ICES Journal of
Marine Science

International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

ICES Journal of Marine Science (2020), 77(3), 1148–1156. doi:10.1093/icesjms/fsy116

Contribution to the Themed Section: '*Decommissioned offshore man-made installations*'

Original Article

Commercial fisheries losses arising from interactions with offshore pipelines and other oil and gas infrastructure and activities

Sally Rouse[1,2]*, Peter Hayes[2], and Thomas A. Wilding[1]

[1]*Science Department, Scottish Association for Marine Science, Oban, Argyll PA37 1QA, UK*
[2]*Offshore Energy Environmental Advice Group, Marine Scotland Science, 375 Victoria Road, Aberdeen AB11 9DB, UK*

**Corresponding author: tel: + 44 (0) 1631 559000; fax: +44 (0) 1631 559001; e-mail: sally.rouse@sams.ac.uk*

Rouse, S., Hayes, P., and Wilding, T. A. Commercial fisheries losses arising from interactions with offshore pipelines and other oil and gas infrastructure and activities. – ICES Journal of Marine Science, 77: 1148–1156.

Received 14 May 2018; revised 2 August 2018; accepted 11 August 2018; advance access publication 5 October 2018.

Interactions between fishing vessels and oil and gas infrastructure can result in damage to fishing gear, loss of fishing time/access, and risks to crew health and safety. The spatial and temporal patterns characterizing previous incidents (and subsequent losses) between fishers and oil and gas infrastructure were quantified and used to identify key risk factors associated with fisheries losses. Between the years 1989 and 2016, 1590 incidents that resulted in a financial loss, vessel abandonment, or an injury/fatality for UK commercial fishers were recorded. The annual number of recorded incidents decreased by 98.6% over a 27-year period. The majority of past incidences resulted in financial losses (rather than injuries or fatalities) and were associated with interactions between single otter trawlers and oil and gas production-related debris. The odds of an incidence occurring varied according to substrate type and fishing intensity. A risk-model for pipeline–fishing interactions in the Fladen Ground showed that there was significant spatial heterogeneity in the risk of an incident along a pipeline according to the angle and intensity of fishing. The results highlight the need to include the full spectrum of potential losses in fisheries impact assessments associated with the installation and decommissioning of oil and gas assets.

Keywords: commercial fishing, decommissioning, marine spatial planning, VMS

Introduction

A significant quantity of infrastructure has been installed in the North Sea to support the offshore oil and gas industry, including pipelines, wellheads, and platforms. There are no restrictions on fishing around oil and gas infrastructure, except for within the 500 m exclusion zones enforced around actively producing platforms (Petroleum Act 1998). Commercial fishing activities in the North Sea frequently share space with other marine industries including the oil and gas industry, offshore renewables and dredging (Jentoft and Knol, 2014; Stelzenmüller *et al.*, 2016). Interactions between commercial fishing vessels and oil and gas infrastructure can lead to negative consequences for both the infrastructure integrity and commercial fishing operations (Herlianto *et al.*, 2012; Wu *et al.*, 2015). For commercial fishers, these consequences can include damage or loss of gear, loss of fishing time, spoilt catches (due to oil, chemicals or clay deposits entering nets) and/or injuries/fatalities (Side, 1999; Gómes and Green, 2013; Lucchetti *et al.*, 2017).

Pipelines and cables are of particular concern to fishers because of their wide spatial distribution across the North Sea, and the potential for "clay berms" or "free spans" to be associated with them (DNV, 2006; Hintzen, 2016). Clay-berms, created during pipeline trenching and burial, are long features consisting of irregular mounds of disturbed substratum that lie parallel to the pipeline (de Groot, 1982). Trawl gear can foul on the clay deposits, putting gear and vessels under strain or spoiling the catch (de Groot, 1982; MAIB, 2006). Free spans (sections of pipeline that lie unsupported above the substratum) tend to occur on irregular seabeds or as a consequence of sediment erosion from underneath a pipeline (Park and Kim, 1997). Trawl doors, clump weights or other towed gear can become snagged under free spanning sections of pipelines, potentially risking crew safety or damage to gear (de Groot, 1982; Van der Abeele *et al.*, 2013). Understanding the risks, and consequences, of interactions between commercial fishing and pipelines (as well as other oil and gas infrastructure) is necessary for the planning of new installations, maintenance of existing assets, and, as the industry matures, optimizing decommissioning solutions to ensure that impacts to the commercial fishing industry are minimized. Over the next ten years, the number of pipelines and installations that will require decommissioning is set to rapidly increase (Philip *et al.*, 2014). In the north east Atlantic, decommissioning practices are primarily driven by the OSPAR 98/3 decision to prohibit the disposal of installations offshore (IOGP, 2017). The decision does not cover pipelines and individual nations are able to establish their own legislation. In order to set pipeline decommissioning regulations, and decide whether *in situ* pipeline decommissioning should be permissible, regulators require an evidence-base on the interactions between other marine users and pipelines. The current UK decommissioning guidelines state that, in general, pipelines which are trenched or buried to a depth of >60 cm (measured from the top of the pipeline) may be decommissioned *in situ*, while operators should seek to remove all small diameter, exposed pipelines (BEIS, 2018). The exact decommissioning method is, however, selected on a case by case basis through a comparative assessment process that evaluates the safety implications, cost, technical feasibility and impacts to the environment and other maritime users of the different pipeline decommissioning options. The comparative assessment process is used in many hydrocarbon producing nations, and again requires an evidence-base to evaluate potential impacts to other users of the sea (IOGP, 2017).

Both the fishing and offshore oil and gas industries have a number of responsibilities in relation to minimizing the risks of a serious incident arising from interactions between fishing gear and oil and gas infrastructure and/or debris in UK waters. Operators are required to consult with the commercial fishing industry before authorization will be granted for pipeline construction. The operator must demonstrate that they have considered the impacts to fishing activities and satisfy the regulator that steps have been taken to avoid or reduce interference with fishing by the pipeline (Petroleum Act 1998). Once a pipeline (and any associated protective materials) has been installed, operators must take "reasonable steps to draw attention to the presence of the pipeline" in order to reduce potential pipeline damage and ensure the safety of other marine users (Pipeline Safety Regulations, 1996). Typically, operators will notify the UK Hydrographic Office (UKHO) of pipeline locations. Operators are also encouraged to submit pipeline locations to the Kingfisher Information Service, which collates information on subsea hazards and distributes it to the fishing industry through bi-monthly bulletins (BEIS, 2018). In 2001, the "FishSafe" unit was developed using the Kingfisher spatial information. The unit can be used on board vessels during fishing operations, and alerts skippers to approaching hazards, based on the vessel's GPS.

When pipelines, and protective structures, are decommissioned, operators must inform the same information services (Kingfisher and the UKHO) of any infrastructure that will be left on the seabed. After decommissioning works are completed, operators must provide evidence that the seabed is clear of debris or snagging hazards (BEIS, 2018) This is typically done through sidescan sonar surveys and/or controlled trawling surveys of the area by a fisheries organization, who then issue a seabed clearance certificate (BEIS, 2018). During the operational phase of infrastructure, operators must notify the relevant authorities (including UK Government's Department of Business, Energy and Industrial Strategy, the Maritime and Coastguard Agency, and fisheries organizations) of any dropped objects, and take reasonable measures to locate and retrieve the objects to prevent them becoming a snagging or safety hazard to other marine users (DECC, 2016).

Whilst there are no legal restrictions preventing fishing in the vicinity of pipelines, vessel owners must ensure that their crew follow safe working practices. This includes undertaking a thorough risk assessment prior to commencing fishing operations and taking action to avoid risks and dangerous practices (Merchant Shipping and Fishing Vessels Regulations, 1997). Additionally, there is a legal obligation to avoid damaging pipelines (Pipeline Safety Regulations, 1996).

The level of risk posed by pipelines (operational or *in situ* decommissioned) to commercial fishing activities will be influenced by the pipeline properties (e.g. diameter), the installation method (buried or surface laid), the substratum type, and nature and intensity of fishing in the vicinity. The angle that fishing gear is pulled across a pipeline also significantly alters the risk that gear becomes snagged (DNV, 2006). More acute crossing angles result in a longer period of interaction between trawl gear and the pipeline, leading to an increase in the probability of trawl-door destabilization (DNV, 2006). A trawl door is considered destabilized when it is dragged on its back along the seabed, thereby digging into the substrate and potentially becoming snagged under nearby pipelines (DNV, 2006; Wu *et al.*, 2015). In order to understand the risks and consequences of fisheries–infrastructure interactions, data on the spatial and temporal patterns of interactions are required. Previous fishing risk assessments [e.g. for the Brent field pipeline decommissioning programme (Shell U\.K\. Limited, 2017)] employed data held by the Marine Accident Investigation Board (MAIB) on fishing-pipeline incidents that resulted in fatalities or injuries. The risks of future fishing-related injuries or fatalities for decommissioned pipelines were then calculated from the MAIB data using the "Potential Loss of Life" (PLL) framework for individual pipelines. The PLL is an offshore industry standard for evaluating safety risks and represents the *per capita* fatality risk during an operation (Flage and Aven, 2009). The MAIB register lists 27 previous incidents involving pipelines and fishing vessels over a 25-year period. These incidents include the sinking of the FV "Westhaven" vessel after a trawl door became snagged under a span, and the sinking of the FV "Harvest Hope" after the vessel's tickler chain snagged on clay boulders over a pipeline (Side, 1999; MAIB, 2006). There are no legal requirements to report snagging incidents to the MAIB, and only incidents that are of serious concern from a safety perspective (i.e. injuries, fatalities or "near-misses") are recorded. The MAIB register, therefore, does not record interactions between fishing gear and pipelines that lead to financial losses for the fishers. Modelling the impacts and risks to fishing from different pipeline installations, management, or decommissioning scenarios using only the MAIB data means that the full spectrum of oil and gas related impacts to the commercial fishing industry might be underestimated.

In 1975, a scheme was established to provide financial compensation to UK commercial fishers for losses arising from offshore oil and gas operations, including loss of fishing time or seabed access, and damage or loss of gear and/or catch. The fund is financed by the UK oil and gas industry and is administered by the UK industry representative body Oil and Gas UK (OGUK). Between 1989 and 2013, claims totalling £11.5 million were submitted to the fund (Gómes and Green, 2013). A record of each claim, including details of the date, location, and nature is maintained by OGUK. These records represent a data source for analysing the spatial and temporal patterns in fishing–pipeline interactions and developing a detailed understanding of the likely consequences when interactions do occur.

This study had three aims:

(1) To understand spatio-temporal trends in fisheries losses arising from interactions with oil and gas pipelines and other infrastructure.

(2) To develop a fishing risk model for pipelines within the Fladen Ground to demonstrate how spatial fisheries data can be used to aid pipeline management and decommissioning decisions.

(3) To provide a common evidence base on infrastructure–fisheries interactions for regulators, the oil and gas, and commercial fishing industries, to facilitate effective, transparent decision making.

Methods

Data sources

Records of fisheries losses suffered by UK vessels interacting with oil and gas within UK waters were obtained from the OGUK's Fishermen Compensation Fund. The dataset records 1574 claims submitted between 1989 and 2016 and included information on the incident date, description, vessel name, and location. The most recent year with the total annual figures available was 2015. Records of pipeline–fishing incidents that were not present in the compensation claim database were extracted from the MAIB database. Spatial data on oil and gas infrastructure and free span locations in the North Sea were obtained from the Common Data Access database, maintained by OGUK (CDA, 2013). The pipeline dataset included pipelines and oil and gas-related cables, which are frequently laid alongside pipelines (Oil and Gas UK, 2013). The dataset only included "significant" free spans which are ≥ 0.8 m high over distances of 10 m or more. Since data on the burial status of pipelines were not available, exposed and buried pipelines are not distinguished in the analysis. Fishing track data for the years 2007–2015 were obtained from the Vessel Monitoring System for UK registered vessels operating demersal gear according to the methods of Rouse *et al.* (2017a, b). Data on the location of other potential snagging hazards (shipwrecks and other oil and gas substructures including anchor blocks, manifolds, moorings, and debris) were obtained from the UKHO and OGUK (CDA, 2013), respectively.

Analysis

Each incident was categorized into one of eight classes (debris, unknown, wires, pipelines and protective coverings, anchors, loss of fishing time, gear or access, spoilt catch, production infrastructure, cables) based on the description of the incident. A gear type was assigned to each incident, by matching the incident date, vessel name and registration with records from the EUROPA Fishing Fleet Registry (http://ec.europa.eu/fisheries/fleet/).

To understand temporal trends in fishing–pipeline incidents, the number of incidents was calculated for each year. Incidents with no positional information were then removed from the dataset. Each incident was classified as occurring on mud, sand, mixed sediment, coarse sediment or rocks, and boulders by spatially overlaying the incident data with the EMODnet seabed substrate data layer (Stevenson, 2012). A log-linear model (Agresti, 2013) was fitted to the data to explore whether the frequency of incidences varied according to substrate type. The model was fitted to a contingency table of incident frequencies (excluding claims relating to loss of access to fishing grounds), for three levels of substrate types (mud, sand or mixed, with the mixed category combining the mixed, coarse and rock/boulder categories extracted from the EMODnet substrate layer) and three levels of fishing intensity (high, medium, or low). Incidents were categorized as occurring in areas of high, medium, or low fishing intensity by spatially overlaying incident records with standardized data layers of fishing intensity for vessels operating otter trawls produced by ICES (ICES, 2017). The mean fishing intensity (hours) plus or minus one standard deviation was used to define the thresholds for high, medium, or low fishing intensity. Inclusion of fishing intensity enabled the confounding effects between fishing effort and substratum type to be removed (e.g. where highest fishing effort is associated with a particular substratum type). Models with and without an interaction term between fishing intensity and substrate were compared using a likelihood ratio test and AIC (Crawley, 2012). The odds of an incident occurring on each substrate according to fishing intensity were calculated as the ratio of conditional probabilities (Agresti, 2013). An alternative method, which would allow for the relationship between incident frequency and the relative quantities of infrastructure to be modelled, would have been to delineate polygons of the six categories of substrate and fishing intensity combinations and then sum the number of incidents and quantity of infrastructure in each polygon. However, due to the relatively low number of incidents and short spatial scales over which substrate and fishing intensity change, this method results in a high number of polygons with zero incidents. Such zero inflation prevented the data from being modelled in this way.

For each incident, the distance to the nearest feature in the "pipeline", "shipwreck", or "substructure" datasets was calculated. The feature with the smallest distance was assigned as the nearest hazard to each incident. For each UK pipeline, the number of incidents categorized as occurring on pipelines, cables, or unknown hazards within 1000 m either side was calculated. A distance of 1000 m was selected to be consistent with previous fisheries–pipeline interactions studies (Glabraith and Rice, 2004; Hintzen, 2016; Rouse *et al.*, 2017b). The probability that an interaction between fishing gear and a pipeline led to an incident was calculated according to the methods of Shell U.K. Limited (2017). The annual number of incidents categorized as occurring on pipelines, cables, or unknown hazards were calculated. This number was divided by the annual number of mobile demersal fishing tracks crossing each pipeline for every year between 2007 and 2015 (years of fishing data available) and averaged across the nine years.

Fishing risk model

A fishing risk model was fitted to pipelines within the Fladen Ground, an area of muddy substrate in the northern North Sea (Figure 1), to demonstrate how fishing activity and pipeline-related incident data can be used to identify high-risk pipelines and model future fisheries losses. The Fladen Ground was selected because it is characterized by a uniform substrate type and hosts intense fishing activity and oil and gas exploitation. To account for the fact that the fishing intensity is not uniform across the entire Fladen Ground, pipelines were first divided into sections, according to whether they occurred in high, medium, or low fishing intensity areas (using the methods described above). Pipeline sections that occurred within the 500 m fisheries exclusion zone around platforms were then removed. For each pipeline section, the total length of associated free spans was calculated. The annual risk of an incident occurring was calculated for each pipeline section according to Equation (1). For every track crossing the pipeline section, the base probability of a crossing resulting in an incident was multiplied by a risk weighting for the angle of that crossing and the length of free span associated with the pipeline section. The individual track risks were then summed and divided by nine (number of years of track data) to give the annual risk of incidents.

$$\text{Risk of incident} = \frac{\sum \text{(probability crossing results in incident} \times \text{Angle weighting} \times \text{Spanning factor)}}{9} \qquad \text{Eq. 1}$$

Angle risk weightings were calculated using angle-specific snagging rates derived by Wu *et al.* (2015). In order to derive a function enabling prediction of risks across the full range of crossing angles, a range of polynomial functions linking snagging rate and angle were assessed. A polynomial order was selected based on empirical assessment of the fitted line and the underlying data (Figure 2). The spanning factor was calculated according to the methods of Shell U.K. Limited (2017) as the proportion of that pipeline section that was free spanning. For example, a 10-km pipeline section with a 1-km free span was assigned a spanning factor of 1.1.

Results

The total number of pipeline–fishing incidents was 1590, 539 of which had no positional information available. The vast majority of incidents led to a financial loss (99.6%), rather than vessel abandonment (0.3%) or fatalities/injuries (0.06%). The only incident that was reported to result in injuries/fatalities was the sinking of the FV "Westhaven" vessel. This single incident was associated with four fatalities. The Westhaven was included in the calculation for both fatality/injury and loss of vessel. The majority of incidents were caused by oil and gas production-related debris (including scaffolding poles, safety equipment and metal frameworks: Table 1). Over one-fifth of the claims were classified as "unknown", where a loss was suffered but the source could not be identified. Of the incidents categorized as "Unknown", ∼64% occurred in locations where pipelines were the closest hazard (Table 1). Pipelines and protective coverings (including rock armouring and grout bags placed on top of pipelines) accounted for approximately 13% of all claims over the 28-year period. The nearest hazards to incident locations included pipelines, shipwrecks, and subsurface structures. However, pipelines were the nearest hazard to the majority of incidents across all claim types (Table 1). Vessels operating single otter trawls were responsible for 58% of the claims. The remaining vessels operated a range of gear types including midwater/beam trawls, dredges, seine/gill/trammel nets, pots and traps, and set longlines, but each gear category represented no more than 5% of total claims. Information on gear type was unavailable for 19% of claims. Claims were submitted from 647 vessels, with the number of claims per vessel ranging from 1 to 19.

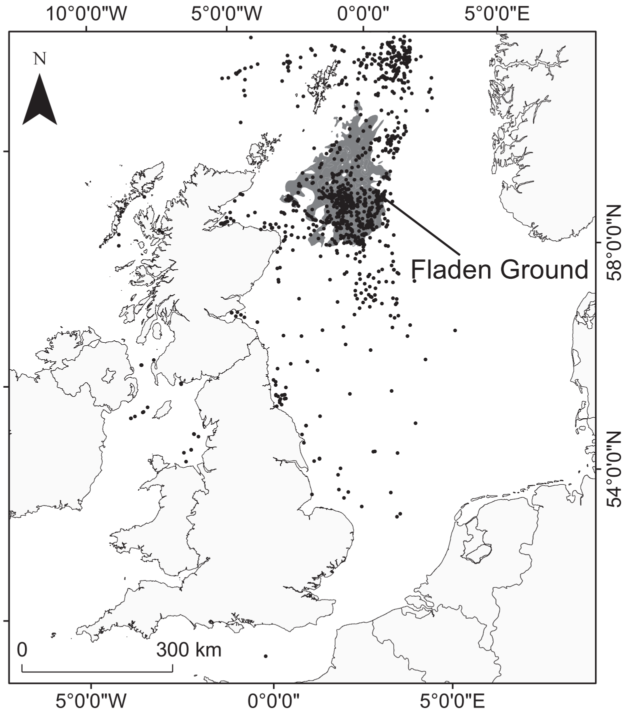

Figure 1. Location of fishing incidents (black dots) with oil and gas infrastructure for which claims were submitted to the compensation claim or were reported to the MAIB. The shaded area shows the Fladen Ground in the northern North Sea.

Temporal and spatial trends

The annual number of incidents showed a general decrease from the 1980s to the present date (Figure 3). In 2015, the number of incidents was 20 times lower than it was in 1990, when incidents peaked at 140. There were 224 (8.3% of total) UK pipelines that had an incident (categorized as relating to a "pipeline", "cable", or "unknown hazard") within 1000 m. The probability that an individual event of fishing gear crossing a pipeline would lead to an incident was estimated as 7.86×10^{-5}. The majority of incidents occurred in the northern North Sea (Figure 1), and 60% of all

Table 1. Percentage of incidents according to category, and the percentage of each category that was assigned pipelines, shipwrecks, or substructures as the nearest hazard.

Claim type	Percentage of claims	Nearest hazard Pipeline	Substructure	Wreck
Debris	24%	64.1%	6.42%	29.4%
Unknown	23%	63.9%	8.33%	27.8%
Wires	18%	58.0%	10.8%	31.2%
Pipelines and protective coverings	13%	88.1%	3.41%	8.52%
Anchors	7%	62.8%	14.1%	23.1%
Loss of fishing time, gear or access	5%	–	–	–
Spoilt catch	4%	61.3%	22.5%	16.3%
Production infrastructure	4%	67.4%	14.0%	18.6%
Cables	3%	53.3%	10.0%	36.7

Data are not provided for claims categorized as loss of fishing grounds, gear or access since these represent instances when vessels could not access grounds or gear due to oil and gas construction/maintenance activities, including towing of oil rig sections through fishing grounds.

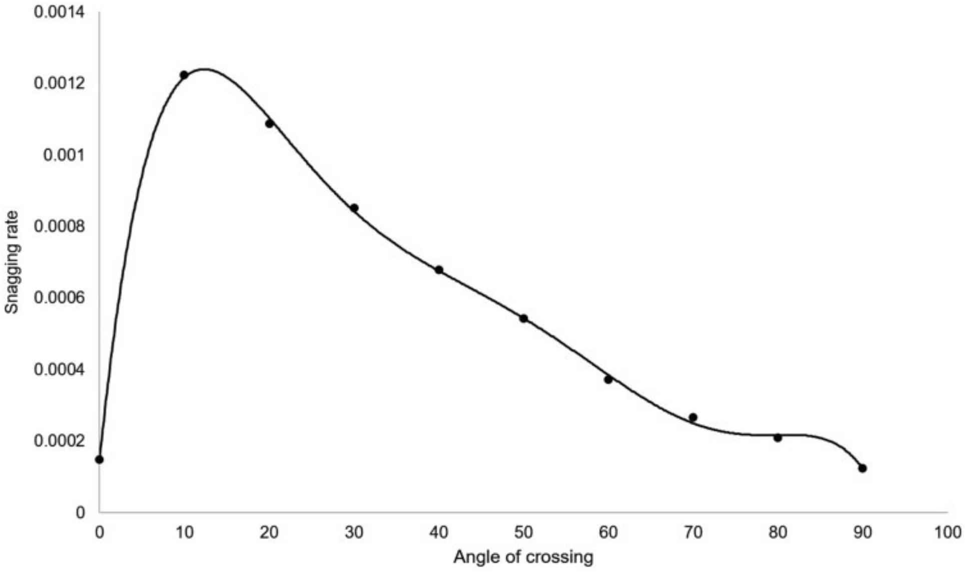

Figure 2. Risk weightings used in the Fladen risk model according to crossing angle between fishing gear and pipelines. Dots represent the snagging rates extracted from Wu *et al.* (2015). The line represents the sixth-order polynomial fitted to the point data to facilitate interpolation of snagging rates at any angle of crossing.

claims occurred on muddy substrate. The inclusion of an interaction term between fishing intensity and substrate significantly improved the log-linear model of incident frequency (likelihood ratio χ^2 165, df = 4, $p < 0.01$), meaning that the effect of substrate on incident frequency varied according to the level of fishing intensity (Table 2). For higher fishing intensity areas, the odds that an incident would occur were 11.4 times higher on mud compared with sand, and 7.35 times higher on mud compared with mixed ground. In contrast, in low fishing intensity areas, the odds that an incident would occur were 17.9 times higher on sand compared with mud, and 22.2 times higher on mixed ground compared with mud.

The results of the Fladen Ground risk model are shown in Figure 4, with darker pipelines sections representing those with a higher annual risk of an incident. The annual risk of incidents for pipeline sections ranged from 0 to 6.1×10^{-5}, and showed spatial heterogeneity along pipeline sections.

Discussion

Analysis of past incidents between UK fishing vessels and pipelines has provided novel insight into the consequences of interactions between mobile fishing and pipelines, which contributes to the evidence base required for pipeline installation and decommissioning decisions. The overwhelming majority of previous incidents that resulted in a loss led to a financial impact rather than a safety-related issue (vessel abandonment, injury, or fatality). This suggests that operators and regulators must incorporate gear damage and loss of fishing time into risk calculations if comprehensive comparative assessments are to accompany installation or decommissioning programmes. The results highlight that debris was the most frequent cause of incidents and this has previously been recognized as a safety issue by operators, regulators, and the fishing industry (Dyson, 2000). Recovery of debris is a challenging aspect of decommissioning and has significant safety and cost implications (Dyson, 2000). Increased fisheries

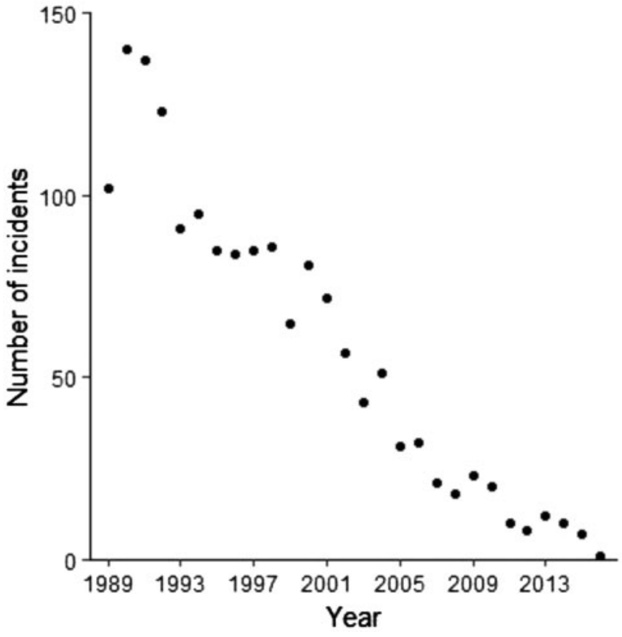

Figure 3. Annual number of incidents between oil and gas infrastructure and commercial fishing vessels that resulted in financial loss, vessel abandonment, fatality, or injury.

awareness among the oil and gas industry, and initiatives to clear debris and declare areas safe for fishing, e.g. by Scottish Fishermen's Federations, are seeking to address this issue and should see snagging on seabed debris decrease in the future. Similarly, the high proportion of incidents categorized as "unknown" suggests that increased communication between oil and gas operators and the fishing industry, and sharing of spatial data on hazardous areas after incidents have occurred, could increase our understanding of the nature of interactions and, consequently, reduce the number of incidents. Pipelines were identified as the nearest hazard to the location of the majority of incidents, for all claim types. This is most likely a result of the widespread distribution of pipelines across the North Sea, and potentially because some vessels actively target pipelines, and associated fish aggregations, within fishing grounds (Rouse *et al.*, 2017a, 2018).

The spatial patterns of incidents found in this study largely reflect trends in UK fishing. The greatest number of incidents occurred on mud in the northern North Sea, which is also where the majority of UK mobile demersal fishing is concentrated (Kafas *et al.*, 2012). It would be expected that substrate would influence the risk of trawl gear becoming snagged on obstructions, independently from the relationship between fishing intensity and substrate type (Nord Stream, 2009). This is due to the potential for hazardous clay berm formation in soft sediments after pipelines have been trenched, and the behaviour of pipelines and trawl doors in soft sediments (MAIB, 2006; Linnane *et al.*, 2000; Nord Stream, 2009; Rességuier *et al.*, 2009). If exposed pipelines sink into soft sediments, the force required to pull trawling gear over the pipeline is smaller and therefore the chance of snagging is reduced (Nord Stream, 2009). However, softer sediments also allow trawl doors to partly penetrate the substrate beside the pipeline, which increases the risks of destabilization and probability of snagging (Askheim and Fyrileiv, 2006; Linnane *et al.*, 2000; Nord Stream, 2009). The results of the present study show a contradictory effect of substrate type on incident frequency according to fishing intensity. In low fishing intensity areas, the odds of an incident occurring were higher on coarser ground (sand and mixed substrate) relative to mud, while in high intensity fishing grounds the reverse was true. It is possible that this pattern may be explained by the relative quantities of obstructions and hazards (which could not be accounted for in the model—see Methods section) present on different substrate types, exposed to various levels of fishing intensity, across the North Sea. If, for instance, sandy areas exposed to low fishing intensity support a higher quantity of oil and gas infrastructure than low fishing intensity muddy areas, the influence of substrate type on snagging may only account for a small proportion of the total snagging risk. Wu *et al.* (2015) suggest that trials and numerical modelling of snagging events that specifically examine the effects of substrate properties would be necessary to inform individual pipeline risk calculations according to substrate type.

The spatial trends of incidents presented in this study must be contextualized with temporal trends, especially when calculating the numbers of incidents that are associated with individual pipelines or other hazards. The reduction in incidents has occurred despite increases in both the total pipeline length installed in the North Sea (120% increase in installed pipeline length between 2001 and 2015) and the overall level of offshore oil and gas activity (CDA, 2013; Oil and Gas UK, 2013). This trend may be explained by a number of factors, including improvements in communication between the fishing and oil and gas industries, improved infrastructure mapping, and advances in vessel GPS technology (Oil and Gas UK, 2013; Eigaard *et al.*, 2014). In particular, the introduction of the "FishSafe" unit in 2001 is likely to have significantly increased awareness among fishers of offshore infrastructure locations.

The decreasing number of incidents (Figure 3) that led to a financial loss, injury or fatality over the past 28 years means that a relatively higher annual incident rate would be attributed to older pipelines. The annual incident rate would be calculated as the total number of incidents associated with a pipeline (since installation) divided by the total number of years that the pipelines has been present on the seabed. If improvements in GPS and data sharing are the principal drivers of the decrease in incidents, then older pipelines would be expected to be associated with a higher frequency of incidents, regardless of the specific risk posed by the individual pipeline. The annual incident rate for individual pipelines could not be calculated in the present study due to incomplete data on the pipeline age. The temporal decrease in incidents should serve as further encouragement for continued, and enhanced, sharing of data between the oil and gas industry and the fishing community.

In addition to assessing the impacts of installations and/or decommissioning on the commercial fishing sector, the present study also suggests that there are significant opportunities to reduce and/or mitigate the risk of fisheries impacts. Analysis of regional scale data on infrastructure, incidents, and fishing activity enables key risk factors associated with fisheries losses to be identified. Knowledge of these risk factors can then be used to assess whether individual pipelines, or other infrastructure, are located within high-risk areas based on fishing type/intensity, substrate-type, and angle of approach. For instance, otter trawls were the most common gear type associated with incidents. This may reflect the fact that otter trawl gear is more prone to snagging or that otter trawls are the most frequently employed gear type for

Table 2. Probabilities of incidents occurring on three substrate types, conditional on fishing intensity.

	Substrate		
Fishing intensity	**Sand**	**Mixed**	**Mud**
High	0.0190	0.0294	0.216
Medium	0.839	0.794	0.776
Low	0.142	0.176	0.00795

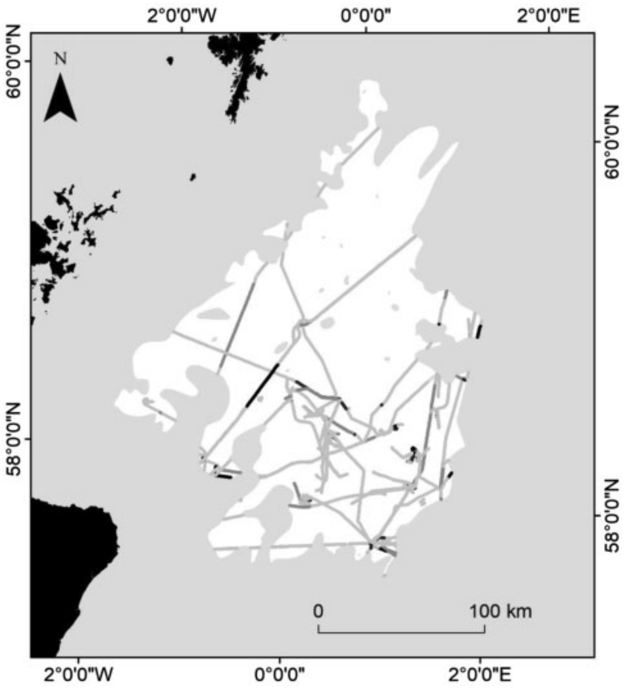

Figure 4. Results of fisheries risk model for the Fladen Ground (white area). Darker lines represent pipeline sections with a higher annual risk of a fisheries incident.

UK vessel (in 2015, otter trawls were used 49% on of UK fishing trips). Using publically available data on the fishing type and intensity associated with individual pipeline sections (Scottish Government, 2017; Rouse *et al.*, 2017b), operators and regulators can make evidence-based decisions on pipeline management and monitoring frequency. Our results show that efforts to bury pipelines and clear clay berms should focus on pipeline sections in areas of high intensity otter trawling. Additionally, a higher frequency of pipeline integrity monitoring should be targeted at these areas, since the chance of pipeline damage is likely to be higher.

The Scottish Government is currently in the process of making data on the angle of interaction between VMS fishing tracks and individual pipelines sections publically available. With data on fishing angle and intensity, operators can apply risk models to estimate the annual probability of a fisheries incident occurring on individual pipeline sections. The annual risk can then be combined with data on expected pipeline degradation rates (e.g. over several centuries) to estimate the lifetime risk of fisheries-related fatalities and financial losses if a pipeline were to be decommissioned *in situ*. Such assessments could also include data on expected future changes in fishing activity and location according climate-related shifts in suitable fish habitat (Serpetti *et al.*, 2017). The risk model presented in this study serves as a demonstration of how fisheries data may be used for pipeline management and highlights that fisheries risk can vary over relatively short spatial scales, even along a single pipeline. The model could be applied to pipelines in any nation where VMS data are available, including outside of British waters. In the North Sea, non-UK vessels are known to have snagged on UK and non-UK pipelines. For example, Wu *et al.* (2015) report nine incidents of lost gear resulting from Norwegian vessels snagging between 2011 and 2013, while Maalø (2011) reported seven snagging events on the Norwegian Shelf between 2000 and 2003. However, there are no equivalent compensation schemes for fisheries losses in non-UK North Sea countries, and as such incident data has not been collated in a comparable format (Gómes and Green, 2013).The fisheries risk model presented in this study must be applied with caution for decommissioning decisions since it excludes a number of factors that would be expected to effect the likelihood of an incident. The development of a universally applicable fisheries risk model for pipelines and other infrastructure in the North Sea is currently limited by the lack of studies that quantify the probability of snagging according to various risk factors, as well as the availability of infrastructure and fisheries-related data (Wu *et al.*, 2015; Rouse *et al.*, 2017a). The angle risk weightings used in this study were derived from a numerical model based on snagging trials (Wu *et al.*, 2015). The numerical model was less able to successfully simulate snagging scenarios when the crossing angle was small ($<10^\circ$), meaning that certainty in risk estimates will be lower where there is a high frequency of low angle crossings. Furthermore, angle risk weightings were only derived for one gear type, but snagging probability varies with both gear type (e.g. beam, dredge, otter) and individual gear design (e.g. size and shape of otter trawl doors) (Wu *et al.*, 2013, 2015, and references therein). Moreover, the exact gear configuration of individual vessels is not included in standard spatial fisheries datasets, preventing gear type from being included in risk models.

While the length of free spans was included in the current risk model, span height and the proximity of spans to track crossings were not included. The height of a free span affects the probability that a trawl door may become "wedged", defined as a door that has been pulled fully underneath a pipeline and is stuck at the opposite side to the warp line (Askheim and Fyrileiv, 2006; DNV, 2006). The critical span height, above which trawl boards may become wedged, is calculated as 0.7 multiplied by half the trawl board height (DNV, 2006). However, even for spans below this critical height, and for pipeline with no spans, "part-penetration" otter trawl snags can occur, where the trawl gear digs into the substrate next to a pipeline and becomes stuck (DNV, 2006). For beam trawls, part-penetration snags will only occur when the span gap is greater than beam trawl height, and wedge spans are not applicable to beam trawls (Wu *et al.*, 2015). In addition to data on gear types used by individual vessels, quantitative data on wedging probability as a function of span height, and the relationship between snag type (wedging or part-penetration) and crew safety and/or loss of fishing time would be required to incorporate the effects of span height into incident risk models. Furthermore, regional assessments of incident risks, which incorporate span effects, would require data on all spans to be collated, rather than the current practice of only collating data on spans with a height of ≥ 0.8 m (CDA, 2013). The presence of rock armouring or other pipeline protection structures is another factor that will alter the probability of fishing gear snagging on a pipeline (Oil and Gas UK, 2013). Rock armouring, in the form of graded crushed rock, is frequently laid on top of pipelines with a smooth 1 in 3 profiles to mitigate snagging hazards (Oil and Gas UK, 2013; Pidduck *et al.*, 2017). Again, neither quantitative data on the relationship between rock armouring and snagging risk, nor regional scale data on the location of armouring are currently available.

Two final, and significant, limitations to undertaking incident risks assessments, particularly at a regional scale, are the lack of data on pipeline burial status and the range of environmental conditions across the North Sea. The model presented for the Fladen Ground does not differentiate between buried and exposed pipeline. The likelihood of fishing gear physically interacting with buried pipelines is low, however on certain substrate types, clay berms may be associated with buried pipelines (Ressèguier *et al.*, 2009). The proportion of pipelines that are surface laid is estimated to be approximately 13% (Rouse *et al.*, 2018), however data on the location of these pipelines are not readily available. Individual operators will be able to adjust risk assessments at the time of installation or decommissioning using their own in house data, but incorporating burial status into regional models is not currently possible. Additionally, the burial status of pipelines can change over time (Gowen *et al.*, 1980; Staub and Bijker, 1990). This is particularly true in the southern North Sea where the dynamic environmental conditions frequently lead to re-exposure of previously buried pipelines and the development of spans on pipeline sections that have been span-free for significant periods of time (e.g. decades) (Angus and Moore, 1982). Modelling future fisheries risks on such pipelines is likely to be highly complex and require a high frequency of pipeline monitoring and continual updating of risk models.

Despite the low number of incidents in recent years, the safety implications of snagging events are potentially very serious. As such, regulators continue to oblige operators to provide evidence to demonstrate *in situ* decommissioned infrastructure does not present a snagging hazard that could interfere with fisheries operations. This obligation has been reiterated in recently published decommissioning guidelines and is unlikely to change over the medium term (∼10 years), during which approximately 30% of UK pipelines will require decommissioning (Oil and Gas UK, 2016). This study represents the first assessment of interactions between commercial fisheries and oil and gas infrastructures that integrates previous incident data from multiple sources and high-resolution spatial fisheries data. It offers a significant improvement on assessments so far based only on fatality and injury data. The results show that there is significant spatial and temporal variation in past fisheries losses, and certain gear types were more frequently involved in incidents. Fishing intensity, angle, and substrate were identified as specific factors influencing incident risk. The fishing risk model presented serves as a demonstration of the methods that can be used by operators to evaluate future incident risks as part of the comparative assessment of decommissioning options. The fishing risk model could be applied in multiple jurisdictions, where equivalent data are available, and can be used to facilitate transparency in the decision-making process for the installation and decommissioning of pipelines. However, significant opportunities exist to further improve models of fisheries losses arising from oil and gas operations and infrastructure. These include both quantitative assessments of snagging risk factors and access to additional datasets, including the history of incidents between non-UK vessels and oil and gas infrastructure. Overall, the present study should serve as an incentive to both the oil and gas, and fisheries, industries to enhance data sharing practices in order to improve risk models and reduce the frequency and severity of incidents. The results also highlight the need to include the full spectrum of potential losses in fisheries impact assessments to maximize the opportunities to conduct offshore decommissioning in a fisheries-sensitive manner.

Acknowledgements

This work was funded by the Natural Environment Research Council's Oil and Gas Innovation Programme (NE/P016537/1). The authors would like to thank Oil and Gas UK and the Marine Accident Investigation Board for supplying data.

References

Agresti, A. 2013. Categorical Data Analysis, John Wiley & Sons, New Jersey.

Angus, N. M., and Moore, R. L. 1982. Scour repair methods in the southern North Sea. *In* Offshore Technology Conference, Houston, TX.

Askheim, D. O., and Fyrileiv, O. 2006. New design code for interference between trawl gear and pipelines: DNV RP-F111. 25th International Conference on Offshore Mechanics and Arctic Engineering, June 4th-9th 2006, Hamburg, Germany. pp. 81–93.

BEIS. 2018. Guidance Notes Decommissioning of Offshore Oil and Gas Installations and Pipelines. Aberdeen UK. 125 pp.

CDA. 2013. UK Oil and Gas data [online]. Oil and Gas UK, Aberdeen, UK.

Crawley, M. J. 2012. The R Book, 2nd edn., pp. 498–536. Wiley, West Sussex, UK.

de Groot, S. J. 1982. The impact of laying and maintenance of offshore pipelines on the marine environment and the North Sea fisheries. Ocean Management, 8: 1–27.

DECC. 2016. UK Offshore Energy Strategic Environmental Assessment 3 (OESEA3). 652 pp.

DNV. 2006. Interference between Trawl Gear and Pipelines, Det Norske Veritas, Høvik, Norway.

Dyson, P. 2000. Oil and Gas seabed infrastructure-whats is it and how does it affect other users of the sea? *In* Man-Made Objects on the Seafloor 2000. Society of Underwater Technology, London, UK.

Eigaard, O. R., Marchal, P., Gislason, H., and Rijnsdorp, A. D. 2014. Technological development and fisheries management. Reviews in Fisheries Science & Aquaculture, 22: 156–174.

Flage, R., and Aven, T. 2009. Expressing and communicating uncertainty in relation to quantitative risk analysis. Reliability & Risk Analysis: Theory & Application, 2: 9–18.

Glabraith, R. D., and Rice, A. 2004. An introduction to commercial fishing gear and methods in Scotland. Scottish Fisheries Information Pamphlet. No 25. Fisheries Research Services, Aberdeen, UK. 43 pp.

Gómes, C., and Green, D. 2013. The impact of oil and gas drilling accidents on EU fisheries. European Parliament, Directorate

General for Internal Policies, Policy Department B: Structural and Cohesion Policies, Brussels, Belgium, Technical Report No. PE, 513.

Gowen, A., Goetz, M., and Waitsman, I. 1980. Choosing offshore pipeline routes: problems and solutions. Final report. New England River Basins Commission, Boston, USA.

Herlianto, I., Chen, Q., and Karunakaran, D. 2012. Lateral buckling induced by trawl gears pull-over loads on high temperature/high pressure subsea pipeline. *In* 31st International Conference on Ocean, Offshore and Arctic Engineering, pp. 235–240. ASME, Rio de Janeiro, Brazil.

Hintzen, N. T. 2016. Fishing intensity around the BBL pipeline. Wageningen Marine Research, Wageningen, Netherlands. 27 pp.

ICES. 2017. Spatial data layers of fishing intensity/pressure per gear type for surface and subsurface abrasion, for the years 2009 to 2016 in the OSPAR area. DOI: 10.17895/ices.pub.2861.

IOGP. 2017. Overview of international offshore decommissioning regulations. Volume 1: Facilities. International Association of Oil and Gas Producers. Aberdeen, UK. 204 pp.

Jentoft, S., and Knol, M. 2014. Marine spatial planning: risk or opportunity for fisheries in the North Sea? Maritime Studies, 12: 13.

Kafas, A., Jones, G., Watret, R., Davies, I., and Scott, B. 2012. Representation of the use of marine space by commercial fisheries in marine spatial planning. ICES Annual Science Conference, 17-21st September, Bergen Norway. ICES CM code 1:23.

Linnane, A., Ball, B., Munday, B. V., Marlen, B., Bergman, M., and Fonteyne, R. 2000. A review of potential techniques to reduce the environmental impact of demersal trawls. Irish Fisheries Investigations No. 7. Marine Institute, Galway Ireland.

Lucchetti, A., Notti, E., Sala, A., and Virgili, M. 2017. Multi-purpose use of side-scan sonar technology for fisheries science. Canadian Journal of Fisheries and Aquatic Sciences, 1.

Maalø, K. 2011. Clump-weight trawl gear interaction with submarine pipelines. Department of Marine Technology, Norwegian University of Science and Technology, Trondheim, Norway, Vol. 999, pp. 1–11.

MAIB. 2006. Report on the investigation of the capsize and foundering of the fv Harvest Hope PD120. Southampton, UK. 107 pp.

Merchant Shipping and Fishing Vessels Regulations. 1997. The Merchant Shipping and Fishing Vessels (Health and Safety at Work) Regulations 1997, SI 1997/2962. UK Government, London, UK.

Nord Stream. 2009. Nord Stream environmental impact assessment. Zug, Switzerland. 32 pp.

Oil and Gas UK. 2013. Decommissioning of pipelines in the North Sea region. Aberdeen, UK. 52 pp.

Oil and Gas UK. 2016. Decommissioning Insight 2016. Aberdeen, UK. 72 pp.

Park, H. I., and Kim, C. H. 1997. Analytical methods for the determination of allowable free span length of subsea pipelines. *In* The Seventh International Offshore and Polar Engineering Conference, 25–30 May, Hawaii.

Petroleum Act 1998, UK Government, London UK. Available online https://www.legislation.gov.uk/ukpga/1998/17/contents [Date of access 01/05/2018].

Philip, N. S., Wilde, S., Arshad, R., Washash, I., and Al-Sayed, T. A. R. 2014. Decommissioning process for subsea pipelines. *In* Abu Dhabi International Petroleum Exhibition and Conference. Society of Petroleum Engineers, Abu Dhabi, UAE.

Pidduck, E., Jones, R., Daglis, P., Farley, A., Morley, N., Page, A., and Soubies, H. 2017. Identifying the possible impacts of rock dump from oil and gas decommissioning on annex I mobile sandbanks. JNCC, Peterborough, UK. 53 pp.

Pipeline Safety Regulations. 1996. Health and Safety (The Pipeline Safety Regulations 1996) SI 1996/825. UK Government, London, UK.

Rességuier, S. B., Bendzovski, R., Strøm, P. J., Wathne, H., Vigsnes, M., and Holme, J. 2009. Assessment of trawl board and anchor penetration in different soils for use in selection of a burial depth to protect submarine cables or pipelines. 151–161 pp.

Rouse, S., Hayes, P., Davies, I. M., and Wilding, T. A. 2018. Offshore pipeline decommissioning: scale and context. Marine Pollution Bulletin, 129: 241–244.

Rouse, S., Kafas, A., Catarino, R., and Hayes, P. 2017a. Commercial fisheries interactions with oil and gas pipelines in the North Sea: considerations for decommissioning. ICES Journal of Marine Science, 75: 279–286.

Rouse, S., Kafas, A., Hayes, P., and Wilding, T. A. 2017b. Development of data layers to show the fishing intensity associated with individual pipeline sections as an aid for decommissioning decision-making. Underwater Technology, 34: 171–178.

Scottish Government. 2017. UK fishing intensity associated with oil and gas pipelines (2007–2015) Dataset. Aberdeen, UK.

Serpetti, N., Baudron, A. R., Burrows, M. T., Payne, B. L., Helaouët, P., Fernandes, P. G., and Heymans, J. J. 2017. Impact of ocean warming on sustainable fisheries management informs the Ecosystem Approach to Fisheries. Scientific Reports, 7: 13438.

Shell U.K. Limited. 2017. Brent field pipelines decommissioning. Technical Document. Aberdeen, UK. 380 pp.

Side, J. 1999. Issues arising from the Westhaven tragedy concerning fishing gear and pipeline interactions. Underwater Technology, 24: 3–9.

Staub, C., and Bijker, R. 1990. Dynamic numerical models for sand waves and pipeline self-burial. Coastal Engineering Proceedings, 1, Vol. 22, pp. 2508–2521.

Stelzenmüller, V., Diekmann, R., Bastardie, F., Schulze, T., Berkenhagen, J., Kloppmann, M., Krause, G., *et al.* 2016. Co-location of passive gear fisheries in offshore wind farms in the German EEZ of the North Sea: a first socio-economic scoping. Journal of Environmental Management, 183: 794–805.

Stevenson, A. 2012. The European marine observation and data network: geological data. Baltica, 25: 87–90.

Van der Abeele, F., Cerezalez Galvan, B., Ramos, P., and Muylle, J. 2013. Numerical simulations of the interference between trawl gear and offshore pipelines. *In* 6th International Pipeline Technology Conference, 6–9 October 2013, Ostend, Belgium.

Wu, X., Longva, V., Sævik, S., and Moan, T. 2013. Simulation of Hooking Event in Fish Trawling Operation. *In* ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering, 9th–14th June, 2013. Nantes, France.

Wu, X., Longva, V., Sævik, S., and Moan, T. 2015. A simplified approach to estimate the probability of otter board hooking at pipelines. Journal of Offshore Mechanics and Arctic Engineering, 137: 061702–061721.

Handling editor: Silvana Birchenough