel detections.
(A) The day with the highest number of vessel detections with a radiance over 500 nW/cm^2/sr in our study area. On this day, 3 October 2018, 130 vessels of this brightness, all likely Chinese, were observed in the study area. Interestingly, some bright detections are seen just to the east of the study area in the South Korean and Japanese joint fisheries management area, which could be more Chinese vessels fishing just over the line, or South Korean and/or Japanese vessels.

(B) The day with the highest number of detections below 50 nW/cm^2/sr in the Russian EEZ outside of the territorial waters and south of 44.5° N. On this day, 13 October 2018, over 3,000 vessels of this radiance were detected. For this analysis, we used the Russian EEZ from marineregions.org, and adjusted the southwestern boundary with North Korea in accordance with our study area, as described in section S1 (Boundaries and access agreements). These are likely small North Korean wooden vessels.

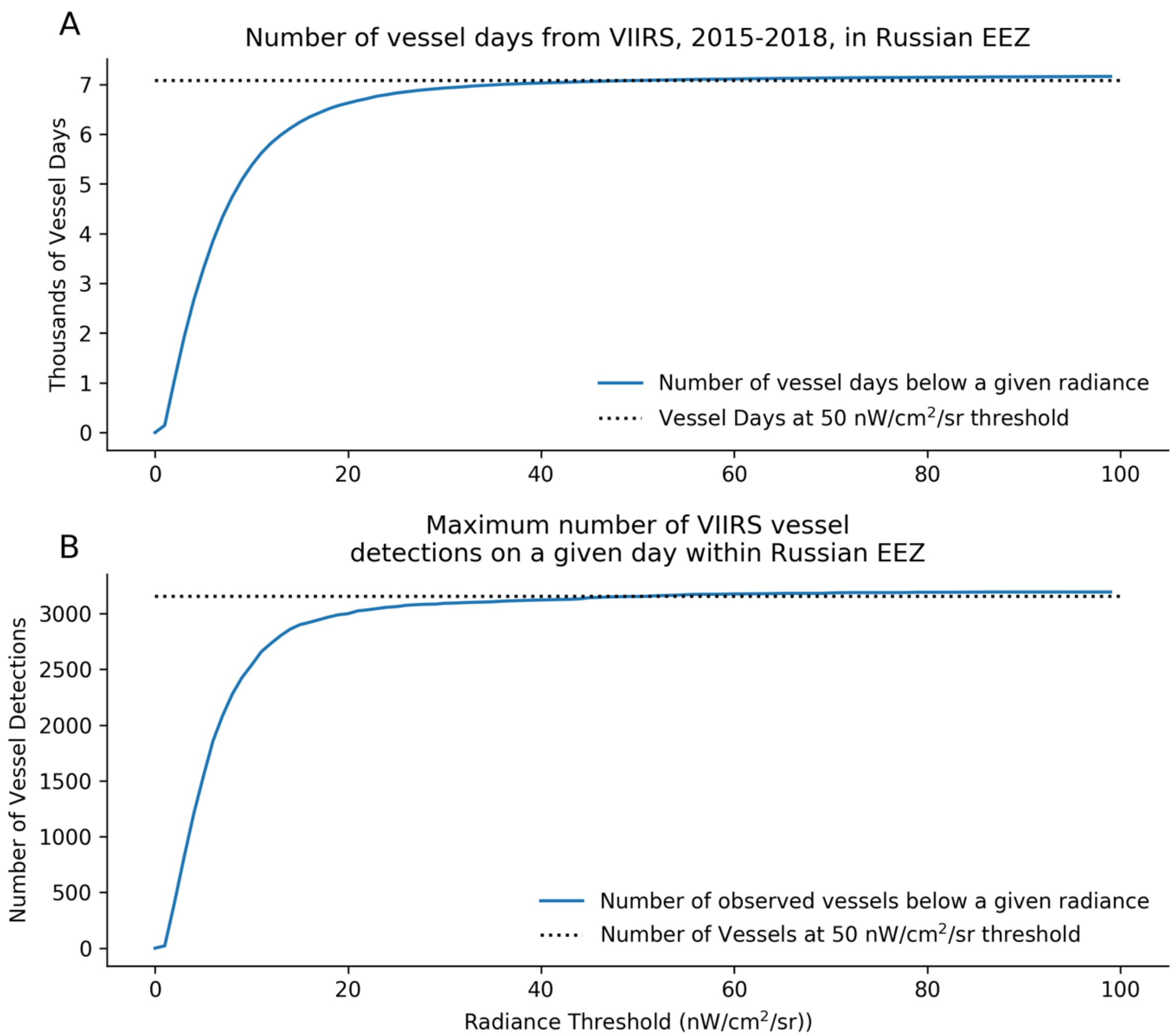


Fig. S22. Sensitivity of the estimated number of vessels and vessel days to radiance thresholds for the North Korean fleet operating in the Russian EEZ.

(A) The estimated number of vessels quickly reaches an asymptote, and above a threshold of about 50 nW/cm^2/sr the number of vessels is very insensitive to the threshold. Selecting a threshold of 50 nW/cm^2/sr for our count of North Korean vessels helps to prevent counting South Korean or Japanese vessels, which may also be present in the Russian EEZ (see fig. S18 and S19). (B) Vessel days were estimated by counting the maximum number of detections in each half month period.

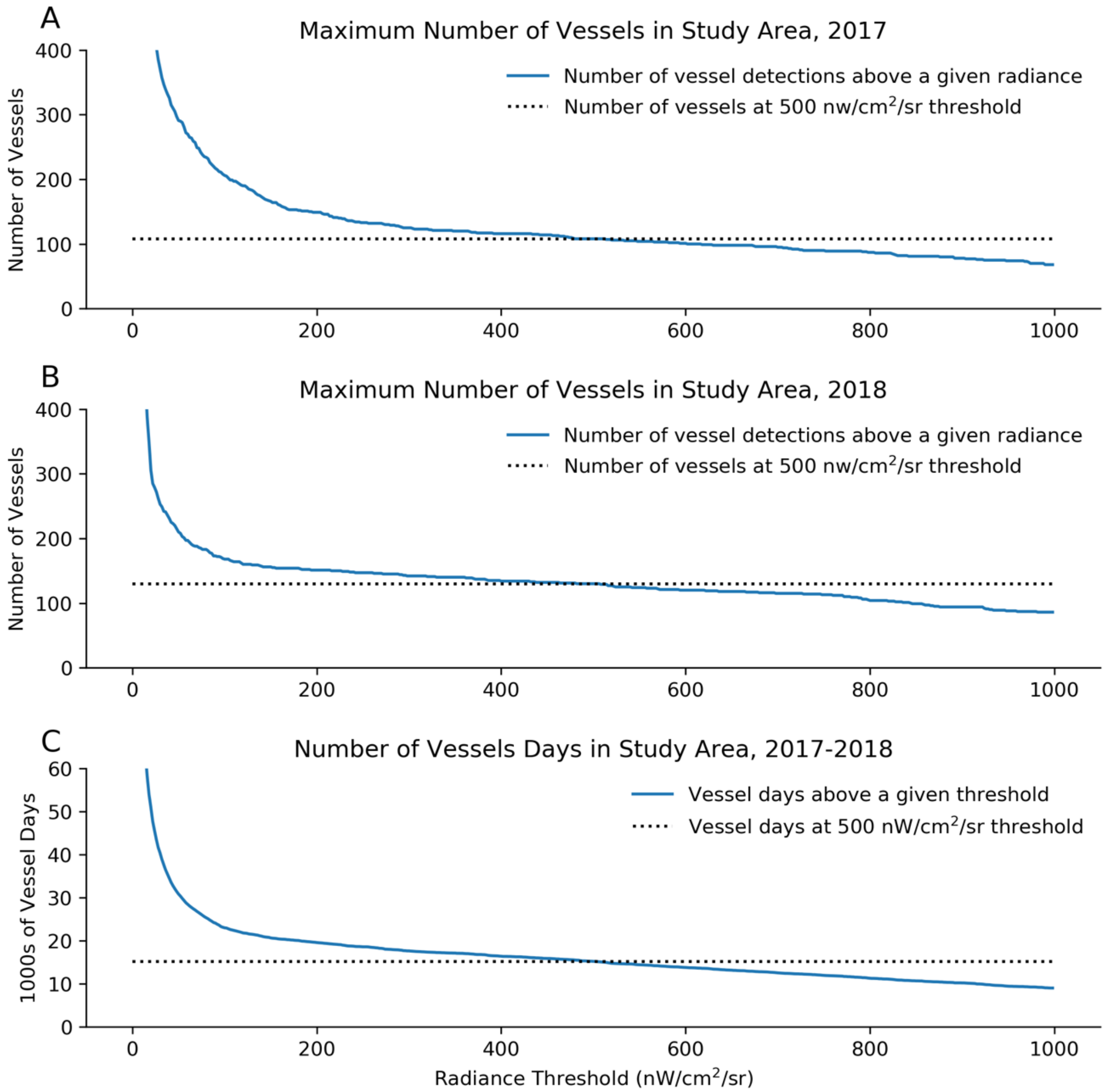


Fig. S23. Sensitivity of the estimated number of vessels and vessel days to radiance thresholds for Chinese lighting vessels operating in our study area.

To count the number of Chinese vessels present in our study area, we selected a threshold that would exclude any North Korean vessels and counted the number of vessels above that threshold. (A) The sensitivity to thresholds for 2017 and (B) for 2018, with the dotted line showing the number of vessels at the threshold chosen for our study, 500 nW/cm^2/sr. (C) The number of vessel days, for 2017 and 2018 combined, depends on the threshold chosen, where we estimate vessel days by counting the maximum number of detections over a given threshold in each half month period. The high values at the lower threshold reflect the large number of smaller North Korean vessels in our study area (our study area does overlap with the Russian EEZ).

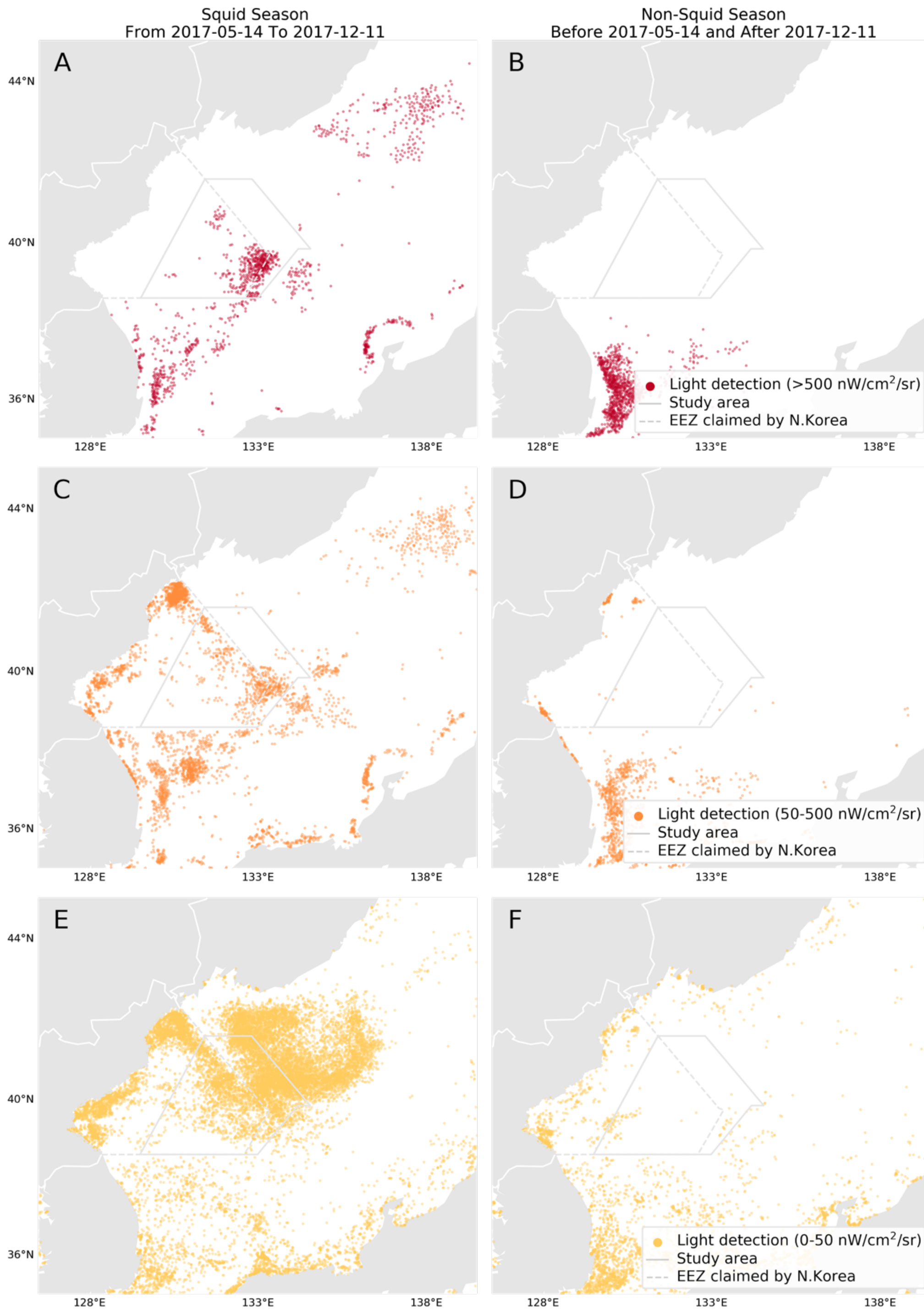


Fig. S24. Comparison of fishing and non-fishing seasons, as detected by VIIRS in 2017.

Comparing the radiance levels in different regions during the squid and non-squid season reveals the different fleets in operation. For these images, in order to use relatively clear nights, only the night with the most detections in each half month was selected.

(A, B) VIIRS light detections with high brightness (>500 nW/cm^2/sr) accumulated (A) over the estimated squid fishing season in 2017 (from 14 May to 11 December) and (B) over the rest of the year. These detections show the locations of the Chinese, South Korean, and Japanese squid jigging fleets.

(C, D) VIIRS light detections with intermediate brightness (50-500 nW/cm^2/sr), distinguishing vessels types becomes more difficult because both dim vessels on clear days and bright vessels on cloudy days can be detected at this brightness. Although (C) and (D) look similar to detections with high brightness (A, B), a cluster of detections in the North Korean claimed military zone the claimed internal waters (in C, near the North Korean shore) indicates that North Korean vessels can also be detected in this range of radiance.

(E, F) VIIRS detections with low brightness (0-50 nW/cm^2/sr) show more lights in the areas where North Korean fishing vessels are known to operate. Note that very few detections of this brightness (or any brightness) are seen in the Russian territorial waters (from shore to about 12nm).

In (A), the dense cluster of high brightness detections (>500 nW/cm^2/sr) at the southeastern part of North Korean waters is likely composed of Chinese lighting vessels; in (E), the large group of detections with low brightness in the southwestern part of the Russian EEZ is likely composed of North Korean squid vessels.

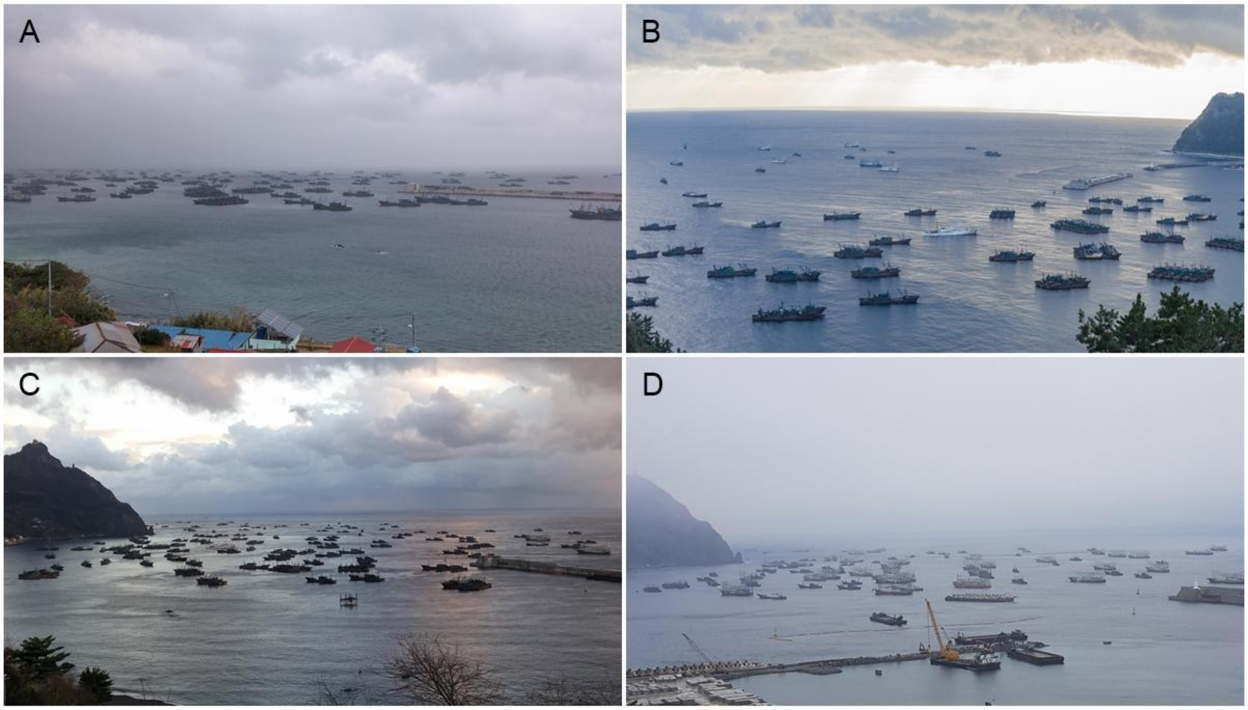


Fig. S25. Chinese pair trawlers and lighting vessels observed near Ulleung-do, South Korea.

Chinese fleets anchored in Sadong port, Ulleung-do, South Korea due to bad weather in North Korean waters. There are two types of boats shown: trawlers (30-35 meters long) and lighting boats (55-60 meters long with much taller structures above deck). Photographs taken on (A) 8 November 2016, (B, C) 6 December 2016, and (D) 18 November 2017. These photos provide visual comparison for the satellite images, and also further proof that the vessels were operating within North Korean waters.

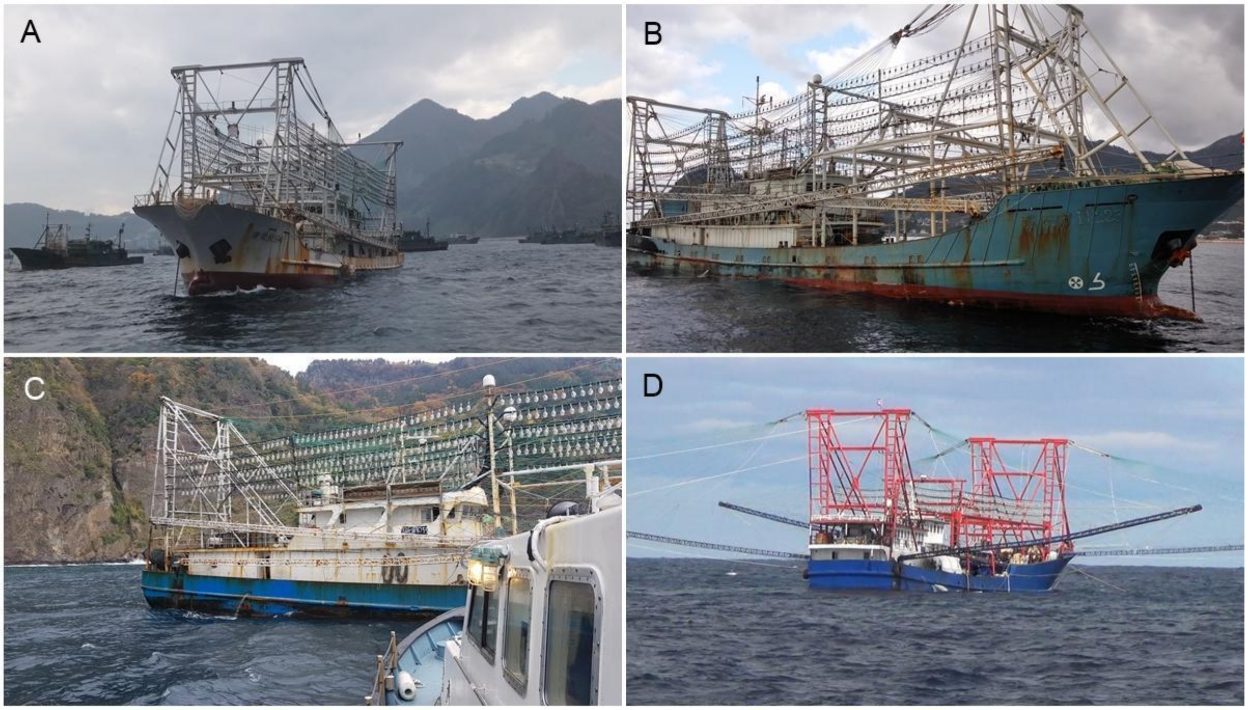


Fig. S26. Chinese lighting vessels observed near Ulleung-do, South Korea.

(A-C) Some Chinese lighting vessels photographed while avoiding typhoons at Ulleung-do in 2016 and 2017. They typically have 400-700 light bulbs aboard. (D) A photograph of a lighting vessel in operation taken at the edge of North Korean waters in October 2018. This vessel had its four arm-like structures deployed and flew both North Korean and Chinese flags.

Fig. S27. North Korean fishing vessels observed in the Russian EEZ.
(A-C) North Korean squid boats in operation in the Russian EEZ recorded between August and October 2018. All are wooden, less than 20 meters long and flew the North Korean flag. They are generally equipped with only 5-20 light bulbs used to lure squid at night. They also use driftnets during the daytime (B), and the squid catch is usually dried on the deck, probably due to the lack of refrigeration systems. (D) A North Korean boat shipwrecked and abandoned half-submerged in the Russian EEZ.

Supplementary Tables

Sensor	Strength	Limitation
Vessel Monitoring Systems (VMS)	● Provides GPS tracks of vessels ● Tamper-proof system ● Reliable information about identity and activity	● Usually not public
Automatic Identification System (AIS)	● Provides GPS tracks of vessel ● Possible to track movements of individual vessels ● Identity information usually available	● Possible to manipulate the device (i.e. intentional switch-off, false identity) ● Few smaller vessels have AIS ● Satellite reception varies across the globe, and is poor in areas of high vessel density.
Daytime optical imagery	● Visual confirmation of vessel type is possible with higher resolution imagery. ● Medium resolution (3 m) is now available globally for coastal waters through Planet, and can be used to identify and count vessels.	● Medium-resolution imagery (3 m), while now available and cheaper than previously, is still costly at scale. ● Higher resolution (<1 m) is usually costly and has very limited spatial coverage. ● Detection is limited by clouds, sea states, and sun glints. ● Impossible to track individual vessels over time
Synthetic Aperture Radar (SAR)	● Large metal vessels can be detected. ● Detection has little dependence on weather. ● Most of global coastal waters are covered by freely available SAR (Sentinel-1).	● Lack of global, regular coverage of the oceans. ● Images on most oceans are costly though decreasing rapidly. ● Types of objects detected are not easily distinguishable (e.g., fishing vessels versus non-fishing vessels). ● Does not give identity of detected vessels. ● Cannot track individual vessels over time.
Nighttime optical imagery (VIIRS)	● Vessel using light to fish can be detected regardless of the use of tracking system. ● Global, daily revisit time ● Freely available	● Does not give vessel identity. ● Detection can be limited by clouds or moon glint. ● Fishing vessels not using light or not in operation cannot be detected. ● Impossible to track individual vessels over time ● Van Allen Belts limit coverage near parts of South America.

Table S1. Comparison of technologies used to monitor vessels.

Sensor	Acquisition date	Acquisition time
PALSAR-2	2017-10-24	15:18:55 UTC
	2017-10-02	03:15:57 UTC
	2017-09-27	03:08:59 UTC
RADARSAT-2	2018-05-26	21:10:21.6 UTC
	2018-06-22	09:08:59.1 UTC
	2018-07-15	07:59:02.5 UTC
	2018-09-28	08:02:58.3 UTC
	2018-10-07	21:01:56.2 UTC
	2018-10-31	21:01:54.8 UTC
	2018-11-12	07:58:47.7 UTC

Table S2. Image acquisition times of PALSAR-2 and RADARSAT-2 data sets.
These 10 SAR images (three in 2017 by PALSAR-2 and seven in 2018 by RADARSAT-2) each cover over 60% of the study area. The acquisition time in the table is the time when the image acquisition started and the acquisition process takes less than 5 minutes.

Dates of Validated Sentinel-1 Scenes	Reference Vessel Count	Predicted Vessel Count	True Positives	False Positives	False Negatives	Precision	Recall
2017-06-01*	475	467	433	34	42	0.927	0.912
2017-10-23**	517	487	471	16	46	0.967	0.911
2018-05-15***	752	730	707	23	45	0.968	0.940
2018-11-23****	192	183	178	5	14	0.973	0.927
Totals	1,936	1,867	1,789	78	147	0.958	0.924

Associated Sentinel-1 Scene ID's:
*S1B_IW_GRDH_1SDV_20170601T212225_20170601T212250_005862_00A475_805F
**S1B_IW_GRDH_1SDV_20171023T212207_20171023T212232_007962_00E10F_E85D
***S1B_IW_GRDH_1SDV_20180515T212231_20180515T212256_010937_01404F_4066
****S1B_IW_GRDH_1SDV_20181123T212238_20181123T212303_013737_019735_4B4F

Table S3. Validating vessel detection with Sentinel-1.

The methods we used to detect vessels by using Sentinel-1 were validated against human-labeled observations. To ground truth the vessel counts, we created a dataset totaling 1,936 vessels from human annotations of four Sentinel-1 scenes, each covering approximately 42,500 km^2. Aggregate precision and recall for Sentinel-1 detections were 0.96 and 0.92, respectively.

Year	Direction	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
2017	Traveling North	0	495	347	200	150	139	297	76	7	1,711
	Traveling South	0	9	93	193	173	89	56	117	724	1,454
2018	Traveling North	71	640	32	162	193	335	120	481	127	2,161
	Traveling South	0	49	351	463	64	78	283	109	762	2,159

Table S4. Monthly count of Chinese vessels by the South Korea Coast Guard.
Number of likely Chinese vessels that passed through the Northern Limit Line between South and North Korea traveling either north (entering into North Korean waters) or traveling south (exiting from North Korean waters) as counted by the South Korea Coast Guard during 2017 and 2018 (none were observed before April in either year). As many Chinese fleets pass by in groups of multiple vessels, and some are obviously transiting from Chinese waters, only a few from each group are inspected (table S5) and the rest of the group is assumed to be of the same nationality. The monthly count is the sum of the daily vessel counts, and the same vessels may be counted more than once over a year. The discrepancy between the total count of vessel traveling north versus south may partially be due to counting errors, but is also due to the fact that vessels can leave North Korean waters to the east (to the North Pacific through the Russian and Japanese EEZs) instead of returning south.

Type of ship	Pair trawler	Light falling-netter	Jigger	Stick-held netter	Carrier	Tanker	Total
Traveling North	629	98	11	1	43	6	788
Traveling South	213	21	1	9	34	8	286

Table S5. Inspection result of Chinese vessels by the South Korean authorities.
Some of the vessels passing through South Korean waters are inspected (through onboard inspection or radio communication) by the East Sea Fisheries Management Service of South Korea in collaboration with the South Korea Coast Guard. They inspected and tabulated the types of vessels operating. Most of the vessels inspected were pair trawlers (about 80%). Light falling-netters, jiggers, and stick-held netters all use light to lure squid, and we, therefore, considered all of them "lighting vessels."

Year	Number of vessels fishing in N.Korea	Total catch in metric tons	Catch per vessel in metric tons	Total catch value in million CNY	Catch value per vessel in million CNY (thousand USD***)	Reference
2015	59	17,000	288	-	-	(*107, 108*)
2014	614	100,000	163	745**	1.21 (198)	(*109*)
2013	604*	-	-	-	-	(*110*)
2012	604	69,000	114	860	1.42 (226)	(*111*)
2011	604*	80,000	133	1,350	2.24 (355)	(*112, 113*)
2010	456	123,000	270	1,540	3.38 (510)	(*114*)

* Permitted number of vessels based on agreement.
** Linearly extrapolated based on the information about the fleets from Shandong province that have operated in North Korea: production of 70,500 metric tons for 525 million CNY by 564 vessels.
*** Converted to US dollar based on conversion value indicated in IMF Exchange Rate of the last available day of each year (1 USD equals to: 6.12 CNY in 2014, 6.29 CNY in 2012, 6.3009 CNY in 2011, 6.62 CNY in 2010).

Table S6. Chinese fishing operation in North Korea reported in Chinese official documents.

Government sourced written records of Chinese fishing in North Korean waters between 2010 and 2015 show the number of Chinese vessels that operated in North Korea and their production in metric tons. The catch per vessel, total catch value, and catch value per vessel were calculated based on these records. In 2013, the total production of these fleets is unavailable, and no record of Chinese fishing operation in North Korea is available after 2016.

Supplementary Captions

Movie S1. North Korean vessels in operation in the Russian EEZ.

While operating in the Russian EEZ in 2018, North Korean vessels were recorded by the captain of a South Korean squid jigger. They are typically 10-20 meters long, wooden, and equipped with a few light bulbs. The markings on the side of the hull indicate that they belong to North Korea. A number of these vessels were detected by marine radar at the vicinity of 43.04° N, 136.55° E.

Movie S2. North Korean vessels sheltering from a typhoon at the port of Olga, Russia.

Hundreds of North Korean vessels took shelter from a typhoon at the port of Olga, Russia in October 2018. They flew both North Korean and Russian flags. After the typhoon, they made a massive departure from the port observed by marine radar. At times, shipwrecked North Korean vessels were observed in the Russian EEZ probably because they are unfit for rough sea condition.

Movie S3. Chinese lighting vessels at the edge of North Korean waters.

In October 2018, Chinese lighting vessels were observed near the edge of North Korean waters. They deployed four arm-like structures designed to hang nets underneath the hull, and flew both Chinese and North Korean flags.

REFERENCES AND NOTES

1. Ministry of Marine Affairs and Fisheries, Republic of Indonesia, Our Ocean Conference Commitments (2018); https://ourocean2018.org/?l=our-ocean-commitments.
2. 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).
3. R. Pelich, M. Chini, R. Hostache, P. Matgen, C. Lopez-Martinez, M. Nuevo, P. Ries, G. Eiden, Large-scale automatic vessel monitoring based on dual-polarization sentinel-1 and AIS data. *Remote Sens.* **11**, 1078 (2019).
4. G. Rowlands, J. Brown, B. Soule, P. T. Boluda, A. D. Rogers, Satellite surveillance of fishing vessel activity in the ascension island exclusive economic zone and marine protected area. *Mar. Policy* **101**, 39–50 (2019).
5. N. Longépé, G. Hajduch, R. Ardianto, R. de Joux, B. Nhunfat, M. I. Marzuki, R. Fablet, I. Hermawan, O. Germain, B. A. Subki, R. Farhan, A. D. Muttaqin, P. Gaspar, Completing fishing monitoring with spaceborne Vessel Detection System (VDS) and Automatic Identification System (AIS) to assess illegal fishing in Indonesia. *Mar. Pollut. Bull.* **131**, 33–39 (2018).
6. J. B. Park, *Regional Environmental Politics in Northeast Asia: Conflict and Cooperation* (Routledge, 2018).
7. H. Kidokoro, T. Goto, T. Nagasawa, H. Nishida, T. Akamine, Y. Sakurai, Impact of a climate regime shift on the migration of Japanese common squid (*Todarodes pacificus*) in the Sea of Japan. *ICES J. Mar. Sci.* **67**, 1314–1322 (2010).
8. J.-S. Lee, J.-G. Ryu, H.-K. Kee, A Study on the Status of Chinese Fishing in the East Sea off North Korea and Directions for Countermeasures. *J. Fish. Bus. Adm.* **48**, 61–74 (2017).
9. Ministry of Oceans and Fisheries of Republic of Korea, [Fisheries Information Portal Service]; https://fips.go.kr/p/S020304/.
10. Fisheries Agency of Japan, [Marine fisheries production statistics]; www.maff.go.jp/j/tokei/kouhyou/kaimen_gyosei/index.html.
11. Fisheries Agency of Japan, [Status of consumption of marine products] (2016); www.jfa.maff.go.jp/j/kikaku/wpaper/h29_h/trend/1/t1_2_4_2.html.
12. The Observatory of Economic Complexity, Products exported by North Korea (2016); http://atlas.media.mit.edu/en/visualize/tree_map/hs92/export/prk/all/show/2016/.

13. See Supplementary Materials.
14. V. Gowlland-Debbas, *United Nations Sanctions and International Law* (Brill Nijhoff, 2001).
15. Ministry of Agriculture and Rural Affairs of the People's Republic of China, [Distant water fisheries management regulations] (2003); www.moa.gov.cn/gk/tzgg_1/bl/200305/t20030519_83829.htm.
16. 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).
17. G. Lemoine, J. Chesworth, G. Schwartz-Juste, N. Kourti, I. Shepherd, in *2004 IEEE International Geoscience and Remote Sensing Symposium (IGARSS'04)* (IEEE, 2004), vol. 7, pp. 4825–4828.
18. C. D. Elvidge, M. Zhizhin, K. Baugh, F.-C. Hsu, Automatic boat identification system for VIIRS low light imaging data. *Remote Sens.* **7**, 3020–3036 (2015).
19. U. Kanjir, H. Greidanus, K. Oštir, Vessel detection and classification from spaceborne optical images: A literature survey. *Remote Sens. Environ.* **207**, 1–26 (2018).
20. Y.-M. Shin, A Strategic Approach for Regional Fisheries Organization Establishment in Northeast Asia. *J. Fish. Bus. Adm.* **44**, 1–14 (2013).
21. Ministry of Oceans and Fisheries of Republic of Korea, Fisheries Information Portal Service; https://fips.go.kr/p/S020108/.
22. Ministry of Oceans and Fisheries of Republic of Korea, 40 Enforcement decree of fisheries act, Articles 40. National Law Information Center (2017); http://law.go.kr/lsInfoP.do?lsiSeq=200503&efYd=20171229#0000.
23. Ministry of Oceans and Fisheries of Republic of Korea, Revised implementation plan for setting and managing the total allowable catch in 2017. National Law Information Center (2017); www.law.go.kr/admRulLsInfoP.do?admRulSeq=2100000116070#AJAX.
24. H. Kubota, M. Miyahara, R. Matsukura, T. Goto, Stock assessment and evaluation for the autumn breeding stock of Common squid (2017), (Japan Sea National Fisheries Research Institute, 2017), pp. 667–704.
25. Korean Statistical Information Service, Status of fishing vessels and fishing activity; http://kosis.kr/statHtml/statHtml.do?orgId=307&tblId=TX_30701_A000&conn_path=I2.
26. Y. Oozeki, D. Inagake, T. Saito, M. Okazaki, I. Fusejima, M. Hotai, T. Watanabe, H.

Sugisaki, M. Miyahara, Reliable estimation of IUU fishing catch amounts in the northwestern Pacific adjacent to the Japanese EEZ: Potential for usage of satellite remote sensing images. *Mar. Policy* **88**, 64–74 (2018).

27. United Nations Convention on the Law of the Sea (1982); www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf.
28. C. Breuil, D. Grima, Baseline Report Somalia, *SmartFish Programme of the Indian Ocean Commission* (Fisheries Management FAO component, Ebene, Mauritius, 2014), p. 22.
29. J. Christensen, in Perspectives on Oceans Past, K. Schwerdtner Máñez, B. Poulsen, Eds. (Springer Netherlands, Dordrecht, 2016), pp. 133–153.
30. T. G. Mallory, China's distant water fishing industry: Evolving policies and implications. *Mar. Policy* **38**, 99–108 (2013).
31. S. Lee, H. E. Lee, in *The Making of International Law in Korea: From Colony to Asian Power* (Brill, 2016), pp. 152–153 and 176–183.
32. C.-h. Park, The 50-Mile Military Boundary Zone of North Korea. *Am. J. Int. Law.* **72**, 866–875 (1978).
33. R. Pedrozo, Military activities in the exclusive economic zone: East asia focus. *Int. Law Stud. Ser. US Nav. War Coll.* **90**, 514–543 (2014).
34. S. Hong, S. Choi, J. Kim, Chapter III. Marine borders and possible fishing areas in the East Sea of North Korea in A study of the North-South Korean cooperation on joint fisheries in the West and the East Sea (1) (Korean Maritime Institute, 2007).
35. Embassy of Russia to the DPRK, Agreement between the Union of Soviet Socialist Republics and the Democratic People's Republic of Korea on the delimitation of the economic zone and the continental shelf (1986); www.rusembdprk.ru/images/lawbase/Document_09.pdf.
36. S. K. Kim, *Disputes Over the Delimitation of the Eez and the Continental Shelf in Maritime Disputes in Northeast Asia: Regional Challenges and Cooperation* (Brill, 2017), vol. 3.
37. Ministry of Agriculture of the Russian Federation, *Order N385, The Rules of Fisheries for the Far Eastern Fishing Basin* (Commonwealth of Independent States, Eastern Europe, Europe, 2013).
38. Ministry of Foreign Affairs of Republic of Korea, Agreement on fisheries between Republic of Korea and Japan (1998); www.korea.kr/archive/expDocView.do?docId=28378.

39. Ministry of Foreign Affairs of Japan, Agreement on fisheries between Japan and Republic of Korea (1998); https://www.mofa.go.jp/mofaj/gaiko/treaty/pdfs/A-H11-1039.pdf.
40. Ministry of Oceans and Fisheries of Republic of Korea, Articles 16, 17, and 23 in Ship safety operation rules (2015); www.law.go.kr/lsEfInfoP.do?lsiSeq=173790#.
41. Ministry of Oceans and Fisheries of Republic of Korea, A more meticulous safety management for offshore fishing vessels (2015); www.mof.go.kr/article/view.do?menuKey=376&boardKey=10&articleKey=18797.
42. Federal Agency of Fisheries of the Russian Federation, Cooperation under bilateral fisheries and fisheries agreements; www.fish.gov.ru/otraslevaya-deyatelnost/mezhdunarodnoesotrudnichestvo.
43. Federal Agency of Fisheries of the Russian Federation, Results of the activities of the Federal Fisheries Agency in 2015 and objectives for 2016 (2016), (available at http://fish.gov.ru/files/documents/ob_agentstve/kollegiya/itogi_2015_zadachi_2016.pdf).
44. Federal Agency of Fisheries of the Russian Federation, Results of the activities of the Federal Fisheries Agency in 2016 and objectives for 2017 (2017); www.fish.gov.ru/files/documents/ob_agentstve/kollegiya/itogi_2016_zadachi_2017-1.pdf.
45. Federal Agency of Fisheries of the Russian Federation, On measures to implement the Protocol of the 30th session of the Russian-Korean mixed commission for cooperation in the field of fisheries and the Protocol of Russian-Korean negotiations on the possibility of organizing fishing activities of Russian and Korean fishing vessels in the exclusive economic zones of the DPRK and the Russian Federation, respectively, in 2018 (2018); http://npb.fishcom.ru/soft_na/bpa/docview.phtml?bpaid=4&code=11589&rdk=0&nv=0.
46. V. V. Barinov, E. V. Osipov, S. V. Lisienko, Technological Improvement of Japanese Flying Squid Fishery. *KSTU News* (2016); http://klgtu.ru/science/magazine/news_kstu/2016_43/%D0%98%D0%B7%D0%B2%D0%B5%D1%81%D1%82%D0%B8%D1%8F_%D0%9A%D0%93%D0%A2%D0%A3%20%E2%84%96%2043.pdf.
47. Federal Agency of Fisheries of the Russian Federation, Monitoring the development of the recommended volumes of production (catch) of aquatic biological resources, the total allowable catch not established as of December 31, 2016 (2016); http://www.fish.gov.ru/files/documents/otraslevaya_deyatelnost/organizaciya_rybolovstva/o

svoenie_rekomendovannyh/kontr-oro-122016-4.xls.
48. Federal Agency of Fisheries of the Russian Federation, Monitoring the development of the recommended volumes of production (catch) of aquatic biological resources, the total allowable catch not established as of October 1, 2017 (2017); http://www.fish.gov.ru/files/documents/otraslevaya_deyatelnost/organizaciya_rybolovstva/osvoenie_rekomendovannyh/kontr-oro-112017-3.xlsx.
49. Federal Agency of Fisheries of the Russian Federation, Monitoring the development of the recommended volumes of production (catch) of aquatic biological resources, the total allowable catch not established as of September 1, 2018 (2018); http://www.fish.gov.ru/files/documents/otraslevaya_deyatelnost/organizaciya_rybolovstva/osvoenie_rekomendovannyh/kontr-oro-010918-3.xls.
50. Fisheries Agency of Japan, Internal document (2018).
51. National Federation of Fisheries Cooperatives, Internal document, available on request, Performance of fishing operation in the Russian EEZ in 2017.
52. Federal Agency of Fisheries of the Russian Federation, Results of the activities of the Federal Fisheries Agency in 2018 and objectives for 2019 (2019); www.fish.gov.ru/files/documents/ob_agentstve/kollegiya/itogi_2018_zadachi_2019.pdf.
53. Fisheries Agency of Japan, Database of fishing report of squid jiggers (2018).
54. Federal Agency of Fisheries of the Russian Federation, Results of the activities of the Federal Fisheries Agency in 2017 and objectives for 2018 (2018); http://fish.gov.ru/files/documents/ob_agentstve/kollegiya/itogi_2017_zadachi_2018.pdf.
55. C. C. Wackerman, K. S. Friedman, W. G. Pichel, P. Clemente-Colón, X. Li, Automatic detection of ships in RADARSAT-1 SAR imagery. *Can. J. Remote Sens.* **27**, 568–577 (2001).
56. K. El-Darymli, P. McGuire, D. Power, C. R. Moloney, Target detection in synthetic aperture radar imagery: A state-of-the-art survey. *J. Appl. Remote Sens.* **7**, 071598 (2013).
57. S. Tian, C. Wang, H. Zhang, Ship detection method for single-polarization synthetic aperture radar imagery based on target enhancement and nonparametric clutter estimation. *J. Appl. Remote Sens*. **9**, 096073 (2015).
58. A. Marino, M. J. Sanjuan-Ferrer, I. Hajnsek, K. Ouchi, Ship detection with spectral analysis of synthetic aperture radar: A comparison of new and well-known algorithms. *Remote Sens.*

7, 5416–5439 (2015).
59. W. Ao, F. Xu, in *2018 IEEE International Conference on Computational Electromagnetics (ICCEM)* (2018), pp. 1–2.
60. W. Ao, F. Xu, Y. Li, H. Wang, Detection and discrimination of ship targets in complex background from spaceborne ALOS-2 SAR images. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **11**, 536–550 (2018).
61. A. Marino, M. Sugimoto, K. Ouchi, I. Hajnsek, Validating a notch filter for detection of targets at sea with ALOS-PALSAR Data: Tokyo Bay. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **7**, 4907–4918 (2014).
62. I. E. Mladenova, T. J. Jackson, R. Bindlish, S. Hensley, Incidence angle normalization of radar backscatter data. *IEEE Trans. Geosci. Remote Sens.* **51**, 1791–1804 (2013).
63. K. Topouzelis, S. Singha, D. Kitsiou, Incidence angle normalization of Wide Swath SAR data for oceanographic applications. *Open Geosci.* **8**, 450–464 (2016).
64. T. Lindeberg, Image matching using generalized scale-space interest points. *J. Math. Imaging Vis.* **52**, 3–36 (2015).
65. N. R. Pal, S. K. Pal, A review on image segmentation techniques. *Pattern Recognit.* **26**, 1277–1294 (1993).
66. R. M. Haralick, S. R. Sternberg, X. Zhuang, Image analysis using mathematical morphology. *IEEE Trans. Pattern Anal. Mach. Intell.* **PAMI-9**, 532–550 (1987).
67. M. Stasolla, C. Santamaria, J. J. Mallorqui, G. Margarit, N. Walker, in *2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)* (2015), pp. 2473–2476.
68. C. Brekke, *Automatic ship detection based on satellite SAR* (Norwegian Defence Research Establishment (FFI), 2009), p. 40.
69. C. Dong, J. Liu, F. Xu, Ship detection in optical remote sensing images based on saliency and a rotation-invariant descriptor. *Remote Sens.* **10**, 400 (2018).
70. Ministry of Oceans and Fisheries of Republic of Korea, Rules on permission and notification of fishing, Articles 3 and 13. National Law Information Center (2017); http://law.go.kr/LSW/lsEfInfoP.do?lsiSeq=199339#.
71. Y. Shikata, J. Mochihira, Y. Takao, K. Sadayasu, T. Watanabe, CPUE Relationship between squid distribution density and CPUE under squid fishing operation. *J. Jpn. Fish. Soc.* **81**,

659–666 (2015).
72. L. Yan, P. Zhang, L. Yang, B. Yang, Y. Tan, Catch composition of light falling-net fishery in the central and southern South China Sea in spring of 2011. *South China Fish. Sci.* **10**, (2014).
73. L. Yan, P. Zhang, B. Yang, S. Chen, Y. Li, Y. Li, P. Song, L. Lin, Relationship between the catch of Symplectoteuthis oualaniensis and surface temperature and the vertical temperature structure in the South China Sea. *J. Fish. Sci. China* **23**, 469–477 (2016).
74. Q. Yang, Y. Li, P. Zhang, Y. Tang, G. Chen, J. Zhang, Acoustic survey of the Symplectoteuthis oualaniensis resources in the South China Sea based on light falling-net. *J. Fish. China.* **37**, 1032 (2013).
75. Q. Wu, G. Yu, Z. Ma, S. Ma, S. Wu, Preliminary Study on the Fisheries Catches in South China Sea via Light Falling-Net Fishing Method. *Int. J. Innov. Stud. Aquat. Biol. Fish.* **2**, 1–4 (2016).
76. P. Zhang, X. Zeng, L. Yang, C. Peng, X. Zhang, S. Yang, Y. Tan, B. Yang, L. Yan, Analyses on fishing ground and catch composition of large-scale light falling-net fisheries in South China Sea. *South China Fish. Sci.* **9**, 74–79 (2013).
77. UEFA Stadium Lighting Guide 2016 (2016); www.uefa.com/MultimediaFiles/Download/uefaorg/General/02/36/26/72/2362672_DOWNLOAD.pdf.
78. The South Korean Coast Guard, internal report Analysis report on Chinese vessels crossing to North Korea and Russian waters, October (2017).
79. X. J. Cheng, Y. J. Feng, Squid resources and development and utilization in the eastern waters of North Korea. *Shandong Fisheries* **22**, 37–38 (2005).
80. United Nations, Security Council, General Assembly resolution 2371 (2017); https://undocs.org/S/RES/2371%20(2017).
81. United Nations, Security Council, General Assembly resolution 2375 (2017); https://undocs.org/S/RES/2375%20(2017).
82. United Nations, Security Council, General Assembly resolution 2397 (2017); https://undocs.org/S/RES/2397%20(2017).
83. D. Cortright, G. A. Lopez, L. Gerber-Stellingwerf, Sanctions. in *Oxf. Handb. U. N.,* S. Daws, T. G. Weiss, Eds. (Oxford Univ. Press, 1 ed, 2008).

84. R. och Regeringskansliet, International sanctions. *Regeringskansliet* (2015); www.government.se/government-policy/foreign-and-security-policy/internationalsanctions/.
85. United Nations, Security Council, Note verbale dated 2 November 2017 from the Permanent Mission of China to the United Nations addressed to the Chair of the Committee (2017); www.un.org/ga/search/view_doc.asp?symbol=S/AC.49/2017/105.
86. United Nations, Security Council, Note verbale dated 12 December 2017 from the Permanent Mission of China to the United Nations addressed to the Chair of the Committee (2017); www.un.org/ga/search/view_doc.asp?symbol=S/AC.49/2017/143.
87. United Nations, Security Council, Note verbale dated 15 March 2018 from the Permanent Mission of China to the United Nations addressed to the Chair of the Committee (2018); www.un.org/ga/search/view_doc.asp?symbol=S/AC.49/2018/35
88. United Nations, Security Council, Note by the President of the Security Council (2019); www.undocs.org/S/2019/171.
89. Ministry of Agriculture and Rural Affairs of the People's Republic of China, Office of the Ministry of Agriculture on strengthening the eastern part of North Korea, Notice of the management of marine fishery cooperation projects (2017); www.moa.gov.cn/nybgb/2016/diqiqi/201711/t20171128_5921825.htm.
90. Jinjiang Municipal Ocean and Fisheries Bureau, 2017 work summary and 2018 work plan (2017); www.jinjiang.gov.cn/zfshow.aspx?id=51907.
91. Quanzhou Municipal Ocean and Fisheries Bureau, Notice of Quanzhou Municipal Ocean and Fisheries Bureau (2017 work summary and 2018 work plan) (2018); www.quanzhou.gov.cn/zfb/xxgk/zfxxgkzl/bgzj/bmgzzj/201806/t20180607_705842.htm.
92. Jinjiang News Network, Jinjiang unicipal Oceans and Fisheries Bureau launches breeding and release of 135 million prawns into Quanzhou Bay (2017); http://news.ijjnews.com/system/2017/09/08/011005595.shtml.
93. Weihai City People's Government, Fishing vessels subject to seasonal closure must return to port and anchor by mid-day on May 1st (2018); www.weihai.gov.cn/art/2018/4/17/art_16952_1275087.html.
94. Weihai City Wendeng District Government, Fishing vessels subject to seasonal closure must return to port and anchor by mid-day on May 1st;

www.wendeng.gov.cn//art/2018/4/19/art_37135_1277494.html.

95. Rongcheng city news center, Rongcheng city people's government local status, Rongcheng opens a new fishing ground in Mauritania (2018); www.rongcheng.gov.cn/art/2018/11/8/art_40745_1466014.html.

96. National Federation of Fisheries Cooperatives, Report on fisheries management, 2018 (2018), vol. 108, pp. 55.

97. National Federation of Fisheries Cooperatives, Report on fisheries management, 2018 (2019), vol. 110, pp. 57.

98. M. Jiang, S. Ma, Z. Ma, J. Zou, S. Wu, F. Lin, J. Qin, Q. Wu, Economic Benefit Analysis of Trawlers and light trap and falling net fishing vessels in South China Sea. *Insights Aquacult. Biotechnol.* **2**, 5 (2018).

99. Fishing knowledge (3) fish net diagram and application technology of pair trawling. Marine Fisheries (1984); www.cnki.com.cn/Article/CJFDTotal-HTYY198403010.htm.

100. C.-S. Jang, W.-S. Song, M. Kang, Y.-H. Cho, B.-Y. Kim, Y.-S. An, Fishing gear and method and improvement of regulation of the middle sized trawl fishery in the East Sea of Korea. J. Korean Soc. Fish. Technol. 52, 162–168 (2016).

101. L. Song, X. Qu, C. Yuan, Analysis of fishing ground and resources of squid Todarodes pacificus in eastern coast of Korea Todarodes pacificus in eastern coast of Korea. *J. Dalian Fish. Univ.* **23**, 123–127 (2008).

102. Y. Tian, H. Kidokoro, T. Fujino, Interannual-decadal variability of demersal fish assemblages in the Tsushima Warm Current region of the Japan Sea: Impacts of climate regime shifts and trawl fisheries with implications for ecosystem-based management. *Fish. Res.* **112**, 140–153 (2011).

103. D. M. Son, National report on the fish stocks and habitats of regional, global and transboundary significance in the South China Sea, *National Report on Fisheries - Vietnam* (2008), 312 p.

104. B. Haas, South Korean heatwave causes record deaths. The Guardian (2018); www.theguardian.com/world/2018/aug/09/south-korean-heatwave-causes-record-deaths.

105. T. K. Herald, S. Korea investigates alleged N. Korean coal trans-shipped to its ports (2018); www.koreaherald.com/view.php?ud=20180717000761.

106. L. Harkell, Squid prices higher in China. Undercurr. News (2018);

www.undercurrentnews.com/2018/04/20/squid-prices-higher-in-china/.

107. Ministry of Agriculture and Rural Affairs of the People's Republic of China Bureau of Fisheries, Development overview in 2016 Chinese Fisheries Yearbook China Agriculture Press, 2016), 52 p.
108. Ministry of Agriculture and Rural Affairs of the People's Republic of China, Ministry's notice on issues related to the 2015 joint fishing projects in the Eastern waters of North Korea (Bureau of Fisheries, No. 51, 2015); www.moa.gov.cn/govpublic/YYJ/201507/t20150727_4764259.htm.
109. Ministry of Agriculture and Rural Affairs of the People's Republic of China Bureau of Fisheries, Development overview and Fisheries by region in 2015 Chinese Fisheries Yearbook (China Agriculture Press, 2016), vol. 85, pp. 5.
110. Ministry of Agriculture and Rural Affairs of the People's Republic of China, Ministry's notice of strengthening the management of fishing vessels going to the Eastern waters of North Korea (Bureau of Fisheries, No. 48, 2013); www.moa.gov.cn/govpublic/YYJ/201307/t20130708_3516174.htm.
111. Fujian Gangshun Pelagic Fishery Co. Ltd., A feasibility study report on China-Asean (Fujian) industrial district project for distant water fishery (2013).
112. Ministry of Agriculture and Rural Affairs of the People's Republic of China Bureau of Fisheries, Development overview in 2012 Chinese Fisheries Yearbook (China Agriculture Press, 2012), 39 p.
113. Ministry of Agriculture and Rural Affairs of the People's Republic of China, Ministry's notice of strengthening the management of distant water fishery in the Eastern waters of North Korea (Bureau of Fisheries, No. 56, 2011); www.moa.gov.cn/govpublic/YYJ/201105/t20110510_1988661.htm.
114. Ministry of Agriculture and Rural Affairs of the People's Republic of China Bureau of Fisheries, Development overview in 2011 Chinese Fisheries Yearbook China Agriculture Press.