Unseen Annihilation: Illegal Fishing Practices and Nautical Patrol

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Abstract

A host of regulations should protect fish, a common-pool resource, from overexploitation, but detecting violations of these regulations is challenging, both at sea and in port. We present a novel approach to uncover a supposedly widespread and particularly harmful illegal fishing practice, the use of nets with illegally small mesh size. Our approach relies on readily available data on reported fish landings. We focus on bottom trawling, the world's most widely used fishing method. We exploit the fact that using illegally small mesh size increases the share of small fish in the catch. Using quasi-random variation in nautical patrol as a source of variation in the incentive to comply, we show that in weeks without patrol the share of small fish in the landed catch is systematically larger than in adjacent weeks with patrol. Our results are in line with widespread use of illegally small mesh. The resulting catch and discard of juvenile fish is many times larger than the gain in the catch of marketable fish. This harm has thus far been largely ignored in estimates of the externalities from fishing.

Keywords: Enforcement, Regulation, Environmental Economics, Fisheries.
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1 Introduction

The growth of industrial fishing since the 1950s has led to widespread and critical marine defaunation. A fourfold increase in reported catches from marine waters has been accompanied by a marked depletion in fish stocks (FAO, 2020) and changes in marine habitats (Jennings and Kaiser, 1998). An increasing number of regulations, introduced mainly in high-income countries over the last thirty years, have attempted to address the problem of over-exploitation of fish, a common pool resource (Hilborn et al., 2020; OECD, 2020). Regulations include fishing quotas and restrictions on how, where and when to fish.

Assessing the impact of these regulations is difficult in the absence of reliable data on compliance. Fishermen's behavior is notoriously difficult to monitor. Nautical patrol and in-port inspections, the dominant forms of monitoring, are limited in their ability to detect violations.[1] The disadvantage of in-port inspection is that a significant proportion of the catch never reaches port. Small, juvenile fish and non-target species that are of little commercial value, known as bycatch, are discarded at sea, usually dead, rather than landed in port. Nautical patrols have their own limitations, as we will discuss, because fishermen act strategically to conceal their illegal practices. As a result, most of what is known about illegal fishing practices is based on rare detections and anecdotal evidence.

This paper presents a novel approach to detecting illegal fishing practices based on readily available data on reported fish landings. We focus on an allegedly widespread illegal practice, the use of fishing nets with illegally small mesh size that results in high bycatch of juvenile fish (Molenaar and Chen, 2018).[2] Our approach builds on the finding from fishing research expeditions that the use of illegal small-mesh nets alters the composition of the landed catch in a distinct manner. Illegal nets skew the size distribution of landed fish, with a disproportionate share of small fish relative to medium and large fish (Molenaar and Chen, 2018). We can use this fact to track the presence of illegal activity, provided that it is more likely to occur in certain situations than in others. In our study, we use quasi-random variation in the deployment of the Dutch inspection vessel in the North Sea as a shock to fishing vessels' compliance incentives. We take advantage of the

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[1] Two other approaches to monitoring fishing practices at sea, an independent observer on board and autonomous video-based monitoring to record catch, are currently still prohibitively expensive and unscalable (Ewell et al., 2020).

[2] For anecdotal evidence of widespread mesh size fraud in the fishery we study, see Posthumus and Rijnsdorp (2016), Van Ginkel (2009), Hoefnagel, Visser and Vos (2004) and Dammers and Langers (2001). As Van Ginkel (2009) notes: "[T]he use of blinders [which reduce mesh size] was also widespread. Their utilization was believed to be necessary to catch marketable sole. Sole larger than the legal minimum size can get through eighty-millimeter mesh; hence the temptation to use blinders (...)." In 2019, when sole recruitment was at its peak, the Dutch Fishermen's Association acknowledged the problem as follows: "It is of utmost importance that the fleet fishes this year's class in a sustainable way (...). We should catch as little undersized sole as possible to give them the chance to reach the minimum size of 24 cm. If necessary, hold others to account!" (VisNed, 2019).

fact that in some weeks, due to vacations, international engagements, and maintenance, the inspection vessel takes full weeks off patrolling. This allows us to identify the strategic use of illegal nets by comparing the size distribution of landed fish in patrolled vs. non-patrolled adjacent weeks.

The analysis uses a wealth of data covering the years 2017-2019, including weekly landings of fish by size from the fish auctions, patrolling information, geo-location data, and daily log-book entries from fishing vessels. Our data relate to fishing vessels that target flatfish in the North Sea. These vessels catch bottom-dwelling fish by trawling a net over the seafloor. Bottom trawling is the most commonly used fishing method across the world (Watson and Tidd 2018: Figure 4B) and is the method that produces by far the largest amount of bycatch (Roda et al., 2019). Among the most common fishing methods, it is also the most expensive in terms of fuel costs (Wageningen Economic Research, 2021). These high operating costs produce strong incentives to seek more efficient alternatives. These include legal innovations such as the use of pulse trawls (now banned), but also include illegal practices such as the use of illegal nets. We focus on vessels that target sole (*solea solea*), which is the most important source of income of the flatfish industry in the Netherlands' exclusive economic zone (EEZ).

Our empirical findings are consistent with the expected relationship between nautical patrol and illegal behavior. For sole, we find that in weeks during which the inspection vessel is patrolling at sea, the share of small fish in the landed catch is significantly lower than in adjacent weeks with no patrolling. We also find that the absence of patrol goes together with some decline in the catch of large fish, a telltale sign of the common way of restricting mesh size. Our results indicate that this strategic behavior is widespread, with about 14 percent of the fishing vessels in our sample induced to use illegal nets when the inspection vessel is absent, affecting about 18 percent of the landed catch of small sole. This effect comes in addition to the illegal behavior that is not affected by variation in deployment of the inspection vessel. Since the inspection vessel patrols a huge sea area, this baseline level of incompliance is likely to be non-negligible. We corroborate these findings by providing evidence of a similar response of fishermen to changes in the fuel price and to variation in nautical patrol between weekends and weekdays.

Our data allow us to assess the environmental harm of the illegal practice in terms of discarded bycatch. The *additional* catch and discard of individual undersized sole resulting from this strategic behavior of fishermen is approximated to be about 17 times greater than the additional catch of individual adult sole during the, on average, 19 weeks of no patrolling per year. This approximation is based on the observed increase in the landed catch of adult sole, combined with what we know from fisheries surveys about the composition of the catch at different mesh sizes, including the undersized fish that are discarded at sea. The illegal practice also affects the bycatch of other species. We approximate the additional catch and discard of undersized individual plaice to be 23 times greater than the additional catch of individual adult sole. These are only the static losses associated with this practice. Considering that juvenile sole and plaice would start to reproduce two to three years later if not caught, the losses are many times larger when looking at a longer time window.

We also discuss the economic rationale for this illegal practice. Increased revenue from fish above minimum size seems to be the most obvious reason, but given the highly variable effect on the total weight of the catch, other factors are likely at play, including illegal sales of undersized fish and savings on fuel costs. Consistent with the latter channel, we provide suggestive evidence that fishermen return to port earlier in weeks without patrols. Fishermen seem to haul in a target catch in less time, a behavior consistent with reference-dependent labor supply of fishermen documented in other fisheries (Hammarlund, 2018).

Our paper fits within a now extensive literature exploiting anomalies in statistical properties to uncover evidence of hidden illegal behavior. This literature, known as 'forensic economics', includes a number of studies in other contexts (see Zitzewitz, 2012: section 2.3 for a review). Like ours, these studies are based on one outcome measure, that reflects both honest activity and potential hidden behavior. A test is then conducted to ascertain whether this measure varies with the profitability or feasibility of hidden behavior. For instance, within the context of agricultural communities in China, Qian (2008) shows how a change in economic incentives for having a boy rather than a girl can be traced to the population sex ratio, suggesting illegal sex-selection. Merriman (2010) traces tax evasion through tax stamps on littered cigarette packs. Within the context of sumo wrestling in Japan, Duggan and Levitt (2002) exploit jumps in the probability of winning at thresholds to infer cheating in tournaments. Studies vary in the specificity of the illegal behavior that can be identified. For instance, in the case of Qian (2008), sex selection can be the result of sex-selective abortion, infanticide or neglect. In our paper, we are able to identify a fairly specific illegal practice rather than a class of illegal practices that leads to a certain outcome.[3]

Apart from uncovering illegal behavior, we also provide rare evidence of a deterrent effect of law enforcement within the context of crimes committed by private sector entities, commonly referred to as 'corporate crime'. That follows from using law enforcement activity as our source of variation in the incentive to comply, in contrast to the many studies within this strand of the literature that rely on changes in technology or other external factors instead (Zitzewitz, 2012). Almost all of the existing evidence on criminal deterrence relates to common crime (see Chalfin and McCrary, 2017), in part because of the ready availability of reliable data on common crime and the all but complete absence of such data for corporate crime (Simpson, 2013, Yeager and Simpson, 2009).

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[3] Related in terms of method but different in focus, Langangen et al. (2019) use the share of large fish in the landed catch in relation to distance from feeding grounds to distinguish between global warming versus harvesting as explanations for changes in the location of spawning grounds.

By studying strategic responses to enforcement, we provide new evidence of how monitoring and enforcement mediates the effect of regulations on environmental outcomes. Our study contributes to the small but growing literature in this area (for reviews of the earlier literature, see Gray and Shimshack, 2011, Shimshack, 2014).[4] Recent studies providing evidence of sizeable deterrent effects within the context of environmental regulations include: Gonzalez-Lira and Mobarak (2021) on audits of fish vendors at open-air markets, Blundell et al. (2020), Duflo et al. (2018), Telle (2013) and Duflo et al. (2013) on inspections of industrial plants by either the regulator or a third party, Kang and Silveira (2021) on resources for enforcement more generally, and Blundell (2020) on an increase in penalties.[5] Related, Zou (2021), Grainger and Schreiber (2019) and Grainger, Schreiber and Chang (2019) look into the strategic interaction between national and subnational regulators. Most related to the current paper is Vollaard (2017) that exploits quasi-random variation in the probability of conviction to reveal patterns in sensor data that result from illegal discharges of oil from shipping.

What sets our study apart from most of the existing work is that our outcome measure is not determined by what the regulator happens to know based on self-reports or detections but on a measure of environmental conditions. This allows us also to assess the environmental harm from the illegal practice. In particular, our paper contributes to better estimates of total extractions from the ecosystem, and this is relevant for quantifying the externalities from fishing. So far, the literature in this area has primarily focused on approximations of a hidden behavior that is not necessarily illegal, namely bycatch and discards resulting from legal fishing practices. Existing work extrapolates the quantity of discarded bycatch observed during fishing research expeditions or fishing trips with an onboard observer to the wider fleet of all fishing vessels.[6] We approximate at the level of the fishing fleet the additional mortality from *illegally* discarded bycatch that is likely to be hidden to independent observers, and we show it to be a sizeable share of catches. As we demonstrate in the analysis of plaice, our method is not limited to assessing illegal bycatch of target species, but can under some assumptions also be used to approximate illegal bycatch of non-targeted marine species. The proposed approach is low-cost and obviates the unrealistic task of monitoring all commercial vessels at sea. It is also incen-

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[4] If the effect of an environmental regulation is evaluated at all – not a given even when a regulation has far-reaching consequences (Keiser and Shapiro, 2019) – then typically studies take an environmental outcome such as water quality or a health outcome such as infant mortality as the dependent variable. In those studies, the degree of compliance among businesses as well as its determinants including law enforcement activity remain unclear.

[5] Some of these studies also look into determinants of the effectiveness of enforcement including scheduling of audits (Gonzalez-Lira and Mobarak, 2021), targeting of inspections (Duflo et al. (2013), discretion in enforcement (Kang and Silveira, 2021), escalating penalties for repeat offenders (Blundell, 2020; Blundell et al., 2020), gaming of measures stipulated in regulations (Reynaert and Sallee, 2021), and colluding against the regulator (Ale-Chilet et al., 2021).

[6] Work in this area includes Pauly and Zeller (2016); Casey (1996); Piet et al. (2009); Aarts and Poos (2009); Heath and Cook (2015).

tive compatible, since the best response for commercial fishing vessels is to fish in such a way that the long run size distribution of their landed fish is not skewed.

Finally, we contribute to the fisheries literature by developing a revealed preference approach to identifying illegal fishing practices. Providing hard evidence of illegal behavior is challenging for an activity that is difficult to monitor. But even now, as location data and vessel registries become more widely available, it is not easy to rule out benign explanations for suspicious behavior. This is true for the behavior under study – to date, the use of illegal nets has not been isolated from other sources of variation in landed catches[7] – but also for other illegal fishing practices.[8] We show how a source of as-good-as-random variation in the incentive to comply can be used to make progress in this context. An alternative method commonly used in this literature, self-reporting of violations in surveys of fishers such as Kuperan and Sutinen (1998), Hatcher and Gordon (2005) and Diekert et al. (2020) can produce highly biased estimates (Cook and Ludwig, 2014).[9] Because our empirical approach is based on readily available data on landed fish, it can be used to study illegal behavior in other fisheries.[10] We also show that the approach works while using a very different source of exogenous variation in the incentive to comply: variation in the price of fuel.

The remainder of the paper proceeds as follows. In the next section, we provide a brief background of relevant fishing regulations and then move on to describe in more detail the specific setting that is subject of study. Section 3 describes the data. In Section 4, we present our empirical approach. Section 5 presents the estimation results. In Section 6, we consider two alternative shocks to the incentive to comply. Section 7 concludes.

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[7] As noted by Jones (1983): "[I]t is not usually possible to demonstrate that an actual change in mesh size has had the expected effect on catches. This is because natural fluctuations in stock size (and catch) tend to be much larger than the expected effects of the changes in mesh size that have been implemented in practice."

[8] In some cases, such as when fishing vessels leave tracks while operating in prohibited areas, the evidence is clear (Park et al. (2020)), but in most cases research identifies suspicious activity, not hard evidence (for example, see Park et al. (2023) on illegal fishing on the high seas).

[9] In addition to the reasons identified in Cook and Ludwig (2014), fishers may not truthfully report violations because they do not want to incriminate the industry (Ainsworth and Pitcher, 2005).

[10] Mesh size fraud appears to be a problem in many fisheries. See Diekert et al. (2022) for evidence of mesh size fraud in Lake Victoria fisheries. For anecdotal evidence of mesh size fraud in other fisheries, see Gulland (1979) on hake and sea bream fisheries in the eastern central Atlantic, Srinivasan (2005) on prawn fishing in the Arabian Sea, Kraan (2006) on beach seine fishing in the Gulf of Guinea and Mohammed (2015) on bottom trawling in the Bay of Bengal.

2 Background

Fisheries regulations and challenges to their enforcement

Fish stocks are a classic example of a common resource (Scott, 1954; Stavins, 2011). In the absence of any mutual arrangements among private parties, they require state regulation to avoid over-exploitation (Ostrom, 1990). Over the twentieth century, growing populations along with constant technological advancement in fishing methods produced inevitable strain on marine life (Thurstan et al. 2010). Overfishing, among other factors, led to the infamous collapse of Peruvian anchoveta in the early 1970s, of Atlantic northwest Cod in the 1990s, and more recently of Pacific bluefin tuna (McCauley et al. 2015). Certain fishing practices such as bottom trawling have also destroyed extensive areas of seabed flora and fauna essential to marine life (Tiano et al. 2019; Jennings and Polunin, 1996). In addition, by disturbing the sea floor, bottom trawling causes about one billion tons of carbon dioxide emissions a year – emissions equivalent to those of Germany (Sala et al., 2021).

Various regulations over the past half century have attempted to limit the depletion of fish stocks and prevent the incidental or intended destruction of the marine environment. Towards the end of the twentieth century, several of the major fishing countries, including those in Europe, North America, and the Far East began tightening fisheries regulations. Certain fishing technologies such as gillnets were banned in some jurisdictions, calendar limitations on fishing seasons were imposed, the number of marine protected areas was expanded, and, perhaps most importantly, fishing quotas were introduced (Costello et al., 2008). Regional fisheries management organizations and governments, including those in the North Sea, use fishing quotas to divide a yearly total allowable landing among the commercial fishing vessels operating (Newel et al. 2005).

In the face of diminishing catches and cost-increasing regulations, commercial fishing vessels have sought and found ways, both legal and illegal, to harvest the remaining fish in a more cost-effective manner (Palomares and Pauly, 2019). For instance, commercial fishing vessels have improved their ability to target high-yield areas (e.g., using high-end sonars), deployed new fishing gear (e.g., pulse-trawling gear), and been found to exceed fishing quotas or use illegal nets (e.g., gillnets or tampered mesh nets). This response from industry may explain the continued increase in the estimated proportion of fish stocks at biologically unsustainable levels, now approximated at 33 percent of all species, as well as the increase in the number of species going extinct (FAO, 2020).

Enforcing regulations in the fishing industry is complicated. *In-port* inspections face the limitation that a considerable part of the catch never reaches port and that part of the catch may be landed illegally, evading any inspections. *At-sea* enforcement of regulations on fishing vessels can only be achieved through three approaches, aside from recently introduced geo-location tracking. The first and surest approach for at-sea monitoring is to include an independent observer on board. The second is to install remote video monitoring systems on commercial fishing vessels and analyze their recordings using machine learning methods capable of parsing the images of different catch. During pilot expeditions, video monitoring has shown early successes at separating endangered marine species from legally saleable fish, but falls short when it comes to distinguishing juvenile from legally saleable adult fish, in particular for large hauls (Van Helmond et al., 2017; Van Helmond et al., 2020). The costs of these two approaches are not trivial, with remote video monitoring costing €8,000-13,000 per ship annually (Mangi et al., 2015) and onboard observers costing €200,000 per ship annually (Kindt-Larsen et al., 2011). As of now, neither are systematically used by major regional fisheries management organizations for the widespread monitoring of fishing practices (Ewell et al., 2020). The third and most prevalent form of at-sea monitoring across the world is the deployment of inspection vessels. The obvious limitation of inspection vessels is that each vessel must cover a vast territory.

Mesh size regulation in the North Sea flatfish fishery

The Dutch fleet in the Greater North Sea consists of about 500 vessels, of which a majority, 275, target sole (dominant in value) and plaice (dominant in volume) among other flatfish in and around the Dutch EEZ (ICES, 2018).

In the 2017-2019 period covered by our data, the main fishing gears used to catch flatfish were beam-trawls, bottom otter-trawls, and the now banned pulse-trawls.[11] These approaches involve dragging a net, shown in Figure 11 of Appendix A, along the seabed. Beam-trawling and bottom otter-trawling use a weighted net that rakes the seafloor to scoop up bottom-dwelling fish, while pulse nets send electrical signals to stun and startle fish up into the net.

Due to the force necessary to rake the seabed, beam-trawls and bottom otter-trawls require the highest fishing effort among the most common fishing methods, with fuel costs representing over 50 percent of revenues (Wageningen Economic Research, 2021; Basurko et al., 2013). Pulse trawls require about half of the amount of fuel per hour of fishing compared to beam-trawls and bottom otter-trawls (Batsleer et al., 2016).

Most fishing techniques, and bottom trawling is no exception, feature a certain amount of bycatch of undersized fish that have not reached spawning age as well as bycatch of non-targeted species. This is partly because fish of different sizes and other marine life within an ecosystem often occupy the same areas. In addition, as nets fill up, some undersized fish will be blocked by larger fish and prevented from escaping. To limit this

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[11] In the Netherlands, the entire fleet of trawl fishing vessels over 24 m switched to pulse-trawls within a few years (Harvey, 2018). Pulse trawling was phased out as of June 2019 and completely banned in EU waters by July 2021.

bycatch, regulations stipulate a minimum mesh size of fishing nets. In the case of sole, the minimum mesh size is 80 mm for the jurisdiction under study. Regulations also stipulate a legal minimum threshold for the size of fish that can be sold on the market. For sole, the minimum size is 24 cm. But even with a legal net, a large part of the catch consists of undersized fish. Fishing research expeditions indicate that no less than 70 percent of sole just below the minimum size of 24 cm remains in a legal 80 mm meshed net, 50 percent of sole sized 20 cm, and 10 percent of sole sized 10 cm or less (Molenaar and Chen, 2018). Undersized fish are discarded at sea, either dead or with low chances of survival.[12]

Fishermen have an incentive to violate the minimum mesh size regulation because smaller mesh size trawl nets produce a higher yield per hour of fishing. Common methods of reducing mesh size in the flatfish fishery are the use of 'liners', where lines are woven through the net, or blinders, where a net within a net is used (Van Ginkel, 2009). Both methods roughly halve the mesh size. This allows fishermen to restrict mesh size without having illegally small mesh size nets on board.

How this illegal practice affects the catch has never been studied empirically, but a research expedition by Molenaar and Chen (2018) provides insight. To find out what proportion of fish is caught in an 80 mm net, they put a large 'sock' with a mesh size of 40 mm around the cod-end of a pulse trawler. They count and weigh the catch of sole and plaice caught in the net and those in the 'sock' over many hauls. Their study can be used to see how the catch changes when mesh size is reduced from 80 to 40 mm. The resulting distributions of sole and plaice are reproduced in Figure 1.[13] First of all, the figures reflect a massive catch of undersized fish, even with legal mesh size: about a quarter of the catch of sole is below minimum size and the catch of undersized plaice exceeds that of the catch of marketable sole. When constricting the mesh to 40 mm, the catch of fish of saleable size, small fish in particular, increases, but this goes at the cost of a much larger increase in the catch of undersized fish. When going from 80 to 40 mm, the weight of the catch of marketable sole goes up by less than 10 percent, but the catch of undersized sole increases by 70 percent and the already large catch of undersized plaice goes up by another 10 percent. Thus, illegally small mesh size leads to a vast increase in bycatch of juvenile fish of both the target species and of other fish species.[14]

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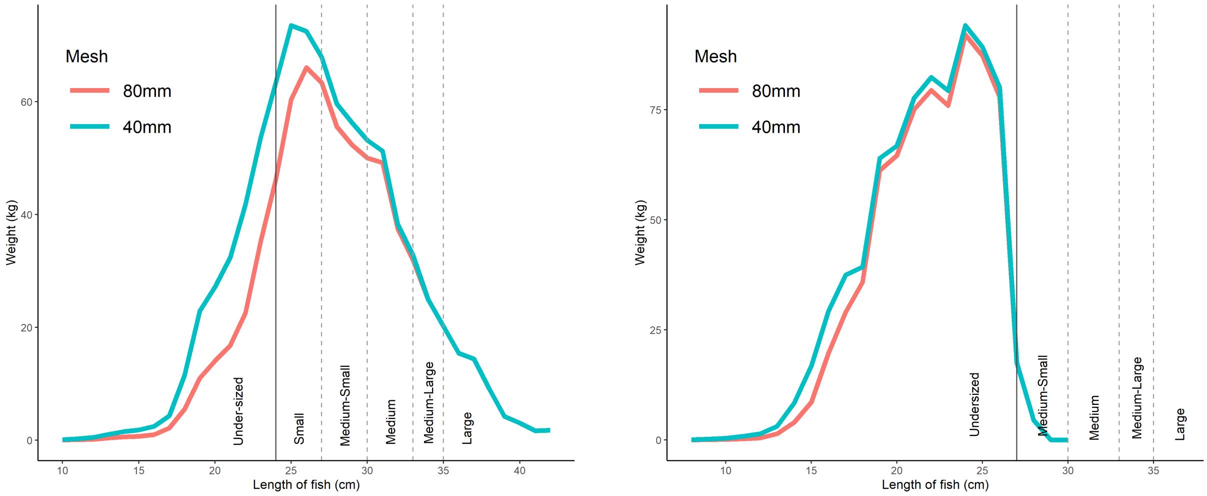
[12] To address the problem of the catch of undersized fish, the EU initiated a "landing obligation" in 2015 (Drupp et al., 2019). The new law, introduced progressively between 2015 and 2019, required (with many exceptions) that bycatch be landed in port. In the Netherlands, the regulation was not strictly enforced. Consequently, the EU started infringement proceedings against the Netherlands in November 2021.

[13] We additionally present distributions in terms of number of fish in Figure 12 of Appendix B. The baseline distribution with 80 mm mesh size nets in Molenaar and Chen (2018) is similar to the results of other expeditions such as Van Overzee et al. (2019).

[14] The conditions in Molenaar and Chen (2018) may not always be similar to those that we encounter in our data. First, the expedition took place in fair weather, limiting possible 'shake out' of small fish from the net when a fishing vessel goes up and down over high waves. Since we also observe vessels under

‘Blinders’ or ‘liners’, the usual way of constricting mesh size, also restrict the flow of water through the net (Hoefnagel et al., 2004: 48). According to anecdotal evidence, the resulting additional turbulence around the entrance of the net allows some larger fish to escape. Thus, next to the increase in the catch of fish documented in Molenaar and Chen (2018), this illegal practice may lead to some loss in the catch of larger fish, something we return to when we discuss our findings in Section 5.



(a) Sole

(b) Undersized plaice

Figure 1: Size distribution of catch in weight using 80 mm and 40 mm trawl nets
Note. Adapted from Molenaar and Chen (2018: Figures 9 and 10). Weights based on fishbase.de.

Anecdotal evidence suggests that incidents of vessels using nets with illegally small mesh are common (see Footnote 2) but difficult to detect. Fishing crews must be caught in the act (Beo da Costa, 2018; NVWA, 2020). However, in the rare event of a surprise inspection while engaging in the illegal practice, the above-mentioned blinders or nets with liners can be hauled in wildly, breaking them and leaving no evidence of wrongdoing. The challenge of catching fishing crews red handed is further complicated by the fact that, in Dutch waters, a single inspection vessel, the Barend Biesheuvel, must monitor the entire Dutch fleet as well as all foreign fishing vessels within the non-coastal areas of its exclusive economic zone. The Dutch inspection vessel follows a fixed Monday to Thursday patrol schedule. In a typical week, the inspectors board approximately one to two vessels per day for inspection. Which vessels will be boarded is unknown, but fishermen actively track and report the whereabouts of the inspection vessel (Posthumus and Rijnsdorp, 2016;

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poor weather conditions, the gain from illegally small mesh size may be larger in our data. Second, due to the set-up of the experiment, everything other than mesh size is kept constant, including towing speed, haul duration and trip duration. As we discuss in Section 5, in practice some of these factors may change with the use of illegally small mesh size. Third, the results of the expedition are based on measuring catch on board, whereas our analysis is based on landed catch. Sale of fish, in particular undersized fish, on the black market could drive a wedge between actual and landed catch. This is not likely to be an issue since our results relate to marketable fish only.

Van Puymbroeck, 2006). In this way, they can engage in illegal practices even when the inspection vessel is deployed but sufficiently far away. In summary, the chance of being caught is extremely low, with about one to two detections per year.

The chance of being caught is low, but the punishment is stiff. If caught in wrongdoing, the fishing vessel must forfeit its entire catch, which can amount to 40 to 50,000 euros, the captain may be fined, although fines are usually limited to a few thousand euros, and the captain may receive penalty points, which can ultimately lead to the suspension of his fishing license. The legal proceedings following a detection can take years. Anecdotal evidence suggests that fishermen are willing to go to great lengths to evade inspection.[15] In addition to inspection at sea, the landed catch may be inspected upon arrival in port.

Crucial to our identification strategy, the Dutch inspection vessel takes entire weeks off from patrolling across the year for three reasons: first, when the crew is on vacation, second, when the Dutch inspection vessel participates in international law enforcement operations in distant waters, and third, when it is out of service for maintenance. Most of these absences are scheduled well in advance and are probably known to the fishermen. Given the communication between fishing vessels and the ability to partially track the whereabouts of the inspection vessel, news of these absences can spread rapidly. Whether the fishermen know the exact whereabouts of the inspection vessel at all times is not something we can say with certainty, but it can be inferred with certainty that the vessel will not be deployed in a given week. Based on publicly available location data, it can be inferred whether the Barend Biesheuvel, as well as any other inspection vessel, is in the harbor or not or on an international operation (for the last signaled position of the Barend Biesheuvel, see marinetraffic.com).

3 Data

To conduct our study, we combine a number of data sources. These include data on fish landings, geo-location data for the fishing fleet and inspection vessels, and separate administrative data on deployment of the Dutch inspection vessel, all provided by the regulator, the Netherlands Food and Consumer Product Safety Authority (NVWA). We complement these data with data on fuel prices from Netherlands Statistics (CBS) and meteorological data from the Royal Netherlands Meteorological Institute (KNMI).

Fishing trips, fish landings, and nautical patrol

The data on fish landings were originally compiled by the fish auctions. Our sample comprises the universe of fishing trips of vessels with reported landings of sole and/or

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[15] For instance, in an interview on the issue in a local newspaper, a fishermen says: “It makes you nervous. All day long you have to be on guard. It is absolutely excruciating.” (Leidsch Dagblad, March 1, 2002).

plaice in Dutch ports in 2017-2019. At the auction and also in our data, landed fish are separated into six size categories for sole, and five size categories for plaice.[16] As noted earlier, the minimum saleable size of plaice is larger than that of sole; 27 vs. 24 cm.

We restrict our sample to vessels that landed an average of at least 50 kg of sole per fishing trip, amounting to 71 percent of our initial set of observations.[17] This selection for our main analysis allows us to focus on fishing vessels that mainly target sole. The resulting dataset comprises 123 fishing vessels that operated a total of 12,972 trips between January 1st 2017 and December 28th 2019. Detailed vessel characteristics are provided in Appendix C. In our sample, we see a bimodal distribution for vessel power, weight and length, with a bunching just below 24 m in length. One third of this sample includes vessels shorter than 24 m ('Eurokotters') that are also permitted to fish along the coastline. The larger vessels ('Bokkers') should stay out of the shallow, coastal waters.

We conduct our analysis at the weekly level given that the majority of fishing trips lasts seven days or fewer and that deployment of the inspection vessel varies on a weekly basis.[18] We assign fishing trips lasting longer than a week or bridging two calendar weeks to the calendar week that accounts for the largest part of the trip. Lastly, we drop the final week of each calendar year from the sample since almost all crews of fishing vessels, as well as the crew of the inspection vessel, are on vacation during that week.

We combine the auction data with information on when the Dutch inspection vessel was monitoring the Dutch EEZ waters. For all but three of the weeks in which the vessel was not patrolling, it was not patrolling for the entirety of the working week. Figure 2 shows the average weight of weekly landings for each of the six size categories of sole in our data over the years 2017-2019. The vertical dashed lines show the weeks in which the Dutch inspection vessel was not patrolling.

Figure 2 shows that landings of small fish greatly exceed those of large fish. Given the lower weight of small fish – the weight of fish in the largest category is over five times that of fish in the smallest category – this implies that a much greater number of small fish than large fish are caught. The figure also shows diminutive landings of undersized

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[16] For sole, these categories are: undersized (below 24 cm), small ('Tong 2', 24-27 cm), medium-small ('Tong 1', 27-30 cm), medium ('Klein Middel', 30-33 cm), medium-large ('Groot Middel', 30-33 cm), large ('Groot' or 'Lap', above 35 cm). In the case of plaice, the undersized category also includes fish between 24-27 cm.

[17] Our sample includes vessels which harvest, on average, over 50 kg of sole per week. However, in any given week, a vessel's yield may be below 50 kg. These weeks with low yield could produce high leverage on the results since a few extra fish of a certain size could tilt the distribution of fish in one way or another. To reduce the leverage of these observations, we set fractions of each of the five size categories to be equal to 0.2 for any vessel-week observation with lower than 50 kg total yield.

[18] 80 percent of fishing trips begin on Sunday night or Monday early morning and 85 percent of trips last six days or fewer. Out of all fishing trips, 75 percent start on a Sunday night or Monday morning and return on Thursday or Friday. Appendix C provides more details on fishing patterns.

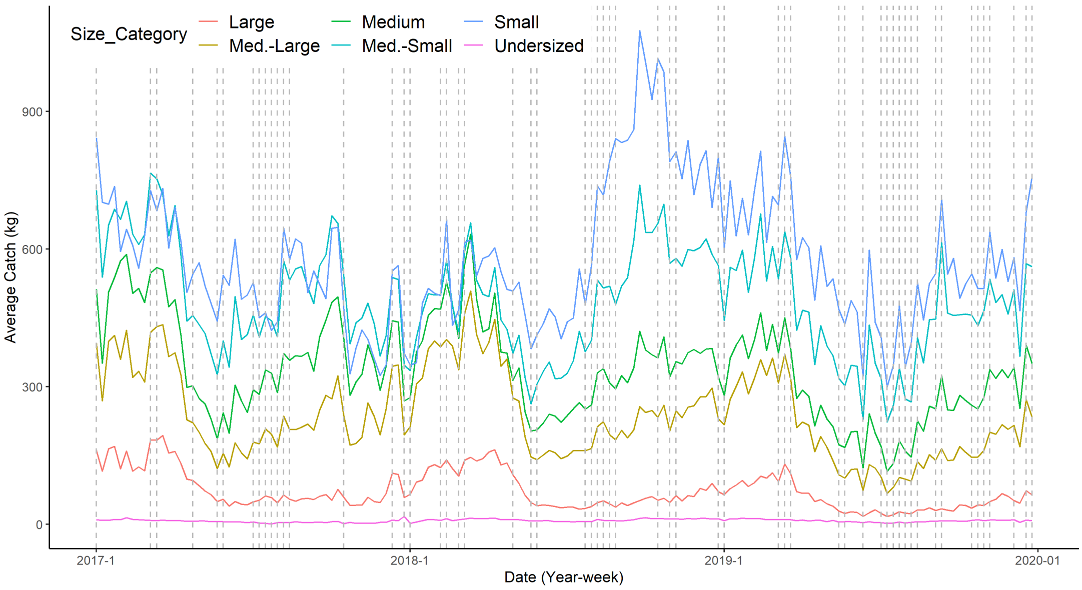


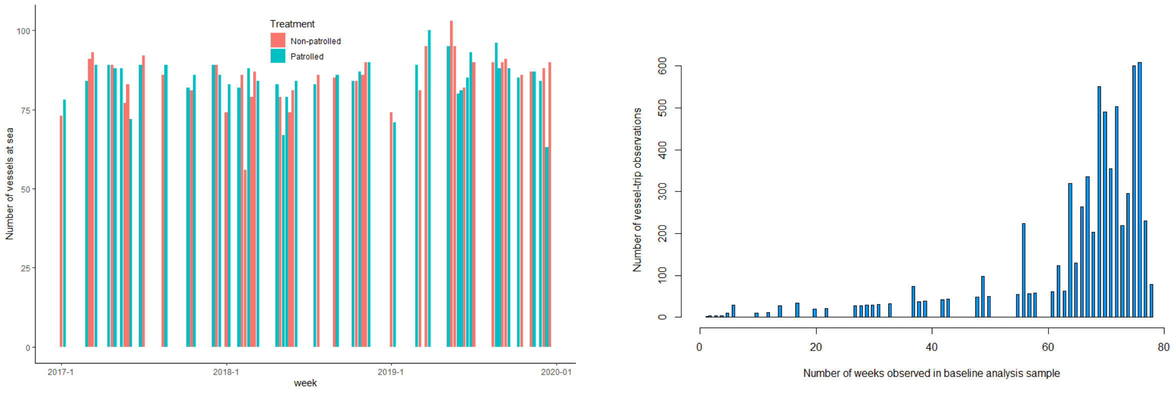
Figure 2: Average landings of sole by size category (in kg) and deployment of inspection vessel, 2017-2019.
Note. Vertical dashed lines denote weeks that the inspection vessel was not deployed.

sole, which stands in contrast to the sizable shares observed in Figure 1a. In other words, and as noted before, nearly all of the undersized fish are not landed but discarded at sea or sold on the black market. For this reason, we mostly ignore the data for landings of undersized fish in our analysis.

Given that the auction data report landed catch in terms of weight, we focus on outcomes in terms of weight rather than in terms of the number of fish in our estimations – even though effects reported in terms of individual fish are more relevant with a view to sustainability. Following the analysis in terms of weight, we approximate the implied number of fish caught illegally based on the average weight of fish per size category.

Seasonal patterns in catches may bias a comparison of landings between weeks with and without deployment of the inspection vessel. This is due to the fact that individual weeks do not have a similar probability of ending up in the treatment group or the control group: deployment (and non-deployment) often occurs for several weeks in a row. Moreover, several periods of non-deployment occur at the same time each year, for example due to crew vacations. With no convincing way to model the underlying time trend, our empirical approach compares only patrolled and non-patrolled *adjacent* calendar weeks. We retain in the analysis sample only those weeks that immediately precede or follow a change in weekly patrol status such that a patrolled (non-patrolled) week is always paired with at least one and at most two adjacent non-patrolled (patrolled) weeks. The resulting sample consists of 41 patrolled weeks and 37 non-patrolled weeks.

Figure 3 shows the activity of the vessels in our baseline analysis sample over the years 2017-2019. Figure 3a shows that the number of vessels going out to sea is fairly stable,



(a) Fishing vessels at sea

(b) Distribution of fishing trips per vessel

Figure 3: Fishing activity, baseline analysis sample, 2017-2019

year-round. Figure 3b shows the distribution of the number of fishing trips per vessel. Most of the vessels are active during the majority of weeks in our analysis sample. More than 80 percent of observations come from vessels that were observed for at least 60 of the 78 possible comparison weeks in the sample. Our main specification includes all vessels that were observed at sea during any of the 78 potential weeks of comparison, resulting in a sample of 6,617 vessel-week observations. In Section 5, we explore whether panel imbalances in our sample affect the results.

We use the auction data as a proxy for the landed catch of fish above the minimum saleable size. These data contain some measurement error. In some cases, the size distribution of the landings looks unreasonable, possibly as a result of inadvertent data entry errors. In other cases, data on auctioned landings by size category are missing for specific fishing trips, even though we know that fish were landed. In some cases, data are anomalous or missing for consecutive weeks for the same vessel. In Section 5, we discuss the robustness of our results when accounting for these sources of measurement error and show that it does not result in bias. Measurement error may also occur if some undersized fish are put in crates meant for fish of saleable size, something we discuss in Section 5.

In addition to the auction data, we also have daily catch data from the logbooks of a 10 percent sample of fishing trips. These data include the weight of the total catch of legally saleable fish and the registered catch of undersized fish. It also includes information on which fishing gear was used to fish on that particular day. Unsurprisingly, given the targeting of flatfish, vessels reported using trawls with nets of mesh sizes above the legal limit of 80 mm in 99.3 percent of days. Although not specified in the datasets, and as discussed in the previous section, close to all vessels above 24 m were equipped with pulse trawls over the period studied. Beyond these basic statistics we do not use the daily catch data since it is not guaranteed to represent a random sample.

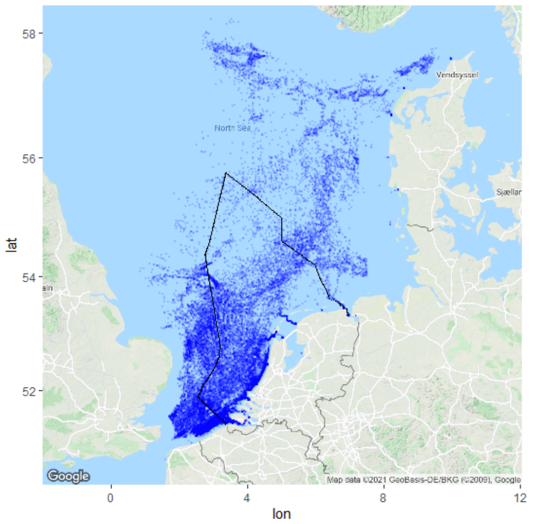


Figure 4: Fishing vessels' navigation patterns

Note. For presentation purposes, figure shows sample of 30 randomly chosen days from 2017/18 data. Border shows Dutch part of North Sea.

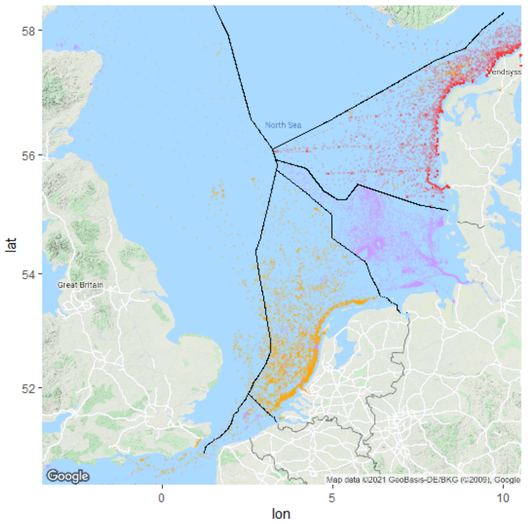


Figure 5: Inspection vessels' navigation patterns

Note. Data relate to Dutch (orange), German (purple) and Danish (red) inspection vessels in 2017/18.

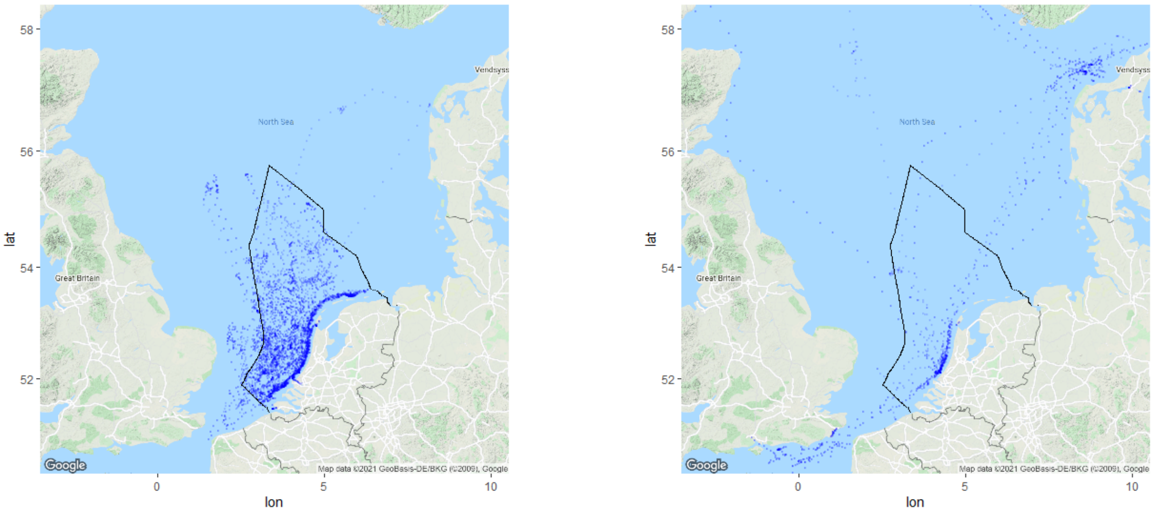
Geo-location of fishing vessels and inspection vessels

The regulator provided us with geo-location data for 96 percent of the fishing vessels in the sample for the years 2017 and 2018, based on the Vessel Monitoring System (VMS). VMS is separate from the publicly available Automatic Identification System (AIS) and a more reliable source (Cauzac, 2019). VMS has historically been restricted to government regulators. The regulator also released confidential geo-location data for the Dutch inspection vessel, as well as that of the German and Danish inspection vessels.

Figure 4 shows that most fishing trips of the fishing vessels in our sample remain inside and closely surround the Dutch EEZ, bordered in black. This pattern can be partially explained by the fact that we select vessels that target flatfish which, as Figure 16 in Appendix D shows, mainly dwell in Dutch EEZ waters.

Navigation patterns for Dutch (orange), German (purple) and Danish (red) inspection vessels displayed in Figure 5 indicate that patrolling is mostly confined to each country's EEZ. This is important for our analysis, because we assume navigation patterns of the Dutch inspection vessel, which we focus on, to be independent from those of foreign inspection vessels. In Appendix E, we discuss the navigation patterns of foreign inspection vessels in weeks during which the Dutch inspection vessel is patrolling vs. weeks during which it is not patrolling as well as the consequences for our analysis.

Figure 6 illustrates the navigation patterns of the Dutch inspection vessel for all weeks during which it was patrolling the Dutch EEZ (6a) as opposed to what we classify as non-patrolling weeks of vacation, maintenance, and long international trips (6b). As expected,



(a) Patrolled weeks (b) Non-patrolled weeks

Figure 6: Navigation patterns of the Dutch inspection vessel

the only plotted points in non-patrolled weeks are due to the inspection vessel departing for long-distance international trips.

Other data sources

To account for weather conditions, we obtained meteorological data from a weather station at an oil rig named K13-A, located in the middle of the Dutch EEZ. These data comprise wave height (centimeter), wind speed (meter/second), air temperature (degree Celsius), air pressure at sea level (hectopascal), and prevailing wind direction (share of time North; share of time West). We compute weekly averages based on the daily averages provided. Our results do not change when we account for heterogeneity in weather conditions within weeks by including an additional covariate that reflects the weekly average of the daily maximum wave height (results available on request from the authors). Lastly, we gathered data on the fuel price in euros by calendar week (for reasons of data availability, we use the price of diesel rather than gasoil; the two are closely linked).

Table 2 in Appendix F provides summary statistics split by weeks with and without patrolling that are part of our sample. We find characteristics of fishing vessels to be, on average, similar across the two sets of weeks. Weather conditions are also largely similar, although we see some small differences, which we return to in the next section. Weekly landings of sole amount to approximately 1,700 kg on average, with a market value of about €42,000. Given uncontrollable biological conditions and the difficulty of predicting fish movement (Rijnsdorp et al., 1998, 2000), catches are highly variable, as reflected in the high standard deviation. In some weeks, no catches of sole are reported, which may be due to some of the smaller vessels targeting other species in certain periods, or measurement error, as discussed earlier. Weekly landings of plaice are almost three times as large as those of sole on average but have a smaller market value of about €18,000.

4 Empirical strategy

We specify our baseline treatment effect model as follows:

$$\mathrm{Y}_{it} = \alpha_i + \delta\,\mathrm{D}_{it} + \beta\,\mathrm{X}_t + u_{it} \tag{1}$$

where Y_{it} is the share in terms of weight of landed sole of a certain size relative to vessel i's total landed sole of saleable size in week t. The size categories encompass small, medium-small, medium, medium-large, and large. Thus, $\mathrm{Y}_{it} = \frac{\text{weight}_k}{\sum_{k=Small}^{Large} \text{weight}_k}$, with k representing these five size categories.

The binary variable D_{it} denotes whether vessel i was subject to patrolling in week t or not. $\mathrm{D}_{it} = 1$ if fishing vessel i was at sea in week t during which the inspection vessel was patrolling, and $\mathrm{D}_{it} = 0$ if vessel i was at sea in week t during which there was no patrolling. The parameter of interest δ therefore represents the change in the share of landed fish of a particular size due to the threat of inspection versus no threat of inspection. Our estimate only captures the average change in landed fish for vessels induced to change their behavior: we do not identify the baseline level of illegal activity that is unaffected by variation in nautical patrol.

In our setting, δ is identified from within-vessel variation in shares between patrolled and non-patrolled weeks, averaged over all vessels. Since our data are not fully balanced, we include vessel-fixed effects α_i to capture residual between-vessel variation. In contrast to a difference-in-differences approach, α_i is not strictly necessary for identification and replacing it with an intercept α does not alter our results substantially. X_t includes time-varying regressors consisting of weather conditions (wave height, wind speed, air temperature, air pressure, wind direction) and the fuel price.

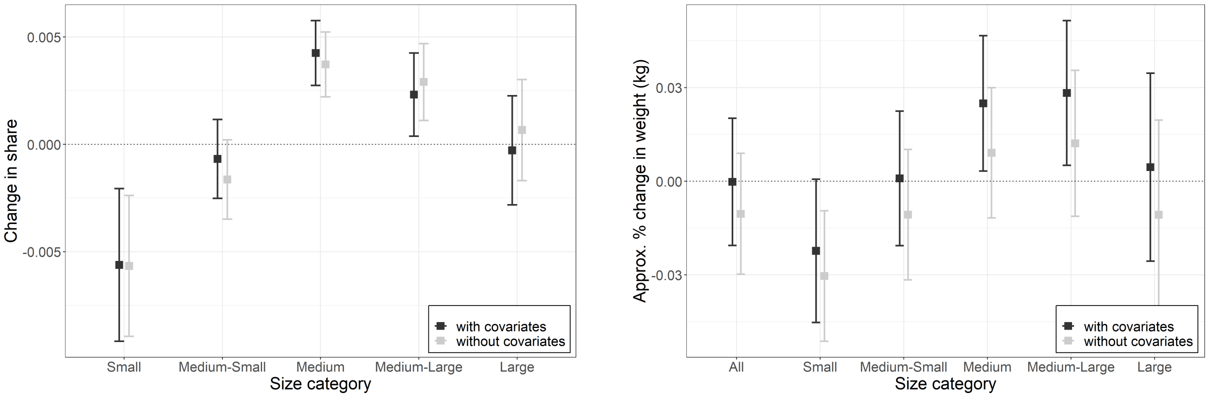
Our identifying assumption is that, withholding the threat of patrolling by the Dutch inspection vessel, fishing vessels active in adjacent patrolled and non-patrolled weeks would on average have the same outcomes in terms of the size distribution of fish landings. Thus, even with full anticipation of deployment of the inspection vessel by fishermen, it can be seen as random in the sense of being independent from the size distribution of the catch. If we do find a difference in the size distribution, then, under some assumptions, this can be interpreted as evidence of the use of nets with illegally small mesh size. Below, we discuss these assumptions.

Fishing conditions First of all, the conditions under which fishing takes place should not differ between patrolled and non-patrolled weeks in ways that affect the size distribution of landings. In particular, the size distribution of fish available for catch should be similar on average. By comparing only adjacent weeks, with sometimes the first week being patrolled and at other times the second week, it is reasonable to assume that the availability of fish is, on average, similar. As discussed in Section 3, by comparing only adjacent weeks, we remove the influence of seasonal patterns in fish stocks which may be related to deployment of the inspection vessel. In addition, weather conditions, a well-known cause of differences in fishing outcomes (Angrist et al., 2000), should not bias our results either. In particular, weather may affect fish landings if the shocks that reverberate in the fishing net due to riding high waves affect the propensity of fish to escape the net. We find weather conditions to be largely similar between the two sets of weeks, as shown in Table 2. Wave height, for instance, is on average 144 cm in both patrolled and non-patrolled weeks. We adjust for any remaining differences in observed weather conditions in our analysis, as stated above. Finally, as discussed in Appendix E, the law enforcement activity of foreign inspection vessels is not problematically dependent on the deployment of the Dutch inspection vessel

Fishermen behavior Second, when comparing adjacent patrolled and non-patrolled weeks, fishing activity and the fishermen's behavior in general should not differ in ways that affect the size distribution of landings. In other words, if fishermen change their behavior in response to patrols in ways other than using illegal nets, then this should not affect the size distribution of landings. In the previous section, we already noted that fishing activity is fairly similar throughout the year. Fishermen go out whenever they can, driven by weekly returns on sole of 30 to 40,000 euros (see Section 3). Consequently, the fishing vessels in our sample have on average similar characteristics in terms of length, weight and engine power in patrolled and non-patrolled weeks, as shown in Table 2. In the next section, we also consider whether patrolling affects the decision to fish for sole and fishing navigation patterns. We assume that any unknown illegal activities do not shift the size distribution of landed fish in the way that has been observed in the fisheries surveys that we discussed earlier.

5 Results

In this section, we present the estimated effect of patrolling on landings of sole by size category. After presenting our main results, we present estimated effects on a number of additional outcomes to test assumptions underlying our approach. Next, we approximate the additional illegal catch as well as the prevalence of strategic behavior. In a last step, we assess the robustness of our findings.



(a) Landed Shares

(b) Landed Weights

Figure 7: Estimated effect of patrolling on landed catch of sole by size category
Note. Figures show results from estimating Equation 1 with covariates (in black) and without covariates (in light gray). Dependent variable is the share of landed sole of a certain size in the left panel on the left and the weight of landed sole of a certain size in the panel on the right. Each point represents a separate regression. Based on data by vessel and week. Number of observations 6,617, of which 3,474 during patrolling; data relate to 121 vessels. Total landings excludes fish below minimum saleable size. Bars show 95 percent confidence intervals generated from standard errors clustered at the level of the vessel. See Appendix G for full regression results.

Main results

Figure 7a presents the estimated effects of patrolling on the average share of landed catch in each size category, based on Equation 1 (see Appendix G for full regression results). Each point estimate and associated 95 percent confidence interval represents a separate regression. Below, we discuss the results of the baseline model with covariates; the results without covariates are qualitatively similar.

We find that the share of small sole decreases by 0.56 percentage points in weeks with patrolling relative to weeks without patrolling. This represents a two percent decrease from the 29 percent average share of small fish landed. A drop in the share of the category ‘small’ must go together with an increase in the share of another category, and this happens to be the share of medium and medium-large sized fish. These shares increase by 0.43 and 0.23 percentage points, respectively. We do not find evidence of an effect on the share of medium-small and large fish, with both point estimates being close to zero. These findings show that the size distribution of the catch varies systematically with nautical patrol. A shift towards smaller fish in weeks without patrolling is consistent with the strategic use of illegally small mesh size as mechanism.

We also estimate the effect of patrolling on the weight of the landed catch by size category, the results of which are shown in Figure 7b. Due to the large week-to-week variation in the landed catch, the estimated coefficients for weights are rather imprecise. The figure shows that behind the results in terms of shares presented in Figure 7a turns out to be not only a decrease in the weight of the catch of small fish, but also an increase in the weight of the catch in the categories ‘medium’ and ‘medium-large’. Thus, a loss in landings of small fish in weeks with patrolling is partially offset by a gain in landings of medium and medium-large fish. That is in line with our discussion in Section 2 of the common ways of restricting mesh size. The use of ‘blinders’ or ‘liners’ does not only lead to a strong increase in the catch of small fish, but also to some loss in the catch of larger fish. Thus, our results suggest that the use of ‘blinders’ and ‘liners’ are indeed commonly used to restrict mesh size, rather than, say, using a net with a mesh size smaller than 80 mm.

The net effect on the total landed catch, which is also shown in Figure 7b, is very imprecisely estimated. An unclear effect on the total catch suggests that higher revenues from catching more fish of saleable size may not be the only reason for engaging in this illegal practice. There may be another benefit to mesh size fraud that we do not observe, particularly since the price per kg of fish in the largest category is about twice as high as the price per kg of fish in the smallest category. A candidate explanation is the illegal sale of fish just below minimum size. Customers may not notice that a fish is a centimeter or two below the minimum size, or they may not care. The increase in the catch of this category of undersized fish from using illegally small mesh size is likely to be at least as large as the increase in the category ‘small’, given what we know about the effect of mesh size on the size distribution of the catch (see Figure 1). We know from law enforcement operations that there are two channels through which undersized fish are sold: either they are mixed with legally sized fish and sold at the auction, or they are sold directly on the black market, bypassing the auction.[19] In the first case, the fish are likely to end up in crates for fish in the smallest category and are included in the category ‘small’.[20] In the latter case, there is another category of sole not shown in the above figures. This is an additional source of benefits from mesh size fraud not reflected in our results.

Next to illegal sale of small fish, illegally small mesh size may be of benefit as it allows fishermen to haul in fish at lower costs, lower fuel costs in particular. Perhaps the fishermen in our sample set revenue targets and reach them quicker when using small

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[19] An inspection of one of the fish auctions at the end of 2021 showed that 19 out of the 21 vessels inspected landed undersized flatfish, representing about a third of the catch, and that these fish were not separated from larger fish at the auction as required (NVWA, 2021). The fishermen involved were convicted in March, 2023. During a raid on another fish auction in April, 2023, three traders of undersized sole were arrested. Law enforcement found thousands of kilograms of undersized fish stowed in secret compartments on four out of five fishing vessels searched. Law enforcement suspects that this fraud was an ongoing practice (Visserijnieuws, 2023).

[20] Estimation bias may result if the tendency to put undersized fish in crates meant for fish of legal size varies with deployment of the inspection vessel. We know that inspections in port – a deterrent of such illegal practices – are independent from the schedule of the inspection vessel, which limits this possible source of bias.

mesh size.[21,22] Then, a shift in the size categories that leaves overall catch largely unaltered pays for itself through reduced costs. Such behavior would parallel findings of reference-dependent labor supply found in other fisheries (see Hammarlund (2018), who also reviews the related literature).[23] We return to this issue when discussing fishing trip duration in the next paragraph.

Effects on other outcomes

We assess the effects of patrolling on a number of other outcomes. First, we test an assertion made when discussing our empirical strategy in the previous section, namely that the probability of landing sole does not vary with the deployment of the inspection vessel. Then, we discuss whether patrolling changes fishing navigation patterns, the duration of fishing trips, or the size distribution of the landed catch of plaice.

Table 1: Estimated effect of patrolling on landing sole and trip duration

	Landing sole (1)	Landing sole (2)	Trip duration (3)
Patrolling	0.002	0.001	1.048*
	(0.007)	(0.007)	(0.443)
Number of observations	9,594	6,617	6,617
... in patrolled weeks	5,043	3,474	3,474
Number of vessels	123	121	121

Note. Table shows results from estimating Equation 1, with landing over 50 kg of sole on a fishing trip as outcome variable in columns (1) and (2) and trip duration in hours in (3). Based on data by vessel and week. Not shown are estimated coefficients for covariates. Between parentheses standard errors clustered at the level of vessels. * $p < 0.05$, ** $p < 0.01$.

Landing sole To evaluate whether patrolling affects the decision to fish for sole, we use the same estimation equation as above, but with an alternative outcome variable: the probability of landing over 50 kg of sole on a fishing trip. We added zeros as outcomes for weeks in which a vessel was not observed to be fishing. A vessel may land less than 50 kg of sole either because it was not targeting sole, because it was unable to catch sole, or because it simply did not go out to fish. The results are reported in the first column of

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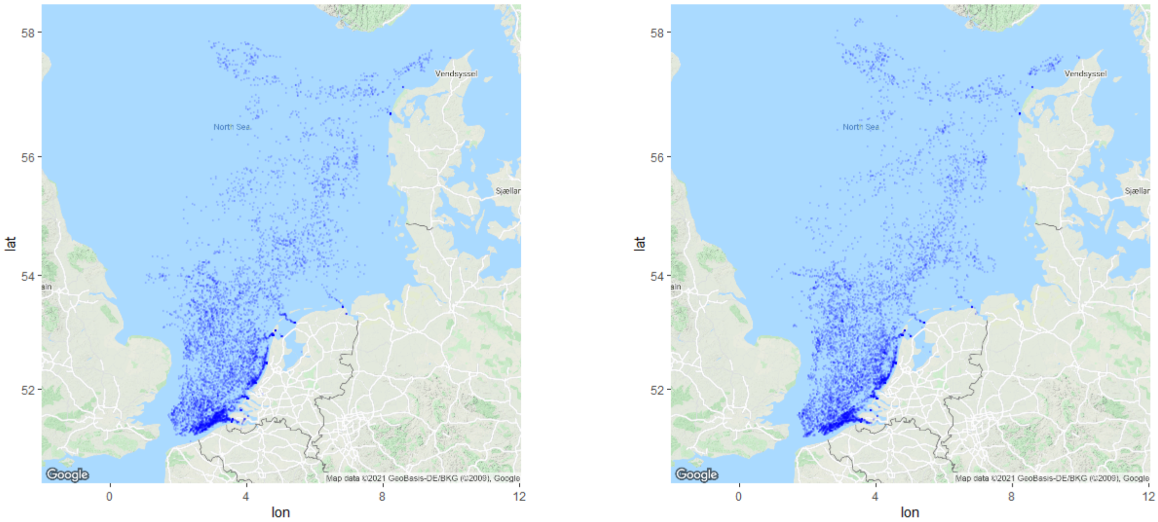
[21] Any catch targets are set by the fishermen themselves and are not determined by the allocated fishing quotas for sole, which were not binding in the years for which we have data.

[22] In line with this assertion, a fisherman who uses larger mesh size states: “A larger mesh size means you have to fish longer.” (Hampel, 2010).

[23] In line with this hypothesis, Poos et al. (2013) predict that optimal towing speed is a decreasing function of fuel price.

Table 1. We find no evidence of an effect of patrolling on the probability of landing more than 50 kg of sole. In the second column, we condition the analysis on vessels that were actually observed to go out to fish, but again we find no evidence of an effect, suggesting that it is indeed reasonable to assume the absence of this type of selection into treatment. We also find no evidence of an effect if we define the outcome as going fishing regardless of the species caught (results available on request from the authors).

Location We consider whether patrolling affects fishing navigation patterns, as shown in Figure 8. Differences in fishing patterns may reflect fishing vessels' desire to avoid the inspection vessel in weeks during which it is patrolling. When we compare all vessel trips which were subject to patrolling to those not subject to patrolling, we do not observe any clear differences in navigation patterns.



(a) Patrolled weeks

(b) Non-patrolled weeks

Figure 8: Fishing patterns and patrolling

Trip duration We can also test whether the duration of fishing trips is affected by patrolling. This is of interest as the higher yield per hour of fishing from illegally small mesh may not only translate into higher revenues due to a greater catch but also into lower costs, as discussed above. In the latter case, this illegal practice allows fishermen to haul in a target catch in a shorter time. In that scenario, fishermen abort the fishing trip if they have hauled in a sufficiently large catch, which may happen earlier when using illegally small mesh size.[24] When we take the duration of a fishing trip in hours as our outcome variable, we find that the presence of patrolling indeed increases the duration of

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[24] Capacity of the hold is not a constraint. The hold is usually filled up to no more than 10 percent of its capacity according to anecdotal evidence. Capacity is ample partly because undersized fish are discarded rather than landed, often in violation of the landing obligation discussed in Section 2.

a fishing trip on average by about one hour (this result remains marginally statistically significant after adjusting for multiple hypothesis testing). This represents approximately a one-percent increase in the mean weekly trip duration. The effect is measured as an average over the whole fleet, only part of which behaves strategically. Based on our approximation of the share of vessels that operate strategically that we present below (14 percent), the estimated effect represents a seven-hour change in the average duration of a fishing trip for vessels induced to fish illegally in the absence of the inspection vessel. This finding suggests that cost savings are indeed another ground for using illegally small mesh size.

Landings of plaice Our baseline results focus on changes in the distribution of landed sole, the target species, to identify the strategic behavior of fishing vessels. Whether strategic behavior also leaves a trace in the catch of other species such as plaice that are caught together with sole depends on how it alters the size distribution of the *landed* catch of these other species. As was shown in Figure 1b, use of illegally small mesh size also leads to a greater share of small plaice in the catch, so the same principle applies, but this change remains unobserved as it relates exclusively to undersized fish that are not landed but discarded at sea (see Appendix H for descriptive statistics for the landings of plaice). Not surprisingly, based on Equation 1 and using landed catch of plaice as our outcome variable, we do not find evidence of a change in the size distribution of landed plaice in response to nautical patrol (see Appendix I).

Approximating additional illegal catch

Based on our results, we can provide an estimate of the additional illegal catch of saleable sole, which is part of reported landings, and also approximate the knock-on effects on the catch and discard of undersized sole and of non-targeted species, which happens out of sight. Catch of plaice of saleable size is unaffected, as reported earlier. Our goal is to see how the additional catch of fish of saleable size compares to approximations of the accompanying additional bycatch, i.e. the collateral damage of this illegal practice.[25]

Here, we focus on the number of fish caught rather than the weight of the catch, given the relevance of individuals for the reproductive capacity of fish stocks. Again, we limit ourselves to changes in the catch due to strategic behavior rather than the overall level of illegal behavior. More details of how we arrived at these approximations are provided in Appendix K.

The additional illegal catch of sole of saleable size is fairly limited, as per the discussion of our main results above, but still sizeable when expressed in terms of the number of

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[25] These are only the static losses associated with this practice. Considering that juvenile sole and plaice would start to reproduce two to three years later if not caught, the losses are many times larger when looking at a longer time window.

individuals rather than in weight. The 19 weeks per year of not having the inspection vessel deployed translates into excess mortality of about 44,000 individual sole of saleable size within our sample of vessels.

For an approximation of the additional catch and discard of undersized sole, we need to rely on what we know about the composition of catches from research expeditions at sea. During the expeditions conducted by Molenaar and Chen (2018), researchers counted each and every fish caught in nets with regular and illegally small mesh size, including the undersized fish that are discarded at sea. Based on back-of-the-envelope calculations that combine our findings with those of the research expeditions, we approximate the excess mortality of individual undersized sole to be about 750,000. That is 17 times larger than the increase in the catch of adult sole.

The illegal practice also affects bycatch of other species. This includes undersized plaice, a major part of the catch of the vessels in our sample, but also other marine life that is not going to be sold such as skates, rays, sharks, sea slugs, and starfish. Based on the findings from the same research expeditions, we approximate the excess mortality of undersized plaice to be around 1.0 m individuals. That is 23 times larger than the increase in the catch of adult sole.

Prevalence of strategic behavior

Beyond showing that illegal fishing practices exist, we would like to find out how widespread the behavior is. To do so, we have to allow for the possibility that fishing vessels only operate strategically part of the time that the inspection vessel is deployed. Fishermen tend to be well informed about the whereabouts of the inspection vessel after all, as noted in Section 2. According to anecdotal evidence, the deterrent effect is strongest when the inspection vessel is within 10 to 15 nautical miles (20 to 30 kilometers) from a fishing vessel. Thus, they may adjust their behavior on a haul-by-haul basis. To approximate the prevalence of strategic behavior, we follow two different approaches.

First, we approximate the share of vessels that operate strategically at least part of the time. We calculate the excess number of vessels which on average show decreases in the share of sole in the size category ‘small’ during patrolled weeks compared to non-patrolled weeks. Under the null hypothesis that patrolling has no effect, we should in expectation due to random variability observe as many increases as decreases in shares of landings within each size category in adjacent patrolled weeks and non-patrolled weeks. However, in accordance with our results, we find on average that during patrolled weeks, 76 vessels display lower shares of sole in the category ‘small’ relative to non-patrolled weeks and 42 vessels display higher shares. Since under the null of no effect we would expect to see $(76 + 42)/2 = 59$ vessels with increases and decreases, we can approximate the share of vessels induced into illegal activity in the absence of patrolling as $(76 - 59)/118 = 0.14$, or 14 percent of vessels.[26] Consistent with our discussion of trip duration earlier in this section and confirming these results, we find that the trip duration of these 76 vessels is statistically significantly greater in patrolled weeks. We find no evidence of such an effect for the other 42 vessels (results available on request from the authors).

Secondly, we approximate the share of the landed catch that is affected by strategic behavior using the Local Average Treatment Effect (LATE) framework. Based on the findings of Molenaar and Chen (2018) discussed in Section 2, we know how the size distribution of the landed catch would change if all fishing vessels would operate strategically all of the time. That can be seen as the LATE, the effect of nautical patrol in case of full compliance. What we estimate with Equation 1 is the intention-to-treat effect (ITT). The approximate share of the landed catch affected by strategic behavior is then equal to the ITT divided by the LATE. For the size category ‘small’, the LATE is about -0.032: it is the difference in the share of the catch in this size category when fishing with 80 *vs.* 40 mm in Figure 1 (the share declines from 0.360 to 0.328).[27] The ITT, our estimate of δ for the size category ‘small’, is -0.0057 (see Appendix G). Thus, following this approach, the share of the landed catch of small sole affected by strategic behavior is 18 percent ($-0.0057/-0.032 = 0.18$).

These findings indicate that the use of illegal nets is widespread, with approximately 14 percent of vessels using illegal nets when the opportunity arises, and approximately 18 percent of the landed catch of small sole being affected. Again, this represents strategic behavior induced by the threat of patrol and ignores all illegal behavior that remains unaffected by variation in deployment of the inspection vessel. Thus, the overall level of illegal behavior is likely to be higher.

Robustness

We vary our baseline model in a number of ways to assess the robustness of our findings. The results of robustness checks are shown in Appendix J.

As a first robustness test, we restrict our sample to vessels that leave port on Sunday/Monday and return on Thursday/Friday only, given that the inspection vessel’s routine is to patrol only from Monday to Thursday. We find very similar results, as shown in Figure 21.

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[26] The associated 95 percent bootstrap confidence interval ranges from 7.7 to 21.4 percent. This confidence interval is based on 399 bootstrap samples from a subset of the 118 unique vessels. Similar calculations for the size categories ‘medium’ and ‘medium-large’ yield approximate shares and associated confidence intervals of 15 percent (9.2 to 22.0 percent) and 14 percent (7.9 to 21.0 percent), respectively.

[27] We assume that ‘blinders’ or ‘liners’ result in some loss in the size categories ‘medium’ and ‘medium-large’, lowering total catch with a 40 mm net by six percent compared to the situation without this unfavorable effect on the catch of larger fish. In addition, we assume that illegal behavior implies use of a mesh size of 40 mm. If the average illegal mesh size is larger, then the approximated share of the catch affected by strategic behavior goes up.

In our baseline model, we adjust for weather conditions. We do not, however, know the exact nature of the relationship between weather conditions and our outcome variable. In the baseline model, we impose a linear relationship. When we allow for a more flexible functional form by including higher order polynomial terms our results remain unchanged, as shown in Figure 22.

Our data are not fully balanced, as shown in Figure 3b. We assess the robustness of our findings to this imbalance by adjusting our sample in three ways. First, we exclude the 400 vessel observations which do not have an observation in an adjacent comparison week. Second, we impute zeroes for all missing observations, bringing the number of observations up to 9,438. Third, we restrict the sample to fishing vessels with at least 60 observed fishing trips. As shown in Figures 23, 24, and 25, the results remain robust when estimating our baseline model with these three adjusted samples, although, unsurprisingly, in the case of the second specification, adding many zero values pulls the estimated effects slightly towards zero.

As discussed in Section 3, the auction data features measurement error. To assess the sensitivity of our results to measurement error in our dependent variable, we estimate our model after adjusting our data in two ways. First, we exclude all observations that look anomalous. These are typically observations for which the size categories are mixed up. This reduces the number of observations by a third, from 6,617 to 4,381. Second, we manually correct observations that have an obvious data entry error and exclude all remaining anomalous observations. This reduces the number of observations from 6,617 to 5,518. As shown in Figures 26 and 27, we find very similar results when estimating our baseline model with these two adjusted samples, suggesting that measurement error has a negligible effect on our findings.

We focus our analysis on fishing vessels that target sole. Even within this sample, some fishing trips produce low landed catch of sole in certain weeks. Those trips may be driving our results towards zero. When we restrict our sample to fishing trips with at least 50 kg of landed sole, our results slightly increase in magnitude and display reduced uncertainty, as Figure 28 shows. In addition, our main analysis applies a low threshold for including a fishing vessel in our sample: an average landing of sole of at least 50 kg (see Section 3). When we use a much higher threshold of 1,000 kg, which trims our sample from 123 to 69 vessels, we again find similar results, as Figure 29 shows.

Lastly, we consider whether our results vary with the length and the engine power of the fishing vessels in our sample. Large, powerful vessels have been found to be particularly sensitive to fuel costs (Davie et al., 2014). Although we find the deterrent effect of nautical patrol to be somewhat smaller for larger and more powerful vessels, as can be seen in Figures 30 and 31, the differences are not significantly different from the estimated effect for smaller, less powerful vessels.

6 Other shocks to the incentive to comply

To corroborate our main results, we explore the response to two other shocks in the incentive to comply with mesh size regulation: variation in patrolling during weekdays vs. weekends and changes in the price of fuel.

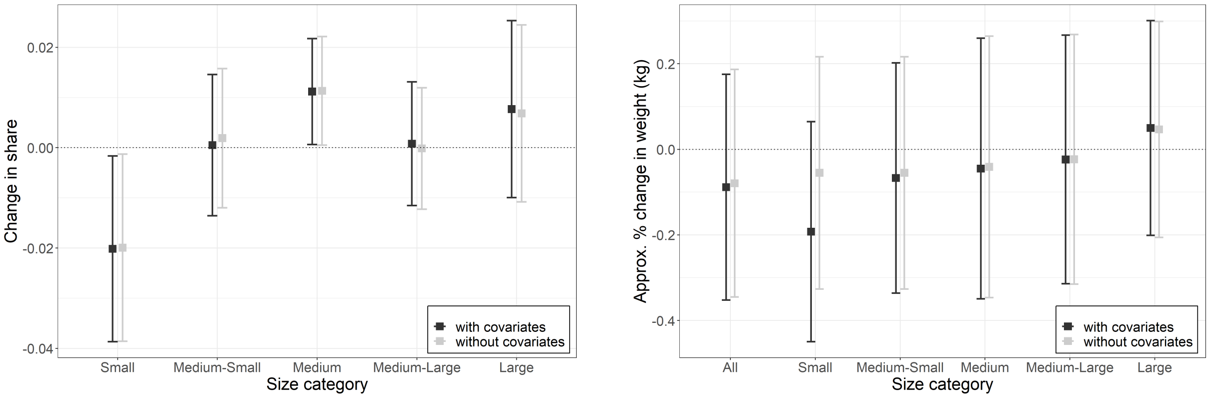
Weekend vs. weekdays

The inspection vessel is never active Friday to Sunday. This is another source of variation in incentives. The main challenge with modeling an effect with this particular source of variation is that fishing activity is much higher during the week than over the weekend, and vessels active during the week may be different from vessels active over the weekend in non-observed ways. This may lead to differences in landed catch regardless of nautical patrol. To account for these contrasts, we use the following differencing model on the sample of all weeks in our data:

$$\mathrm{Y}_{it} = \alpha_i + \lambda_t + \pi_w \, \mathrm{W}_{it} + \pi_{wp} \, \mathrm{P}_t \cdot \mathrm{W}_{it} + \beta \, \mathrm{X}_{it} + u_{it} \tag{2}$$

In the above model, α_i accounts for systematic differences between the landings of vessels. It is identified from repeated observations of the same vessels fishing in multiple weeks. λ_t are vessel and week fixed effects. P_t is equal to one if the inspection vessel was patrolling in week t and zero otherwise. W_{it} is an indicator describing whether a vessel spent the majority of its time at sea during weekdays (Monday to Thursday). More precisely, $\mathrm{W}_{it} = 1$ if two thirds of vessel i's fishing trip in week t fell within Monday to Thursday. We choose the two third cutoff such that vessels that leave port on Sunday night and return on Friday morning are counted as fishing during the week. $\mathrm{W}_{it} = 0$ if vessel i spent at least 50 percent of its time at sea over Friday, Saturday and Sunday, the days during which the Dutch inspection vessel never patrols. To avoid partial contamination of the control group we drop the observations for which the vessel was at sea between 50 and 66 percent of Monday through Thursday (our results are robust to variations on these treatment thresholds). Due to the relatively small sample of vessels fishing over the weekend, we conduct this analysis on the full sample of observations, not just on adjacent patrolled and non-patrolled weeks.

The above model is simply a treatment heterogeneity model which exploits the panel dimension of our data. $\alpha_i + \lambda_t$ captures the average outcome in patrolled and non-patrolled weeks for vessels which operated a majority of time during weekends. π_w captures the average change in the fishing outcome for vessels operating a majority of time during the week relative to the weekend for weeks in which there was no patrolling. π_{wp} captures the average change in the fishing outcome for vessels operating a majority of time during the week relative to the weekend for weeks in which there was patrolling relative to that ratio in non-patrolled weeks. According to our hypothesis, we should observe similar patterns of π_{wp} from this model as the parameter δ in our baseline model, Equation 1. π_w only serves to identify π_{wp} in our model and is not presented in the results. The standard errors are again clustered at the level of fishing vessels.



(a) Landed Shares

(b) Landed Weights

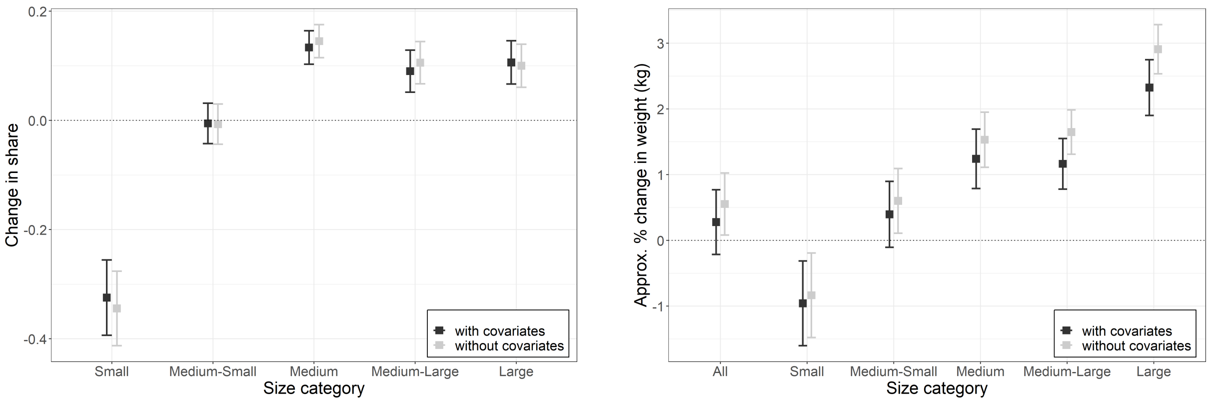
Figure 9: Estimated effect of patrolling on landed catch of sole by size category, weekends vs. weekdays

Note. Figure shows results from estimating Equation 2 with covariates (in black) and without covariates (in light gray). Dependent variable is the share of landed sole of a certain size in the panel on the left and the weight of landed sole of a certain size in the panel on the right. Each point represents a separate regression. Based on data by vessel and week. Number of observations 11,324; data relate to 123 vessels. Total landings excludes fish below minimum saleable size. Bars show 95 percent confidence intervals generated from standard errors clustered at the level of the vessel.

Figure 9a shows the two-way fixed effects estimates from Equation 2 in terms of changes in the share of the landed catch by size category. We see that the observed patterns in the size distribution of the landed catch are broadly similar to those reported earlier. Specifically, during the patrolled weekdays we find a 2.02 percentage point reduction in the amount of sole landed in the size category ‘small’ relative to vessels operating most of the time on unpatrolled weekend days, which is a 6.9 percent reduction from the mean share of this size category. The changes in terms of weight of the landings are less pronounced and less precise than our baseline results, but show similar patterns.

Price of fuel

Given that bottom trawling is the most expensive fishing method in terms of fuel costs, an increase in the price of fuel puts pressure on fishermen to increase the yield per hour of fishing. For unscrupulous fishermen, an evident way to maintain profit margins in the face of rising costs is to use illegally small mesh size. If that is how fishermen operate, then the fuel price should affect the size distribution of the landed catch in a manner similar to nautical patrol. We examine this by estimating our baseline model, Equation 1, on the full sample of weeks with the independent variable D_{it} replaced by the fuel price. To make the results comparable to the findings that we reported earlier, we take the additive inverse of the fuel price. We are, therefore, looking at the effect of a decrease in the fuel price. In the analysis, we take the fuel price for a given fishing trip as the price on the day of departure of that trip.



(a) Landed Shares

(b) Landed Weights

Figure 10: Estimated effect of a one eurocent-drop in the fuel price on landed catch of sole by size category

Note. Figure shows results from estimating Equation 1 with covariates (in black) and without covariates (in light gray). Dependent variable is the share of landed sole of a certain size in the panel on the left and the weight of landed sole of a certain size in the panel on the right. Each point represents a separate regression. Based on data by vessel and week. Number of observations 12,923; data relate to 123 vessels. Total landings excludes fish below minimum saleable size. Bars show 95 percent confidence intervals generated from standard errors clustered at the level of the vessel.

Figure 10 presents results in terms of changes in the share and the weight of the landed catch of sole by size category. Once again, we find similar patterns. More precisely, a decrease of €0.10 in the fuel price, which under normal circumstances occurs over the course of many months, implies an average decrease of 3.24 percentage points in the share of the size category 'small'. We also find an increase in the size categories 'medium' and 'medium large', and, in contrast to our earlier findings, an increase in the size category 'large'. The net effect on total landed catch is small, again suggesting that costs savings are a ground for the use of illegally small mesh size, next to increasing revenues. The estimated effect of a decrease in the fuel price is larger than the estimated deterrent effect, probably because a change in the fuel price affects all vessels similarly, whereas the deterrent effect may be limited to cases that the inspection vessel is not too far away or not busy inspecting another fishing vessel.

7 Conclusion

Fishing regulations should protect the marine environment, but their enforcement is challenging. Illegal behavior of fishermen is hard to detect, both when they are out at sea and when inspecting the results of their behavior in port. Illegal fishing practices may leave a trace in the data, however, and may be uncovered with the right methods. We propose and test a novel approach to detect a hidden illegal practice that is supposedly widespread: the use of fishing nets with illegally small mesh size. We focus on bottom trawling, the world's most widely used fishing method. We exploit the fact that using illegally small mesh size alters the size distribution of the landed catch in a distinct manner: it increases the share of small fish in the catch. Based on readily available data on landed catch of sole by Dutch fishing vessels and using as-good-as-random variation in compliance incentives, we show that the share of small fish in the landed catch varies in the predicted manner, suggesting that fishermen indeed engage in this type of illegal behavior.

Our results imply that the deployment of a single inspection vessel in a huge maritime area like the one we studied can still make a difference. The resulting change in the probability of being caught affects the behavior of about 14 percent of the fishing vessels in our sample. Thus, consistent with anecdotal evidence, the illegal practice is not limited to a few 'bad apples'. Part of the economic rationale for this practice seems to be the illegal sale of undersized fish as well as the reduction of fuel costs, which are extremely high for this fishing technique.

Our approach of identifying illegal behavior may also be used in daily practice. Law enforcement can flag vessels for potential unlawful behaviour by comparing changes of the size distribution of the landed catch in patrolled weeks relative to non-patrolled weeks over an extended time period for each vessel. They can then target their scarce monitoring resources on these vessels.

Rather than just pointing out that this particular illegal practice leads to large amounts of bycatch, as is widely known, our approach makes it possible to approximate the actual number of fish caught illegally, both below and above minimum size. Our findings unveil a consequential additional catch of juvenile fish below reproduction age, exposing yet another pressure on the marine environment.

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Appendix: For Online Publication

A Fishing technology

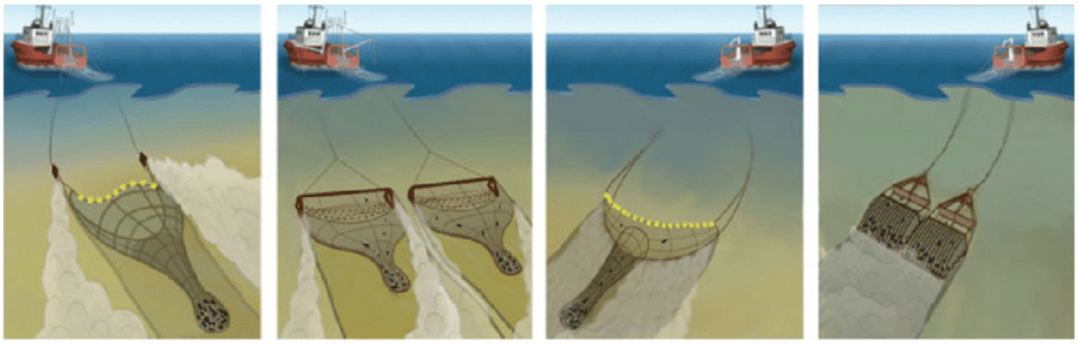


Figure 11: Bottom trawling types (left to right): Otter board trawl, beam trawl, demersal seine trawl and scallop dredges.

Note: Generally speaking, ground gear (ground ropes, sweeps and net) penetrates less deep into the seabed but causes wider disturbance than trawling doors and sleds. Source: Oberle et al. (2017).

B Effect of mesh size on number of fish caught

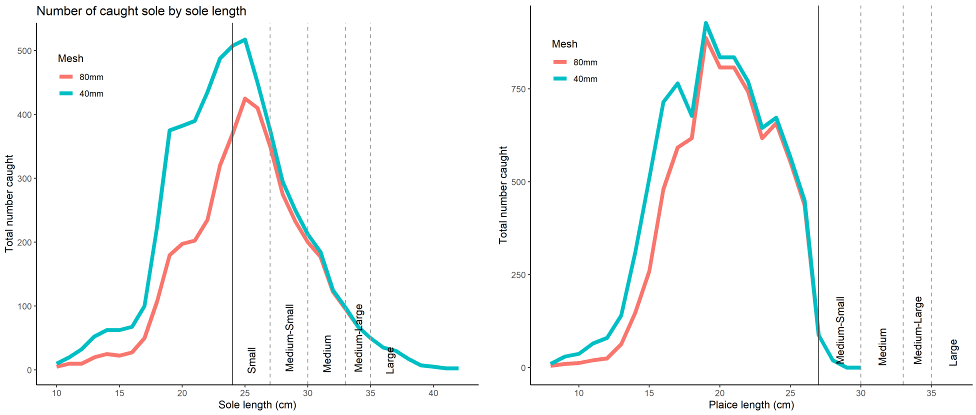


Figure 12: Number of sole (left) and undersized plaice (right) caught, 80mm and 40mm mesh size

Reproduced from Molenaar and Chen (2018).

C Fishing vessel and fishing trip characteristics

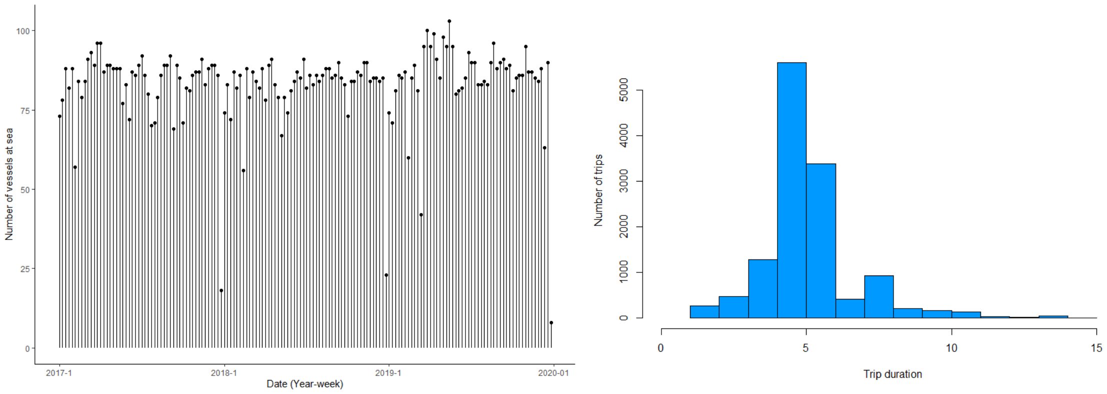


Figure 13: Number of fishing vessels out at sea per week and fishing trip duration in days

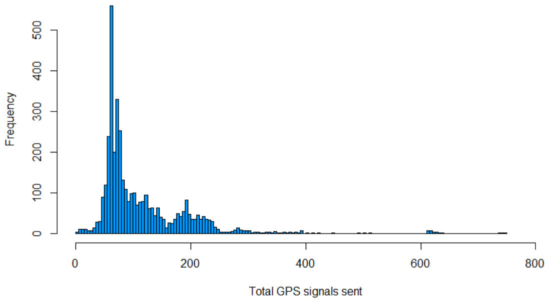


Figure 14: Number of GPS signals sent by vessels in baseline model sample

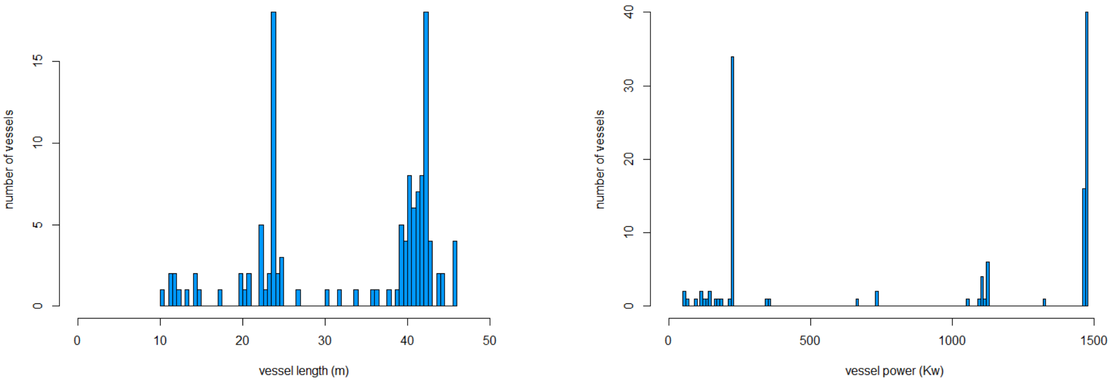


Figure 15: Fishing vessels' characteristics

D Disturbance of bottom trawl fisheries

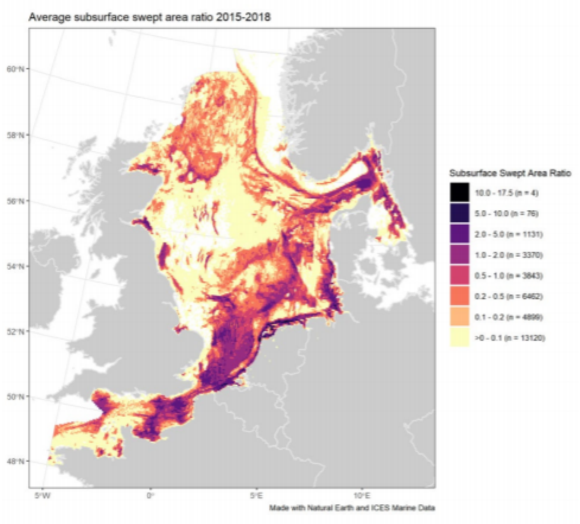
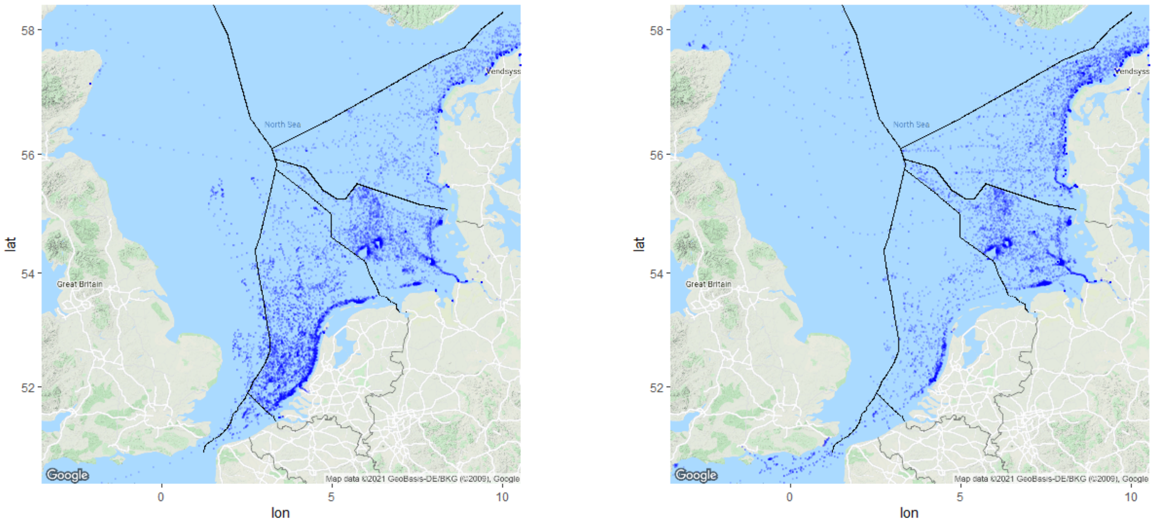


Figure 16: Average subsurface disturbance by mobile bottom contacting fishing gear, North Sea, 2015-2018

Source: ICES (2020).

E Dutch vs. foreign inspection vessels

The figure below shows the deployment of the Dutch inspection vessel as well as the deployment of the two German and one Danish inspection vessel.



(a) Patrolled weeks

(b) Non-patrolled weeks

Figure 17: Dutch, German and Danish inspection vessels' navigation signals

Comparing the two figures, it is clear that there is some patrolling by foreign inspection vessels in the Dutch EEZ. The baseline probability that a foreign vessel reports its position from within the Dutch EEZ when the Dutch inspection vessel is deployed is 0.7 percent. Their presence is somewhat higher in weeks when the Dutch inspection is not deployed. In these weeks, foreign vessels are 2.8 percentage points more likely to report their position from within the Dutch EEZ. Thus, the probability of the presence of a foreign inspection vessel is then 3.5 percent (0.7+2.8). In comparison, the Dutch inspection vessel has an 80 percent probability to report its position from within the Dutch EEZ when deployed. To conclude, the spillover from foreign inspection vessels is very limited. If anything, it would lead to an underestimate of the deterrent effect of the Dutch inspection vessel.

F Summary statistics

Table 2: Summary Statistics

	Non-patrolled		Patrolled		Difference
	Mean	SD	Mean	SD	
Auctioned sole, weight (kg)					
Undersized	8.03	(16.73)	7.98	(18.04)	-0.05
Small	586.40	(705.99)	565.57	(686.43)	-20.83
Medium-small	481.67	(446.84)	470.84	(440.95)	-10.83
Medium	328.35	(297.69)	327.19	(293.54)	-1.16
Medium-large	230.69	(212.21)	230.72	(212.10)	0.03
Large	71.64	(81.94)	70.34	(80.21)	-1.30
Total (excl. undersized)	1,698.74	(1,551.60)	1,664.66	(1,526.18)	-34.08
Auctioned sole, share					
Small	0.29	(0.14)	0.28	(0.14)	-0.01*
Medium-small	0.26	(0.07)	0.26	(0.07)	-0.00
Medium	0.20	(0.06)	0.21	(0.06)	0.00***
Medium-large	0.16	(0.08)	0.17	(0.08)	0.00*
Large	0.08	(0.08)	0.08	(0.08)	0.00
Auctioned plaice, weight (kg)					
Total (excl. undersized)	4,451.72	(6,849.60)	4,457.93	(6,672.06)	6.21
Weather conditions					
Wave height (cm)	144.13	(58.11)	143.70	(62.90)	-0.43
Air temperature (°C)	10.84	(4.56)	11.10	(4.19)	0.26
Wind speed (m/s)	7.92	(2.06)	8.08	(2.02)	0.16
Air pressure (hPa)	1,013.47	(9.27)	1,014.97	(7.86)	1.50
North wind	0.19	(0.19)	0.21	(0.26)	0.02
West wind	0.37	(0.25)	0.37	(0.28)	-0.01
Fishing vessel characteristics					
Ship length (m)	36.58	(8.46)	36.52	(8.54)	-0.07
Ship weight (tonnes)	369.40	(163.76)	368.08	(164.62)	-1.33
Engine power (Kw)	1,076.19	(533.24)	1,077.38	(534.09)	1.19
Other					
Price diesel (euro)	1.31	(0.07)	1.31	(0.07)	-0.01
Signaling location (nr. of times)†	114.69	(77.69)	113.40	(80.28)	-1.29
Trip length (hr)	103.30	(36.95)	102.76	(36.14)	-0.54
Number of observations	3,143		3,474		

Note. (†) 2017 and 2018 only. Stars correspond to significance level of F-test * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

G Baseline model, full regression results

1. Landed sole by size category in shares as dependent variable

Table 3: Estimated effect of patrolling on landed catch of sole by size category

	Share in total landed catch				
	small	*med.-small*	*medium*	*med.-large*	*large*
Without covariates					
Patrolling	-0.0057**	-0.0016	0.0037**	0.0029**	0.0007
	(0.0017)	(0.0009)	(0.0008)	(0.0009)	(0.0012)
With covariates					
Patrolling	-0.0056**	-0.0007	0.0043**	0.0023*	-0.0003
	(0.0018)	(0.0009)	(0.0008)	(0.0010)	(0.0013)
North wind	0.0006	-0.0100*	-0.0041	0.0026	0.0109
	(0.0101)	(0.0040)	(0.0032)	(0.0060)	(0.0057)
West wind	-0.0140**	0.0037	0.0044*	0.0032	0.0027
	(0.0046)	(0.0029)	(0.0019)	(0.003)	(0.0031)
Wind speed	-0.0037*	-0.0037**	0.0012*	0.0041**	0.0021*
	(0.0016)	(0.0009)	(0.0006)	(0.0011)	(0.0010)
Temperature	0.0047**	0.0012**	-0.0028**	-0.0036**	0.0005
	(0.0006)	(0.0004)	(0.0002)	(0.0004)	(0.0004)
Wave height	0.0001	0.0002**	0.0000	-0.0001**	-0.0001**
	(0.0001)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Air pressure	0.0006**	-0.0001	-0.0003**	0.0000	-0.0002
	(0.0002)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Price diesel	0.2904**	0.0189	-0.1145**	-0.0863**	-0.1086**
	(0.0382)	(0.0181)	(0.0166)	(0.0196)	(0.0190)

Note. Table shows results from estimating Equation 1. Based on data by vessel and week. Number of observations 6,617, of which 3,474 during patrolling; data relate to 121 vessels. Total landings excludes fish below minimum saleable size. Between parentheses standard errors clustered at the level of vessels. * $p < 0.05$, ** $p < 0.01$.

2. Landed sole by size category in kg as dependent variable

When taking the weight of landed sole of size k as our dependent variable in Equation 1, we estimate a fixed effects Poisson model to account for the right skew of the weekly landings distribution. We present results from a Poisson regression as opposed to those of a log-transformed model since the former is less sensitive to changes in landings near zero (see Ciani and Fisher, 2019). In the Poisson regression, our parameter of interest δ represents the proportional effect of patrolling on the weight of landed sole. Given the small magnitude of our estimated effects, these proportional effects are approximately equivalent to percentage changes.

Table 4: Estimated effect of patrolling on landed catch of sole by size category, Poisson model

	Weight					
	total	*small*	*med.-small*	*medium*	*med.-large*	*large*
Without covariates						
Patrolling	-0.0104	-0.0304**	-0.0107	0.0091	0.0122	-0.0108
	(0.0099)	(0.0107)	(0.0107)	(0.0106)	(0.0119)	(0.0155)
With covariates						
Patrolling	-0.0002	-0.0223	0.0009	0.0250*	0.0283*	0.0045
	(0.0104)	(0.0117)	(0.0110)	(0.0111)	(0.0118)	(0.0154)
North wind	-0.1721**	-0.1636*	-0.2171**	-0.1905**	-0.0701	0.1908**
	(0.0533)	(0.0700)	(0.0565)	(0.0499)	(0.0426)	(0.0464)
West wind	0.1202**	0.0190	0.1387**	0.1704**	0.2362**	0.4429**
	(0.0299)	(0.0421)	(0.0318)	(0.0302)	(0.0297)	(0.0414)
Wind speed	-0.0106	-0.0329**	-0.0289**	0.0033	0.0449**	0.0859**
	(0.0089)	(0.0112)	(0.0098)	(0.0093)	(0.0083)	(0.0096)
Temperature	-0.0209**	0.0062	-0.0069	-0.0372**	-0.0681**	-0.1042**
	(0.0050)	(0.0053)	(0.0055)	(0.0058)	(0.0058)	(0.0067)
Wave height	0.0002	0.0014*	0.0011*	-0.0005	-0.0023**	-0.0049**
	(0.0004)	(0.0006)	(0.0004)	(0.0004)	(0.0004)	(0.0004)
Air pressure	0.0005	0.0030	0.0001	-0.0025**	-0.0010	0.0001
	(0.0011)	(0.0016)	(0.0011)	(0.0010)	(0.0010)	(0.0010)
Price diesel	-0.0731	0.9979**	-0.1232	-0.8414**	-0.9175**	-2.2537**
	(0.2559)	(0.3359)	(0.2641)	(0.2396)	(0.2152)	(0.2806)

Note. Table shows results from estimating Equation 1, with weight of landed catch by size category as dependent variable. Based on data by vessel and week. Number of observations 6,617, of which 3,474 during patrolling; data relate to 121 vessels. Total landings excludes fish below minimum saleable size. Between parentheses standard errors clustered at the level of vessels. * $p < 0.05$, ** $p < 0.01$.

H Descriptive statistics for landed catch of plaice

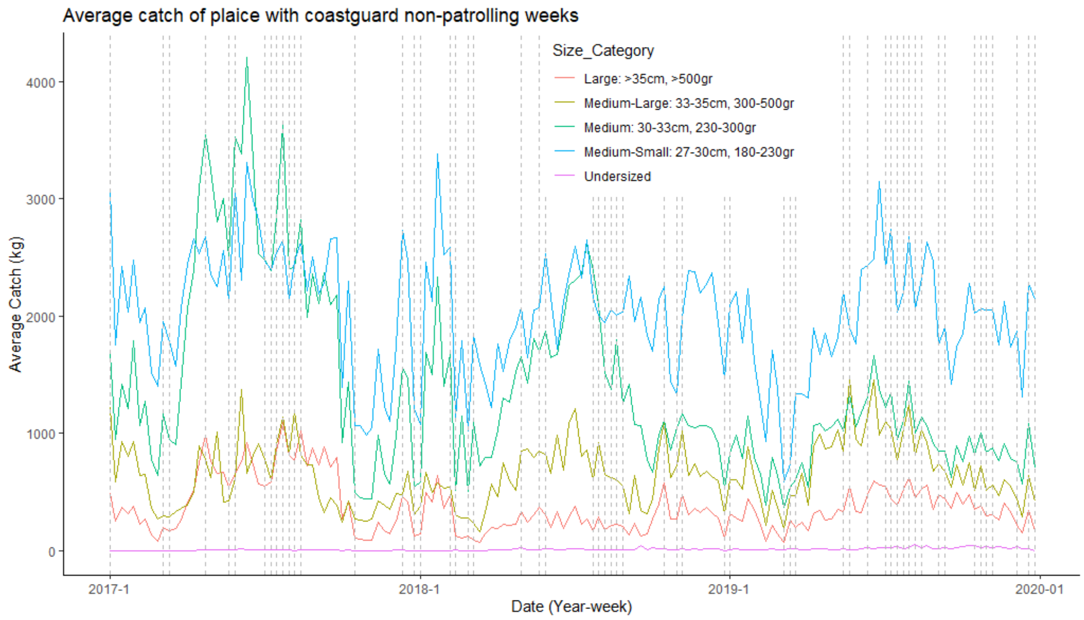
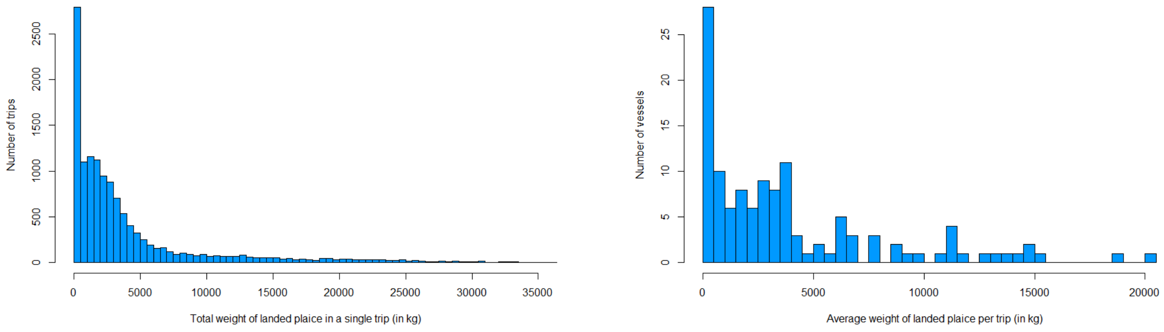


Figure 18: Average landings of plaice by size category (in kg) and deployment of inspection vessel, 2017-2019

Note. Vertical dashed lines denote weeks of non-patrolling.



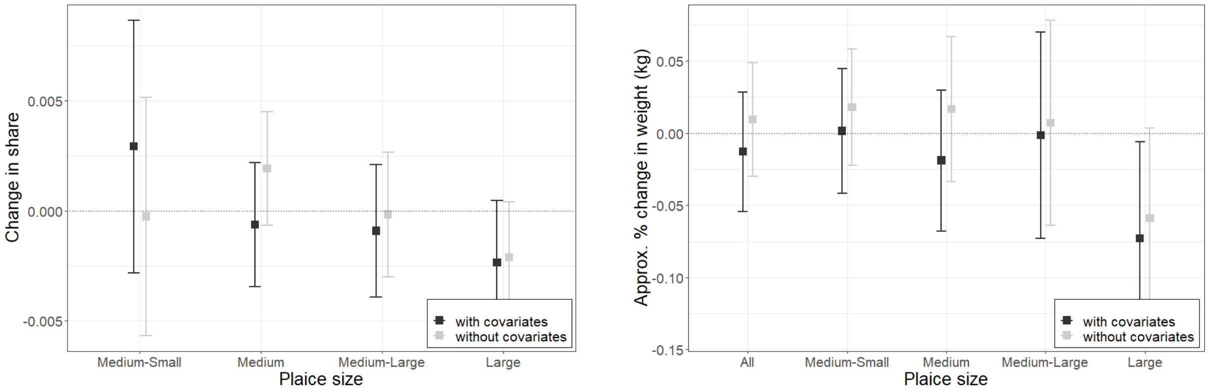
(a) Landed fish per fishing trip (kg)

(b) Landed fish, average per vessel (kg)

Figure 19: Distribution of landings per trip, plaice, 2017-2019

I Effect on landed catch of plaice

As discussed in Section 5, we also consider the effect of nautical patrol on the landed catch of plaice. We estimate Equation 1 with landings of plaice as dependent variable. Figure 20 shows the estimation results, both for shares and weights.[28]



(a) Landed Shares

(b) Landed Weights

Figure 20: Estimated effect of patrolling on landed catch of plaice by size category

Note. Figure shows results from estimating Equation 1 with landings of plaice as dependent variable, both with covariates (in black) and without covariates (in light gray). Dependent variable is the share of landed plaice of a certain size in the panel on the left and the weight of landed plaice of a certain size in the panel on the right. Each point represents a separate regression. Based on data by vessel and week. Number of observations 6,617, of which 3,474 during patrolling; data relate to 121 vessels. Total landings excludes fish below minimum saleable size. Bars show 95 percent confidence intervals generated from standard errors clustered at the level of the vessel.

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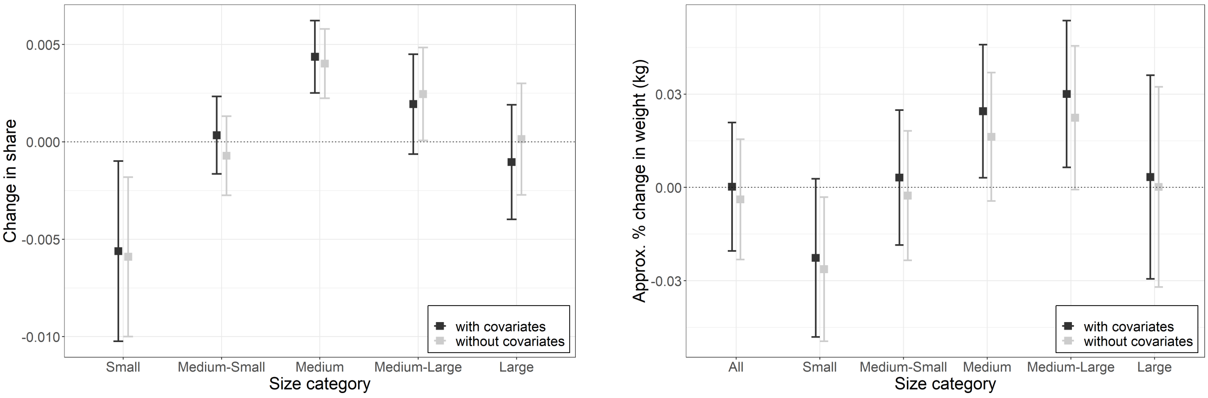
[28] Results are similar when restricting the sample to vessels which land on average more than 50 kg of plaice (not shown).

J Robustness

Sample restricted to fishing trips from Sunday/Monday to Thursday/Friday

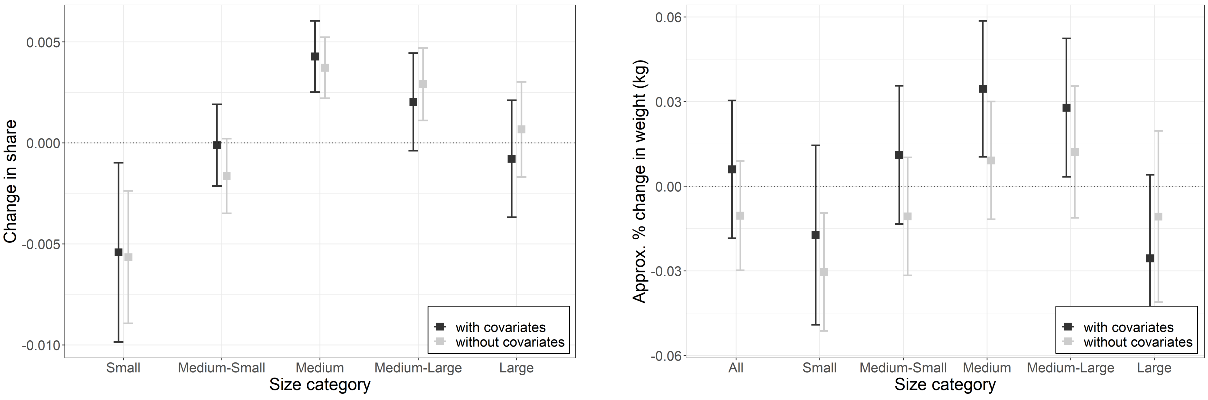


(a) Landed Shares

(b) Landed Weights

Figure 21: Estimated effect of patrolling on landed catch of sole by size category
Note. Figures show results from estimating Equation 1 with covariates (in black) and without covariates (in light gray). Dependent variable is the share of landed sole of a certain size in the panel on the left and the weight of landed sole of a certain size in the panel on the right. Sample restricted to fishing trips starting Sunday/Monday and ending Thursday/Friday. Each point represents a separate regression. Based on data by vessel and week. Number of observations 5,118, of which 2,735 during patrolling; data relate to 118 vessels. Total landings excludes fish below minimum saleable size. Bars show 95 percent confidence intervals generated from standard errors clustered at the level of the vessel.

Alternative functional form covariates

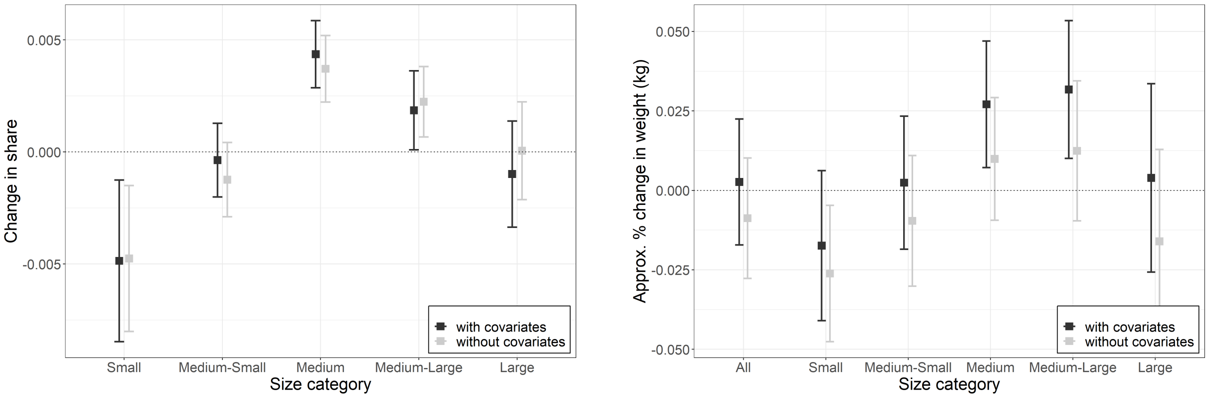


(a) Landed Shares

(b) Landed Weights

Figure 22: Estimated effect of patrolling on landed catch of sole by size category
Note. Figures show results from estimating Equation 1 with covariates (in black) and without covariates (in light gray). Dependent variable is the share of landed sole of a certain size in the panel on the left and the weight of landed sole of a certain size in the panel on the right. Baseline model with additional second and third degree polynomial terms for covariates. Each point represents a separate regression. Based on data by vessel and week. Number of observations 6,617, of which 3,474 during patrolling; data relate to 121 vessels. Total landings excludes fish below minimum saleable size. Bars show 95 percent confidence intervals generated from standard errors clustered at the level of the vessel.

Excluding observations that result in imbalance

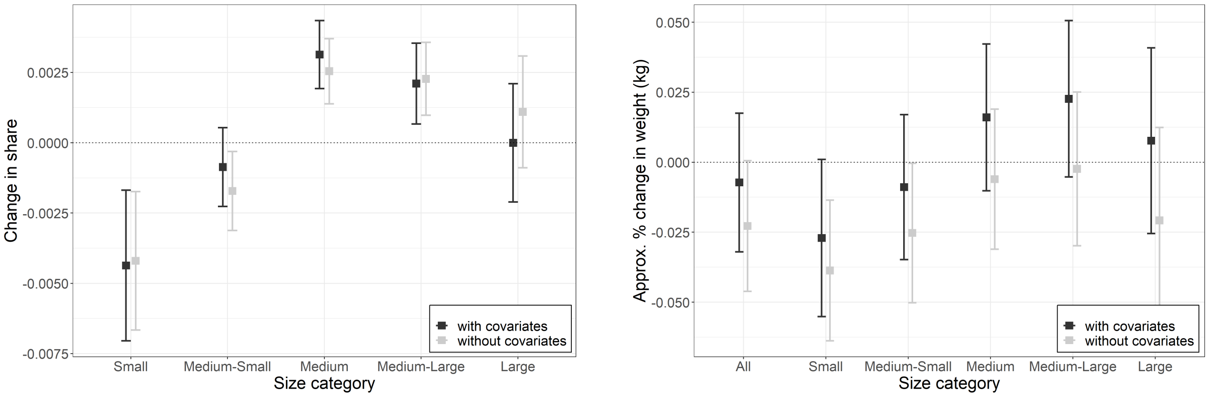


(a) Landed Shares

(b) Landed Weights

Figure 23: Estimated effect of patrolling on landed catch of sole by size category
Note. Figures show results from estimating Equation 1 with covariates (in black) and without covariates (in light gray). Dependent variable is the share of landed sole of a certain size in the panel on the left and the weight of landed sole of a certain size in the panel on the right. Sample excludes vessel-fishing trip observations without an observed fishing trip in an adjacent week. Each point represents a separate regression. Based on data by vessel and week. Number of observations 6,217, of which 3,232 during patrolling; data relate to 118 vessels. Total landings excludes fish below minimum saleable size. Bars show 95 percent confidence intervals generated from standard errors clustered at the level of the vessel.

Imputing zeroes for missing observations in comparison weeks

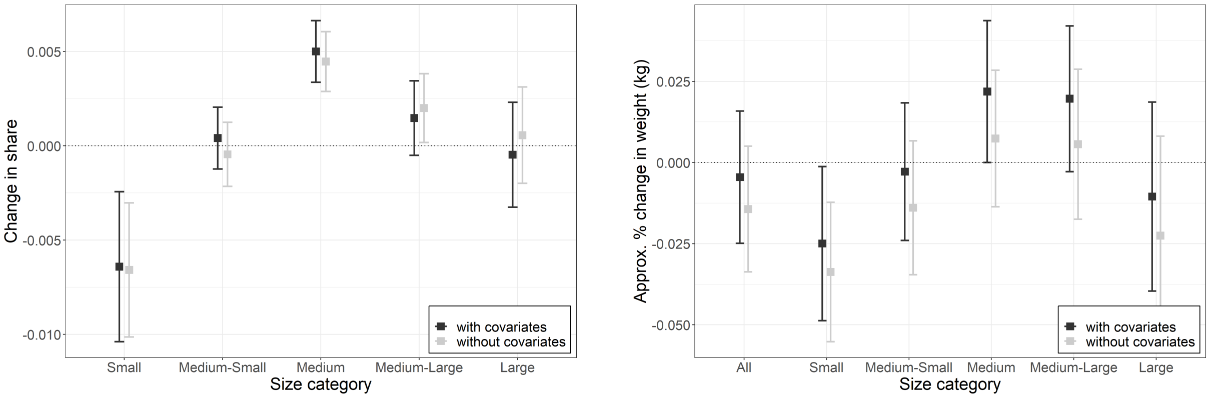


(a) Landed Shares

(b) Landed Weights

Figure 24: Estimated effect of patrolling on landed catch of sole by size category
Note. Figures show results from estimating Equation 1 with covariates (in black) and without covariates (in light gray). Dependent variable is the share of landed sole of a certain size in the panel on the left and the weight of landed sole of a certain size in the panel on the right. Zeroes imputed for all missing fishing trips of a vessel over the period 2017-2019. Each point represents a separate regression. Based on data by vessel and week. Number of observations 9,438, of which 5,043 during patrolling; data relate to 123 vessels. Total landings excludes fish below minimum saleable size. Bars show 95 percent confidence intervals generated from standard errors clustered at the level of the vessel.

Sample restricted to frequently observed fishing vessels



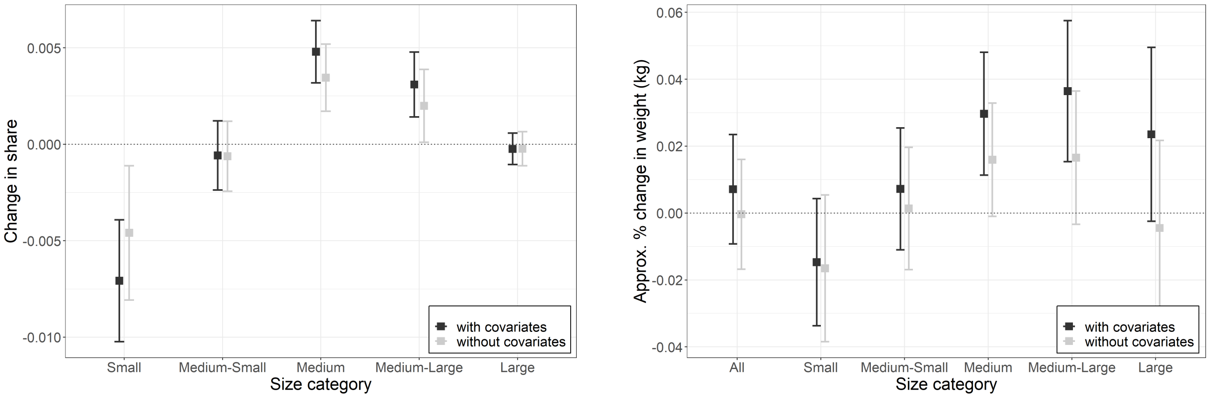
(a) Landed Shares

(b) Landed Weights

Figure 25: Estimated effect of patrolling on landed catch of sole by size category

Note. Figures show results from estimating Equation 1 with covariates (in black) and without covariates (in light gray). Dependent variable is the share of landed sole of a certain size in the panel on the left and the weight of landed sole of a certain size in the panel on the right. Sample restricted to fishing vessels with at least 60 observed fishing trips (out of the 78 comparison weeks). Each point represents a separate regression. Based on data by vessel and week. Number of observations 5,434, of which 2,846 during patrolling; data relate to 77 vessels. Total landings excludes fish below minimum saleable size. Bars show 95 percent confidence intervals generated from standard errors clustered at the level of the vessel.

Excluding seemingly anomalous observations in auction data



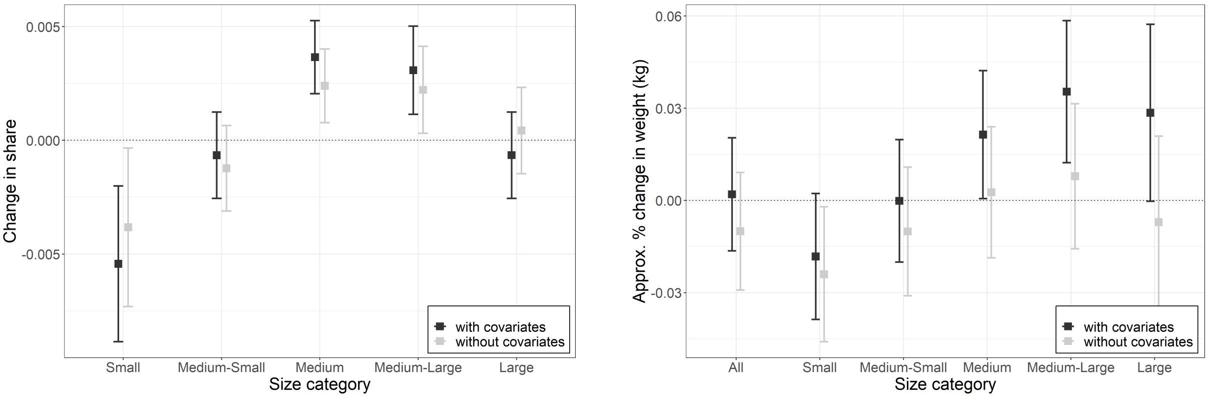
(a) Landed Shares

(b) Landed Weights

Figure 26: Estimated effect of patrolling on landed catch of sole by size category, excluding any anomalous observations

Note. Figure shows results from estimating Equation 1 with covariates (in black) and without covariates (in light gray). Each point represents a separate regression. Based on data by vessel and week. Number of observations 4,381, of which 2,275 during patrolling; data relate to 120 vessels. Total landings excludes fish below minimum saleable size. Bars use 95 percent confidence intervals generated from standard errors clustered at the level of the vessel.

Excluding seemingly anomalous observations, but correcting obvious data entry errors

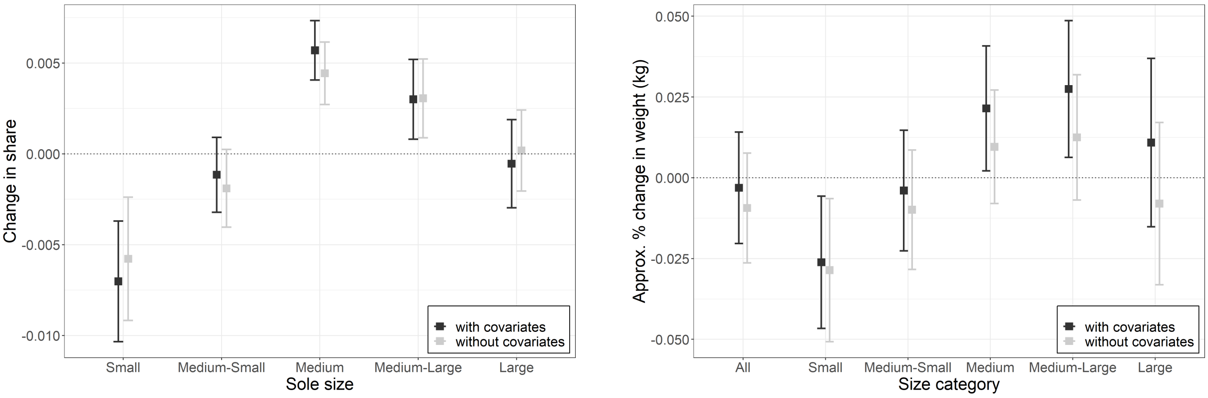


(a) Landed Shares (b) Landed Weights

Figure 27: Estimated effect of patrolling on landed catch of sole by size category, correcting anomalous observations

Note. Figure shows results from estimating Equation 1 with covariates (in black) and without covariates (in light gray). Each point represents a separate regression. Based on data by vessel and week. Number of observations 5,158, of which 2,691 during patrolling; data relate to 120 vessels. Total landings excludes fish below minimum saleable size. Bars use 95 percent confidence intervals generated from standard errors clustered at the level of the vessel.

Excluding fishing trips with less than 50 kg of landed sole

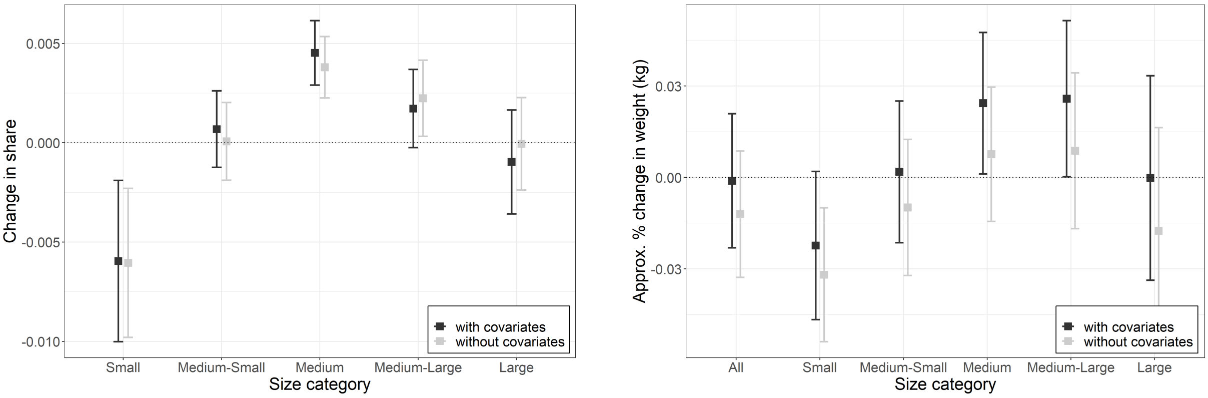


(a) Landed Shares (b) Landed Weights

Figure 28: Estimated effect of patrolling on landed catch of sole by size category

Note. Figures show results from estimating Equation 1 with covariates (in black) and without covariates (in light gray). Dependent variable is the share of landed sole of a certain size in the panel on the left and the weight of landed sole of a certain size in the panel on the right. Excluding fishing trips with less than 50 kg of landed sole. Each point represents a separate regression. Based on data by vessel and week. Number of observations 5,267, of which 2,758 during patrolling; data relate to 121 vessels. Total landings excludes fish below minimum saleable size. Bars show 95 percent confidence intervals generated from standard errors clustered at the level of the vessel.

Sample restricted to vessels with avg. landed catch of sole of at least 1,000 kg

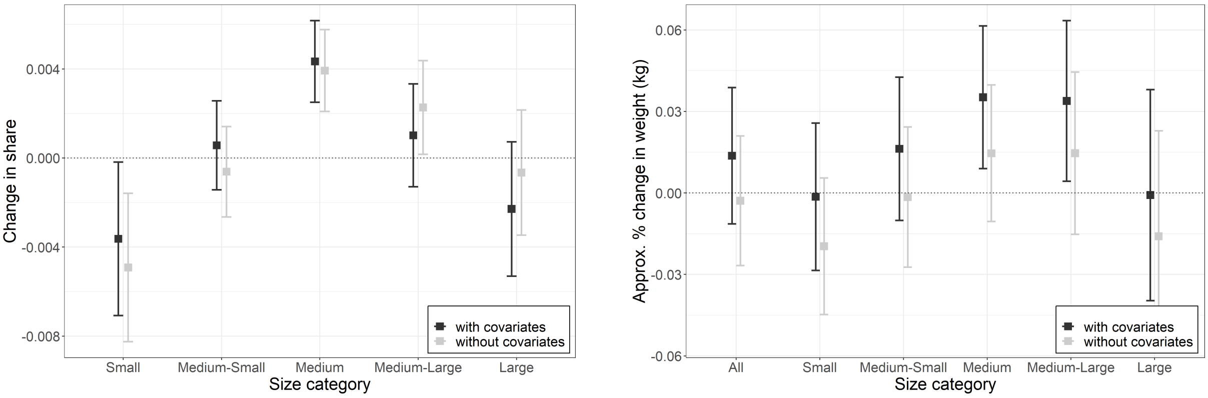


(a) Landed Shares

(b) Landed Weights

Figure 29: Estimated effect of patrolling on landed catch of sole by size category
Note. Figures show results from estimating Equation 1 with covariates (in black) and without covariates (in light gray). Dependent variable is the share of landed sole of a certain size in the panel on the left and the weight of landed sole of a certain size in the panel on the right. Sample restricted to vessels with an average landed catch of sole of at least 1,000 kg. Each point represents a separate regression. Based on data by vessel and week. Number of observations 4,703, of which 2,455 during patrolling; data relate to 69 vessels. Total landings excludes fish below minimum saleable size. Bars show 95 percent confidence intervals generated from standard errors clustered at the level of the vessel.

Sample restricted to vessels above 40 m in length

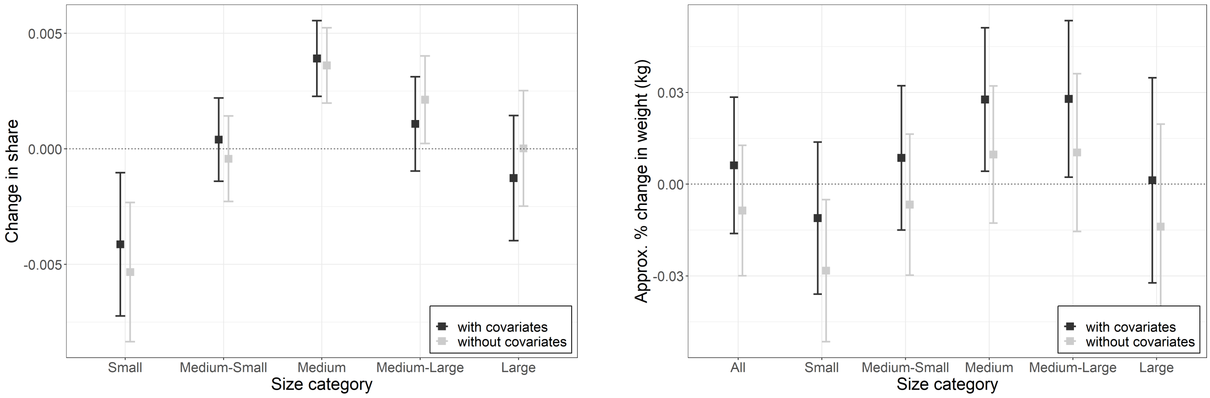


(a) Landed Shares

(b) Landed Weights

Figure 30: Estimated effect of patrolling on landed catch of sole by size category
Note. Figures show results from estimating Equation 1 with covariates (in black) and without covariates (in light gray). Dependent variable is the share of landed sole of a certain size in the panel on the left and the weight of landed sole of a certain size in the panel on the right. Sample restricted to vessels above 40 m in length. Each point represents a separate regression. Based on data by vessel and week. Number of observations 4,031, of which 2,110 during patrolling; data relate to 59 vessels. Total landings excludes fish below minimum saleable size. Bars show 95 percent confidence intervals generated from standard errors clustered at the level of the vessel.

Sample restricted to vessels above 1,000 kW in power



(a) Landed Shares

(b) Landed Weights

Figure 31: Estimated effect of patrolling on landed catch of sole by size category

Note. Figures show results from estimating Equation 1 with covariates (in black) and without covariates (in light gray). Dependent variable is the share of landed sole of a certain size in the panel on the left and the weight of landed sole of a certain size in the panel on the right. Sample restricted to vessels above 1,000 kW in power. Each point represents a separate regression. Based on data by vessel and week. Number of observations 4,737, of which 2,487 during patrolling; data relate to 70 vessels. Total landings excludes fish below minimum saleable size. Bars show 95 percent confidence intervals generated from standard errors clustered at the level of the vessel.

K Approximating additional illegal catch

Below, we work out how we arrived at an estimate of the annual additional illegal catch of sole and plaice resulting from strategic behavior of fishermen. Given that our estimates pertain to strategic behavior, we estimate the additional catch in the 19 calender weeks without deployment of the inspection vessel per year, involving 1,523 fishing trips.[29] The 33 other calender weeks denote the control condition.

Sole, saleable size We rely on the estimated effects of nautical patrol on the landed catch in terms of weight for an estimate of the additional illegal catch of sole of saleable size (see Table 4 in Appendix G, specification with covariates). We assume that landed sole of saleable size approximates caught sole of saleable size. The point estimates for the effect of patrolling on the weight of the catch by size category are as follows. 'Small': 2.2 percent reduction from mean of 565.6 (see Appendix F) equals reduction of 11.3 kg. 'Medium-small': no effect. 'Medium': 2.5 percent increase from mean of 327.2 equals increase of 8.2 kg. 'Medium-large': 2.8 percent increase from mean of 230.7 equals increase of 6.5 kg. 'Large': no effect.

We convert catch in terms of weight into catch in terms of number of fish by dividing the above totals by the average weight of a fish in a size category. Sole in the category 'small' weighs about 152 gr on average, providing an increase in the total number of small sole caught illegally in non-patrolled weeks of 74.3 (11.3/0.15).[30] Similarly, we find an increase for the category 'medium' of 28.0 and for 'medium-large' of 17.5. The total excess fish caught is therefore $74.3 - 28.0 - 17.5 = 28.8$ on average per vessel-trip. Given an average of 1,523 non-patrolled trips per year, this is equivalent to $28.8 \cdot 1,523 = 43,909$, or approximately $44,000$ excess mortality of individual adult sole.

Sole, below minimum size We infer the effect on undersized sole from our findings for sole of saleable size paired by what we know about the ratio of undersized sole to sole of saleable size, based on Molenaar and Chen (2018). To start, we find an effect of nautical patrol on catch in the size category 'small' of -2.2 percent. The effect on the

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[29] In the sample of adjacent patrolled vs. non-patrolled adjacent weeks there are 39 non-patrolled weeks over three years, resulting in an average of 13 weeks non-patrolled a year. In terms of fishing trips, there are 3,143 fishing trips observed over 2017-2019 during non-patrolled weeks, or, on average, 1,048 trips per year in weeks in which there is no patrolling. However, for the full reconstruction of results, we extrapolate our results to the full sample of 57 non-patrolled weeks representing 4,570 observed trips. Or, more concisely, 19 non-patrolled weeks per year on average and 1,523 trips per year in weeks in which there is no patrolling.

[30] We obtain weight-length correspondence measurements from fishbase.de for sole and plaice. For instance, for sole in size category 'small', we derive the average weight as follows: 24 cm=125 gr, 25 cm=142 gr, 26 cm=161 gr, 27 cm=181 gr resulting in an average weight of 152 gr.

catch of undersized sole must be larger, given that the increase in the catch as a result of using illegally small mesh size is about three times larger for undersized sole than for the size category 'small'.[31] When taking 3.0 as multiplier, the effect on undersized fish is -6.6 percent.

We approximate the average catch of undersized sole in terms of weight in the control condition at 707 kg.[32] Taking 6.6 percent of 707 implies a reduction of 46.7 kg in undersized sole in response to patrolling. Assuming that 18 percent of these fish make it out alive after being discarded, the actual reduction is 38.3 kg.[33] Taking the average weight of an undersized sole to be 78 gr, this amounts to 491 individual sole. Given an average of 1,523 non-patrolled fishing trips per year, this is equivalent to $491 \cdot 1523 = 747,106$, or approximately $750,000$ excess mortality of individual undersized sole.

Plaice, saleable size As discussed in Section 5, we find a negligible effect on legally saleable plaice.

Plaice, below minimum size From Figure 1, we can infer that the increase in the catch of undersized plaice resulting from using 40 mm rather than 80 mm mesh is smaller than the increase for sole, about 80 percent smaller (in terms of weight). When we scale the 6.6 percent decrease in catch of undersized sole with this difference between the two species, we get a decrease in the weight of undersized plaice caught of $-6.6 \cdot 0.2 = -1.3$ percent.

We approximate the average catch of undersized plaice in terms of weight in the control condition at $2,828$ kg.[34] Applying the 1.3 percent to the average catch gives us 37.3 kg or 888 individual undersized plaice (when we take the average weight of an undersized plaice, mainly in the lower ranges, to be 42 gr). About 24 percent of discarded plaice make it out alive (see Footnote 33), leaving $888 \cdot 0.76 = 675$ individuals. Given an average of 1,523 non-patrolled fishing trips per year, this is equivalent to $675 \cdot 1,523 = 1,027,952$, or approximately 1 m excess mortality of individual undersized plaice.

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[31] As can be inferred from Figure 1, the increase in the catch with illegally small mesh size relative to legal mesh size is 23 percent for size category 'small' and 68 percent for undersized sole.

[32] The average catch of undersized sole in terms of weight is a factor of 1.25 higher than the catch in the size category 'small', i.e. equal to $565.6 \cdot 1.25 = 707$

[33] Survival estimates are based on fish of saleable size: under 10 percent for both sole and plaice in Van Beek et al. (1990); 14 percent for sole and 48 percent for plaice in Depestele et al. (2014); 29 percent for sole and 15 percent for plaice in Van der Reijden et al. (2017).

[34] Figure 1 shows that the catch of undersized plaice in terms of weight is about four times higher than the catch of undersized sole in the control condition: $4.0 \cdot 707 = 2,828$ kg.