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**TEMPORAL DISPLACEMENT OF ENVIRONMENTAL CRIME.
EVIDENCE FROM MARINE OIL POLLUTION**

By

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Temporal displacement of environmental crime. Evidence from marine oil pollution^{*}

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Abstract

The probability of conviction commonly varies across different circumstances due to imperfect monitoring. Evidence of whether and how offenders exploit gaps in monitoring provides insight into the process by which deterrence is produced. We present an empirical test of temporal displacement of illegal discharges of oil from shipping, a major source of ocean pollution, in response to a monitoring technology that features variation in the probability of conviction by time of day. After sunset and before sunrise, evidence collected using airborne radar day-round becomes contestable in court because the nature of an identified spot cannot be verified visually. Using data from surveillance flights above the Dutch part of the North Sea during 1992-2011, we only find evidence for temporal displacement after 1999, with further tightening of the regulations. By that time, the overall level of discharges had been reduced considerably, making the observed temporal displacement relatively small in absolute levels.

JEL-codes: K32, K42

Keywords: deterrence, pollution, environmental crime

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1. Introduction

Potential offenders often operate in an environment with a varying probability of detection. They may be less likely to get caught under certain circumstances, such as during the nighttime. A primary cause of the variation in the probability of detection are the particular characteristics of the monitoring technology used by law enforcement agencies.¹ The human senses have their limitations and so do monitoring technologies. For instance, the technologies used in speed limit enforcement – including license-plate recognition, radar and laser – each have their own weaknesses. These are not a given, however, technologies evolve over time. Radar guns are gradually being displaced by laser guns to prevent a speeding driver from hiding in traffic, and single-point speed measurement is complemented with measurement over longer stretches to limit all-too-easy avoidance of speed cameras.

When choosing a monitoring technology and the way it is deployed, law enforcement agencies face a dilemma that is more complicated than the standard case with a monitoring technology that produces a similar probability of detection across all circumstances (Becker 1968). In addition to the challenge of setting a probability of detection and penalty within one particular situation, say the daytime, an agency needs to choose a monitoring technology that produces a deterrent effect across a set of circumstances, say the daytime and the nighttime. Usually, none of the available technologies is equally effective under all circumstances. That is also not necessary because exploitation of gaps in enforcement is not a given. First, an offender will need to become familiar with gaps in monitoring. Potential offenders often have only a limited understanding of how law enforcement agencies go about their work. This explains why enforcement activity at a certain time and place has repeatedly been found to also affect illegal behavior at other times and places (so-called diffusion of benefits, see Clarke and Weisburd 1994). Second, the offender needs to devise an evasive strategy.² This is not without its costs and regularly requires the development of new knowledge and skills (Cook 1986, Cornish and Clarke 1987). In other words, not the possible but the *actual* displacement of illegal behavior to circumstances with a relatively low chance of getting caught is of importance in choosing a monitoring technology. Empirical evidence on whether and how offenders exploit variation in the chance of getting caught is of direct importance for an effective enforcement strategy.

The interaction between law enforcement and affected parties can be characterized as a repeated game. The game may be cut short by effective counter-measures by law enforcement, but these measures may be undermined eventually. The adaptive behavior of both offenders and law enforcement is a cat-and-mouse game involving constant pursuit, near captures, and repeated escapes. In practice, the sequence of moves and counter-moves may be slow in unfolding; the point is that the chain of action and reaction is an integral part of the process underlying deterrence, and its study should improve our understanding of how deterrence works (McCrary 2010).

Evasive strategies may be particularly challenging in the context of the enforcement of environmental law. Legitimate business activities and activities that are in contravention of environmental law are

¹ Another important cause of variation in the probability of detection is the behavior of victims. For instance, victims may vary in their propensity to report a crime to the police. This has been found to be relevant in the context of illegal working conditions, with illegal immigrants as particularly vulnerable to exploitation because they rarely report their employers to the authorities out of fear of deportation (Foo 1994).

² Evasive strategies include displacement of illegal behavior to times or places where law enforcement is less effective; other forms are a change in target, tactics and offense type (Cornish and Clarke 1987).

often jointly produced, providing continuous pressure to engage in criminal behavior. For instance, as in the case discussed in this paper, an environmentally harmful substance may be generated as a by-product of a legal production process. With one way of illegal disposal of the substance closed off, the need to dispose of it is not diminished. If the legal alternative is sufficiently costly, then the potential offender may simply look for other ways of illegal disposal (Sigman 1998). Within the context of environmental crime there may be more of a 'lump of criminal activity' that seeks a way out than in other types of crime, even though the elasticity of environmental crime with respect to law enforcement activity has repeatedly proven to be negative rather than zero (Gray and Shimshack 2011).

Temporal displacement of illegal behavior in response to law enforcement is thought to be a common evasive strategy – since it requires less from the potential offender compared to other strategies such as a change in tactics – but it is also one of the least studied (Guerette and Bowers 2009). In this paper, we study temporal displacement of illegal discharges of oily waste from shipping. Worldwide, the shipping industry is subject to regulation of the disposal of environmentally harmful substances, including oil and oily mixtures. Radar-guided surveillance by aircraft and satellite is a broadly used monitoring technology to detect illegal discharges, next to port state control. Actual detection of oil discharges still relies on visual inspection, however, since radar also picks up other anomalies on the water surface. In the jurisdiction under study, the Netherlands, the courts only accept evidence from observers who are trained to detect the particular rainbow sheen of oil on the water surface. As a consequence, the probability of conviction is negligible during low-visibility conditions. Disposal of oily substances can easily be postponed for a number of hours and the shipping industry has long been suspected of illegally disposing in the nighttime and during adverse weather conditions (Meetskundige Dienst 1981, Crist 2003, Carpenter 2007: 162, HELCOM 2011). Temporal displacement of illegal discharges in response to this variation in the probability of being convicted has never been studied however, primarily because in most countries surveillance effort during the nighttime is at too low a level to collect meaningful data. This is known to be the case for Belgium, Canada, Finland, France, Poland, Russia and Sweden, but could apply to other countries as well.

The Netherlands is unique in conducting relatively intensive nightly surveillance activities, allowing us to analyze temporal displacement.³ The Dutch part of the North Sea provides a good area of study because it is one of the busiest navigated seas in the world and also one of the most polluted seas (Camphuysen and Vollaard 2015). The data collection is unaffected by visibility conditions because it relies on radar. We develop a test for the presence of temporal displacement. For nightly discharges to be strategic in nature, a necessary condition is that the timing is robust to seasonal variation in the time of sunset and sunrise. These times vary widely over the year, with the time window between sunset and sunrise being some 6 to 7 hours in June and some 15 to 16 hours in December.

We use detailed data on radar-identified spots on the water surface and on the flight paths of all Coast Guard surveillance flights for the Dutch part of the North Sea for the period 1992-2011. We combine the geographical data with meteorological data on wind speed, water temperature and air temperature. The focus on daily variation in the probability of radar-identified spots effectively eliminates measurement error from other substances that may also be picked up by radar but are not

³ Apart from collecting statistics on illegal discharges for all hours of the day, nightly surveillance is mainly conducted to secure a rapid response in case of an emergency at sea and to enforce traffic regulations around the clock.

oil, including subsurface sand banks, seaweed and algae blooms: the sources of false positives do not vary with the time of day.

We find that until 1999 the general pattern of nightly discharges do not pass the test. The hour-by-hour upswings in the probability of detecting a spot – a sign of a surge in illegal oil discharges – also happened in broad daylight, albeit often at night or in the early morning. This suggests that earlier suspicions of displacement confounded year-round daily routines on board that favored relatively late or early hours with strategic timing of discharges. Only after 1999, with further tightening of the regulations, the upswings were limited to the hours after sunset and before sunrise. On-board routines started to diverge between the seasons, in line with the variation in the time of sunset and sunrise. The findings suggests that after 1999 temporal displacement was all but complete.

In absolute terms, we find temporal displacement to be limited over the study period. Temporal displacement only emerged after a major drop in illegal discharges during the 1990s, rendering it a relatively mild consequence of the monitoring technology that enforcement relied on: the human eye. In other words, most shipping companies chose to stop illegal discharges in the North Sea area rather than to displace them to the nighttime (allowing the possibility of displacement to other less-patrolled areas such as the Atlantic).

The context of oil pollution from shipping is particularly relevant because ocean pollution is a major source of environmental degradation. The legal discharge of oil and oily wastes is a standard part of operations of a large sea-going vessel, and these discharges are internationally regulated. Some vessel operators opt to discharge oily wastes illegally, and these discharges cumulatively are an important and chronic contributor to ocean pollution (National Research Council 2003). Oil spills can present a hazard by causing damage and death to birds and marine mammals and by exerting a toxic stress on subsurface organisms. Oil dissolved in the water can be taken up by organisms and affect their physiology, behavior, reproductive potential and survival. Oil may also be transferred to the sediment, where it might persist for many years, and impact on organisms on and in the sea bed. Marine oil pollution remains a great environmental concern globally (National Research Council 2003, Gullo 2011), even though the incidence of illegal oil discharges has been reported to have declined in some areas including the North Sea (Camphuysen 2010, Lagring et al. 2012), the Baltic Sea (HELCOM 2011) and the Pacific Ocean off the Canadian coast (Serra-Sogas et al. 2008). The policy relevance of the findings of this study extends beyond the confines of the Dutch part of the North Sea: many coastal countries in the western world use deterrence technology that is similar to the Netherlands, including the UK, the US, Germany, Belgium, Canada and France.

This paper contributes to the literature on the dynamics of criminal behavior. Empirical evidence on the interaction between law enforcement and potential offenders is scant, which also applies to evidence on temporal displacement of crime in response to law enforcement activity (McCrary 2010).⁴ In a review of empirical evaluations of crime prevention initiatives, Guerette and Bowers (2009) found that displacement and diffusion effects were only examined in half of all studies. Out of 574 evaluations that examined displacement and diffusion effects, temporal displacement was analyzed in only 5 percent of cases. This is also typical for the literature on monitoring and enforcement of environmental

⁴ An exception is Jacob, Lefgren and Moretti (2007). They find evidence for temporal displacement of crime in response to weather shocks, which they explain by the presence of income effects for property crime and by decreasing marginal utility from violent crime in the amount of violent crime committed previously.

regulations. In their review of this literature, Gray and Shimshack (2011) do not discuss any empirical evidence on evasive strategies other than falsification of self-reported violations of regulations, which Telle (2013) finds to be a common practice. Better insight into how and when evasive strategies are developed can have a high pay-off. Heyes (1994) shows theoretically that an increase in enforcement resources while leaving opportunities to evade punishment unchecked may actually *lower* overall compliance, which is confirmed empirically in a study into avoidance of import duties (Yang 2008). In addition, effectiveness of monitoring and enforcement may be lower than it seems when evasive actions are not taken into account, which is relevant for addressing the question of how to cost-effectively limit environmental degradation. Finally, I also contribute to the empirical literature on the effectiveness of measures to combat marine pollution from operational discharges. So far the evidence on what policies work in this area is limited.⁵

The remainder of the paper is structured as follows. The next section describes the regulations governing the management of oily waste from shipping and their enforcement. Section 3 discusses the data. In section 4, we present the empirical test for the presence of temporal displacement. Section 5 presents the estimation results. Section 6 concludes.

2. Regulation of oily waste disposal and deterrence technology

Oily waste products from shipping are mainly generated by three processes. First, pre-treatment of high-viscosity bunker oil, which is often used as fuel in shipping, results in a relatively solid residue. This residue, called fuel oil sludge, consists of oil, water, and dirt. Second, in all ships, contaminated waste water, mainly from the engine room, gradually builds up at the bilge, the lowest space of the ship. This so-called bilge water contains a varying mixture of lube oil, fuel, water, solvents, detergents and other substances. Bilge water needs to be pumped out regularly to prevent the bilge wells from overflowing and to maintain stability of the ship. Third, the cleaning of cargo tanks of oil tankers creates oily slop.⁶

A low-cost and time-saving solution to handle these waste products is to simply dispose the bilge water, the fuel oil sludge and the slop into the sea (Crist 2003, Gullo 2011). Up into the 1970s this was common practice. Even though the spills are small compared to accidental oil spills – ranging from less than 100 liters for minor bilge water discharges to dozens of tons for tank washings – spill size is not necessarily a good predictor of environmental impact (Burger 1993). These smaller discharges can have

⁵ Camphuysen (2010) finds that rates at which different types of beached seabirds are oiled are correlated with law enforcement activity in the habitats of these birds, suggesting a deterrent effect, but leaving open alternative explanations such as differences in shipping intensity. Lagring et al. (2012) correlate time-series data on possible oil spills from the Belgian Coast Guard with regulatory changes, and their findings suggest a positive impact, but the influence of other factors cannot be excluded. O'Hara et al. (2013) model how aerial surveillance efforts are related to the number of observed spills in the Pacific Ocean. They find lower levels of illegal discharges than predicted by the model in the area closest to the airbase of the surveillance aircraft, suggesting a deterrent effect from aerial surveillance – at least on discharges during the day. Close to all of the literature on marine oil pollution focuses on the prevention of non-intentional oil spills. See Knapp and Franses (2009) on the effect of mandatory changes in ship design; Gawande and Bohara (2005) on the effect of Coast Guard inspections and penalties; Eppele and Visscher (1984), Cohen (1986, 1987) and Viladrich Grau and Groves (1997) on the effect of Coast Guard surveillance on oil spills during oil transfer operations within the harbor.

⁶ Currently, oil residues are mostly removed by spraying the tanks with pure oil (crude oil washing), rather than water. However, about twice a year a tanker is washed with water to be able to perform inspections and maintenance, resulting in some 6,000 m³ of slop per tanker per year (Crist 2003: 12).

large detrimental effects on marine life because they contribute cumulatively more to oil pollution input into the marine environment than accidental spills, and are more likely to occur at the wrong place at the wrong time (National Research Council 2003, Camphuysen 2010). The pollution is chronic, putting continuous pressure on ecosystems in and close to major shipping lanes.

To limit environmental harm from shipping, a set of regulations was drafted in the 1973 International Convention for the Prevention of Pollution from Ships (MARPOL), organized under auspices of the International Maritime Organization (IMO). After some modifications, and after ratification in most of the countries participating in the IMO, the regulations that relate to oil pollution came into force in 1983. Close to all countries with some presence at sea are parties to the Convention. The regulations involve pollution standards, ship design standards, and mandatory self-reporting. The aim is to force the shipping industry to use alternatives to illegal discharges into the sea. Vessels have oil-water separation systems that remove the water component of waste products that build up during normal operations. Separated water should contain hydrocarbon concentrations of no more than 15 parts per million (15 mg per liter), which can be discharged legally while the vessel is at sea and underway. The oily slops that remain have to be stored for future disposal, which can occur legally in two ways. The first, most commonly used method of disposal is to incinerate oil sludge and other oily waste products in shipboard incinerators, which are present on most large vessels. The second method is to dispose sludge and slop at port reception facilities.

Under current pollution standards, all discharges of oil in the North Sea area are prohibited. Only substances contaminated with less than 15 parts per million oil can be legally discharged. Prior to the North Sea becoming a Special Area in 1999, discharges of up to 100 parts per million were allowed outside the 12 miles zone. The ship design standards involve the fitting and proper functioning of an oil discharge monitoring and control system, an oily water separator, tanks for the storage of slop and sludge, and related piping and pumping arrangements. Shipping crews are also mandated to self-report how they handled oily waste products (and movement of cargo oil) in the Oil Record Book, which can be inspected by the authorities when visiting the harbor. Finally, incineration of cargo oil residues is prohibited. MARPOL regulations also require countries to provide legal alternatives in the form of port reception facilities for oily waste products.

The regulations are primarily enforced by aerial surveillance and port-side inspections. In this paper, we focus on aerial surveillance. Coast Guard aircraft conduct surveillance flights above the Dutch Continental Shelf on a daily basis. Most of the flights occur during the day (70 percent). Radar on board of the aircraft detects possible oil spills through anomalies on the water surface. For about a third of the surveillance flights, satellite images are also used to guide the aircraft to potential oil spills. The combination of satellite and airborne remote sensing technology allows monitoring of vast sea areas at day and night, under all sky conditions and under most weather conditions.

All identified oil spots can be characterized as illegal, because oil spots containing less than 15 ppm are never detected by airborne radar; and oil spots containing less than 100 ppm are very unlikely to be detected (Dienst Noordzee 1992). The radar is fine-tuned to identify oil spots, but it is not perfectly accurate, particularly at very low and very high wind speeds. False positives occur when other phenomena produce similar anomalies on the water surface, including fresh water slicks, seaweed, algae blooms, and subsurface sand banks (Fingas and Brown 2012). Generally, after radar has detected a spot, the aircraft swerves back for a visual inspection and for an investigation of the size and thickness

of the spot. The monitoring technology did not undergo fundamental changes since it was first used about 25 years ago. The number of flight hours gradually increased from 600 to 1,200 per year between 1990 and 1996 and has remained fairly constant since then.

The chance of being convicted for an illegal oil discharge is remote. First, the Coast Guard aircraft are not in the air for 85 percent of time, and when in the air, it takes about five hours to cover all of the relevant area.⁷ Oil spills may have disappeared for the radar before the area is surveyed. The duration depends on local weather conditions including wind speed, air temperature and water temperature (Helmers 2002). Generally, spills disappear or at least become undetectable 1 to 7 hours after the discharge (given prevailing wind speeds of 2 to 6 Beaufort (*ibid.*)). The limited number of flight hours also means that shipping crews' chances of observing a Coast Guard aircraft or having radio contact with the aircraft are very small.

Second, even when Coast Guard aircraft observe an oil spill, it is difficult to link the spill with a particular vessel in the busy shipping lanes of the North Sea. The data collected by the aircraft show that in 9 out of 10 cases the offending vessel cannot be identified. In other words, the offender needs to be caught in the act or just after the act.

Third, on the off chance that an offender is detected, the case may still be dropped because of a lack of evidence. In the Netherlands, for a prosecutor to proceed with a case, an aerial observer needs to have confirmed the illegal nature of the substance based on visual inspection from the air.⁸ The courts rely on the aerial observer's ability to identify the specific appearance of oil on the water surface. In other words, all of the advanced monitoring technology can only be used to guide the aerial observer to a potential oil spill for a visual inspection. This is useful in and of itself, however, because it improves the efficiency of aerial surveillance. Clearly, the standard of evidence has large implications for the chance of being convicted. In low-visibility conditions, including the hours between sunset and sunrise, fog as well as heavy precipitation, the probability of conviction drops to zero.

In the Netherlands, over the period 2006-2012, yearly some 10 to 15 vessels were identified as suspects of an illegal oil discharge. In about half of the cases, the prosecutor proceeded with the case.

3. Data and descriptive statistics

Data on all radar-identified spots and the flight paths of all Coast Guard aircraft surveillance flights above the Dutch Continental Shelf during 1992-2011 were provided by the Netherlands Ministry of Infrastructure and the Environment. The data are part of the 'VluVerO'-database and are unique in covering a long period.⁹ The original data are in GIS-format and have been transferred into a grid of 2.5 by 2.5 kilometer. The grid is based on UTM31N-coordinates. We assume the airborne radar to cover an area of 20 km to the right and 20 km the left of the aircraft. Unit of time is an hour.

⁷ The chance that a discharge is detected is limited to the flight hours conducted: reports of oil spots by third parties such as other ships or civilian aircraft crossing the North Sea are exceedingly rare, and cases of a whistle-blower reporting an illegal discharge to the authorities, not unheard of in the US, seldomly occur in the Netherlands.

⁸ In some countries, the standard of evidence is even higher. For instance, in Denmark, it is also necessary to provide a sample of the substance, which is obtained from an oil sampling buoy.

⁹ We exclude spots identified by satellite only since data on the frequency of orbit and which area was covered at what resolution could not be obtained.

For each grid cell we know when it was surveyed by airborne radar. We exclude grid cells that were not covered at least once by airborne radar during 1992-2011 (this involves 24m cell-hour combinations). We also excluded the very north of the Dutch Continental Shelf since it has very low shipping traffic intensity (this involves 2.6m cell-hour combinations). Finally, we excluded areas where not a single spot was identified during 1992-2011 (this involves 13m cell-hour combinations). The resulting data set relates to an area of 17,450 km² – compared to 57,000 km² for the complete Dutch Continental Shelf. These restrictions make the data more tractable and do not affect our estimation results. Within this area, on average each grid cell was surveyed 214 times per year during 1992-2011. Coverage varied between 1 and 510 times on average per year. Figure 1 shows the annual flight intensity.

[FIGURE 1]

All 6,610 spots that were identified during 1992-2011 were assigned to a grid cell. When matching spots to the grid, we allowed for a one-hour or two-hour difference between the time that a spot was observed and the time that the aircraft was noted to be crossing that grid cell. These differences could arise because aerial observers incidentally used Universal Time, the default in aviation, rather than local time in Amsterdam, the prescribed time standard for the database. The difference between the two is limited to two hours during daylight saving time and one hour otherwise. Further information on a spot, including the nature of the substance, its size and thickness, is incomplete, in particular during darkness, and not used in the analysis.

Figure 2 shows the trend in the probability of detecting a spot during 1992-2011. Clearly, the trend is downwards. The suggested drop in illegal oil discharges is confirmed in counts of beached seabirds that are oiled (Camphuysen 2010) and in the trend in radar-identified spots in the German and Belgian part of the North Sea (Carpenter 2007, Lagring et al. 2012). The decline has been attributed to a range of factors including changes in ship design, better facilities for legal disposal in the harbor, strengthened port state control and greater environmental awareness of shipping crews (*ibid.*). Shipping intensity remained roughly stable when measured by the number of sea-going vessels visiting the harbors of Rotterdam and Amsterdam (tonnage increased because of the trend towards larger vessels).¹⁰

[FIGURE 2]

Figure 3 shows the incidence of radar-identified spots during 1992-2011 in the Dutch part of the North Sea. The areas with the highest incidence are concentrated in the three major shipping lanes along the coast and in the approaches towards the harbors of Antwerp, Rotterdam, Amsterdam and IJmuiden. This confirms that the data relate to discharges from shipping rather than oil from other sources, such as oil and gas exploration in the North Sea. Figure 3 shows that the area with the most oil and gas platforms, the southwestern part of the Friese Front (around coordinates 575000, 5900000) has a relatively low incidence of observed spots.

¹⁰ According to locally administered harbor statistics, the number of vessels visiting Rotterdam varied around 30,000 per year during 1992-2011; the number of ships visiting Amsterdam around 4,700 during 1992-2005 and around 5,400 during 2006-2011.

[FIGURE 3]

The time at which a spot was observed is usually not the time at which it was discharged (assuming that the spot is an illegal oil discharge). As discussed, oil spills remain on the water surface for a limited time only. This implies that a relatively high tendency to discharge at some hours will result in a build-up of discharges during these hours, and a gradual phase out after these hours. In other words: discharges that are concentrated in time accumulate because they do not disappear immediately. Figure 4 shows the probability of detecting a spot by hour of the day in the raw data. The line with the black dots suggests that the probability of detecting a spot strongly increases after 6pm and starts to decline after 10pm. This suggests a tendency to discharge between 6pm and 10pm. The line with the open dots in Figure 4 shows that most flights are conducted at times that the probability of detecting a spot is relatively low.

[FIGURE 4]

We match the geographical data discussed above with meteorological data. The meteorological data are provided by the Royal Netherlands Meteorological Institute (KNMI) and include air temperature and wind speed on an hourly basis. Measurements are taken at Lichteiland Goeree weather station, which is located 30 km off the coast, southwest from Hoek van Holland (the approach of Rotterdam harbor). The Ministry of Infrastructure and the Environment provided data on the water temperature at the Europlatform weather station, 60 km off the coast from Hoek van Holland. We exclude observations at wind speeds lower than 1.5 m/s (1 Beaufort) and higher than 20.8 m/s (9 Beaufort). In these weather conditions, the radar is ineffective (see Section 3). This affects about 2 percent of observations. We assume similar water and air temperatures and wind speeds across the Dutch part of the North Sea, which is a reasonable approximation for our purposes according to the KNMI. The KNMI also provided the time of sunset and sunrise at 52°00' northern latitude and 5°00' eastern longitude on a daily basis for 1992-2011. Table 1 presents the summary statistics.

[TABLE 1]

4. A test for temporal displacement

It is cheaper and more expedient to discharge the oily waste products into the sea rather than to dispose them at the harbor or to incinerate them on board (Crist 2003, Gullo 2011). Temporal displacement of illegal discharges to hours with no chance of being convicted is straightforward since disposal of oily substances can easily be postponed for a number of hours.¹¹ A similar evasive response may also be driven by a belief that surveillance is at lower levels during low-visibility conditions or a belief that discharges are more likely to be reported to the authorities by other ships and air traffic during high-visibility conditions.

The descriptive statistics discussed in the previous section show that oil discharges are concentrated in the nighttime. That is not necessarily a sign of evasive behavior, however. The crews operate on a

¹¹ Crews may also decide to discharge the products in areas with no chance of being detected, say somewhere on the Atlantic Ocean, but many ships navigate along the coast, and the operational discharges cannot always be postponed for several days.

rigid system of 4 or 6-hour watches; the ship is operational 24/7. A nightly routine may simply fit the schedule of the crew best. To identify whether the timing of discharges is the result of evasive behavior rather than considerations of other nature, we analyze whether the timing changes over the seasons. The time window for evading conviction is many hours shorter during the summer time than during the winter time. Nights are some 9 to 10 hours shorter in June than in December. A necessary condition for the general hourly pattern to reflect evasive behavior is that the timing should be robust to the wild swings in the time of sunset and sunrise during the year. Clearly, we can only distinguish strategic from non-strategic behavior if the discharges are not limited to the few hours that are dark regardless of the season.

For the results of the test to be reliable, measurement error in the observation of oil spots should be orthogonal to the hour of the day.¹² First, all the known sources of false positives either do not vary with time (subsurface sand banks, seaweed, fresh water slicks) or vary at a much slower time scale (algae blooms) (see Section 2). The only exception could be other illegal discharges that shipping crews like to hide from the authorities such as environmentally harmful cargo residues. These discharges are very rarely observed by the Coast Guard aircraft however, as evidenced by the data used in this paper, and therefore cannot explain daily patterns. We exclude times at which the radar does not work (very low and very high wind speeds). Second, it is reasonable to assume that false negatives are equally likely during the daytime and during the nighttime. Observation by radar is unaffected by the absence of daylight and anecdotal evidence from experienced aerial observers suggests that spots are rarely identified by visual inspection only.¹³

The identified hourly pattern relates to aggregate behavior of all vessels navigating the North Sea. If a sizeable number of ships concentrate their illegal discharges at specific hours, then we will observe an upswing in the number of spots. This implies that we test for a general tendency for temporal displacement, allowing individual ships to diverge from the general pattern.

A number of major events may have altered a tendency to discharge at night during 1992-2011. First, the greater enforcement effort since 1996 may have lowered this tendency. Second, illegal discharges became less permissible as of 1999 when the North Sea became a MARPOL Special Area – reflecting the particular sensitivity of this marine environment to oil discharges because of its shallowness. Since

¹² Differences in shipping intensity or in types of vessels between day and night can be excluded as a source of bias. Commercial shipping is a 24/7 business, and both shipping intensity and the mix of vessels are roughly stable over the course of the day. The relatively great presence of pleasure craft during the day is not likely to lead to a downward estimation bias because they are responsible for only a tiny percentage of illegal oil discharges (about 1 percent, see Beco 2013: 6).

¹³ The smaller surveillance effort during the night than during the day may be a source of measurement error in the probability of detecting a discharge. As worked out in O'Hara et al. (2013), the relationship between surveillance effort and detection probability may be s-shaped rather than linear. This is related to the fact that oil spots can be detected for only a limited number of hours after the discharge. At low (high) levels of surveillance effort, greater surveillance effort leads to a more-than-proportional (less-than-proportional) increase in the detection probability. Given the fact that oil spots tend to be on the water for some hours and the North Sea area is patrolled no more than once a day, our observations are likely to be at the left part of the s-shaped curve (for a discussion, see also Lagring et al. 2012 on the southern North Sea). In that case, the difference in the incidence of spots between the day and the night is even more pronounced than can be deduced from the data – in particular given a trend towards a greater share of small volume-discharges that disappear relatively quickly for the radar. Consequently, estimates of equation (1) may provide lower-bound estimates of the day/night pattern.

then, ship companies had to comply with the most stringent oil discharge provisions when navigating in the North Sea. This could have both lowered illegal discharges and increased displacement. The new regulations came only in effect from August 1999, which is why we assume that effects on illegal behavior, if any, can be identified as of the year 2000. Third, doing the right thing became easier with better port reception facilities for disposal of oily waste that were the result of the implementation of the EU Directive 2000/59/EC. Dutch law was brought in line with EU-regulations at the end of 2004. Volumes of legally disposed oily waste greatly increased as a result.¹⁴ This is likely to have lowered the rate of illegal discharges. In the analysis, we separately test for the presence of temporal displacement in each of the following periods: 1992-1995; 1996-1999; 2000-2004; 2005-2011.

5. Estimation results

As a first step, we graphically examine the hourly pattern in detected spots. We specify a linear probability model that flexibly estimates variation in radar-identified spots by hour of the day.¹⁵ To be able to detect seasonal variation in the timing of discharges, we allow the effects by hour of the day to vary between autumn/winter (September 22-March 20) and spring/summer (March 21-September 21). A break-up of the year into more than two seasons is not possible because of the low incidence of detected spots. We estimate the following equation:

$$P(SPOT_{i,t}) = HOUR_t AUTUMN/WINTER_t \alpha + HOUR_t SPRING/SUMMER_t \alpha' + X_t \beta + \delta_i + \mu_j + \lambda_m + \varepsilon_{i,t} \quad (1)$$

The dependent variable $P(SPOT_{i,t})$ is the probability of detecting a spot at grid cell i and at hour t . We estimate the variation in this probability by hour of the day with the vector of hour-fixed effects $HOUR_t$. We allow these effects to vary between *AUTUMN/WINTER* and *SPRING/SUMMER*. Because of the seasonal swings in the time of sunset and sunrise, the time window for evading conviction is on average 5 hours shorter during autumn/winter compared to spring/summer. X_t is a vector of observable factors that are related to the probability of detecting a spot and to the hour of the day, including water temperature, air temperature and wind speed. Wind speed is somewhat higher during the night than during the day. Temperatures are generally higher during the day than during the night. We do not know the exact nature of the relation between weather conditions and the dependent variable, which is why we also include quadratic terms for each of these three covariates. δ_i represents area-fixed effects that are constant over time, for instance whether grid cell i is inside or outside a major shipping route. μ_j represents the year-fixed effects, which picks up general shocks to the chance of observing a spot, such as any effects of the increase in surveillance effort in 1996. The month-fixed effects λ_m capture any seasonal effects that are constant over time such as algae blooms in the spring. $\varepsilon_{i,t}$ is an error term.

Figure 5 presents the results from estimation equation (1) for each of the four periods. The left vertical axis shows the probability of detecting a spot relative to 12pm. To relate the hourly changes in detected spots to the overall rate, the intercept is not set at 0 but at the average probability of

¹⁴ For instance, in the harbor of Rotterdam, disposal of oily waste from commercial shipping almost doubled from 131,650 m³ in 2004 to 227,569 m³ in 2011 (Lagring et al. 2012: 645).

¹⁵ The findings are similar when estimating a logit model. Given the rarity of observed spots, I also estimated the logit model for rare event data suggested by King and Zeng (2001). Again, the results are similar (results available upon request).

observing a spot at 12pm during the respective time period. The right vertical axis shows the probability of darkness by hour of the day. The black line denotes the pattern in autumn and winter; the grey line the pattern in spring and summer.

[FIGURE 5]

The first graph, for the period 1992-1995, suggests that the timing of illegal discharges is not driven by variation in the time of sunset and sunrise. During both seasons, the upswings in the probability of detecting an oil-like spot are concentrated in the hours 5-11pm, 12-2am, and 7-8am, suggesting that these are popular times for illegal oil discharges. As discussed above, if discharges are concentrated in time, then the spills tend to accumulate, resulting in an increasing probability of observing a spot. Most of the upswing during spring/summer occurs in broad daylight, suggesting that the year-round on-board routines have not been fine-tuned to avoid conviction. The identified pattern shows a close fit with the schedule of watches. Most of the action occurs during the watch of the chief engineer (6pm-12am and 6am-12pm for vessels on a 6 hour watch system or 8pm-12am and 8am-12pm for vessels on a 4-hour watch system). Lower-level engineers seem to be involved to a lesser extent, given the relatively small upticks after midnight. To conclude, during 1992-1995, we do not find clear evidence for temporal displacement.

The second graph shows that during 1996-1999 the pattern in detected oil-like spots for the two seasons are no longer as similar as they used to be. More of the wave in spots during the spring/summer-season is now concentrated in the nighttime. Some of the early-night peak during spring/summer still occurs before sunset, however. This suggests that temporal displacement, if at all present, is not widespread. The primary change is a drop in the overall level of discharges, not a displacement towards the nighttime.

During 2000-2004, when regulations are more stringent than in previous years, close all of the upward swings in oil-like spots occur during the nighttime. The identified patterns diverge for the two seasons. The early-night wave in detected spots during spring/summer starts at 8pm, two hours later than during the autumn/winter, and at the average time of sunset during spring/summer. The early-morning peak in spring/summer also stops right before sunrise, and also occurs three hours earlier than during autumn/winter. This suggests that if oily waste is discharged illegally, then it is done at times that conviction can be evaded. These signs of evasive behavior go together with a drop in the overall rate of detected spots by more than 50 percent compared to the previous period. Apparently, the stricter regime resulted in both greater deterrence of illegal discharges in the North Sea area and a stronger tendency to evade conviction.¹⁶ Some of the discharges may have been displaced to other, less-patrolled areas such as the Atlantic coast off France and the Bay of Biscay, but this spatial displacement effect has not been studied. The third graph also shows that the peaks become more

¹⁶ It could be that daily discharges are deterred and nightly discharges are not deterred. In that case, there is no temporal displacement of crime. This is not a plausible explanation for our findings, because oil discharges can be planned. It would imply that ships use legal and illegal alternatives interchangeably, which is implausible. For instance, the same ship that sails in the North Sea would put the oily waste in storage tanks during the day and dispose it at the harbor later (or incinerate the waste on board), but would illegally discharge oil at night. Clearly, if the option of an illegal discharge is in the choice set of the crew, it makes more sense to wait until after sunset rather than going through the effort of doing the right thing during the day.

accentuated. This is in line with a trend towards a higher percentage of relatively small discharges (especially in volumes between 1-10 m³). Small discharges disappear relatively quickly for the radar (Helmers 2002), resulting in a relatively steep downward slope after the accumulation of discharges.

In the last period, 2005-2011, the rate of detected oil-like spots is even lower than in the previous period, probably as a result of the much-improved facilities for legal disposal in the harbor (see Section 4). The daily pattern is similar, but less articulated than in the previous period given the lower rate of detected spots. The autumn/winter early night-uptick starts at 6pm, well after the average time of sunset in this season; the spring/summer early night-uptick starts at 10pm, also well after the average time of sunset. In the early morning, the pattern is reversed, with the major peak in the spring/summer season ending at 4am and in the autumn/winter season at 8am.

As a second step, we test whether incidence of detected spots in the nighttime is statistically significantly different from the incidence in the daytime – while controlling for daily routines on board that are fixed across the seasons. We estimate the following equation:

$$P(SPOT_{i,t}) = \alpha DARKNESS_t + HOUR_t \alpha + X_t \beta + \delta_i + \mu_j + \lambda_m + \varepsilon_{i,t} \quad (2)$$

The variable *DARKNESS_t* has a value of 1 after sunset and before sunrise and is 0 otherwise. The hour-fixed effects *HOUR_t* reflect year-round daily routines on board.¹⁷ Table 2 summarizes the results.

[TABLE 2]

The first two columns of Table 2 relate to the 1992-1995 period. In the first column, we do not find a statistically significant relationship between the probability of detecting a spot and the time between sunset and sunrise, while controlling for a year-round daily trend in detected spots. The other estimated parameters show a positive relationship between air temperature and the probability of detecting a spot, and a negative relationship for water temperature and wind speed. In the second column, we correct for possible measurement error in our data due to varying use of Universal Time and local time by aerial observers. As discussed in Section 3, the difference between the two goes up from one to two hours during Daylight Saving Time, the exact dates of which differ between the years. We add a Daylight Saving Time-fixed effect and an interaction of the hour-fixed effects with Daylight Saving Time to estimation equation (2). This does not alter the results. The findings for 1996-1999 are similar (columns 3 and 4). Again, we do not find evidence for temporal displacement.

In line with the discussion of the graphical evidence, we find a statistically significant relationship between the probability of detecting a spot and the time that it is dark for the period 2000-2004 (columns 5 and 6). Relative to the rate at 12pm, it is more than 70 percent higher during the nighttime. Based on these parameter estimates, it is not easy to say how much oil was discharged at the nighttime rather than the daytime, given the fact that oil tends to remain on the water surface for several hours (Section 3). The graphical evidence in Figure 5 suggests that close to all illegal oil discharges occur during the nighttime, because all upswings in the probability of detecting a spot are concentrated in

¹⁷ In this specification, we do not include time lags to capture the effect of a discharge before sunrise that may still be detected after sunrise. The graphical analysis showed that including a time lag is not essential, which is why we prefer this simple specification.

the nighttime. The size of the other estimated parameters changes compared to the previous period, which may be related to oil discharges slowly becoming smaller in volume (Lagring et al. 2012).

For the period 2005-2011, we no longer find a statistically significant relationship between the probability of detecting a spot and darkness – even though Figure 5 showed that the graphical pattern remained similar to 2000-2004. This is most likely due to the low rate of detected spots during the most recent years in our data. The limited variation in the probability of detecting a spot cannot be reliably related to the time that it is dark after controlling for a year-round fixed hourly pattern.

6. Conclusions

This paper illustrates the relevance of uncovering the dynamics of illegal behavior in response to imperfect monitoring and enforcement. For many years, the shipping industry has been suspected from shifting illegal oil discharges to the nighttime, when the probability of conviction is effectively zero. This conjecture has never been investigated before, however. It is not clear whether the primary deterrence technology employed for decades by a great number of western countries, airborne radar, has resulted in a tendency for temporal displacement.

We provide the first empirical evidence that the gap in enforcement only has been actively exploited by a significant share of shipping traffic after 1999, when regulations of oily waste discharges in the North Sea area were tightened. Prior to this regulatory change, a substantial part of illegal oil discharges occurred during the nighttime, but the hourly pattern in oil-like spots on the surface is found not to be robust to the wild swings in the time of sunset and sunrise during the year. A more likely explanation for the tendency to discharge at relatively late or early hours are the year-round daily routines on board driven by the schedule of watches. Only after 1999, with further tightening of the regulations and a considerable drop in the overall level of discharges, did the hourly pattern in discharges become robust to the variation in time of sunset and sunrise. In these years displacement to the nighttime is all but complete. Our findings suggest that most shipping companies chose to stop illegal oil discharges in the North Sea area rather than to displace them to the nighttime.

The findings are relevant to all coastal countries with shipping traffic along the coast. Marine oil pollution is a worldwide problem – and remains so even after a period of prolonged decline after regulations came in place in the beginning of the 1980s. Highly advanced remote sensing technologies based on airborne radar and satellite imagery that is employed in the Netherlands, but also in many other nations including the US, Canada and France, may have had a deterrent effect, but may push illegal discharges towards times where deterrence is ineffective. We find this tendency to be limited, but our findings may be conditional on other policies that put downward pressure on the overall level of discharges, including mandated changes in ship design, better facilities for legal disposal in the harbor, strengthened port state control and educational efforts to foster greater environmental awareness of shipping crews.

References

- Beco Consultancy, 2003, *Afvalstoffenemissies van zeeschepen*, unpublished report, Rotterdam.
- Burger, A.E. 1993, Estimating the mortality of seabirds following oil spills: effects of spill volume, *Marine Pollution Bulletin*, 26 (3), 141-143.
- Camphuysen, Kees, 2010, Declines in oil-rates of stranded birds in the North Sea highlight spatial patterns in reductions of chronic oil pollution, *Marine Pollution Bulletin*, 60, 1299-1306.
- Camphuysen, Kees and Ben Vollaard, 2015, Oil pollution in the Dutch sector of the North Sea, in: Angela Carpenter (ed.), *Oil pollution in the North Sea*, Handbook of Environmental Chemistry, Springer, Berlin.
- Carpenter, A., 2007, The Bonn Agreement aerial surveillance programme: trends in North Sea oil pollution 1986-2004, *Marine Pollution Bulletin*, 54, 149-163.
- Clarke, Ronald V., and David Weisburd, 1994, Diffusion of crime control benefits, in: R.V. Clarke (ed.), *Crime Prevention Studies*, Vol. 2. Criminal Justice Press, Monsey (NY).
- Cohen, Mark A., 1986, The costs and benefits of oil spill prevention and enforcement, *Journal of Environmental Economics and Management*, 13, 167-188.
- Cohen, Mark A., 1987, Optimal enforcement strategy to prevent oil spills: an application of a principal-agent model with 'moral hazard', *Journal of Law and Economics*, 30 (1), 23-51.
- Cornish, Derek B., and Ronald V. Clarke, 1987, Understanding crime displacement: an application of rational choice theory, *Criminology*, 25 (4), 933-947.
- Crist, P., 2003, Cost savings stemming from non-compliance with international environmental regulations in the maritime sector, OECD/Maritime Transport Committee, Paris.
- Dienst Noordzee, 1992, Visibility limits of oil discharges, Ministerie van Infrastructuur en Milieu/DNZ, Rijswijk.
- Fingas, Mervin, and Carl Brown, 2012, Oil spill remote sensing, in: Robert A. Meyers (ed.), *Encyclopedia of Sustainability Science and Technology*, Springer, 7491-7527.
- Foo, Lora Jo, 1994, The vulnerable and exploitable immigrant workforce and the need for strengthening worker protective legislation, *Yale Law Journal*, 103 (8), 2179-2212.
- Gawande, Kishore, and Alok K. Bohara, 2005, Agency problems in law enforcement: theory and application to the US Coast Guard, *Management Science*, 51 (11), 1593-1609.
- Gray, Wayne B., and Jay P. Shimshack, 2011, The effectiveness of environmental monitoring and enforcement: a review of the empirical evidence, *Review of Environmental Economics and Policy*, 5 (1), 3-24.
- Guerette, R.T., and K. Bowers, 2009, Assessing the extent of crime displacement and diffusion of benefit: A systematic review of situational crime prevention evaluations, *Criminology*, 47(4), 1331-1368.
- Gullo, Benedict S., 2011, The illegal discharge of oil on the high seas: the US Coast Guard's ongoing battle against vessel polluters and a new approach toward establishing environmental compliance, *Military Law Review*, vol. 209, 122-185.
- HELCOM, 2011, Annual 2011 HELCOM report on illegal discharges observed during aerial surveillance, Helsinki Commission, Baltic Marine Environment, Protection Commission.
- Helmers, R., 2002, Statistical analysis of oil pollution data (1992-2000) from the Dutch part of the North Sea, Centre for Mathematics and Computer Science, Amsterdam.
- Heyes, Anthony G., 1994, Environmental enforcement when inspectability is endogenous, *Environmental and Resource Economics*, 4 (5), 479-494.
- Jacob, Brian, Lars Lefgren, and Enrico Moretti, 2007, The dynamics of criminal behavior. Evidence from weather shocks, *Journal of Human Resources*, 42 (3), 489-527.

- King, Gary, and Langche Zeng, 2001, Logistic regression in rare events data, *Political Analysis*, 9, 137–163.
- Lagring, Ruth, Steven Degraer, Géraldine de Montpellier, Thierry Jacques, Ward van Roy, and Ronny Schallier, 2012, Twenty years of Belgian North Sea aerial surveillance: a quantitative analysis of results confirms effectiveness of international oil pollution legislation, *Marine Pollution Bulletin*, 64, 644-652.
- McCrary, Justin, 2010, Dynamic perspectives on crime, Chapter 4 in: Bruce L. Benson and Paul R. Zimmerman (eds.), *Handbook of the Economics of Crime*, Edward Elgar, Cheltenham, 82-108.
- Meetkundige Dienst, 1981, *Een halve eeuw Meetkundige Dienst 1931-1981*, Rijkswaterstaat, The Hague.
- National Research Council, 2003, Oil in the sea III: Inputs, fates and effects, Committee on Oil in the Sea, U.S. National Academy of Sciences, The National Academies Press, Washington DC.
- O'Hara, P.D., N. Serra-Sogas, R. Canessa, P. Keller, and R. Pelot, 2013, Estimating discharge rates of oily wastes and deterrence based on aerial surveillance data collected in western Canadian marine waters, *Marine Pollution Bulletin*, in press.
- Serra-Sogas, Norma, Patrick O'Hara, Rosaline Canessa, Peter Keller, Ronald Pelot, 2008, Visualization of spatial patterns and temporal trends for aerial surveillance of illegal oil discharges in western Canadian marine waters, *Marine Pollution Bulletin*, 56, 825-833.
- Sigman, Hilary, 1998, Midnight dumping: public policies and illegal disposal of used oil, *RAND Journal of Economics*, 29(1), 157-178.
- Telle, Kjetil, 2013, Monitoring and enforcement of environmental regulations. Lessons from a natural field experiment in Norway, *Journal of Public Economics*, 99, 24-34.
- Viladrich Grau, Montserrat, and Theodore Groves, 1997, The oil spill process: the effect of Coast Guard monitoring of oil spills, *Environmental and Resource Economics*, 10, 315-339.
- Yang, Dean, 2008, Can enforcement backfire? Crime displacement in the context of customs reform in the Philippines, *Review of Economics and Statistics*, 90 (1), 1-14.

Table 1. Summary statistics

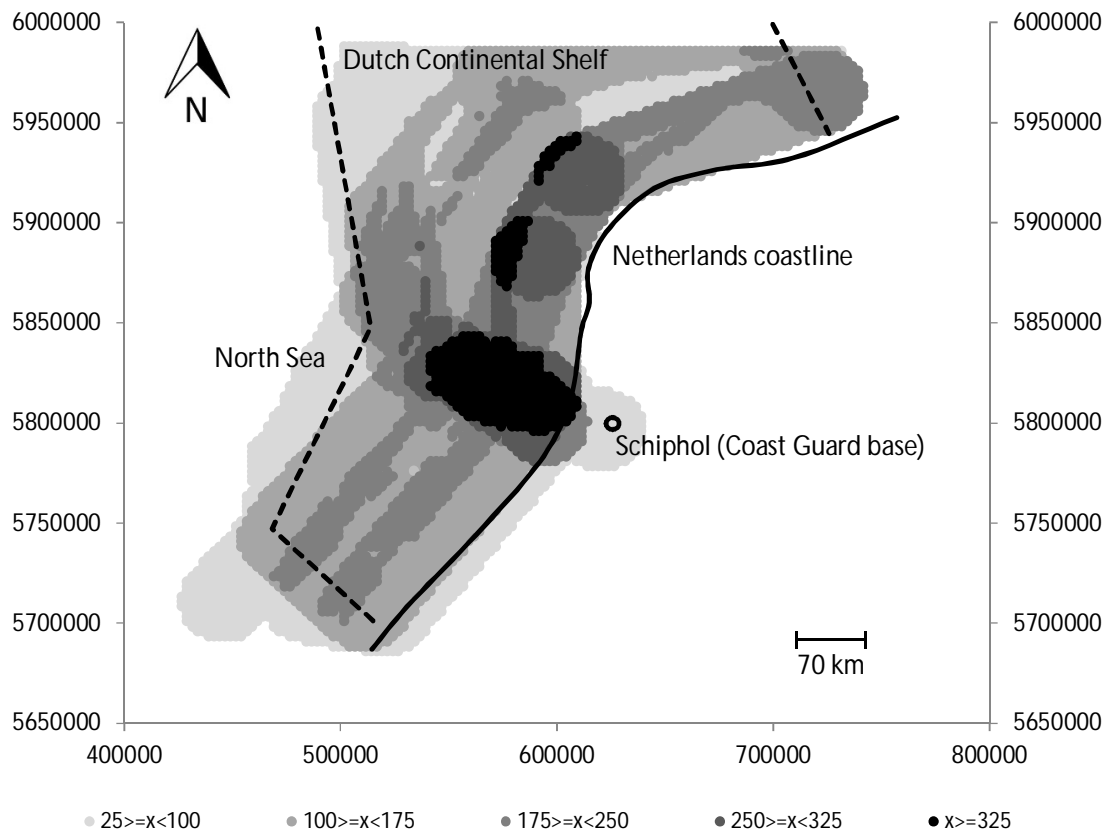
	Mean	Standard deviation	Min	Max
Spot (*1,000)	0.63	25.01	0	1
Darkness	0.32	0.47	0	1
Water temperature (°C)	11.95	4.55	3.80	20.80
Air temperature (°C)	11.05	5.33	-8.80	28.30
Wind speed (m/s)	8.05	3.49	2.00	20.6
Number of observations	10.759.697			

Table 2. Estimated effect of darkness on probability of detecting a spot

Dependent variable: probability of detecting a spot	1992-1995		1996-1999		2000-2004		2005-2011	
Darkness	-0.102 (0.123)	0.139 (0.141)	0.096 (0.090)	0.036 (0.115)	0.215 (0.060)***	0.202 (0.077)***	-0.014 (0.030)	0.042 (0.039)
Air temperature (C°)	0.138 (0.031)***	0.141 (0.031)***	0.058 (0.015)***	0.061 (0.015)***	0.032 (0.013)***	0.028 (0.013)***	0.017 (0.007)**	0.017 (0.007)**
Air temperature ²	-0.001 (0.002)	-0.001 (0.002)	0.000 (0.000)	0.000 (0.000)	-0.000 (0.000)	-0.000 (0.000)	-0.000 (0.000)	-0.000 (0.000)
Water temperature (C°)	-0.447 (0.100)***	-0.454 (0.100)***	-0.205 (0.079)***	-0.200 (0.080)***	-0.021 (0.064)	-0.022 (0.064)	-0.011 (0.025)	-0.014 (0.025)
Water temperature ²	0.012 (0.004)***	0.012 (0.004)***	0.005 (0.003)*	0.005 (0.003)*	0.000 (0.002)	0.002 (0.002)	-0.000 (0.000)	0.000 (0.001)
Wind speed (m/s)	-0.035 (0.004)***	-0.035 (0.004)***	-0.025 (0.003)***	-0.025 (0.003)***	-0.015 (0.002)***	-0.015 (0.002)***	-0.005 (0.001)***	-0.005 (0.001)***
Wind speed ²	0.000 (0.000)***	0.000 (0.000)***	0.000 (0.000)***	0.000 (0.000)***	0.000 (0.000)***	0.000 (0.000)***	0.000 (0.000)	0.000 (0.000)
Daylight Saving Time-offset	No	Yes	No	Yes	No	Yes	No	Yes
Number of grid cells	2,792	2,792	2,293	2,293	2,792	2,792	2,756	2,756
Number of observations	1,871,580	1,871,580	2,256,327	2,256,327	2,744,315	2,744,315	3,887,475	3,887,475

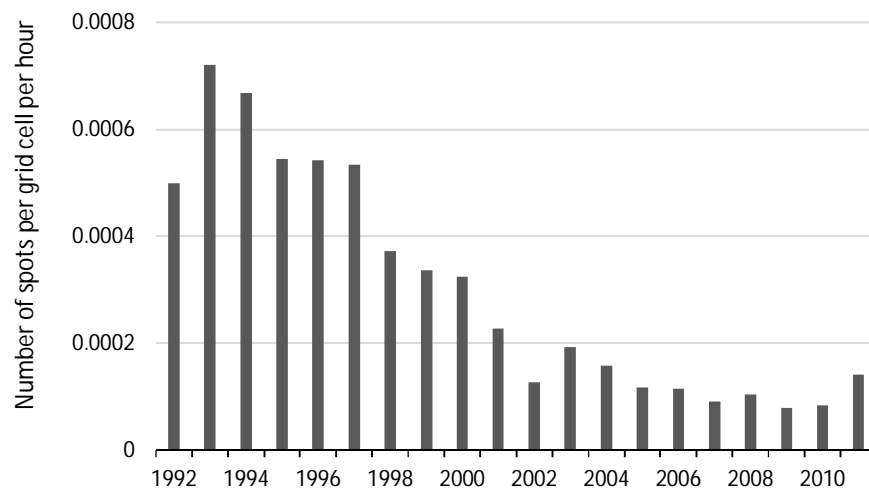
Note. Coefficients * 1,000. Based on data by grid cell and hour. Not shown are coefficients for grid-fixed effects, year-fixed effects, month-fixed effects and hour-fixed effects. Standard errors between parentheses are clustered at the grid cell-level. ***, ** and * indicate statistical significance at the 1, 5 and 10 percent level.

Figure 1. Flight intensity above the Dutch Continental Shelf, 1992-2011



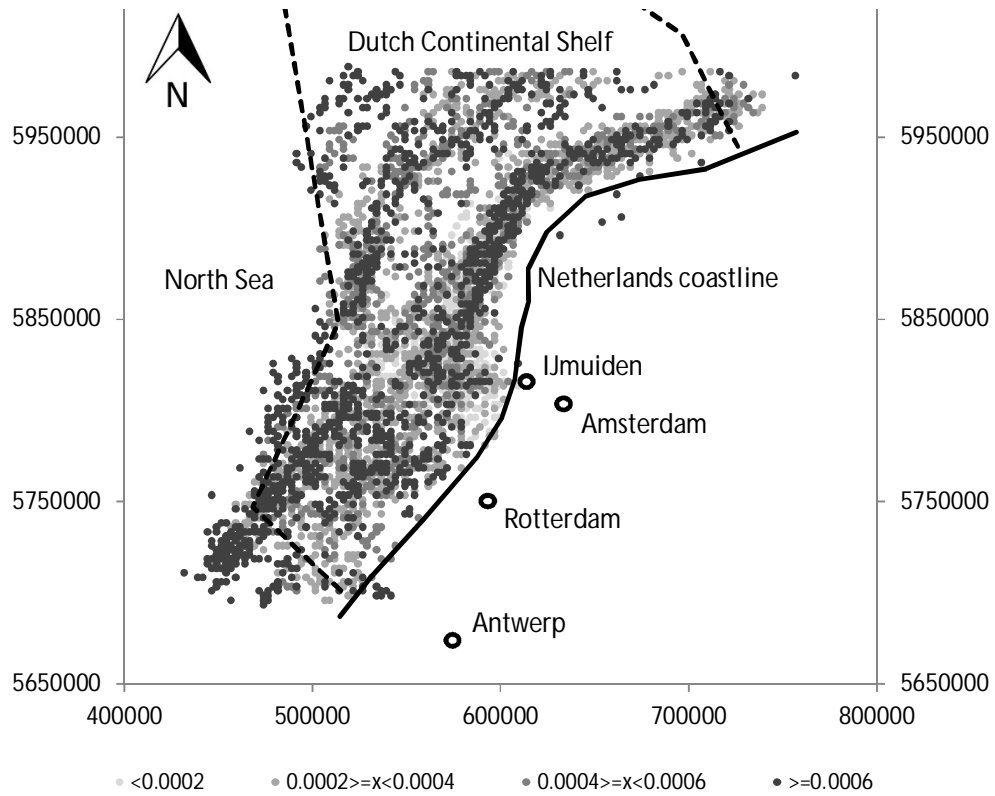
Note. Flight intensity is defined as the average number of times per year that a grid cell was patrolled during 1992-2011. DCS stands for Dutch Continental Shelf. On the axis are UTM31N-coordinates.

Figure 2. Radar-identified spots per grid cell-hour, Dutch Continental Shelf, 1992-2011



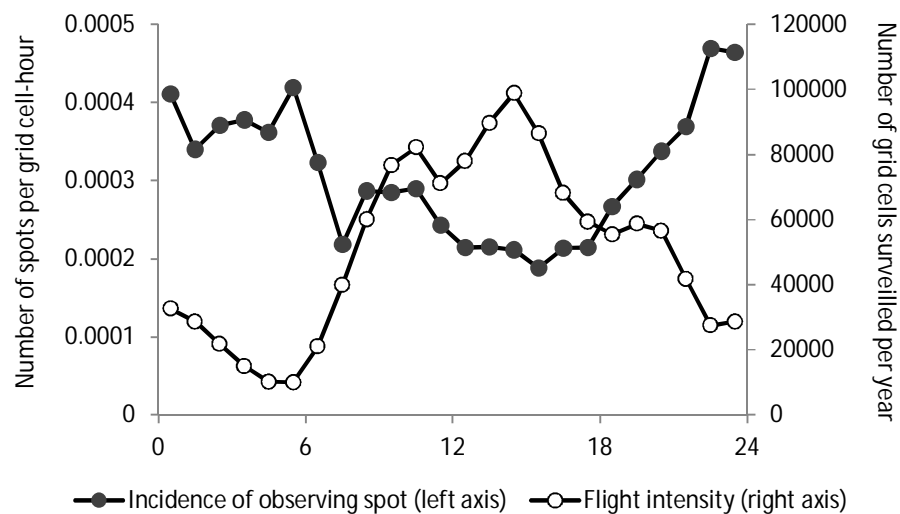
Note. Incidence is defined as the number of yearly identified spots per grid cell per hour. The grid cell size is 2.5 by 2.5 kilometers. On average, a year has 1.2m grid cell-hours.

Figure 3. Average yearly incidence of radar-identified spots, Dutch Continental Shelf, 1992-2011



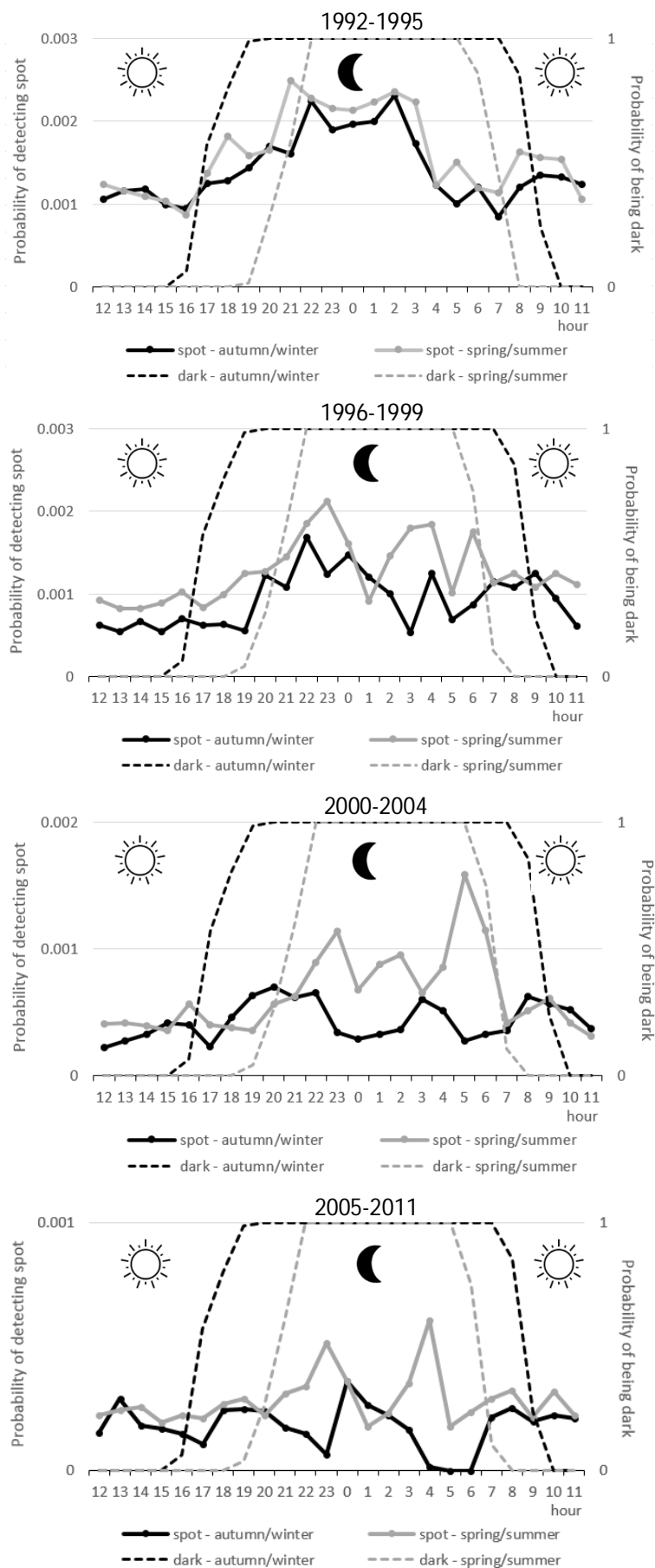
Note. Incidence is defined as the number of yearly identified spots per grid cell-hour. On the axis are UTM31N-coordinates.

Figure 4. Average incidence of detected spots and flight intensity, by hour of the day, Dutch Continental Shelf, 1992-2011



Note. Incidence is defined as the number of yearly identified spots per grid cell by hour of the day. Flight intensity is defined as the yearly number of grid cells patrolled by hour of the day. Both are averaged over calendar years 1992-2011.

Figure 5. Estimated probability of detecting a spot, by season



Note: Graphs plots hour-fixed effects α and α' from estimation equation (1), with the probability of detecting a spot relative to 12 pm on the vertical axis. The intercept is the average probability of detecting a spot at 12pm during selected calendar years. Based on data by grid cell and hour for the Dutch Continental Shelf.

