ENVIRONMENTAL STUDIES

# Illuminating dark fishing fleets in North Korea

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**Illegal, unreported, and unregulated fishing threatens resource sustainability and equity. A major challenge with such activity is that most fishing vessels do not broadcast their positions and are "dark" in public monitoring systems. Combining four satellite technologies, we identify widespread illegal fishing by dark fleets in the waters between the Koreas, Japan, and Russia. We find >900 vessels of Chinese origin in 2017 and >700 in 2018 fished illegally in North Korean waters, catching an estimated amount of *Todarodes pacificus* approximating that of Japan and South Korea combined (>164,000 metric tons worth >$440 million). We further find ~3000 small-scale North Korean vessels fished, mostly illegally, in Russian waters. These results can inform independent oversight of transboundary fisheries and foreshadow a new era in satellite monitoring of fisheries.**

## INTRODUCTION

In October 2018, world leaders pledged more than $10 billion to protect the world's oceans (*1*). A major objective of this initiative is to reduce illegal, unreported, and unregulated (IUU) fishing, which results in the loss of billions of dollars, threatens fish stocks and marine ecosystems, and jeopardizes the livelihoods and food security of legitimate fishers and communities (*2*). IUU fishing, however, is often conducted by "dark fleets"—vessels that do not appear in public monitoring systems (*3*, *4*)—and is therefore difficult to monitor and enforce (*5*). Although many dark vessels operate legally and broadcast their positions on country-mandated vessel monitoring systems, these data are often tightly guarded, limiting usability for third-party oversight or transboundary management. Revealing the activities of dark vessels could address this information gap, improving transparency and accountability.

These challenges with dark fleets and IUU fishing are epitomized in the waters between North Korea, South Korea, Japan, and Russia, where geopolitical tensions and disputed boundaries create a vacuum of shared data and management (*6*). In these poorly observed waters, the same stocks of *Todarodes pacificus* (Japanese flying squid) are targeted by several fleets, including the Chinese distant-water fleet (*7*, *8*). Although the Chinese fleet has fished in North Korean waters since 2004, its fishing activity and catches are only intermittently published, and not since 2016 (table S6). This lack of information sharing prevents accurate stock assessment in a fishery where reported catches have dropped by 80 and 82% in South Korean and Japanese waters, respectively, since 2003 (*9*, *10*). This inability to assess the stock is concerning considering the critical importance of squid in the region. *T. pacificus* is South Korea's top seafood by production value (*9*), one of the top 5 seafoods consumed in Japan (*11*), and, until recent sanctions, was the third largest North Korean export (*12*).

In 2017, following North Korea's testing of ballistic missiles, the United Nations (UN) Security Council adopted resolutions to sanction the country, restricting foreign fishing after September 2017. These resolutions prohibit (i) the procurement of seafood from North Korea, (ii) joint ventures between North Korea and other countries without UN approval, and (iii) North Korea from selling or transferring fishing rights (*13*). Because sanctions under Chapter VII of the UN Charter are binding and implemented via domestic law and policy, any violations of these sanctions by Chinese vessels since September 2017 would constitute a violation of public international law and domestic Chinese law (*13*–*15*). Despite this, the South Korean Coast Guard has observed hundreds of vessels crossing into North Korean waters, and random inspections of these vessels by the East Sea Fisheries Management Service suggest that they are of Chinese origin (*13*). Evidence of continued Chinese fishing in North Korean waters is also supported by domestic Chinese documentation (*13*).

Here, to illuminate the activities of dark fleets in one of the most contested regions of the world's ocean, we combine local expertise with four satellite technologies. Individual technologies have distinct limitations but, when combined, can provide an informative picture of fishing activity (table S1). Automatic Identification Systems (AIS) provide detailed movement and identity information but are used by only a fraction of vessels (*16*). Satellite synthetic aperture radar (SAR) can identify all large metal vessels and penetrate clouds but lacks regular, global coverage of the oceans (*17*). The Visible Infrared Imaging Radiometer Suite (VIIRS) sensor has global, daily revisit time and can detect vessels with bright lights but is limited by clouds (*18*). Last, high-resolution optical imagery provides the best visual confirmation of vessel activity and type but is also limited by clouds and, until recently, was not available at high enough resolution and frequent enough revisit time to monitor fishing fleets spanning exclusive economic zones (EEZ) (*19*). Although these four technologies have previously been used to estimate fishing and identify individual vessels (*16*–*19*), they have not been combined to publicly reveal the activities and estimated catches of entire fleets at this scale.

## RESULTS

To monitor the activity of these vessels, we obtained 22 days of 3-m resolution optical imagery from Earth-imaging company Planet's

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satellite constellation, PlanetScope, covering most of the claimed North Korean EEZ in 2017 and 2018 (see fig. S1 for a map of our study area). We then trained a convolutional neural network to identify pair trawlers in this imagery, as these vessels show a distinctive fishing pattern and comprise the largest proportion of foreign vessels in the region (Fig. 1, A, B, and D, and figs. S2 to S4 and S25). After identifying the location of the fleet with the neural network, we tasked Planet's 0.72-m resolution SkySat satellites to image these vessels, further verifying that they are pair trawlers (Fig. 1C). We also used SAR imagery from three different satellites to verify the location and size of the fleet (Fig. 1E, figs. S7 to S11, and tables S2 and S3). With these data, we estimate that at least 796 distinct pair trawlers operated in North Korean waters in 2017 and at least 588 did so in 2018. Only a fraction of these vessels broadcast AIS (fig. S15); but the signals from these AIS-broadcasting vessels demonstrate that the vessels originated from Chinese ports and fished in Chinese waters (Fig. 2 and figs. S12 to S17). To further verify their Chinese origin, we matched AIS detections from 140 of these vessels to Planet imagery (Fig. 1, B and D, and fig. S5). The AIS signals of these vessels corroborate the South Korean Coast Guard's inspections, confirming that they originated from China.

The second most common fishing vessels thought to be of Chinese origin in North Korean waters are large, 55- to 60-m "lighting vessels" that use bright lights to lure target species (Fig. 3A, fig. S26, and movie S3); we identify these vessels by using low-resolution, high-sensitivity optical imagery (VIIRS) acquired at night. Although several fleets in the region use lights, Chinese vessels are known to be by far the brightest, carrying up to 700 incandescent bulbs and generating over 1000 lux, equivalent to the light of some football stadiums (*13*). This brightness allows us to distinguish these vessels from other fleets in the area (figs. S18 to S24), and we confirmed this vessel classification by tasking Planet's higher-resolution SkySat to image an area where these bright vessels clustered (Fig. 3B). VIIRS enables us to estimate a minimum of 108 lighting vessels of Chinese origin operating in North Korean waters in 2017 and 130 in 2018. We also detected low-intensity lighting vessels, identified as the North Korean small-scale fleet. This fleet consists of small 10- to 20-m wooden vessels with only 5 to 20 bulbs (Fig. 3C and fig. S27). We further verified vessel type through SAR (Fig. 3D) and Planet imagery of the port of Chongjin, North Korea (fig. S6). We estimate that about 3000 North Korean vessels fished in the Russian EEZ during 2018 (Fig. 4D).

Data from these satellites also allow us to quantify changes in vessel activity over time. For the North Korean small-scale vessels, we estimate that the number of fishing days has increased every year in the past 4 years from 39,000 in 2015 to 222,000 in 2018 (Fig. 4D). For vessels originating from China, we estimate 91,400 fishing days during 2017 (82,600 by pair trawlers and 8800 by lighting vessels) and 67,300 fishing days during 2018 (60,700 by pair trawlers and 6600 by lighting vessels) (Fig. 4, A to C). These figures account for 70% in 2017 and 91% in 2018 of the number of fishing days one would estimate based on the number of Chinese vessels crossing into or out of North Korean waters each month, as counted by the South Korean Coast Guard (Fig. 4C and tables S4 and S5). If we conservatively assume that the catch per unit effort (CPUE) for pair trawlers and lighting vessels of Chinese origin is similar to that of

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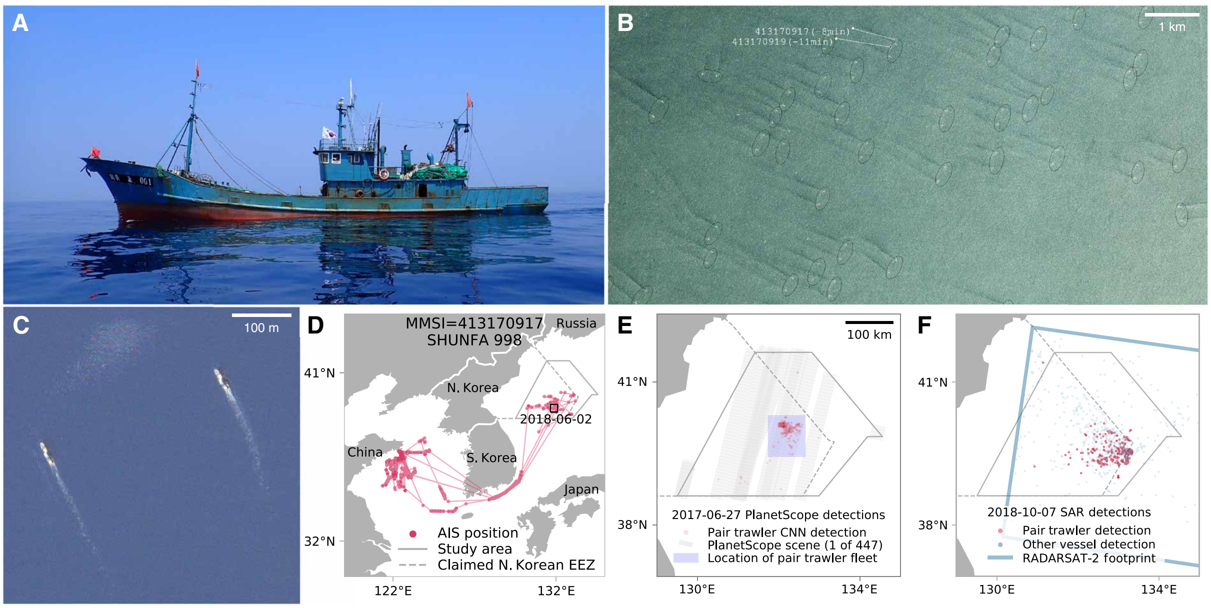


**Fig. 1. Activity of pair trawlers originating from China in North Korean waters.** (**A**) Pair trawler of Chinese origin on its way to North Korean waters (photographed by the South Korean authorities). (**B**) A satellite image of the pair trawler fleet operating in North Korea (PlanetScope, 3-m resolution). Gray ovals show where the neural net classifier identified pair trawlers. In this area, we received AIS messages from several vessels (only two are shown). White lines connect their most recent AIS position to the estimated position during the time of the satellite image based on extrapolating the vessel's speed and course. In white is the 9-digit Maritime Mobile Service Identity (MMSI) of each. (**C**) Higher-resolution image of pair trawlers in operation in North Korea (SkySat, 0.72 m). (**D**) AIS tracks for one of the two vessels matched to (B), showing the vessel originating from Shandong province, China. (**E**) Pair trawlers across our study area identified by the convolutional neural network (CNN) classifier and optical imagery. Each Planet image (24 km by 7 km) is a gray rectangle on the map, with 447 total images for this day. Light purple box shows the location of the main fleet. (**F**) Pair trawlers identified through another technology, SAR, by counting vessels within 535 m of one another.

smaller vessels in nearby waters, the total estimated likely Chinese catch would correspond to approximately 101,300 metric tons of squid worth $275 million in 2017 and 62,800 metric tons of squid worth $171 million in 2018 (*13*). Such catch figures would approximate those of Japan and South Korea combined from all their surrounding seas (*13*).

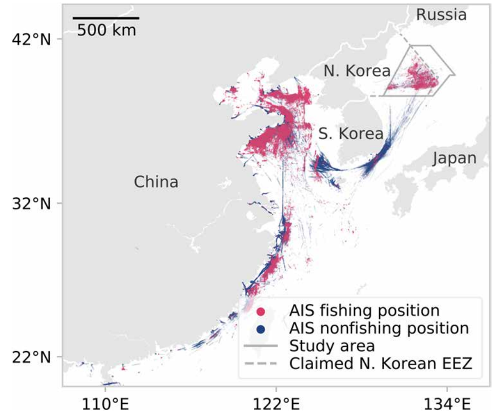


**Fig. 2. Origin of vessels fishing in North Korean waters.** During 2017 and 2018, vessels that fished in North Korean waters originated from Chinese ports and also fished in Chinese waters. Included are all AIS positions broadcast by all vessels identified as likely fishing within the claimed North Korean EEZ. Each position was identified as fishing or nonfishing by the model described in (*16*).

## DISCUSSION

This large number of previously unmonitored vessels poses a substantial challenge for stock management. A political stalemate due mainly to sovereignty conflicts and maritime boundary disputes has prevented regional joint fisheries management (*20*), while existing state-based efforts are ineffective because of a lack of shared vessel monitoring data, management arrangements, and comprehensive stock assessments. For instance, to prevent overfishing, South Korea sets the total allowable catch for squid, limits the lighting power of squid jiggers, bans pair trawling, and permits fewer than 40 small trawlers (*13*, *21*–*23*). The likely Chinese fleet, however, targeting the same stock, uses brighter lighting power, pair trawling, and a greater number of vessels (*13*). Given the declining CPUEs of South Korean and Japanese squid jiggers and the drastic decline in squid larval densities since 2003 (*24*, *25*), the large number of vessels revealed through this study is particularly concerning.

In addition to sustainability concerns, there are also substantial implications for fisheries governance and regional geopolitics. These vessels originate from China and, based on inspections by the South Korean authorities, are assumed to be owned and operated by Chinese interests (*13*). However, because the vessels often do not carry appropriate papers, they may plausibly be so-called "three-no boats" operating outside of official Chinese authority, with no registration, no flag, and no license to operate (*26*). If these vessels do not have approval from both the Chinese and North Korean governments, they are fishing illegally; Chinese regulations require ministerial approval to fish in foreign waters (*15*), and the UN Convention on the Law of the Sea grants coastal states sovereign rights to manage living marine

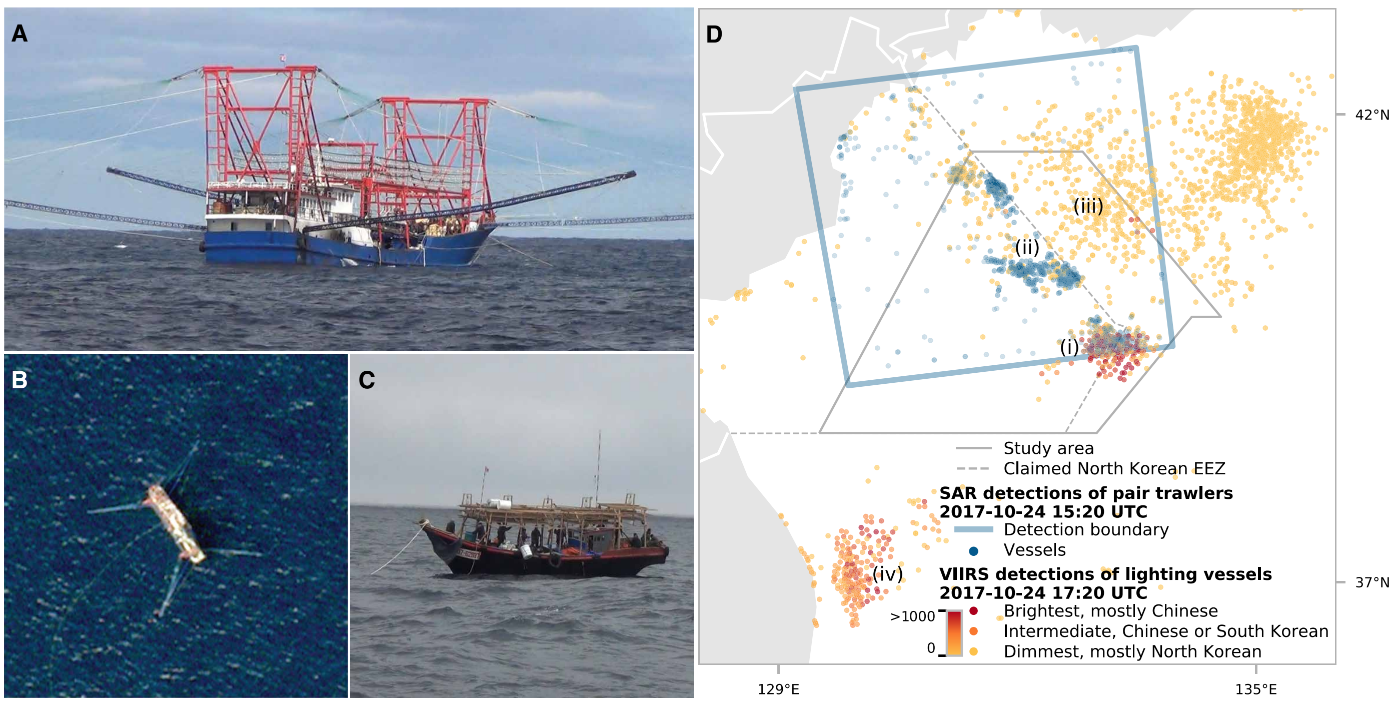


**Fig. 3. Chinese and North Korean lighting vessels.** (**A**) A 55- to 60-m Chinese lighting vessel near North Korean waters. (**B**) A Planet SkySat (0.72-m resolution) image of a Chinese lighting vessel. (**C**) A 10- to 20-m wooden North Korean lighting vessel in the Russian EEZ. (**D**) Vessel detections on 24 October 2017 by SAR, which detects large, metallic vessels but not smaller wooden ones [by PALSAR-2 (Phased Array L-band Synthetic Aperture Radar-2); blue box shows detection footprint, and blue dots show vessels]; and by VIIRS, 2 hours later, revealing lighting vessels with the brightest lights (red, >1000 nW/cm$^2$/sr, mostly Chinese), with medium lights (orange, 50 to 1000 nW/cm$^2$/sr, South Korean or Chinese), and the dimmest lights (yellow, <50 nW/cm$^2$/sr, mostly North Korean). Vessels in (D) (i) are Chinese lighting vessels, (ii) Chinese pair trawlers (detected only by SAR), (iii) North Korean squid vessels (detected only by VIIRS), and (iv) the South Korean squid fleet.



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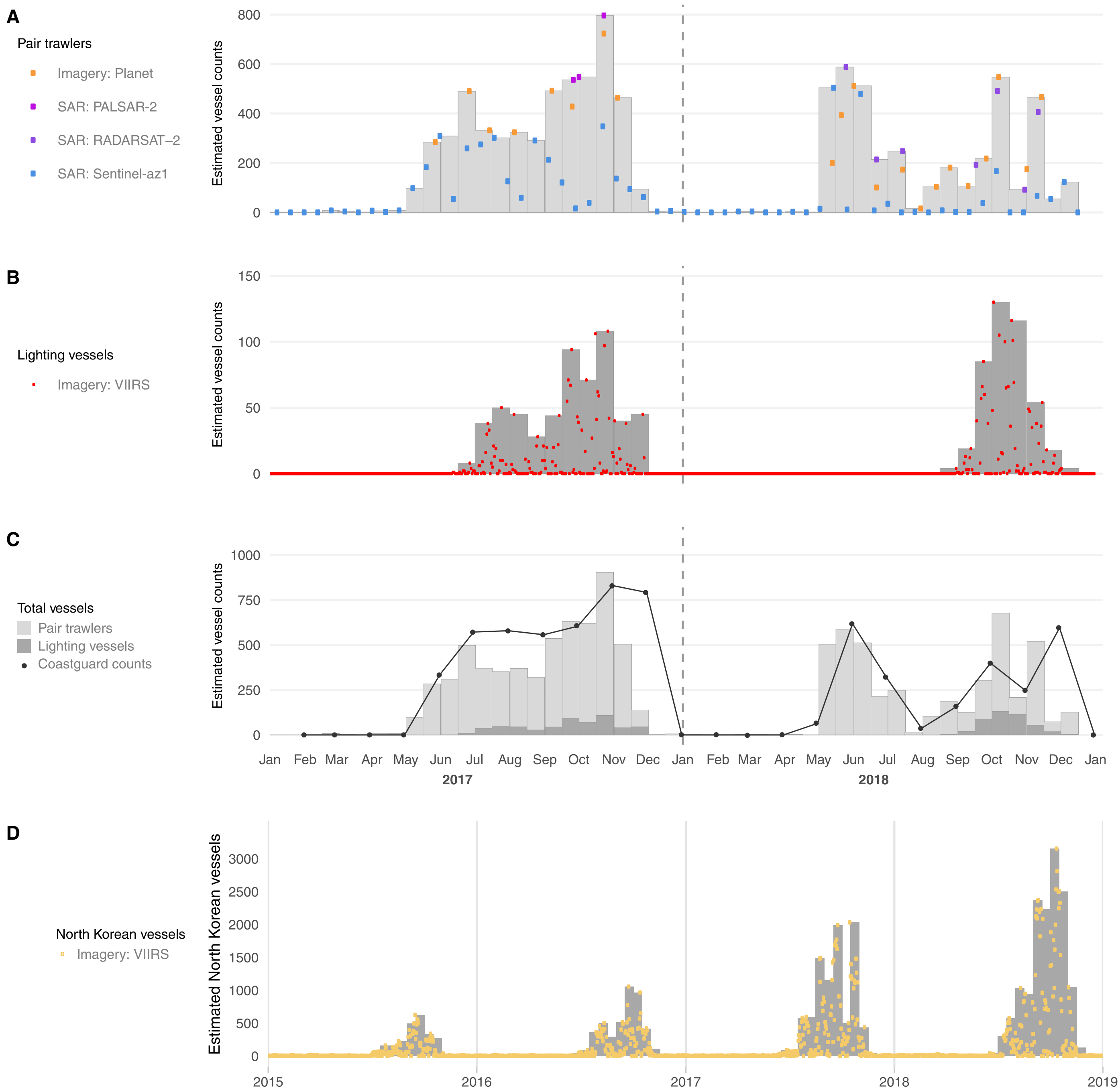


**Fig. 4. Satellites track fishing by Chinese and North Korean vessels.** (**A**) Counts of Chinese pair trawlers and (**B**) lighting vessels operating in our study area during 2017 and 2018. Because of weather conditions or incomplete coverage of the study area [e.g., Sentinel-1 footprint covers $<{}^{1}/_{2}$ of the study area (fig. S9)], vessel counts are mostly underestimates, so we use the maximum value over a half-month period to estimate the number of active vessels, which is shown by the gray bars. (**C**) Estimated total number of Chinese vessels operating in each half month (gray bars) is largely consistent with the counts of vessels from the South Korean Coast Guard (black line). (**D**) Estimated number of North Korean lighting vessels operating in the Russian EEZ, 2015–2018; data for each half-month period are the maximum number of VIIRS detections below 50 nW/cm$^2$/sr.

resources in their waters (*27*). Alternatively, if they are operating with approval from either or both governments, those state(s) are in violation of UN Security Council sanctions. Notably, the Chinese government has repeatedly refuted this latter scenario, confirming its support for the current sanctions (*13*). Regardless of the scenario, each results in the violation of either or both international and domestic law. Bearing this in mind, our analysis identified over 900 distinct illegal vessels in 2017 after sanctions began and over 700 in 2018, representing the largest known case of illegal fishing perpetrated by a single distant-water fleet (*2*, *28*, *29*).

The presence of this foreign fleet also has severe consequences for North Korean small-scale fishers. Evidence suggests that competition

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from these larger trawlers displaces these small-scale wooden boats, shifting substantial effort to neighboring Russian waters. This kind of shift in response to foreign fleets has been documented elsewhere (*30*) and is also consistent with local fisheries ecology in this region. During the last trimester of the year, Japanese flying squid migrate south, through the Russian EEZ (*7*), providing an opportunity for the North Koreans to fish before the foreign fleets deplete the stock. A large portion of this North Korean fishing in Russian waters is, however, also illegal. The Russian government has authorized fewer than 100 North Korean boats since 2014, and in 2017, no permits were granted (*13*). In contrast, we estimate about 3000 vessels fished in these waters during 2018. North Korean artisanal boats are severely underequipped for the long-distance travel required to reach Russian fishing grounds (movies S1 and S2). As a result, between 2014 and 2018, 505 North Korean boats washed ashore on Japanese coasts. These incidents frequently involve starvation and deaths, and local media reports that many fishing villages on the eastern coast of North Korea have now been coined "widows' villages" (*13*). The illegal fishing patterns documented here likely exert a heavy toll on fish and fishers alike.

We suggest that this analysis represents the beginning of a new era in satellite monitoring of fisheries. Multiple satellite sources have long been available to government agencies for targeted surveillance. However, it is only with recent increases in data availability, accessibility, and computing power that these techniques can now be performed at large enough spatial and temporal scales—and by small, independent groups of researchers—to enable transparent fisheries monitoring. Although some aspects of this study are particular to the region (e.g., prevalence of pair trawlers), most techniques are easily transferable, such as matching AIS to vessel detections from freely available global satellite imagery or radar. And for the satellite data sources that are not yet freely available, such as commercial satellite radar or high-resolution optical imagery, the cost per image is decreasing rapidly (*13*). Combining these satellite technologies can reveal the activities of dark fleets, filling a major gap in the management of transboundary fisheries. Furthermore, these technologies, when accompanied by local expertise, can identify potential hot spots of illegal, unregulated, or unreported fishing. Global fisheries have long been dominated by a culture of confidentiality and concealment, and achieving a comprehensive view of fishing activities at sea is an important step toward sustainable and cooperative fisheries management.

## MATERIALS AND METHODS

The analysis on fishing access agreements in the region is presented in section S1. All satellite data sources and methods to identify fishing vessels operating in and around North Korean waters are explained in detail in sections S2 to S5 (optical imagery in section S2, SAR in section S3, AIS in section S4, and VIIRS in section S5). We describe in section S6 the information obtained from South Korean authorities and various observations on the waters to validate our estimate of vessel presence and fishing activity. The legal analysis of the detected fishing activity is provided in section S7. Section S8 demonstrates the method for estimating the amount and the monetary value of the total catch in 2017–2018.

## SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/30/eabb1197/DC1

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