**Direct impacts of oil and gas development:**

**Risk of major oil spills**

Prepared for

Uplift UK

By

MarFishEco Fisheries Consultants

October 2022

Contents

[Brief 4](#_Toc117615188)

[Executive summary 5](#_Toc117615189)

[Key statistics 7](#_Toc117615190)

[Main content 8](#_Toc117615191)

[Introduction to major oil spills 8](#_Toc117615192)

[Marine Mammals 8](#_Toc117615193)

[Introduction 8](#_Toc117615194)

[Harbour porpoise *(Phocoena phocoena)* 8](#_Toc117615195)

[Bottlenose dolphin (*Tursiops truncatus*) 9](#_Toc117615196)

[Humpback whale *(Megaptera novaeangliae)* 10](#_Toc117615197)

[Northern minke whale *(Balaenoptera acutorostrata)* 10](#_Toc117615198)

[Killer whale *(Orcinus orca)* 10](#_Toc117615199)

[Pinnipeds (seals) 11](#_Toc117615200)

[Fish 13](#_Toc117615201)

[Introduction 13](#_Toc117615202)

[Fish overview 13](#_Toc117615203)

[Atlantic haddock *(Melanogrammus aeglefinus)* 14](#_Toc117615204)

[Atlantic cod *(Gadus morhua)* 15](#_Toc117615205)

[Other commercial fish species 17](#_Toc117615206)

[Invertebrates 19](#_Toc117615207)

[Introduction 19](#_Toc117615208)

[Cold-water coral communities, including sea fan colonies 19](#_Toc117615209)

[Deep-sea sponges 21](#_Toc117615210)

[Ocean quahog (*Arctica islandica*) 22](#_Toc117615211)

[Mussels 22](#_Toc117615212)

[Blue Carbon 24](#_Toc117615213)

[Blue Carbon - Habitats 24](#_Toc117615214)

[Blue Carbon - Animals 25](#_Toc117615215)

[Case study - Rosebank Field Development 26](#_Toc117615216)

[Context 26](#_Toc117615217)

[Species at risk from an oil spill at the Rosebank Field development site 26](#_Toc117615218)

[Summary 28](#_Toc117615219)

[The effectiveness of guidance and mitigation measures around offshore oil spills 29](#_Toc117615220)

[Guidance and mitigating measures on offshore oil spills in UK waters 29](#_Toc117615221)

[Are the guidance and mitigating measures effective? 29](#_Toc117615222)

[1. A lack of mitigating measures 29](#_Toc117615223)

[2. Fines are ineffective measures to mitigate oil spills or incentivise less risky practices. 30](#_Toc117615224)

[3. Poor guidance on the protection of European Protected Species (cetaceans) from oil pollution 30](#_Toc117615225)

[4. The OESEA4 severely lacks knowledge on the impact of oil spills on UK marine species and habitats 30](#_Toc117615226)

[5. Strong post-spill impact monitoring guidelines are in place 32](#_Toc117615227)

[Summary 32](#_Toc117615228)

[Conclusion 34](#_Toc117615229)

[References 35](#_Toc117615230)

[Follow-up research ideas 42](#_Toc117615231)

# Executive summary

Offshore oil spills are a major risk of oil and gas development, with oil known to be an acute and chronic stressor to the marine environment and life within it. Nevertheless, increasing oil and gas exploration activities have gone ahead in the absence of sufficient baseline data on offshore ecosystems and their tolerance to oil contamination.

This review assesses the evidence for the impacts of oil spills on marine life, including priority species such as marine mammals, fish and invertebrates. It also considers the effectiveness of UK guidance and mitigating measures surrounding offshore oil spill events. Key findings are:

**Marine mammals**

* Marine mammals are exposed to oil spills through several pathways, including; swimming within contaminated waters, accidental ingestion of contaminated water or food or inhalation of polycyclic aromatic hydrocarbons (PAHs).
* Evidence strongly suggests that bottlenose dolphins are vulnerable to long-lasting population effects following an oil spill, with reductions in reproductive success lasting for several years post-spill.
* There is limited research on the impact of oil spills on baleen whales (including humpbacks and the northern minke whale). However, new research has indicated that inhalation through an open blowhole is possible and may lead to oil entering the respiratory tract.
* Killer whales are vulnerable to population-level effects following oil spills through the loss of just a small number of individuals in a pod. The loss of reproductive-age females can result in a depressed population for decades.
* Pinnipeds are threatened by hypothermia and increased vulnerability to starvation following an oil spill.

**Fish**

* Fish are exposed to oil spills via a number of pathways also, including;oil fouling of eggs, ingestion of contaminated prey or oil droplets, or the uptake of contaminants through body surfaces, e.g., the gills.
* Oil exposure to fish, in general, has been observed to have population-level effects, including delayed growth, physical deformities, and impaired cardiac development.
* Sublethal toxic oil impacts on juvenile and adult fish include behavioural defects such as decreased cohesion in fish groups that can lead to altered antipredator behaviours and reduced ecological success.
* Atlantic haddock are far more susceptible to amplified embryotoxicity from oil than any other species due to an adherent outer egg that retains oil droplets. Delayed growth, DNA damage and physical abnormalities have also been observed in hatched haddock, with effects including hindered swimming, foraging and predator avoidance ability and increased susceptibility to disease.
* Atlantic cod exhibited acute and delayed toxicity when exposed to oil as an embryo, including mortality, reduced growth and development and deformities. If severe enough, deformities may restrict feeding and lead to delayed mortality. Juvenile and adult Atlantic cod have exhibited increased immune stress and susceptibility to infection, cancer and other diseases when exposed to oil.
* Other commercial fish species, including European plaice, yellowfin sole, Atlantic salmon and herring, experience similar impacts following oil exposure, including mortality, DNA damage, reduced growth, deformation and impaired cardiorespiratory function.

**Invertebrates**

* Invertebrates in offshore waters are at risk of exposure to oil spills through similar pathways to fish, including contact with contaminated water and sediment, ingestion of oil droplets or contaminated food.
* Deep-water ecosystems such as cold-water coral and sea fan colonies are vulnerable to oil pollution over several kilometres. Wide-spread signs of stress and mortality, including tissue loss, bleaching, broken branches and covering by brown flocculent material, have been observed over 10kms from an oil spill source. Depending on the level of impact, recovery (to a ‘healthy’ state) is estimated to take decades. However, pre-spill recovery is expected to take hundreds of years.
* The deep-sea sponge microbiome is highly sensitive to oil spill events, with changes in gene expression and microbial disruption expected to impact the ecosystem services that the microbial sponge community provide.
* A loss of critical biological function following oil exposure has also been observed in sea sponges, with results negatively impacting sponge recruitment to the adult population.
* Bivalve molluscs have displayed a high sensitivity to cardiac activity in the presence of oil spills, with cardiac arrest and disrupted heart rate observed in mussel and horse mussels.
* Differences in recovery time between mussel species appear to depend on their tolerance of environmental disturbance. Therefore, less studied, deep-sea living molluscs are thought to be similarly sensitive to oil exposure, if not more so.

In general, research into the effects of oil spills on UK offshore species is lacking. The majority of studies to date have either taken place via laboratory experiments or in international waters that are comparably different to UK water conditions. Despite this, there is evidence of acute and sublethal impacts of oil spills on many species found in UK waters.

Guidance and mitigation measures around offshore oil spills are mostly ineffective. Legal requirements and guidance are too heavily focused on post-spill action, while mitigation action is lacking. Penalties for oil spill events are not severe enough to incentivise strengthening mitigating measures.

# Key statistics

* Decreased reproductive success was observed in bottlenose dolphins following the 2010 Deepwater Horizon oil spill (Lane *et al.*, 2015; Kellar *et al.*, 2017; Morey *et al.*, 2022). Only 20% of mothers (10 individuals) in a heavily oiled site produced viable calves following the spill (following a 47-month monitoring programme), a significant drop from the reproductive success rate of 83% in a reference population (Lane *et al.*, 2015).
* Following the 1989 Alaskan Exxon Valdez oil spill, two orca pods suffered population losses of 33% and 41%, respectively, in the year following the spill (Matkin *et al.*, 2008, 2012).
* The 2010 Deepwater Horizon oil spill resulted in the direct death of between 2 and 5 trillion fish larvae in the area (Joye *et al.*, 2016). Forgone production associated with these losses was further estimated to be between 86 million to 26 billion fish larvae (Joye *et al.*, 2016).
* Laboratory experiments at the Austevoll Research station in Norway found Haddock embryos to be approximately ten times more sensitive to crude oil than cod embryos (Sørensen *et al.*, 2017; Sørhus *et al.*, 2021).
* Following the 1993 Braer oil spill, 5,399 tonnes of farmed salmon had to be destroyed, resulting in a financial loss of roughly £38.5 million in today’s money (Goodlad, 1996), (Roughneen, 2022).
* The financial compensation provided to the Shetland seafood industry following the Braer disaster totalled £60,179,287.98 in today’s money (Goodlad, 1996), (INFLATION TOOL, 2022).
* Acute toxicity of oil pollution can significantly impact deep-water ecosystems over several kilometres (Girard, Shea and Fisher, 2018; Montseny *et al.*, 2021).
* Signs of injury to deep-sea ecosystems following the 2010 Deepwater Horizon oil spill stretched 22 km from the wellhead and to depths of 1370m (Girard, Shea and Fisher, 2018; Montseny *et al.*, 2021).
* Depending on the level of impact, it has been estimated that it could take up to three decades for coral communities impacted by the 2010 Deepwater Horizon oil spill to recover to a state where all remaining branches appear healthy. However, further estimates predict that it could take hundreds of years for affected communities to grow back to their initial biomass (due to the loss of branches) (Girard, Shea and Fisher, 2018; Montseny *et al.*, 2021).

# Main content

## Introduction to major oil spills

Offshore oil spills are a major risk of oil and gas development, with oil known to be an acute and chronic stressor to the marine environment and life within it. Nevertheless, increasing oil and gas exploration activities have gone ahead in the absence of sufficient baseline data on offshore ecosystems and their tolerance to oil contamination. Therefore, there is a clear need to bring together current knowledge on the impacts of oil exposure on offshore ecosystems and the regulations and mitigating measures in place to protect them.

The following sections will detail the scientific knowledge surrounding the impacts of oil spills on priority species, covering marine mammals, fish and invertebrates. A risk radii case study on an actual proposed Oil and Gas field in the UK EEZ is then used to highlight these potential impacts in a real-world scenario. The final section will then assess the effectiveness of UK guidance and mitigation measures put in place for offshore oil spill events.

## Marine Mammals

### Introduction

UK waters are home to several marine mammal species, all of which are protected in offshore waters under national and international legislation. In addition, harbour porpoise, bottlenose dolphins and the UK’s seal species; grey and harbour seals, are species for which the designation of Special Areas of Conservation (SACs) is required (JNCC, 2021).

Marine mammals are at risk of exposure to oil spills through multiple pathways (Ruberg, Elliott and Williams, 2021; Wright *et al.*, 2022). For example, via direct contact with oil when swimming at the surface or within the water column of a contaminated area (Ruberg, Elliott and Williams, 2021); via the accidental ingestion of contaminated water and sediment when foraging (Wright *et al.*, 2022) or contaminated prey (Schwacke *et al.*, 2014), or via the inhalation of polycyclic aromatic hydrocarbons (PAHs) at the air-water interface (Venn-Watson *et al.*, 2015).

Acute mortalities of marine mammals may not be observed regularly in the immediate aftermath of an oil spill (Wright *et al.*, 2022), but sublethal impacts are likely to occur that may result in delayed mortalities or population reduction and long-term failure to recover as was observed following the 1989 Exxon Valdes oil spill in Alaska (Matkin *et al.*, 2008) and the 2010 Deepwater Horizon (DWH) oil spill in the Gulf of Mexico (Schwacke *et al.*, 2014; Takeshita *et al.*, 2017) (Table 1).

### Harbour porpoise *(Phocoena phocoena)*

No research was uncovered that investigated the impacts of oil exposure on harbour porpoise. The UK Dolphin and Porpoise Conservation Strategy produced in March 2021 appears to confirm this; however, they state that there have been no published records of any oil spill in which a harbour porpoise has been affected (Scottish Government, 2021b). No measurable effects on harbour porpoise were acknowledged by research following the 1999 MV Erika oil spill off the coast of France (Ridoux *et al.*, 2004), or the Braer oil spill off the coast of the Shetland Islands, Scotland (Kingston, 1999). However, this lack of acknowledgement of any measurable impacts on harbour porpoise does not indicate that the species was unaffected by both spills. In contrast, it merely means that post-spill research on the species was not carried out. Therefore, an increased research focus on the effects of oil exposure on harbour porpoise is needed to thoroughly investigate the sensitivity of this species to oil spills.

### Bottlenose dolphin (*Tursiops truncatus*)

Prior to the 2010 DWH oil spill, there was limited evidence for the impacts of oil on cetaceans. Health assessments carried out in the area following the DWH spill suggested notable impacts of oil toxicity on dolphins in the Gulf of Mexico (Schwacke *et al.*, 2014).

Bottlenose dolphins observed in an area heavily oiled over a prolonged period showed evidence of hypoadrenocorticism (immune-mediated destruction of the adrenal glands), consistent with adrenal toxicity previously reported for laboratory mammals exposed to oil. Bottlenose dolphins from this site were also five times more likely to have moderate to severe lung disease, generally categorised by significant alveolar interstitial syndrome, lung masses and pulmonary consolidation (Schwacke *et al.*, 2014; Ruberg, Elliott and Williams, 2021). Pulmonary abnormalities were observed to have long-term impacts, lingering for up to four years following the spill (Smith *et al.*, 2017). Furthermore, disease conditions in bottlenose dolphins from the heavily oiled site were significantly greater in prevalence and severity compared to dolphins from the site where no oil was observed, as well as those reported in other wild bottlenose dolphin populations. The disease conditions observed in the dolphins from heavily oiled sites were found to be uncommon but consistent with petroleum hydrocarbon exposure and toxicity. Of the 29 bottlenose dolphins examined from the heavily oiled site, 48% were given a guarded or worse prognosis of health, and 17% were considered poor or grave, indicating that they were not expected to survive the sublethal impacts of the oil spill in the long-term (Schwacke *et al.*, 2014).

Decreased reproductive success was observed in bottlenose dolphins following the DWH oil spill (Lane *et al.*, 2015; Kellar *et al.*, 2017; Morey *et al.*, 2022). Only 20% of mothers (10 individuals) in a heavy oil site produced viable calves following the spill (following a 47-month monitoring programme), a significant drop from the reproductive success rate of 83% in a reference population (Lane *et al.*, 2015). Similarly, low reproductive success rates of Bottlenose dolphins from another DWH oil-contaminated region of the Gulf of Mexico were also observed following the spill (Kellar *et al.*, 2017). Overall, bottlenose dolphin reproductive rates significantly decreased in heavily contaminated areas for nearly four years afterwards (Lane *et al.*, 2015). Furthermore, the bottlenose dolphin population from the initial site experienced an increased annual mortality rate of 9%. Reduced reproduction and survival rates were sustained in this population following the spill, indicating that the exposure of bottlenose dolphins to oil was associated with long-lasting poor maternal health (Lane *et al.*, 2015).

### Humpback whale *(Megaptera novaeangliae)*

Research that investigates the impact of oil spills on humpback whales is lacking. However, studies on baleen whales generally provide some comparable insights (Wright *et al.*, 2022). Previously, it was thought that baleen whales may experience oil fouling as they skim feed at the surface or within the water column of an affected oil spill area (Geraci and St Aubin, 1990). However, more recent laboratory experiments suggest that humpback whales in particular (along with three other baleen whale species; bowhead, Balaena mysticetus; North Atlantic right, Eubalaena glacialis; fin, Balaenoptera physalus) are oleophobic and therefore repel oil rather than adsorb it (Werth, Blakeney and Cothren, 2019). However, ingestion and inhalation risks in these species remain. One particular study has found that humpback whales may inhale oil drops at the surface through their blowhole, which could enter the upper respiratory tract as the whale submerges with its blowhole open (Martins *et al.*, 2020). This pathway of oil ingestion in baleen whales has only been realised in recent years following research into the respiration cycle of baleen whales and the seawater flux through their open blowholes. Whether inhaled oil drops can also make their way down to the lower respiratory tract is currently unknown (Martins *et al.*, 2020).

### Northern minke whale *(Balaenoptera acutorostrata)*

There is no evidence within the UK on the impacts of oil on northern minke whales; however, exposure is expected to be low (Scottish Government, 2021b). A small amount of international research on oil toxicity in marine mammals briefly includes minke whales (Ruberg, Elliott and Williams, 2021). That research states (Wright *et al.*, 2022) that when oil and hydrocarbons are adsorbed into the circulation of marine mammals (including minke whales), they can attach the liver, nervous system, and blood-forming tissues (Geraci and St Aubin, 1990). However, Minke whales, like other marine mammals, have the ability to metabolise petroleum hydrocarbons through the mixed-function oxidase system (Gøksoyr *et al.*, 1986). However, the extent to which this metabolism and elimination of hydrocarbons occur is unclear, with some concerns that PAHs may accumulate in the mammal's blubber (Rainer Engelhardt, 1983; Marsili *et al.*, 2001; Ruberg, Elliott and Williams, 2021).

### Killer whale *(Orcinus orca)*

Killer whales (*Orcinus orca*) are known to be vulnerable to population-level effects following oil spills (Matkin *et al.*, 2008; Ruberg, Elliott and Williams, 2021). Monitoring of the species following the 1989 Alaskan Exxon Valdez oil spill observed notable reductions in the number of two pods close to the spill. In the year following the spill, a resident pod suffered losses of 33% of the population just by losing 13 individuals (Matkin *et al.*, 2008, 2012). The population of the resident species remained depressed for 20 years after the spill. A transient pod lost just nine individuals but led to a 41% loss of the population, including the remaining reproductive females (Matkin *et al.*, 2008). This population of the transient pod has still not recovered, with a continued decline in numbers and is listed as depleted under the Marine Mammal Protection Act (Fisheries, 2022). Although there may be other contributing factors to this decline, the loss of reproductive-age females likely accelerated the populations trajectory towards extinction (Matkin *et al.*, 2008).

### Pinnipeds (seals)

There have been few studies specifically investigating the short and long-term impacts of oil spills on the UK’s seal species (the harbour seal, *Phoca vitulina;* and grey seal, *Halichoerus grypus*). However, research undertaken on pinnipeds, in general, has identified that furred marine mammals such as (furred) seals and sea otters are at a higher risk of injury from oil spills compared to other marine mammals (Tarasoff *et al.*, 1972). The fur coat of these mammals creates a waterproof barrier that provides critical insulation and buoyancy in the water. However, if the hair follicles become oiled, water can penetrate deeply into the insulating layer, exposing them to the harsh elements (NOAA, 2012; Wright *et al.*, 2022). Without the ability to repel water and insulate from the cold, increased heat loss and the threat of hypothermia are expected. The decreased insulation also results in a significantly greater basal metabolic rate to maintain core body temperature. Ultimately, this can result in an increased vulnerability to starvation due to the metabolism of stored body fat (Wright *et al.*, 2022). Furthermore, the penetration of the insulating layer with water can reduce the capacity of the mammal to swim or float in the water, which can lead to an inability to forage or to escape predation (Wright *et al.*, 2022).

Seal pups are likely more vulnerable to oil exposure than adults, with pups potentially trapped on beaches and haul-out sites if oil reaches the shoreline. Therefore, a seasonal aspect to young seal vulnerability needs to be considered (Geraci and St Aubin, 1990; Kirkby *et al.*, 2018). Furthermore, following the 1989 Exxon Valdez oil spill in Alaska, oil toxicity in harbour seals was found to be passed from mother to pup via the mother’s milk (Frost *et al.*, 1994).

Finally, seals trapped near the source of an oil spill are expected to be vulnerable to toxic effects associated with oil vapours and aerosols, particularly if the crude oil is light, with a large portion of aromatic hydrocarbons. Severe toxic effects observed include impaired respiration and nervous system function, which can lead to mortality (Geraci and St Aubin, 1990).

Table 1. Table shows the varying impacts of major oil spills on priority marine mammal species at distance from the source. Hyperlinks are provided to references.

|  |  |
| --- | --- |
|  |  |
|  |  | **Distance from source** | | | | |
|  |  | **Impact** | **At source** | **10's m** | **10's km** | **100s 'km** |
| **Species** | *Humpback whale* | Oil can enter the upper respiratory tract via open blowholes. | [(Matins et al., 2020).](https://onlinelibrary.wiley.com/doi/full/10.1111/mms.12703) | [(Matins et al., 2020).](https://onlinelibrary.wiley.com/doi/full/10.1111/mms.12703) |  |  |
| *Northern minke whale* | Oil can attack the liver, nervous system and blood-forming tissues. | [(Geraci & St Aubin., 1990).](https://www.elsevier.com/books/sea-mammals-and-oil-confronting-the-risks/geraci/978-0-12-280600-1) | [(Geraci & St Aubin., 1990).](https://www.elsevier.com/books/sea-mammals-and-oil-confronting-the-risks/geraci/978-0-12-280600-1) |  |  |
| *Bottlenose dolphin* | Hypoadrenocorticism |  |  | [(Ruberg et al., 2021).](https://link.springer.com/article/10.1007/s10646-021-02373-x#Sec1) |  |
| Lung disease and long-term pulmonary abnormalities. |  |  | [(Ruberg et al., 2021).](https://link.springer.com/article/10.1007/s10646-021-02373-x#Sec1), [(Schwacke et al., 2014).](https://pubs.acs.org/doi/10.1021/es403610f) |  |
| Prevalent and severe disease conditions. |  |  | [(Schwacke et al., 2014).](https://pubs.acs.org/doi/10.1021/es403610f) |  |
| Decreased reproductive success. |  |  | [(Lane et al., 2015).](https://royalsocietypublishing.org/doi/10.1098/rspb.2015.1944) | [(Kellar et al., 2017).](https://www.int-res.com/articles/esr2017/33/n033p143.pdf), [(Morey et al., 2022).](https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0272345) |
| Long-lasting poor maternal health (4 years post-spill). |  |  | [(Lane et al., 2015).](https://royalsocietypublishing.org/doi/10.1098/rspb.2015.1944) |  |
| Increased annual mortality rate. |  |  | [(Lane et al., 2015).](https://royalsocietypublishing.org/doi/10.1098/rspb.2015.1944) |  |
| *Killer whale* | Vulnerable to population-level effects, even with small mortalities. | [(Ruberg et al., 2021),](https://link.springer.com/article/10.1007/s10646-021-02373-x) [(Matkin et al., 2008).](https://www.int-res.com/articles/meps2008/356/m356p269.pdf) |  | [(Ruberg et al., 2021),](https://link.springer.com/article/10.1007/s10646-021-02373-x) [(Matkin et al., 2008).](https://www.int-res.com/articles/meps2008/356/m356p269.pdf) | [(Ruberg et al., 2021),](https://link.springer.com/article/10.1007/s10646-021-02373-x) [(Matkin et al., 2008).](https://www.int-res.com/articles/meps2008/356/m356p269.pdf) |
| Loss of reproductive-age females can push populations towards extinction. | [(Matkin et al., 2008).](https://www.int-res.com/articles/meps2008/356/m356p269.pdf) |  | [(Matkin et al., 2008).](https://www.int-res.com/articles/meps2008/356/m356p269.pdf) | [(Matkin et al., 2008).](https://www.int-res.com/articles/meps2008/356/m356p269.pdf) |
| *Seals* | Threat of hyperthermia from oiled fur. | [(Wright et al., 2022).](https://link.springer.com/chapter/10.1007/978-3-030-87853-5_7) | [(Wright et al., 2022).](https://link.springer.com/chapter/10.1007/978-3-030-87853-5_7) |  |  |
| Vulnerability to starvation due to the use of stored body fat in the insolation layer. | [(Wright et al., 2022).](https://link.springer.com/chapter/10.1007/978-3-030-87853-5_7) | [(Wright et al., 2022).](https://link.springer.com/chapter/10.1007/978-3-030-87853-5_7) |  |  |
| Reduced ability to swim, forage and avoid predators if water reaches the insulating layer. | [(Wright et al., 2022).](https://link.springer.com/chapter/10.1007/978-3-030-87853-5_7) | [(Wright et al., 2022).](https://link.springer.com/chapter/10.1007/978-3-030-87853-5_7) |  |  |
| Impaired respiration, nervous system function, and delayed mortality from oil vapours. | [(Geraci & St Aubin., 1990).](https://www.elsevier.com/books/sea-mammals-and-oil-confronting-the-risks/geraci/978-0-12-280600-1) | [(Geraci & St Aubin., 1990).](https://www.elsevier.com/books/sea-mammals-and-oil-confronting-the-risks/geraci/978-0-12-280600-1) |  |  |
| Seal pups can become trapped on beaches/haul-out sites if oil reaches shore. |  |  | [(Wright et al., 2022).](https://link.springer.com/chapter/10.1007/978-3-030-87853-5_7) |  |

## Fish

### Introduction

Fish may be exposed to oil spills via a number of pathways, including; the uptake of contaminates through body surfaces (e.g., respiration structures such as gills) or ingesting contaminated prey or oil droplets in the water column (Wright *et al.*, 2022). Oil droplets can also adhere to the outer surface of fish eggs, causing oil fouling and direct interaction between an oil spill and an embryonic fish (Hansen *et al.*, 2019), making spawning grounds and egg/larva drift areas especially vulnerable (Langangen *et al.*, 2017; Wright *et al.*, 2022).The impacts of oil exposure on fish can vary (Table 2) and depend on various factors, including exposure conditions, species, and life stage.

While some species of fish appear to respond uniquely to the exposure of oil, the majority of species studied appear to have many impacts in common. Therefore, to reduce repetition in this section, the impacts of oil toxicity on fish are initially discussed more generally (i.e., non-species specific). Following that, key commercial fish species are discussed in greater detail, as they have been the focus of more research. In the UK and surrounding waters (such as Scandinavia and the Arctic), there is a substantial research interest in the response of Atlantic cod and haddock to oil pollution. Consequently, these species make up a large chunk of the section. Finally, where possible, economic values of key commercial species have been given to provide context for the potential economic losses that could be incurred following a catastrophic oil spill.

### Fish overview

Fish habitats are frequently impacted by accidental oil spills. The consequences of oil toxicity in fish, however, is stage-dependent, with early life stages (eggs and larvae) thought to the highly vulnerable to oil exposure due to the inability to control their drift (Olsen *et al.*, 2010; Carroll *et al.*, 2018; Sørhus *et al.*, 2021), and the potential disruption of the critical developmental processes taking place (Incardona, 2017; Pasparakis *et al.*, 2019; Sørhus *et al.*, 2021). Oil exposure during these highly sensitive stages could have detrimental consequences for juvenile survival (Sørhus *et al.*, 2021). For example, the 2010 DWH oil spill that released millions of gallons of crude oil into the Northern Gulf of Mexico resulted in the direct death of between 2 and 5 trillion fish larvae in the area (Joye *et al.*, 2016). Forgone production associated with these losses was further estimated to be between 86 million to 26 billion fish larvae (Joye *et al.*, 2016).

In addition to direct larvae mortality, several sublethal yet potentially significant effects of oil exposure on fish development have been found that may contribute to population-level effects, including delayed growth (Heintz *et al.*, 2000), craniofacial deformities (Heintz *et al.*, 2000; de Soysa *et al.*, 2012; Armstrong *et al.*, 2019) and impaired cardiac development and function among developing larvae (Joye *et al.*, 2016). The abnormal development of the heart following short-term exposure (days) to oil during embryonic development can result in substantial reductions in the ability to perform high-speed swimming (Mager *et al.*, 2014). Sustained high-speed swimming is likely important for predator avoidance, prey capture, migrations, and spawning events. Impaired swimming resulting from sublethal oil exposure may therefore translate to reduced survival later in life (Joye *et al.*, 2016). The impact of oil exposure on swimming performance, however, is not limited to exposure during larval development. Juvenile and young adult fish have also displayed a reduced ability to sustain high swimming speed following even shorter exposure (hours) to oil (Mager *et al.*, 2014; Joye *et al.*, 2016; Stieglitz *et al.*, 2016).

The effect on fish at later life stages, however, cannot be explained by cardiac development defects and are, at least in those fish species studied, associated with a reduced ability to consume oxygen (Stieglitz *et al.*, 2016). Limitations in oxygen consumption, for example, can be attributed to reduced uptake at the gills or limited circulating oxygen in the blood that is needed to fuel metabolically demanding activities such as swimming (Joye *et al.*, 2016). Furthermore, sublethal toxic oil impacts on juvenile and adult fish include changes in normal metabolismresulting inphysiological stress (Klinger *et al.*, 2015) and behavioural defects that may lead to reduced ecological success. Behavioural defects include decreased cohesion in fish social groups, which can alter antipredator behaviours (Johansen *et al.*, 2017) and reduced voluntary movement speed that limits the foraging range (Armstrong *et al.*, 2019).

### Atlantic haddock *(Melanogrammus aeglefinus)*

Atlantic haddock is not a threatened species; however, the sustainability of stocks differs between seas around the UK (Marine Conservation Society, 2022b). Haddock in the North Sea and West of Scotland are not overfished or subjected to overfishing. Management is following scientific advice, and catches are in line with management measures. However, discards are high, and observers have indicated illegal discharging at sea (ICES, 2022a). Consequently, improvements to management measures are required (Marine Conservation Society, 2022c). The Irish Sea haddock stock is similarly in a good place, with no overfishing reported. However, discards are also relatively high, and no management plan is in place to ensure stocks do not become depleted (Marine Conservation Society, 2022d). In Celtic Seas and the English Channel, haddock stocks are not overfished yet are in a worse state (Marine Conservation Society, 2021). In 2019 and 2020, low recruitment of young fish into the stock was observed, which is expected to cause the stock size to decrease in the coming years. As a result, the ICES advised a decrease in catch by 13% for 2022 (Marine Conservation Society, 2021). Therefore, UK oil and gas licensing expansion may not be as much of a threat to haddock compared to threatened fish species in UK waters. However, poor management of UK stocks could result in a delayed acknowledgement of any decline in the species, which could lead to an increased vulnerability of haddock to cumulative anthropogenic impacts including oil spills.

There are similarities in the impacts of oil exposure on Atlantic haddock and other fish species. However, laboratory experiments in Norway have found that Atlantic haddock embryos are far more susceptible to amplified embryotoxicity from dispersed oil than any other species (Sørhus *et al.*, 2015). The haddock embryo is known to have an adherent chorion (the outermost membrane around the embryo), which retains micro-droplets of oil, creating a direct connection between the toxic components of the dispersed oil and the embryo, and thereby enhancing the exposure (Sørhus *et al.*, 2015). The surface outer layer of the embryonic haddock egg is also stickier than other species, resulting in more significant oil droplet fouling. High rates of oil droplet fouling, for example, were not observed in the Atlantic haddock's close relative, Atlantic cod, making haddock embryos approximately ten times more sensitive to crude oil (Sørensen *et al.*, 2017; Sørhus *et al.*, 2021).

Atlantic haddock, exposed to short-term high concentrations of oil at the early embryonic stages, may experience reduced growth and skeletal malformations, including abnormalities of the upper jaw and craniofacial deformations (Olsvik *et al.*, 2021). Once hatched, delayed mortality is likely in larvae displaying severe upper jaw abnormalities due to reduced feeding ability (Olsvik *et al.*, 2021). Haddock that has survived into adulthood with skeletal deformations following oil toxicity during early life stages may experience impacted physiological processes such as swimming, reproduction, growth, resistance to disease and susceptibility to predation (Olsvik *et al.*, 2021). Reduced eye size and increased incidence of abnormal morphology has also been observed in pre-hatched haddock larvae exposure (Lie *et al.*, 2019). These sublethal effects have been linked to oil disruption of vitamin A signalling and retinol metabolism and may impede feeding abilities and predator avoidance (Lie *et al.*, 2019).

Juvenile Atlantic haddock exposed to low concentrations of PAHs associated with oil pollution experience DNA damage and health effects. Juvenile haddock react very quickly to long-term (months) oil pollution, with DNA adducts detectable within days of exposure (Meier *et al.*, 2020). Like other organisms, fish can repair DNA damage from low concentrations of oil to some extent (Kienzler, Bony and Devaux, 2013). However, there is currently a lack of research on the potential for fish to recover from DNA damage caused by an extreme oil spill event or persistent oil concentrations in the marine environment.

Atlantic haddock is the most landed demersal fish by UK vessels (25,000 tonnes), valued at £35,534,000 in 2021 (Marine Management Organisation, 2021). North sea stocks, in particular, are currently classed as ‘Best Choice’ by the Marine Conservation Society in terms of stock sustainability. However, DNA damage-inducing contaminants have been recorded in wild haddock caught near North Sea oil fields (Varanasi *et al.*, 1989; Balk *et al.*, 2011; Meier *et al.*, 2020). Further development of oil and gas in the UK EEZ, therefore, has the potential to increase the risk of carcinogenic DNA damage in Atlantic haddock and potentially risk stock health and the economic sustainability of the fishery.

### Atlantic cod *(Gadus morhua)*

Atlantic cod is listed by OSPAR as a threatened and/or declining species. Stocks in the North Sea are overfished, outside safe biological limits, and suffering reduced reproductive capacity (Marine Conservation Society, 2022a). Furthermore, the southern North Sea population already appears to have collapsed, with recent surveys showing no rebuilding of stock (Marine Conservation Society, 2022a). Catch quotas for North Sea cod have been severely restricted as a result, which, when combined with high consumer demand (cod is in the top 5 of most consumed fish in the UK) (Uberoi *et al.*, 2021)) has led to the prices reaching record highs; the price for a kilo of fresh Atlantic cod in March 2022 was selling at an average of £3.78, a 56% increase from the previous year (Nilsen, 2022). In 2021, the UK catch of Atlantic cod was valued at £37,025,000 (13, 000 tones) (Marine Management Organisation, 2021). The International Council for the Exploration of the Sea (ICES) reported in 2022 that although fishing pressure had reduced, catches were still not in line with ICES advice and spawning stock biomass (of the North Sea stock in particular) was below the reference point. Consequently, an ongoing risk of impaired recruitment is predicted (ICES, 2022b). The UK introduced a national [cod avoidance plan](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/949293/UK_National_North_Sea_Cod_Avoidance_Plan_PDF_Whole_Document.pdf) in 2020 in an attempt to support the recovery of Atlantic Cod stocks; however, many class it as inadequate (Marine Conservation Society, 2022a). The expansion of oil and gas licencing in UK waters adds an additional anthropogenic threat to the recovery and conservation of Atlantic cod through the increased risk of future oil spills. The impacts of oil exposure on cod due to an accidental oil spill event could critically hinder already poor attempts to recover the species in the North sea (Marine Conservation Society, 2022a).

When subjected to short-term oil exposure (days) as an embryo, the survival and development of embryonic Atlantic cod is impacted (Enerstvedt, Sydnes and Pampanin, 2018). Exposure can lead to acute and delayed toxicity in hatched larvae, including mortality, reduced condition of larvae (standard length, body surface, and yolk sac size), spinal deformations and alterations in craniofacial and jaw development (Hansen *et al.*, 2019). Similar to Atlantic haddock, if severe enough, these deformities may restrict feeding and ultimately kill the developing larvae (Olsvik *et al.*, 2021). The timing of oil exposure during sensitive early stages may be linked to the effects that develop in cod. Higher acute mortality, for example, has been observed in cod embryos exposed to oil from the start of gastrulation (an early cell developmental process) compared to those exposed during organogenesis (the formation of organs). The scale of mortality in exposed embryos during organogenesis, however, appears to be oil concentration-dependent, with more mortalities in those exposed to higher concentrations of oil observed during recovery (Hansen *et al.*, 2019).

In juvenile and adult Atlantic Cod, alterations related to the immune response have been observed following low concentrations of long-term exposure (around one year). These alterations suggest an increased immune stress level and potential increased susceptibility to infection, cancer, and other diseases (Enerstvedt, Sydnes and Pampanin, 2018). Similar observations have been found following short-term (weeks) chronic exposure to environmentally relevant oil concentrations. The innate immune system of the fish was found to be weakened, potentially causing increased vulnerability to infections, cancer and other diseases (Enerstvedt, Sydnes and Pampanin, 2018). Towards the end of the experiment (week 4), mortality was observed in some fish at high concentrations. Thus, short-term, high-concentration exposure over months (instead of weeks) could impact the survival of Atlantic juvenile and adult cod (Enerstvedt, Sydnes and Pampanin, 2018).

### Other commercial fish species

This section includes uncovered impacts of oil spills on European plaice *(Pleuronectes platessa),* yellowfin sole*(Limanda aspera),* Shanny *(Lipophrys pholis),* Atlantic salmon *(almo salar)* and Atlantic herring *(Clupea harengus)*,

DNA damage to cells has been observed in UK commercial fish species due to oil contamination. Following the grounding of the Sea Empress oil tanker in 1996, for example, 72,000 tonnes of crude oil was accidentally released into Milford Haven, Wales (Harvey *et al.*, 1999). Elevated levels of DNA adduct were observed in European plaice *(Pleuronectes platessa) and* yellowfin sole*(Limanda aspera)* in the area, as well as in the Welsh native fish,Shanny (*Lipophrys pholis*)(Harvey *et al.*, 1999)*.* All three species are known to be able to recover from the genetic impact following oil exposure at low concentrations. However, it remains possible that DNA adducts detected could lead to genetic changes in the species in the future (Harvey *et al.*, 1999). Plaice and sole fisheries in the UK are lower in volume than other UK commercial fisheries but receive a higher price (Uberoi *et al.*, 2021). Small vessels are, therefore, able to sell smaller quantities at a more valuable price. Potential long-term impacts of DNA damage to these flat fish species from previous and future spills could increase the species' vulnerability and the economic stability of the UK’s small vessel fleet.

Atlantic salmon *(Almo salar)* and herring *(Clupea harengus)* have been found to experience similar toxic effects of oil exposure to other fish species, including mortality at short-term (days) high concentrations and sublethal impacts, including reduced growth and spinal deformation (Heintz, Short and Rice, 1999; Stagg *et al.*, 2009; Ingvarsdóttir *et al.*, 2012). Abnormal hearts and reduced cardiorespiratory function have also been observed in juveniles of both species, with cardiorespiratory function as a key determinant of individual survival and population recruitment (Incardona *et al.*, 2015).

Quick hydrocarbon concentration of the body tissue has also been found to occur relatively quickly in Atlantic salmon, making the species a good bio-indicator of contaminates such as oil in the marine environment (Stagg *et al.*, 2009). Following the 1993 Braer oil spill off the coast of Shetland, Scotland, for example, farmed salmon was severely contaminated (Goodlad, 1996). Unlike wild capture commercial fish in the area, farmed salmon were confined to cages and could not swim away from the oil. The oil spill contamination led to a total of 5,399 tonnes of farmed salmon in the area being destroyed over two years following the spill (Goodlad, 1996). In today’s money, this scale of the necessary destruction of contaminated salmon would result in a financial loss of roughly £38.5 million (based on a £7.90 per kg value of farmed Scottish salmon from April 2022 (Roughneen, 2022). If a similar scale oil spill to the Braer disaster were to take place along the coast of Scotland today, a significant financial hit to Scottish salmon farmers would be expected.

Furthermore, the financial compensation provided to the Shetland seafood industry following the spill was paid out by the inter-governmental organisation, The International Oil Pollution Compensation Funds, and totalled £29,058,000 (Goodlad, 1996). Today, that amount would equate to £60,179,287.98 (INFLATION TOOL, 2022). Therefore, a spill of similar size and commercial damage would cost not only the UK seafood industry significantly but also the UK government and taxpayers.

Table 2. Table shows the varying impacts of major oil spills on priority commercial and non-commercial fish species at distance from the source. Hyperlinks are provided to references.

|  |  |
| --- | --- |
|  |  |
|  |  | **Distance from source** | | | |
|  |  | **Impact** | **At source** | **10's m** | **10's km** |
| **Species** | *Atlantic cod* | Mortality in embryonic and larvae. | [(Hansen et al., 2019).](https://www.sciencedirect.com/science/article/pii/S014111361930251X?via%3Dihub) |  |  |
| Reduced condition of larvae (length, body surface and yolk sac size). | [(Hansen et al., 2019).](https://www.sciencedirect.com/science/article/pii/S014111361930251X?via%3Dihub) |  |  |
| Spinal deformations. | [(Hansen et al., 2019).](https://www.sciencedirect.com/science/article/pii/S014111361930251X?via%3Dihub) |  |  |
| Alterations in craniofacial and jaw development. | [(Hansen et al., 2019).](https://www.sciencedirect.com/science/article/pii/S014111361930251X?via%3Dihub) |  |  |
| Delayed mortality if jaw deformations restrict feeding ability. | [(Olsvik et al., 2021).](https://www.frontiersin.org/articles/10.3389/fmars.2021.726828/full) |  |  |
| Increased immune stress in juveniles and adult after short and long-term low exposure. | [(Enerstvedt et al., 2018).](https://www.sciencedirect.com/science/article/pii/S0141113618300874?via%3Dihub) |  |  |
| Susceptibility to infection, cancer and other diseases. | [(Enerstvedt et al., 2018).](https://www.sciencedirect.com/science/article/pii/S0141113618300874?via%3Dihub) |  |  |
| Direct embryonic exposure via extensive oil fouling of egg. | [(Sørhus et al., 2015).](https://doi.org/10.1371/journal.pone.0124376) |  |  |
| Reduced growth in exposed larvae. | [(Sørhus et al., 2015).](https://doi.org/10.1371/journal.pone.0124376) |  |  |
| *Atlantic haddock* | Alterations in craniofacial and jaw development. | [(Olsvik et al., 2021).](https://www.frontiersin.org/articles/10.3389/fmars.2021.726828/full) |  |  |
| Delayed mortality if jaw deformations restrict feeding ability. | [(Olsvik et al., 2021).](https://www.frontiersin.org/articles/10.3389/fmars.2021.726828/full) |  |  |
| Delayed impacts on physiological processes from skeletal deformities, including swimming, growth, resistance to disease and predator avoidance. | [(Olsvik et al., 2021).](https://www.frontiersin.org/articles/10.3389/fmars.2021.726828/full) |  |  |
| Reduced eye size in exposed embryos – could impede feeding abilities and predator avoidance. | [(Lie et al., 2019).](https://www.frontiersin.org/articles/10.3389/fmars.2019.00368) |  |  |
| DNA damage in juveniles and adults. | [(Meier et al., 2020).](https://doi.org/10.1371/journal.pone.0240307) |  |  |
| *European plaice* | DNA damage | [(Harvey et al., 1999).](https://www.sciencedirect.com/science/article/pii/S1383571899000376?via%3Dihub) | [(Harvey et al., 1999).](https://www.sciencedirect.com/science/article/pii/S1383571899000376?via%3Dihub) | [(Harvey et al., 1999).](https://www.sciencedirect.com/science/article/pii/S1383571899000376?via%3Dihub) |
| *Yellowfin sole* | DNA damage | [(Harvey et al., 1999).](https://www.sciencedirect.com/science/article/pii/S1383571899000376?via%3Dihub) | [(Harvey et al., 1999).](https://www.sciencedirect.com/science/article/pii/S1383571899000376?via%3Dihub) | [(Harvey et al., 1999).](https://www.sciencedirect.com/science/article/pii/S1383571899000376?via%3Dihub) |
| *Shanny* | DNA damage | [(Harvey et al., 1999).](https://www.sciencedirect.com/science/article/pii/S1383571899000376?via%3Dihub) | [(Harvey et al., 1999).](https://www.sciencedirect.com/science/article/pii/S1383571899000376?via%3Dihub) | [(Harvey et al., 1999).](https://www.sciencedirect.com/science/article/pii/S1383571899000376?via%3Dihub) |
| *Atlantic salmon* | Mortality at short-term high concentrations. | [(Heintz et al., 2000),](https://www.int-res.com/articles/meps/208/m208p205.pdf) [(Stagg et al., 2009).](https://setac.onlinelibrary.wiley.com/doi/10.1002/etc.5620191126) |  |  |
| Reduced growth. | [(Heintz et al., 2000),](https://www.int-res.com/abstracts/meps/v208/p205-216/) [(Stagg et al., 2000),](https://setac.onlinelibrary.wiley.com/doi/10.1002/etc.5620191126) [(Ingvarsdóttir et al., 2012)](https://www.sciencedirect.com/science/article/pii/S0924796311002557?via%3Dihub). |  |  |
| Spinal deformations. | [(Heintz et al., 2000),](https://www.int-res.com/abstracts/meps/v208/p205-216/) [(Stagg et al., 2000),](https://setac.onlinelibrary.wiley.com/doi/10.1002/etc.5620191126) [(Ingvarsdóttir et al., 2012)](https://www.sciencedirect.com/science/article/pii/S0924796311002557?via%3Dihub). |  |  |
| Abnormal heart formation and reduced cardiorespiratory function in juveniles. | [Incardona et al., 2015).](https://www.nature.com/articles/srep13499) |  |  |
| *Herring* | Mortality at short-term high concentrations. | [(Ingvarsdóttir et al., 2012)](https://www.sciencedirect.com/science/article/pii/S0924796311002557?via%3Dihub). |  |  |
| Reduced growth. | [(Heintz et al., 2000),](https://www.int-res.com/abstracts/meps/v208/p205-216/) [(Stagg et al., 2000),](https://setac.onlinelibrary.wiley.com/doi/10.1002/etc.5620191126) [(Ingvarsdóttir et al., 2012)](https://www.sciencedirect.com/science/article/pii/S0924796311002557?via%3Dihub). |  |  |
| Spinal deformations. | [(Heintz et al., 2000),](https://www.int-res.com/abstracts/meps/v208/p205-216/) [(Stagg et al., 2000),](https://setac.onlinelibrary.wiley.com/doi/10.1002/etc.5620191126) [(Ingvarsdóttir et al., 2012)](https://www.sciencedirect.com/science/article/pii/S0924796311002557?via%3Dihub). |  |  |
| Abnormal heart formation and reduced cardiorespiratory function in juveniles. | [(Ingvarsdóttir et al., 2012)](https://www.sciencedirect.com/science/article/pii/S0924796311002557?via%3Dihub). |  |  |

## Invertebrates

### Introduction

Invertebrate populations and communities form the foundation for marine ecosystems (Suchanek, 1993). However, there is far less documentation on the impacts of oil spills on invertebrates compared to vertebrate species, particularly those found offshore and in the deep sea.

Invertebrates in UK offshore waters are at risk of exposure to oil spills through similar pathways to fish, such as contact with contaminated water and sediment, ingestion of oil droplets, particulates contaminated with oil, and contaminated food (Wright *et al.*, 2022).

### Cold-water coral communities, including sea fan colonies

Most deep-sea cold-water coral (CWC) species and sea fan colonies are long-lived and slow-growing, taking hundreds to thousands of years to grow to a large size. Therefore, they are particularly vulnerable to anthropogenic impact/ potential threats, with slow recovery expected after disturbance (Girard and Fisher, 2018). Many CWCs, such as the Lophelia species (common in UK waters), are classed as ‘Data Deficient’ on the IUCN Red List of Threatened Species (IUCN, 2011). Therefore, with the planned expansion of oil and gas licencing in UK waters, these foundation species are increasingly exposed to the risk and impacts of oil spills without adequate baseline monitoring data.

Acute toxicity of oil pollution can significantly impact deep-water ecosystems over several kilometres (Girard, Shea and Fisher, 2018; Montseny *et al.*, 2021). When surveying the impact of the DWH oil spill on deep-water coral (DWC) colonies within the Gulf of Mexico, for example, signs of impact were visible 13 km from the wellhead (at a depth of 1370m) (Girard, Shea and Fisher, 2018; Montseny *et al.*, 2021). DWC colonies exhibited widespread signs of stress and mortality, including varying degrees of tissue loss, sclerite enlargement, excess mucous production, bleached commensal ophiuroids, and covering by brown flocculent material (floc). Although the site was discovered nine months after the spill, analysis of the floc revealed that the hydrocarbon fingerprint could be traced to the DWH wellhead (Girard, Shea and Fisher, 2018; Montseny *et al.*, 2021). Nearly a quarter of all corals analysed at the site exhibited evidence of impact on >90% of the colony, while almost 50% showed impacts on half of the colony. Around a year and a half after the spill, two other coral communities impacted by the DWH oil spill were uncovered, with one 22 km away from the wellhead and at around 50% deeper depths (1850-1950 metres) (Fisher, Hsing, *et al.*, 2014). While the coral communities found within this site were more lightly impacted by similar injuries observed at the site 13km from the wellhead, the discovery considerably extends the distance and depth range of significant acute oil toxicity to benthic macrofaunal communities, specifically DWCs (Fisher, Hsing, *et al.*, 2014).

Acute toxicity of oil pollution can cause long-term impacts on deep-water ecosystems over varying time scales (Girard and Fisher, 2018). One year after the DWH oil spill, apparent signs of impact to the coral colony 13km from the wellhead had decreased. However, the onset of hydroid colonisation (a sign of coral deterioration) had developed on the branches previously covered in floc (Hsing *et al.*, 2013). The onset of hydroid colonisation increased on impacted branches over the remainder of a 17-month study (ending just over two years after the spill). Thus, researchers hypothesised that future site visits would likely reveal additional deterioration to the typically long-lived corals (Hsing *et al.*, 2013). Seven years after the DWH oil spill, this hypothesis was confirmed. DWCs initially impacted by oil exposure (moderate to heavy impact) had not recovered, indicating a long-term, non-acute impact on the coral colonies. Furthermore, abnormally high branch loss was still occurring at the impact site 13km from the wellhead, indicating an ongoing effect of the spill and the potential for delayed mortality (Girard and Fisher, 2018).

Similar long-term impacts were observed for at least four sea fan species within DWC communities affected by the DWH spill. In 2011, a year after the spill occurred, roughly 50% of these sea fan colonies showed substantial injury, including eroded polyps, discolouration, and bare, missing, and broken branches (Etnoyer *et al.*, 2016). Most impacted sea fans had declined further in condition by 2014. Other studies have shown consistent benthic impacts on deep-sea sea fan communities (White *et al.*, 2012; Hsing *et al.*, 2013; Fisher, Demopoulos, *et al.*, 2014; Silva, Etnoyer and MacDonald, 2016). It has since been estimated that depending on the level of impact, it could take up to three decades for the impacted coral communities to recover to a state where all remaining branches appear healthy. However, it could take hundreds of years for affected communities to grow back to their initial biomass (due to the loss of branches) (Girard, Shea and Fisher, 2018; Montseny *et al.*, 2021).

Finally, exposure to oil dispersants via spill clean-up methods can further damage coral communities and impact recovery (Joye *et al.*, 2016). A significant decline in the average health of DWCs has been observed following short-term exposure (24-96 hours) to chemical dispersants alone and when mixed with oil (DeLeo *et al.*, 2016; DeLeo, Lengyel and Cordes, 2016). Lophelia pertusa, the most common CWC in British waters, is among the corals that have displayed this observed toxicity to dispersants (Weinnig *et al.*, 2020). While the pre-exposure health state is expected to return fairly quickly (24 hours) following dispersant exposure, increased water temperature can result in a recovery delay (72 hours). Therefore, using dispersants as a clean-up measure within warming oceans (as a result of climate change) (Intergovernmental Panel on Climate Change (IPCC), 2014) could affect the resilience of corals to environmental stresses such as oil pollution. CWCs are, therefore, highly vulnerable to the various long-term, far-reaching sublethal impacts of oil exposure discussed and the clean-up chemicals used in response to such a spill. Consequently, the cumulative impacts of oil pollution, dispersant toxicity and climate change effects on the marine environment should be considered when determining the threat of oil spills on CWCs (DeLeo *et al.*, 2016).

### Deep-sea sponges

Like CWCs and sea fans, deep-sea sponges (DSS) are slow-growing, taking several decades to reach a large size (A. Maddock, 2008). Therefore, recovery from any disturbance is likely to take many years if adversely affected (Gubbay, 2002). DSS aggregations are also on the OSPAR Threatened and/or Declining species/habitat list (OSPAR Commission, 2022). Nevertheless, few studies have looked at the impact of oil spill pollution on deep-water sponges in the UK or globally.

With the extension of oil and gas licencing in the UK, the **Faroe-Shetland Sponge Belt MPA, along the** West Shetland Slope of the Faroe-Shetland Channel, **has already come under threat of future oil exposure, with plans to run a pipeline from the proposed Cambo oil field through the MPA** (BBC News, 2021)**. Increasing the scientific understanding of the impacts of oil exposure on deep-water sponges is vital to safeguard ecologically valuable species from future oil and gas development.**

Sea sponge communities can survive exposure to high concentrations of oil pollution over short-term periods (from hours to several days) (Luter *et al.*, 2019). However, a loss of critical biological function has been found to occur at environmentally relevant concentrations, evidenced by adverse effects on the larvae's ability to undergo successful settlement and metamorphosis, which is crucial for recruitment (Luter *et al.*, 2019). Exposure to oil pollution, therefore, can negatively impact sponge recruitment to adult populations, which can have adverse consequences for the ecology of reef systems (Luter *et al.*, 2019).

Marked changes in sponge gene expression and disruption of the associated microbiome have been observed at low sublethal oil concentrations (Luter *et al.*, 2019). The responsiveness of the microbial communities to low levels of oil pollution highlights the extreme sensitivity of the sponge microbiome to oil spill events. Microbial shifts or loss in the abundance of key symbionts can lead to adverse impacts on the ecosystem services the microbial sponge community provides, including the loss of shelter and habitat for other organisms (Luter *et al.*, 2019), the filtration of nutrients from the pelagic to the benthic environment, and the capture of carbon sequestrated by the ocean from the atmosphere (Kahn *et al.*, 2015). The impact of oil toxicity on sea sponge communities can, therefore, have a knock-on effect on blue carbon stores and the ocean's contribution to climate change mitigation.

Sea sponges have been found to exhibit cellular stress (reduced lysosomal membrane stability) following short-term exposure (days) to oil, displaying destabilisation of lysosomal membranes. Cellular stress could impede cellular processes and lead to cellular damage and compromised sponge health. Although rapid cell turnover has been observed in tropical sponges, dominant UK sea sponge species are known to be slow-growing (JNCC, 2008). Therefore, UK sea sponge communities are more vulnerable to cellular damage, as it would take decades to centuries for damaged sea sponges to be replaced (Stévenne, 2018). Furthermore, a higher rate of destabilised lysosomes have been observed in sea sponges exposed to increased temperatures (Stévenne, 2018). The cumulative impact of oil spills alongside rising sea temperatures resulting from climate change should therefore be considered when assessing the threat that oil contamination could have on sea sponge communities under future scenarios.

### Ocean quahog (*Arctica islandica*)

The ocean quahog is an extremely slow growing (one of the longest-lived known marine organisms in the world) and maturing organism currently on the OSPAR list of threatened and/or declining species and habitats in the North Sea (OSPAR Commission, 2022). In the UK, the ocean quahog is a protected Feature of Conservation Importance and a Primary Marine Feature for which Marine Conservation Zones (MCZ) can be designated (Marine Scotland Information, 2018; The Wildlife Trusts, 2022). However, very few studies have investigated any effects of oil spills on the species, with the only known impacts observed during a 1977 study, including mortality and slow growth following embryonic and larvae exposure (Byrne and Calder, 1977). To continue improving ocean quahogs' conservation status in the UK, further research into the effects of oil exposure on the protected species is essential to safeguard current stock from the expansion of UK oil and gas licencing.

### Mussels

The sensitivity of two common UK bivalve molluscs to oil contamination have recently been studied. Both the blue mussel *(Mytilus edulis)* and horse mussel (Modiolus modiolus) were found to have a high sensitivity to cardiac activity in the presence of environmentally relevant oil concentrations (Bakhmet, Fokina and Ruokolainen, 2021). An initial sharp decrease in heart rate was observed in both species, followed by notable fluctuations in cardiac activity as the species began to acclimate to the pollution. However, abrupt cardiac arrest was observed in horse mussels exposed to medium and high oil concentrations. Heartbeat was also observed to halter in some blue mussels, although only at high concentrations. Acclimation to the oil pollution was observed after several days, with the recovery of both species’ cardiac activity. However, a difference between the recovery time of the two species was observed, with horse mussels requiring significantly more time for adaptation to oil pollution (heart rate returned to pre-exposure speeds within ten days) compared to blue mussels (heart rate returned within two days). The difference in recovery time could suggest that the adaptation mechanisms of horse mussels are not as effective as blue mussels, potentially due to the different levels of exposure between the habitats of the two species. Blue mussels, for example, have an extremely changeable habitat within the tidal zone. In contrast, horse mussels have a reasonably stable habitat under shelf water conditions. From these findings, it is possible to hypothesise that bivalve molluscs found in stable deep-sea habitats in offshore UK waters could be similarly sensitive to oil pollution, if not more so. Less exposure to fluctuating environmental conditions in these benthic habitats could potentially result in a higher risk of cardiac arrest from oil spill contamination and an extended recovery period. However, focused research on such deep-water molluscs, e.g., the ocean quahog (Arctica islandica), is needed to investigate the plausibility of this hypothesis.

Table 3. Table shows the varying impacts of major oil spills on priority invertebrate species at distance from the source. Hyperlinks are provided to references.

|  |  |
| --- | --- |
|  |  |
|  |  |
|  |  | **Distance from source** | | |
|  |  | **Impact** | **At source** | **10's km** |
| **Species** | *Deep-water coral colonies* | Mortality. |  | [(Girard et al., 2018),](https://d.docs.live.net/981ecd15c761f3ee/Desktop/MarFishEco/2022%20Projects/Uplift%202/Report/Available%20at:%20https:/doi.org/10.1016/j.biocon.2018.06.028) [(Montseny et al., 2021).](https://www.frontiersin.org/articles/10.3389/fmars.2021.621151) |
| Tissue loss. |  | [(Girard et al., 2018),](https://d.docs.live.net/981ecd15c761f3ee/Desktop/MarFishEco/2022%20Projects/Uplift%202/Report/Available%20at:%20https:/doi.org/10.1016/j.biocon.2018.06.028) [(Montseny et al., 2021).](https://www.frontiersin.org/articles/10.3389/fmars.2021.621151) |
| Sclerite enlargement. |  | [(Girard et al., 2018),](https://d.docs.live.net/981ecd15c761f3ee/Desktop/MarFishEco/2022%20Projects/Uplift%202/Report/Available%20at:%20https:/doi.org/10.1016/j.biocon.2018.06.028) [(Montseny et al., 2021).](https://www.frontiersin.org/articles/10.3389/fmars.2021.621151) |
| Excess mucous production. |  | [(Girard et al., 2018),](https://d.docs.live.net/981ecd15c761f3ee/Desktop/MarFishEco/2022%20Projects/Uplift%202/Report/Available%20at:%20https:/doi.org/10.1016/j.biocon.2018.06.028) [(Montseny et al., 2021).](https://www.frontiersin.org/articles/10.3389/fmars.2021.621151) |
| Bleached commensal ophiuroids. |  | [(Girard et al., 2018),](https://d.docs.live.net/981ecd15c761f3ee/Desktop/MarFishEco/2022%20Projects/Uplift%202/Report/Available%20at:%20https:/doi.org/10.1016/j.biocon.2018.06.028) [(Montseny et al., 2021).](https://www.frontiersin.org/articles/10.3389/fmars.2021.621151) |
| Covering of brown material (floc). |  | [(Girard et al., 2018),](https://d.docs.live.net/981ecd15c761f3ee/Desktop/MarFishEco/2022%20Projects/Uplift%202/Report/Available%20at:%20https:/doi.org/10.1016/j.biocon.2018.06.028) [(Montseny et al., 2021).](https://www.frontiersin.org/articles/10.3389/fmars.2021.621151) |
| Long-term onset of hydroid colonisation. |  | [(Hsing *et al.*, 2013).](https://doi.org/10.12952/journal.elementa.000012) |
| After 7 years – abnormally high branch loss (potentially delayed mortality). |  | [(Girard et al., 2018),](https://d.docs.live.net/981ecd15c761f3ee/Desktop/MarFishEco/2022%20Projects/Uplift%202/Report/Available%20at:%20https:/doi.org/10.1016/j.biocon.2018.06.028) |
| *Deep-sea sea fan communities* | After 1 year – eroded polyps. |  | [(Etnoyer et al., 2016).](https://doi.org/10.1007/s00338-015-1363-2) |
| After 1 year – discolouration. |  | [(Etnoyer et al., 2016).](https://doi.org/10.1007/s00338-015-1363-2) |
| After 1 year – bare, missing, and broken branches. |  | [(Etnoyer et al., 2016).](https://doi.org/10.1007/s00338-015-1363-2) |
| After 3 years – further decline, |  | [(Etnoyer et al., 2016).](https://doi.org/10.1007/s00338-015-1363-2) |
| *Deep-sea sponges* | Loss of critical biological function e.g., unable to settle or metamorphose. | [(Luter et al., 2019).](https://doi.org/10.1128/mSystems.00743-19) |  |
| Impact sponge recruitment to adult populations. | [(Luter et al., 2019).](https://doi.org/10.1128/mSystems.00743-19) |  |
| Marked changes in gene expression. | [(Luter et al., 2019).](https://doi.org/10.1128/mSystems.00743-19) |  |
| Disruption of the associated microbiome at low oil concentrations. | [(Luter et al., 2019).](https://doi.org/10.1128/mSystems.00743-19) |  |
| Cellular stress following short-term exposure. | [(Luter et al., 2019).](https://doi.org/10.1128/mSystems.00743-19) |  |
| *Horse mussels* | Abrupt cardiac arrest at medium and high oil concentrations. | [Bakhmet et al., 2021.](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8162556/#sec4-jox-11-00004title) |  |
| *Blue mussels* | Halted heartbeat at high oil concentrations. | [Bakhmet et al., 2021.](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8162556/#sec4-jox-11-00004title) |  |

## Blue Carbon

The ocean sequesters carbon in a similar way to terrestrial ecosystems such as forests and peatlands (Macreadie *et al.*, 2017). Carbon is removed from the atmosphere through biological and chemical processes, which is then accumulated and stored in organic matter (Mcleod *et al.*, 2011).

Blue carbon refers to the carbon captured and stored in coastal and marine ecosystems, particularly by vegetated habitats such as seagrass meadows, saltmarshes, wetlands, mangroves, seaweed and microalgae. Carbon is also stored in offshore seabed sediment and sequestered by marine animals such as marine vertebrates (e.g. cetaceans and fish) and invertebrate organisms (e.g. corals and bivalves) (see references in Stephenson and Johnson, 2021). If left undamaged, significant volumes of blue carbon can remain stored in the marine environment for millennia, decreasing the volume of carbon in the atmosphere that contributes to climate change (Macreadie *et al.*, 2019).

### Blue Carbon - Habitats

Marine habitats in coastal and offshore waters sequester carbon through various processes, including photosynthesis, calcification and draw-down and burial in seafloor sediment (Mcleod *et al.*, 2011). Coastal ecosystems, dominated by marine plants such as salt marshes and seagrass meadows, sequester carbon over the short term within living biomass (leaves, stems, roots etc.). When these marine plants die and decompose on the seafloor, the carbon gets buried in the sediment, where it is stored for much longer time scales. Buried carbon can remain locked away for millennia if undisturbed (Lo Lacono *et al.*, 2008).

Dispersed oil in coastal waters can lead to decreased photosynthesis and increased respiration in marine plants (Hawkins *et al.*, 2018). Therefore, oil spills have the potential to reduce carbon sequestration in coastal habitats whilst increasing the amount of carbon released back into the water column through respiration. Furthermore, coating marine plants such as seagrasses and microalgae in oil from spills and oil effluents can act as a barrier to the diffusion of carbon across cell walls (Hawkins *et al.*, 2018). Consequently, major oil spill events that form a thick oil cover over marine vegetation can restrict the carbon sequestered by the plants while the oil slick persists.

### Blue Carbon - Animals

Marine animals sequester and interact with the ocean carbon cycle through various natural processes, including storing carbon in their biomass and excreting carbon-rich water products that eventually sink into the deep sea (Barnes, 2020). When marine organisms die, their carcasses sink to the deep seafloor, where the blue carbon is eventually buried and sequestered in the sediment (known as deadfall carbon). If undisturbed, this carbon is potentially locked away from the atmosphere for millions of years (Mariani *et al.*, 2020).

Oil spills can lead to the morality of marine animals (Matkin *et al.*, 2008, 2012; Schwacke *et al.*, 2014; Sørhus *et al.*, 2021) and, therefore, have the potential to significantly reduce the amount of carbon that an animal would naturally sequester over its average lifespan. For example, large marine mammals such as cetaceans which weigh several tonnes and live for decades, store large quantities of carbon in their bodies over their entire life span (Pearson, 2019). Lethal impacts of an oil spill on large marine mammal species can therefore cut their lives short by decades, drastically reducing the amount of carbon that an individual can sequester. Furthermore, observed mortality of reproductive-age killer whales and long-term reductions in reproductive success rates following an oil spill (Matkin *et al.*, 2008) could subsequently prevent the birth of future calves and the associated carbon they could sequester in their lifetimes. A female killer whale, for example, can live for 40 years and, on average, produce 5 or 6 calves in total. Therefore, a mother and her calves' lifespan could equate to roughly 280 years worth of sequestered biomass carbon and eventual deadfall carbon (assuming that all live to 40 years old).

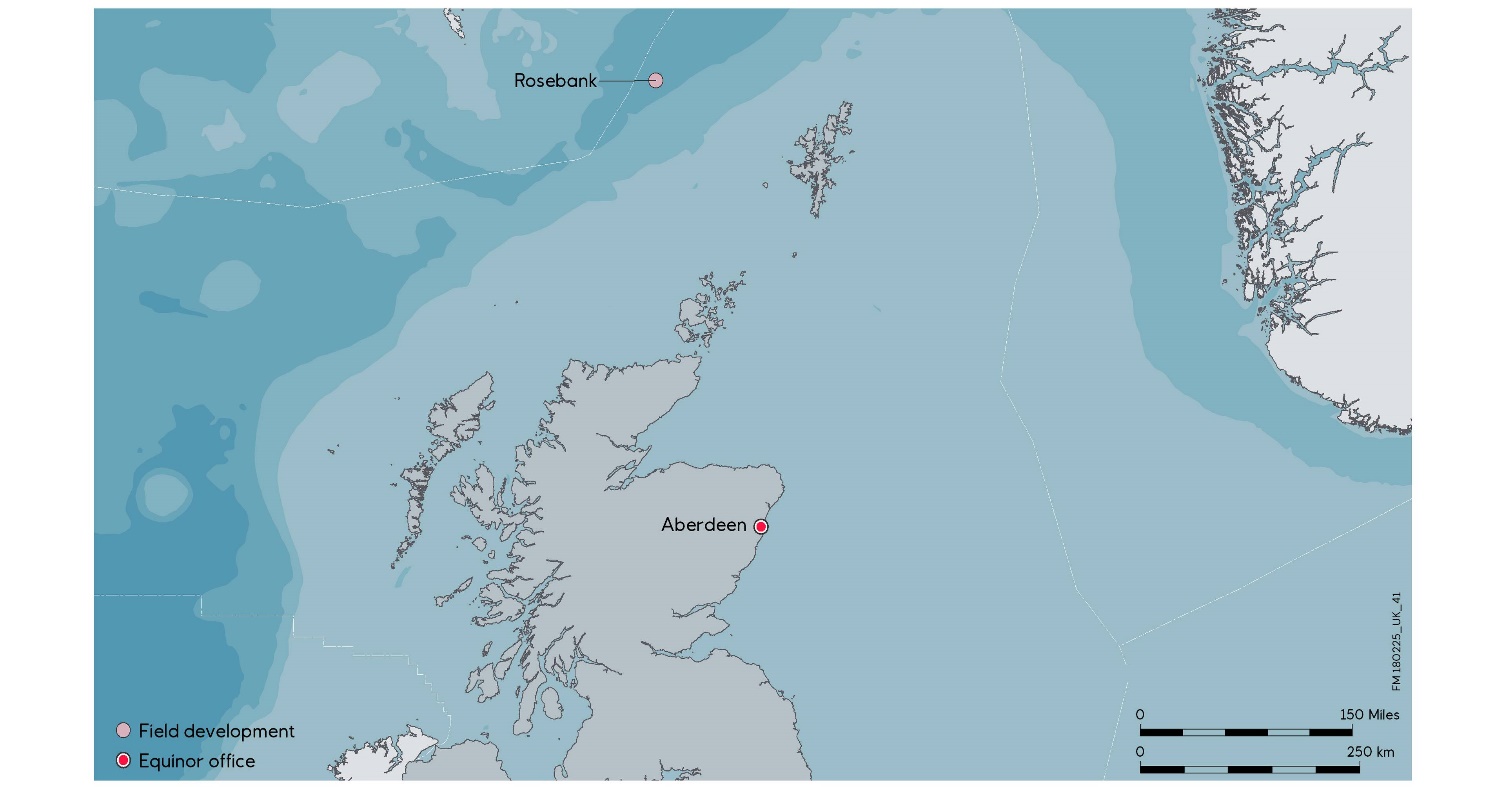
Oil spills, therefore, can potentially disrupt the sequestration of carbon by marine habitats and animals and reduce the long-term stored carbon buried in marine plants and sediments. The expansion of oil and gas licencing in UK waters, therefore, not only risks severe harm to UK marine priority species but also jeopardises the UKs net zero target and climate change mitigation efforts that are now focusing more attention on marine sources of carbon storage.

# Case study - Rosebank Field Development

The following section presents a risk radii of a currently proposed oil and gas field in the UK EEZ to highlight the potential risks of an oil spill to priority species in a real-world context.

### Context

The Rosebank Field Development (RFD) is an oil and gas field situated in the Faroe-Shetland Channel on the northwest edge of the UK Continental Shelf (UKCS). The location is approximately 130km northwest of Shetland in water depths of around 1100 metres (UK Parliament, 2020). The oil field is estimated to have an approximate field life of 25 years.



**Shetland Islands**

**Orkney**

**Mainland UK**

**Hebrides**

Figure 1. Map shows the location of the Rosebank Field Development (a grey circle marks the location). Land masses are labelled for reference. [Map taken from Equinor website](https://www.equinor.com/news/uk/20220805-rosebank-investment).

The proposed project includes;

* Subsea infrastructure installation and commissioning and a new gas export pipeline (connecting to the existing West of Shetland Pipeline System) (installation planned for summer 2024).
* Drilling of four production wells and three water injection wells (planned for 2025).
* New flowlines and the deployment of a Floating Production Storage Offloading Vessel (FPSO) for hydrocarbon extraction and processing purposes.
* The utilisation of tankers for offloading (first oil is expected in 2026).

### Species at risk from an oil spill at the Rosebank Field development site

#### Deep-sea sponges

The RFD is located within the Faroe-Shetland Sponge Belt, a designated Marine Protected Area (MPA) of sensitive deep-sea sponges. If an oil spill were to occur at the RFD, the deep-sea sponge aggregations would be within the source area of impact. Adverse consequences for the ecology of the entire reef system would be expected at such close range, including loss of critical biological function, which is essential for recruitment to adult populations (Luter *et al.*, 2019).

If a spill of low concentrations or short-term exposure occurs at the RFD site, sponge aggregations are still expected to experience cellular change (Stévenne, 2018), disruption of the associated microbiome and cellular stress (Luter *et al.*, 2019). Therefore, a full-well blowout event does not have to occur at the site for sponge health to be compromised and reduced microbiome ecosystem services to occur, e.g. loss of shelter and health of other organisms (Luter *et al.*, 2019).

Recovery of the Faroe-Shetland Sponge Belt from an oil spill would be expected to take many years to decades due to the slow-growing nature of cold-water sponges (A. Maddock, 2008). Therefore, the threat of an oil spill of small or large magnitude at the RFD site adds further risk to an already threatened and declining species.

#### Marine mammals

Marine mammals expected within the immediate area of the RFD include the Minke whale *(Balaenoptera acutorostrata)* and the long-finned pilot whale (*Globicephala melas*). Other marine mammals within close enough proximity to be affected by a major oil spill at the site include Harbour porpoise (*Phocoena phocoena*), various dolphin species (including the Common dolphin (*Delphinus delphis*) and the Killer whale *(Orcinus orca)* (Scottish Government, 2021a)*.*

Minke whales found within 10 km of a major oil spill at the RFD are at risk of oil and hydrocarbons entering the circulation via adsorption. If this occurs, the contaminants may attack the mammal's liver, nervous system and blood-forming tissue, with unknown long-term impacts on the individual and population (Geraci and St Aubin, 1990). Furthermore, as the known impacts of oil toxicity on cetaceans are relatively similar between species, similar effects could likely stretch across other cetaceans close to an oil spill at the site.

A major oil spill at the RFD site could potentially cause population-level impacts to some marine mammals, even over tens of km away from the source. Any loss of reproductive-aged female killer whales from oil ingestion, for example, could result in a repressed population of the impacted pod for decades (Matkin *et al.*, 2008). Furthermore, if exposed to heavily oiled areas, some cetaceans (such as bottlenose dolphins) are at risk of experiencing long-lasting poor maternal health, with a decreased reproductive rate for several years (Lane *et al.*, 2015).

#### Fish

The channel waters around the RFD are used for spawning and nursery grounds by several commercially important fish species, including herring, blue whiting and anglerfish. Atlantic cod and haddock are also supported by the continental shelf around the site (Equinor, 2022).

Larvae within an oil spill’s footprint would be at high risk of mortality and abnormal development (Hansen *et al.*, 2019). Delayed mortality could also be expected if internal organ abnormalities and physical deformities were present once hatched (Olsvik *et al.*, 2021). Reduced ecological success may also occur in the area if adult fish experience behavioural defects from oil toxicity (Johansen *et al.*, 2017).

Juvenile and adult fish within the area would be at risk of experiencing changes in normal metabolismresulting inphysiological stress (Klinger *et al.*, 2015) and behavioural defects that may lead to reduced ecological success. Landings of commercial fish species in the area would likely be negatively impacted due to reduced larvae replenishment and reduced survival in adult fish populations.

### Summary

The RFD is a proposed new oil field situated in the Faroe-Shetland Channel. Developers of the site (Equinor) have stated that the impacts of an oil spill event at the RFD are considered ‘not significant’ (Equinor, 2022). A risk radii of the area, however, has shown that an oil spill at the site could have potentially significant impacts on several UK-priority marine species over several kilometres, including deep-water sponges, cetaceans and commercial fish.

Deep-water sponges would be expected to suffer severe impacts from an oil spill, with the RFD located in such close proximity to the Faroe-Shetland Sponge Belt. The impacts could include cellular change/stress, disruption to the associated biome and a loss of critical biological function of the entire reef system. Recovery of the sponge belt would be expected to take years to decades and could therefore risk the species' long-term survival.

Cetaceans within 10 kilometres of the site are at risk of oil toxicity of the internal organs with unknown long-term impacts on the individual and population. Any loss of reproductive-aged females due to oil toxicity from the site could also lead to long-lasting poor maternal health and a repressed population in some species.

Fish spawning and nursery grounds near the site would be expected to suffer high larvae mortality and deformed development. While adult fish exposed to oil contamination risk developing behavioural defects that could lead to reduced ecological success. Catch reductions of commercial fish species would be expected, with socioeconomic implications for local fishers.

# The effectiveness of guidance and mitigation measures around offshore oil spills

## Guidance and mitigating measures on offshore oil spills in UK waters

The key requirements and guidance for the preparation and mitigation of an offshore oil spill in UK waters include;

1. All ‘Responsible Person’s’ (Installation Operators, Well Operators and Owners of Non-Production Installations) must have an Oil Pollution Emergency Plan that sets out arrangements for responding to incidents that cause marine pollution by oil.

The Oil Pollution Emergency Plan must be prepared and implemented in accordance with the [Merchant Shipping (Oil Pollution Preparedness, Response and Co-operation) Regulations 2015 (Amended)](https://www.legislation.gov.uk/uksi/2015/386/contents/made) and the Department’s [Guidance Notes for Preparing Oil Pollution Emergency Plans.](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1082788/OPEP_Guidance_-_Rev_7_-_June_2022.pdf)

1. Under the [Offshore Installations (Emergency Pollution Control) Regulations 2002](https://www.legislation.gov.uk/uksi/2002/1861/contents/made) the Secretary of State (and any person/s they authorise) has the power to prevent and reduce pollution and the risk of pollution by monitoring and, if necessary, intervening in the event of a threatened or actual pollution incident in connection with an offshore installation (Offshore Petroleum Regulator for Environment and Decommissioning and Department for Business, Energy & Industrial Strategy, 2013).
2. [Guidance on the Offshore Installations (Emergency Pollution Control) Regulations 2002](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/838509/EPC_Guidance_-_Version_1_-_July_2016.pdf) details the powers exercisable by the UK’s Secretary of State (and any person/s they authorise) to prevent and reduce pollution and the risk of pollution following an accident involving an Offshore Installation.
3. If an oil spill occurs, [guidance/guidelines and standards](https://www.cefas.co.uk/media/frwmhths/ccs0118760460-1_prem_2nd_ed_web.pdf) for post-spill environmental monitoring and assessment have been provided by the [Pollution Response In Emergencies: Marine Impact Assessment and Monitoring (PREMIAM)](https://www.cefas.co.uk/premiam/) programme, led by Cefas (Kirkby *et al.*, 2018).
4. The Department for Business, Energy & Industrial Strategy (BEIS) will undertake an [Offshore Energy Strategic Environmental Assessment (SEA)](https://www.gov.uk/guidance/offshore-energy-strategic-environmental-assessment-sea-an-overview-of-the-sea-process) on UK offshore energy resources projects. The SEA process aims to help inform decisions by considering the environmental implications of the outcome of a proposed plan. Part of the SEA process is to present the known impacts of marine discharge (such as an oil spill) on the marine environment (Department for Business, Energy & Industrial Strategy (BEIS), 2013).

## Are the guidance and mitigating measures effective?

The following section outlines the effectiveness of the key requirements and guidance for preparing and mitigating a UK offshore oil spill.

### A lack of mitigating measures

There is a lack of mitigating measures around UK offshore oil spills. Legal requirements and guidance instead focus heavily on the post-spill response rather than mitigating measures to avoid an incident. Post-spill action is ineffective at protecting the marine environment from oil spills as it merely attempts to reduce further harm by containing the spread of the spill. To improve the effectiveness of pre-spill mitigating measures, more focus should be put on reducing the overall threat of oil spills on marine habitats and species. For example, by improving habitat mapping and monitoring of protected and threatened/declining species in UK offshore waters.

### Fines are ineffective measures to mitigate oil spills or incentivise less risky practices.

Mitigating measures around oil pollution focus on fines (as set out in the [Merchant Shipping (Oil Pollution Preparedness, Response and Co-operation) Regulations 2015 (Amended)).](https://www.legislation.gov.uk/uksi/2015/386/contents/made) However, these fines are so small in comparison to a typical oil and gas company’s net worth and annual profit that they are unlikely to be an incentive for UK oil and gas companies to work to mitigate oil spills. In 2020, for example, British Petroleum (BP) were fined £7000 for an oil spill of 95 tonnes of crude oil into seas west of the Scottish Shetland islands (Watts, 2020). The company, in comparison, had an annual profit of roughly £11.8 billion in 2021 (Meredith, 2022). Therefore, it is unlikely that fines of a few thousand GBP will effectively incentives the strengthening of oil spill mitigation methods or incentivise the company to work towards less risky practices. In addition, oil companies operating in the North Sea have been fined for oil spills on only seven occasions since 2000, even though 4,123 separate spills have been recorded over the same period (Hickman, 2012). Therefore, this form of mitigation does not work and is ineffective.

### Poor guidance on the protection of European Protected Species (cetaceans) from oil pollution

Guidance on the protection of European Protected Species (EPS), such as cetaceans, from oil pollution in UK waters is poor and incomplete. In 2010, the Joint Nature Conservation Committee (JNCC), National England and Countryside Council for Wales produced a [draft guidance document on the protection of marine EPS’s from injury and disturbance](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/850708/Draft_Guidance_on_the_Protection_of_Marine_European_Protected_Species_from_Injurt_and_Disturbance.pdf) for the marine area of England and Wales and the UK offshore marine area (Joint Nature Conservation Committee, Natural England and Countryside Council for Wales, 2010). Oil and gas-related seismic and other geophysical surveys, drilling and decommissioning activities were covered in the guidance. However, there was no mention of guidance on the protection of EPS from a potential oil spill. Furthermore, there does not appear to be a finalised version of this report, with the draft version still signposted as the most up-to-date guidance document on EPS 12 years later.

### The OESEA4 severely lacks knowledge on the impact of oil spills on UK marine species and habitats

The Strategic Environmental Assessment (SEA) carried out to evaluate the implications of the expansion of UK oil and gas licencing on the marine environment ([OESEA4](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1103149/OESEA4_Public_Consultation_Government_Response.pdf)) is severely lacking in up-to-date scientific knowledge on the impacts of oil pollution on species and habitats within UK waters. Furthermore, many of the impacts outlined in the OESEA4 are downplayed, shown in a positive light or cherry-picked to exclude the specific impacts mentioned (Table 4). Therefore, the OSEA4 cannot be seen as effective in mitigating the impacts of an oil spill in UK waters.

Table 4. The table shows whether the proven impacts of oil spills on offshore UK habitats and species are included in the Strategic Environment Assessment (SEA) for the expansion of UK oil and gas licencing (OESEA4). The left column details the proven impact presented in scientific papers, the middle column states if that impact has been acknowledged in the OESEA4, and the right column provides a reason (if known) or note.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Scientific understanding of the impacts of oil spills on offshore habitats and species | Are these impacts included in the Strategic Environment Assessment for the expansion of UK oil and gas licencing? (OESEA4) | Notes / reason |
| Marine mammals | Mortality has been observed in marine mammals following exposure to oil. | The OESEA4 states that mortality in marine mammals following oil exposure is “unlikely”. | Multiple studies have observed mortality of marine mammals following exposure to oil in the marine environment. |
| Sublethal impacts of oil spills on baleen whales such as the minke whale include; damage to the liver, nervous system and blood-forming tissue. | There is no mention of oil spill impacts on any whale species in the OESEA4. | Unsure why these impacts are not included in the OESEA4 - the northern minke whale is a common species found in UK waters, so any potential impact from the expansion of oil and gas should be appropriately acknowledged. |
| It has been scientifically proven that oil exposure from the DWH spill significantly contributed to the Unusual Mortality Event (UME) that affected dolphins in the Northern Gulf of Mexico between 2010 and 2016. | The OESEA4 downplays the significant role of the DWH oil spill in the UME. It fails to mention that the research undertaken as part of the NOAA's investigation into the UME concluded that oil exposure from the DWH spill significantly contributed to decreased reproduction and survival of the species in the area. | Multiple studies were undertaken as part of the NOAA's investigation into UME. |
| Neurological lesions, concentrations of fluorescent aromatic compounds in bile and contamination passed through nursing are all known impacts of oil spills on UK seals. | The only impact of oil spills on seals mentioned in the OESEA4 relates to external impacts, e.g., hyperthermia from oiled fur. | As a UK-protected species, the complete scientific understanding of the impact of oil pollution on seals (both grey and harbour) should be an essential inclusion in SEA process relating to oil and gas licencing expansions. |
| Fish | Widespread sublethal effects of oil exposure on fish have been observed through a large volume of studies. | The OESEA4 does a significantly poor job of acknowledging any specific short or long-term impact on fish species in UK waters. | Significant sublethal impacts on fish include abnormalities and deformities in early development, impacted physiological processes and behavioural changes, which may contribute to population-level effects.  Many have also been linked to delayed mortality, a point that surely should be included in an EIA. |
| The impact of an oil spill could hinder the recovery of key commercial fish stocks such as Atlantic cod. | The OESEA does not consider the effect of an oil spill on population levels of commercial UK fish stocks that are below safe biological levels. | The OESEA4 states that “In open waters deeper than 10m, the likelihood that contaminant concentrations will be high enough to affect fish populations is very small, even if chemical dispersants are used.” |
| Billions of pelagic fish larvae have been directly killed in the offshore area following oil spills. | There is little to no impact of oil spills mentioned on fish in the offshore area. | The 2010 Deep Water Horizon oil spill resulted in the direct death of between 2 and 5 trillion fish larvae in the area. |
| Invertebrates | Acute toxicity of oil pollution has been found to significantly impact deep-water ecosystems (coral and sea fan communities) over several kilometres (0-13km) | The OESEA4 has cherrypicked evidence to reduce the distance and depth range of acute oil toxicity known to impact benthic macrofaunal communities. | Substantial and potentially unrecoverable injuries from oil toxicity were heavily documented on coral communities 13km from the Deepwater Horizon oil spill.  The OESEA4 report, however, mentions only ‘greatest impacts’ at 3kms away.  Furthermore, Deep-water coral communities were shown in the downplayed reference to be impacted at depths 500m lower than acknowledged in the OESEA4. |
| The impact of oil exposure on benthic coral communities has been found to be severe and potentially unrecoverable. | The impact on deep-water coral communities is significantly downplayed in the EIA related to the expansion of UK oil and gas licencing (OESEA4). | ND |

### Strong post-spill impact monitoring guidelines are in place

Strong guidance and standards for post-spill environmental marine monitoring are in place through the Cefas-led Pollution Response in Emergencies: Marine Impact Assessment and Monitoring (PREMAIAM) programme (Kirkby *et al.*, 2018). Detailed key methodologies are provided for each species and habitat within UK waters. Each methodology includes; a detailed breakdown of the known vulnerabilities and sensitivities of the species/ habitat to oil contamination and a clear strategy for assessing the damage. Recommended references to studies on monitoring methodologies for each species/habitat are also given (Premiam, 2022). While post-spill monitoring guidance does not help mitigate an oil spill event, it can help establish effective monitoring that builds scientific knowledge on the impact of oil spills on UK offshore species/ habitats.

### Summary

In summary, the guidance and mitigation measures around offshore oil spills are mostly ineffective. Legal requirements and guidance on offshore oil spills focus too heavily on post-spill action and not enough on mitigating the likelihood of an oil spill event. Furthermore, the penalty for oil pollution focuses heavily on fines. However, they are far too small size in size when compared to the billionaire oil and gas companies made to pay them. Consequently, such small fines are unlikely to be an incentive to strengthen spill mitigation measures or less risky practices. Finally, the Strategic Environmental Assessment (SEA) carried out by the UK Government to evaluate the environmental implications of an expansion of UK offshore oil and gas licencing does a poor job of acknowledging known impacts of oil spills on the species and habitats within UK waters.

# Conclusion

Although the majority of uncovered research investigating the impacts of oil spills on marine life has centred on laboratory experiments or taken place in international seas with different physical conditions to the UK, the scale of impacts observed cannot be ignored. Oil spills have a multitude of severe impacts on marine life, including UK offshore priority species such as bottlenose dolphins, seals, commercial fish species, deep-water coral colonies, and sea sponges.

In marine mammals, long-lasting population effects have been observed in cetaceans within hundreds of kilometres from the source of an oil spill. Poor maternal health in bottlenose dolphins following a spill has been found to lead to perinatal losses for several years. While even a slight loss of individual reproductive-age female killer whales from a single pod can lead to population depressions that last decades. However, a lack of knowledge on the impacts of oil spills on key UK baleen whales (including humpbacks and the northern minke whale) is concerning, with the species’ vulnerability to future oil spill events unknown.

In fish, lethal and acute sublethal impacts (such as reduction in swimming speed, foraging ability and predator avoidance) have been observed in numerous key UK commercial species, including Atlantic haddock, cod, European plaice, yellowfin sole, Atlantic salmon and herring. Losses of UK commercial fish species following previous UK oil spills have resulted in roughly £38.5 million (in today's money) cost to the UK seafood industry.

Few studies have investigated the impact of oil spills on offshore invertebrate ecosystems. Most of the limited knowledge on the impact of oil on cold-water coral communities, sea fan colonies and deep-water sponges has come from species health assessments following the 2010 Deepwater Horizon oil spill off the Gulf of Mexico. This work has highlighted the significant distance (over 20km from the spill source) and depth range (almost 2000 metres deep) of acute oil toxicity to benthic macrofaunal communities. Estimations given for the recovery of injured deep-water ecosystems following the Deepwater Horizon spill (hundreds of years) highlight offshore benthic communities' severe long-term vulnerability to oil spill events.

Fewer studies have investigated the impact of oil exposure on offshore benthic bivalve molluscs. However, the difference in cardiac sensitivity to oil exposure and recovery speed observed between mussel species from habitats with different levels of disturbance has allowed researchers to hypothesise that less studied, deep-sea living molluscs in relatively stable habitats may be similarly sensitive to oil, if not more so.

Despite the severity of oil spill impacts on UK priority species, UK guidance and mitigation measures around offshore oil spills are mostly ineffective at reducing the risk of an event and harm to marine life. Improved mitigation measures are required that focus less on post-spill action and more on prevention.

# References

A. Maddock (2008) *UK Biodiversity Action Plan Priority Habitat Descriptions : Coastal Saltmarshes*. UK: UK Biodiversity Action Plan; Priority Habitat Descriptions. Available at: https://data.jncc.gov.uk/data/6e4e3ed1-117d-423c-a57d-785c8855f28c/UKBAP-BAPHabitats-08-CoastSaltmarsh.pdf.

Armstrong, T. *et al.* (2019) ‘Oil exposure alters social group cohesion in fish’, *Scientific Reports*, 9(1), p. 13520. Available at: https://doi.org/10.1038/s41598-019-49994-1.

Bakhmet, I., Fokina, N. and Ruokolainen, T. (2021) ‘Changes of Heart Rate and Lipid Composition in Mytilus Edulis and Modiolus Modiolus Caused by Crude Oil Pollution and Low Salinity Effects’, *Journal of Xenobiotics*, 11(2), pp. 46–60. Available at: https://doi.org/10.3390/jox11020004.

Balk, L. *et al.* (2011) ‘Biomarkers in Natural Fish Populations Indicate Adverse Biological Effects of Offshore Oil Production’, *PLOS ONE*, 6(5), p. e19735. Available at: https://doi.org/10.1371/journal.pone.0019735.

Barnes, D. (2020) *What Is Blue Carbon and Why Is It Important?*, *Frontiers for Young Minds*. Available at: https://kids.frontiersin.org/articles/10.3389/frym.2019.00154 (Accessed: 19 October 2022).

BBC News (2021) ‘Cambo oil field project “could jeopardise deep sea life”’, *BBC News*, 9 November. Available at: https://www.bbc.com/news/uk-scotland-north-east-orkney-shetland-59210899 (Accessed: 6 October 2022).

Carroll, J. *et al.* (2018) ‘Assessing impacts of simulated oil spills on the Northeast Arctic cod fishery’, *Marine Pollution Bulletin*, 126, pp. 63–73. Available at: https://doi.org/10.1016/j.marpolbul.2017.10.069.

DeLeo, D.M. *et al.* (2016) ‘Response of deep-water corals to oil and chemical dispersant exposure’, *Deep Sea Research Part II: Topical Studies in Oceanography*, 129, pp. 137–147. Available at: https://doi.org/10.1016/j.dsr2.2015.02.028.

DeLeo, D.M., Lengyel, S.D. and Cordes, E.E. (2016) ‘Assessing Oil Spill Impacts to Cold-Water Corals of the Deep Gulf of Mexico’, 2016, pp. PO13F-05.

Department for Business, Energy & Industrial Strategy (BEIS), O.P.R. for E. and D. (2013) *Offshore Energy Strategic Environmental Assessment (SEA): An overview of the SEA process*, *GOV.UK*. Available at: https://www.gov.uk/guidance/offshore-energy-strategic-environmental-assessment-sea-an-overview-of-the-sea-process (Accessed: 6 October 2022).

Enerstvedt, K.S., Sydnes, M.O. and Pampanin, D.M. (2018) ‘Study of the plasma proteome of Atlantic cod (Gadus morhua): Changes due to crude oil exposure’, *Marine Environmental Research*, 138, pp. 46–54. Available at: https://doi.org/10.1016/j.marenvres.2018.03.009.

Equinor (2022) *Rosebank Environmental Statement ES/2022/001*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\_data/file/1097880/Rosebank\_Environmental\_Statement\_-\_Final\_for\_Submission\_To\_OPRED\_Equinor\_3rd\_August\_2022.pdf.

Etnoyer, P.J. *et al.* (2016) ‘Decline in condition of gorgonian octocorals on mesophotic reefs in the northern Gulf of Mexico: before and after the Deepwater Horizon oil spill’, *Coral Reefs*, 35(1), pp. 77–90. Available at: https://doi.org/10.1007/s00338-015-1363-2.

Fisher, C.R., Demopoulos, A.W.J., *et al.* (2014) ‘Coral Communities as Indicators of Ecosystem-Level Impacts of the Deepwater Horizon Spill’, *BioScience*, 64(9), pp. 796–807. Available at: https://doi.org/10.1093/biosci/biu129.

Fisher, C.R., Hsing, P.-Y., *et al.* (2014) ‘Footprint of Deepwater Horizon blowout impact to deep-water coral communities’, *Proceedings of the National Academy of Sciences*, 111(32), pp. 11744–11749. Available at: https://doi.org/10.1073/pnas.1403492111.

Fisheries, N. (2022) *Designation of the AT1 Group of Transient Killer Whales as a Depleted Stock Under MMPA | NOAA Fisheries*, *NOAA*. Available at: https://www.fisheries.noaa.gov/action/designation-at1-group-transient-killer-whales-depleted-stock-under-mmpa (Accessed: 3 October 2022).

Frost, K.J. *et al.* (1994) ‘Alaska, and Adjacent Areas Following the Exxon Valdez Oil Spill Marine Mammal Study Number 5’.

Geraci, J.R. and St Aubin, D.J. (1990) *Sea Mammals and Oil: Confronting the Risks.* Academic Press.

Girard, F. and Fisher, C.R. (2018) ‘Long-term impact of the Deepwater Horizon oil spill on deep-sea corals detected after seven years of monitoring’, *Biological Conservation*, 225, pp. 117–127. Available at: https://doi.org/10.1016/j.biocon.2018.06.028.

Girard, F., Shea, K. and Fisher, C.R. (2018) ‘Projecting the recovery of a long-lived deep-sea coral species after the Deepwater Horizon oil spill using state-structured models’, *Journal of Applied Ecology*, 55(4), pp. 1812–1822. Available at: https://doi.org/10.1111/1365-2664.13141.

Gøksoyr, A. *et al.* (1986) ‘Initial characterization of the hepatic microsomal cytochrome P-450-system of the piked whale (Minke) Balaenoptera acutorostrata’, *Marine Environmental Research*, 19(3), pp. 185–203. Available at: https://doi.org/10.1016/0141-1136(86)90015-2.

Goodlad, J. (1996) ‘Effects of the Braer oil spill on the Shetland seafood industry’, *Science of The Total Environment*, 186(1–2), pp. 127–133. Available at: https://doi.org/10.1016/0048-9697(96)05091-7.

Gubbay, S. (2002) *The Offshore Directory. Review of a selection of habitats, communities and species of the north-east Atlantic.* WWF. Available at: http://www.charlie-gibbs.org/sites/all/themes/motion/pdf/Offshore\_directory.pdf.

Hansen, B.H. *et al.* (2019) ‘Developmental effects in fish embryos exposed to oil dispersions – The impact of crude oil micro-droplets’, *Marine Environmental Research*, 150, p. 104753. Available at: https://doi.org/10.1016/j.marenvres.2019.104753.

Harvey, J.S. *et al.* (1999) ‘An assessment of the genotoxic impact of the Sea Empress oil spill by the measurement of DNA adduct levels in selected invertebrate and vertebrate species’, *Mutation Research/Genetic Toxicology and Environmental Mutagenesis*, 441(1), pp. 103–114. Available at: https://doi.org/10.1016/S1383-5718(99)00037-6.

Hawkins, S.J. *et al.* (2018) ‘Chapter 5: Impacts and Environmental Risks of Oil Spills on Marine Invertebrates, Algae and Seagrass.’, in *Oceanography and Marine Biology*. Available at: https://library.oapen.org/viewer/web/viewer.html?file=/bitstream/handle/20.500.12657/47258/9780429454455\_oachapter5.pdf?sequence=1&isAllowed=y.

Heintz, R.A. *et al.* (2000) ‘Delayed effects on growth and marine survival of pink salmon Oncorhynchus gorbuscha after exposure to crude oil during embryonic development’, *Marine Ecology Progress Series*, 208, pp. 205–216. Available at: https://doi.org/10.3354/meps208205.

Heintz, R.A., Short, J.W. and Rice, S.D. (1999) ‘Sensitivity of fish embryos to weathered crude oil: Part II. Increased mortality of pink salmon (Oncorhynchus gorbuscha) embryos incubating downstream from weathered Exxon valdez crude oil’, *Environmental Toxicology and Chemistry*, 18(3), pp. 494–503. Available at: https://doi.org/10.1002/etc.5620180318.

Hickman, L. (2012) ‘Oil companies going unpunished for thousands of North Sea spills’, *The Guardian*. Available at: https://www.theguardian.com/environment/2012/oct/25/oil-companies-north-sea-spills (Accessed: 7 October 2022).

Hsing, P.-Y. *et al.* (2013) ‘Evidence of lasting impact of the Deepwater Horizon oil spill on a deep Gulf of Mexico coral community’, *Elementa: Science of the Anthropocene*. Edited by J.W. Deming and L. Thomsen, 1, p. 000012. Available at: https://doi.org/10.12952/journal.elementa.000012.

ICES (2022a) *Haddock (Melanogrammus aeglefinus) in Subarea 4, Division 6.a, and Subdivision 20 (North Sea, West of Scotland, Skagerrak)*. report. ICES Advice: Recurrent Advice. Available at: https://doi.org/10.17895/ices.advice.19447943.v1.

ICES (2022b) *ICES Advice on fishing opportunities, catch, and effort - Greater North Sea ecoregion. Cod (Gadus morhua) in Subarea 4, Division 7.d, and Subdivision 20 (North Sea, eastern English Channel, Skagerrak)*.

Incardona, J.P. *et al.* (2015) ‘Very low embryonic crude oil exposures cause lasting cardiac defects in salmon and herring’, *Scientific Reports*, 5(1), p. 13499. Available at: https://doi.org/10.1038/srep13499.

Incardona, J.P. (2017) ‘Molecular Mechanisms of Crude Oil Developmental Toxicity in Fish’, *Archives of Environmental Contamination and Toxicology*, 73(1), pp. 19–32. Available at: https://doi.org/10.1007/s00244-017-0381-1.

INFLATION TOOL (2022) *Value of 1991 British Pounds today - Inflation Calculator*. Available at: https://www.inflationtool.com/british-pound/1991-to-present-value?amount=29058000&year2=2022&frequency=yearly (Accessed: 5 October 2022).

Ingvarsdóttir, A. *et al.* (2012) ‘Effects of different concentrations of crude oil on first feeding larvae of Atlantic herring (Clupea harengus)’, *Journal of Marine Systems*, 93, pp. 69–76. Available at: https://doi.org/10.1016/j.jmarsys.2011.10.014.

Intergovernmental Panel on Climate Change (IPCC) (2014) *Climate Change 2014 Synthesis Report Summary for Policymakers*. Geneva, Switzerland. Available at: https://www.ipcc.ch/site/assets/uploads/2018/02/AR5\_SYR\_FINAL\_SPM.pdf.

IUCN (2011) *The IUCN Red List of Threatened Species*, *IUCN Red List of Threatened Species*. Available at: https://www.iucnredlist.org/en (Accessed: 7 October 2022).

JNCC (2008) *UK Biodiversity Action Plan Priority Habitat Descriptions. Deep-sea Sponge Communities.* Available at: https://data.jncc.gov.uk/data/0a9b6b43-4827-44a4-ab06-0f94d5ad6b93/UKBAP-BAPHabitats-12-DeepSeaSpongeComms.pdf.

JNCC (2021) *Marine mammals and offshore industries*. Available at: https://jncc.gov.uk/our-work/marine-mammals-and-offshore-industries/.

Johansen, J.L. *et al.* (2017) ‘Oil exposure disrupts early life-history stages of coral reef fishes via behavioural impairments’, *Nature Ecology & Evolution*, 1(8), pp. 1146–1152. Available at: https://doi.org/10.1038/s41559-017-0232-5.

Joint Nature Conservation Committee, Natural England and Countryside Council for Wales (2010) *The protection of marine European Protected Species from injury and disturbance*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\_data/file/850708/Draft\_Guidance\_on\_the\_Protection\_of\_Marine\_European\_Protected\_Species\_from\_Injurt\_and\_Disturbance.pdf.

Joye, S.B. *et al.* (2016) ‘The Gulf of Mexico ecosystem, six years after the Macondo oil well blowout’, *Deep Sea Research Part II: Topical Studies in Oceanography*, 129, pp. 4–19. Available at: https://doi.org/10.1016/j.dsr2.2016.04.018.

Kahn, A.S. *et al.* (2015) ‘Benthic grazing and carbon sequestration by deep-water glass sponge reefs’, *Limnology and Oceanography*, 60(1), pp. 78–88. Available at: https://doi.org/10.1002/lno.10002.

Kellar, N.M. *et al.* (2017) ‘Low reproductive success rates of common bottlenose dolphins Tursiops truncatus in the northern Gulf of Mexico following the Deepwater Horizon disaster (2010-2015)’, *Endangered Species Research*, 33, pp. 143–158. Available at: https://doi.org/10.3354/esr00775.

Kienzler, A., Bony, S. and Devaux, A. (2013) ‘DNA repair activity in fish and interest in ecotoxicology: A review’, *Aquatic Toxicology*, 134–135, pp. 47–56. Available at: https://doi.org/10.1016/j.aquatox.2013.03.005.

Kingston, P. (1999) ‘Recovery of the Marine Environment Following the Braer Spill, Shetland’, *International Oil Spill Conference Proceedings*, 1999(1), pp. 103–109. Available at: https://doi.org/10.7901/2169-3358-1999-1-103.

Kirkby, M.F. *et al.* (2018) *Post-incident monitoring guidelines*. Lowestoft: Cefas - PREMIAM – Pollution Response in Emergencies – Marine Impact Assessment and Monitoring, p. 176. Available at: https://www.cefas.co.uk/media/frwmhths/ccs0118760460-1\_prem\_2nd\_ed\_web.pdf.

Klinger, D.H. *et al.* (2015) ‘Exposure to Deepwater Horizon weathered crude oil increases routine metabolic demand in chub mackerel, Scomber japonicus’, *Marine Pollution Bulletin*, 98(1), pp. 259–266. Available at: https://doi.org/10.1016/j.marpolbul.2015.06.039.

Lane, S.M. *et al.* (2015) ‘Reproductive outcome and survival of common bottlenose dolphins sampled in Barataria Bay, Louisiana, USA, following the Deepwater Horizon oil spill’, *Proceedings of the Royal Society B: Biological Sciences*, 282(1818), p. 20151944. Available at: https://doi.org/10.1098/rspb.2015.1944.

Langangen, Ø. *et al.* (2017) ‘The effects of oil spills on marine fish: Implications of spatial variation in natural mortality’, *Marine Pollution Bulletin*, 119(1), pp. 102–109. Available at: https://doi.org/10.1016/j.marpolbul.2017.03.037.

Lie, K.K. *et al.* (2019) ‘Offshore Crude Oil Disrupts Retinoid Signaling and Eye Development in Larval Atlantic Haddock’, *Frontiers in Marine Science*, 6. Available at: https://www.frontiersin.org/articles/10.3389/fmars.2019.00368 (Accessed: 2 October 2022).

Lo Lacono, C. *et al.* (2008) ‘Very high-resolution seismo-acoustic imaging of seagrass meadows (Mediterranean Sea): Implications for carbon sink estimates’, *Geophysical Research Letters*, 35(18). Available at: https://doi.org/10.1029/2008GL034773.

Luter, H.M. *et al.* (2019) ‘The Effects of Crude Oil and Dispersant on the Larval Sponge Holobiont’, *mSystems*, 4(6), pp. e00743-19. Available at: https://doi.org/10.1128/mSystems.00743-19.

Macreadie, P.I. *et al.* (2017) ‘Can we manage coastal ecosystems to sequester more blue carbon?’, *Frontiers in Ecology and the Environment*, 15(4), pp. 206–213. Available at: https://doi.org/10.1002/fee.1484.

Macreadie, P.I. *et al.* (2019) ‘The future of Blue Carbon science’, *Nature Communications*, 10(1), p. 3998. Available at: https://doi.org/10.1038/s41467-019-11693-w.

Mager, E.M. *et al.* (2014) ‘Acute Embryonic or Juvenile Exposure to Deepwater Horizon Crude Oil Impairs the Swimming Performance of Mahi-Mahi (Coryphaena hippurus)’, *Environmental Science & Technology*, 48(12), pp. 7053–7061. Available at: https://doi.org/10.1021/es501628k.

Mariani, G. *et al.* (2020) ‘Let more big fish sink: Fisheries prevent blue carbon sequestration—half in unprofitable areas’, *Science Advances*, 6(44). Available at: https://doi.org/10.1126/sciadv.abb4848.

Marine Conservation Society (2021) *Haddock - Rating ID: 958 | Good Fish Guide*. Available at: https://www.mcsuk.org/goodfishguide/ratings/wild-capture/958/ (Accessed: 17 October 2022).

Marine Conservation Society (2022a) *Atlantic cod | Good Fish Guide*. Available at: https://www.mcsuk.org/goodfishguide/species/atlantic-cod/ (Accessed: 2 October 2022).

Marine Conservation Society (2022b) *Haddock | Good Fish Guide*. Available at: https://www.mcsuk.org/goodfishguide/species/haddock/ (Accessed: 17 October 2022).

Marine Conservation Society (2022c) *Haddock (Melanogrammus aeglefinus)*. Available at: https://www.mcsuk.org/goodfishguide/ratings/wild-capture/62/.

Marine Conservation Society (2022d) *Haddock Rating ID: 71*. Available at: https://www.mcsuk.org/goodfishguide/ratings/wild-capture/71/.

Marine Management Organisation (2021) *UK Sea Fisheries Statistics 2021*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\_data/file/1107359/UK\_Sea\_Fisheries\_Statistics\_2021.pdf.

Marsili, L. *et al.* (2001) ‘Polycyclic aromatic hydrocarbons (PAHs) in subcutaneous biopsies of Mediterranean cetaceans’, *Chemosphere*, 44(2), pp. 147–154. Available at: https://doi.org/10.1016/S0045-6535(00)00206-X.

Martins, M.C.I. *et al.* (2020) ‘Respiration cycle duration and seawater flux through open blowholes of humpback (Megaptera novaeangliae) and North Atlantic right (Eubalaena glacialis) whales’, *Marine Mammal Science*, 36(4), pp. 1160–1179. Available at: https://doi.org/10.1111/mms.12703.

Matkin, C.O. *et al.* (2008) ‘Ongoing population-level impacts on killer whales Orcinus orca following the “Exxon Valdez” oil spill in Prince William Sound, Alaska’, *Marine Ecology Progress Series*, 356, pp. 269–281. Available at: https://doi.org/10.3354/meps07273.

Matkin, C.O. *et al.* (2012) ‘Contrasting abundance and residency patterns of two sympatric populations of transient killer whales (Orcinus orca) in the northern Gulf of Alaska’, *http://aquaticcommons.org/id/eprint/8678* [Preprint]. Available at: https://aquadocs.org/handle/1834/25328 (Accessed: 3 October 2022).

Mcleod, E. *et al.* (2011) ‘A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2’, *Frontiers in Ecology and the Environment*, 9(10), pp. 552–560. Available at: https://doi.org/10.1890/110004.

Meier, S. *et al.* (2020) ‘DNA damage and health effects in juvenile haddock (Melanogrammus aeglefinus) exposed to PAHs associated with oil-polluted sediment or produced water’, *PLOS ONE*, 15(10), p. e0240307. Available at: https://doi.org/10.1371/journal.pone.0240307.

Meredith, S. (2022) *Oil giant BP reports highest profit in 8 years on soaring commodity prices*, *CNBC*. Available at: https://www.cnbc.com/2022/02/08/bp-earnings-q4-2021.html (Accessed: 7 October 2022).

Montseny, M. *et al.* (2021) ‘Active Ecological Restoration of Cold-Water Corals: Techniques, Challenges, Costs and Future Directions’, *Frontiers in Marine Science*, 8. Available at: https://www.frontiersin.org/articles/10.3389/fmars.2021.621151 (Accessed: 6 October 2022).

Morey, J.S. *et al.* (2022) ‘Transcriptome profiling of blood from common bottlenose dolphins (Tursiops truncatus) in the northern Gulf of Mexico to enhance health assessment capabilities’, *PLOS ONE*, 17(8), p. e0272345. Available at: https://doi.org/10.1371/journal.pone.0272345.

Nilsen, S.H. (2022) *Atlantic cod prices are at record highs; Russia could send them even higher | IntraFish*, *IntraFish | Latest seafood, aquaculture and fisheries news*. Available at: https://www.intrafish.com/prices/atlantic-cod-prices-are-at-record-highs-russia-could-send-them-even-higher/2-1-1185985 (Accessed: 2 October 2022).

NOAA (2012) *Oil Spills at the Water Surface | response.restoration.noaa.gov*, *Office of Response and Restoration*. Available at: https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/oil-spills-water-surface.html (Accessed: 3 October 2022).

Offshore Petroleum Regulator for Environment and Decommissioning and Department for Business, Energy & Industrial Strategy (2013) *Oil and gas: offshore environmental legislation*, *GOV.UK*. Available at: https://www.gov.uk/guidance/oil-and-gas-offshore-environmental-legislation (Accessed: 6 October 2022).

Olsen, E. *et al.* (2010) ‘Cod, haddock, saithe, herring, and capelin in the Barents Sea and adjacent waters: a review of the biological value of the area’, *ICES Journal of Marine Science*, 67(1), pp. 87–101. Available at: https://doi.org/10.1093/icesjms/fsp229.

Olsvik, P.A. *et al.* (2021) ‘Ontogeny-Specific Skeletal Deformities in Atlantic Haddock Caused by Larval Oil Exposure’, *Frontiers in Marine Science*, 8. Available at: https://www.frontiersin.org/articles/10.3389/fmars.2021.726828 (Accessed: 2 October 2022).

OSPAR Commission (2022) *Deep-Sea Sponge Aggregations*, *OSPAR Commission*. Available at: https://www.ospar.org/work-areas/bdc/species-habitats/list-of-threatened-declining-species-habitats/habitats/deep-sea-sponge-aggregations (Accessed: 6 October 2022).

Pasparakis, C. *et al.* (2019) ‘Physiological impacts of Deepwater Horizon oil on fish’, *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology*, 224, p. 108558. Available at: https://doi.org/10.1016/j.cbpc.2019.06.002.

Pearson, H. (2019) *Sea creatures store carbon in the ocean – could protecting them help slow climate change?* Available at: https://phys.org/news/2019-04-sea-creatures-carbon-ocean-climate.html (Accessed: 17 October 2022).

Premiam (2022) *Premiam - Cefas (Centre for Environment, Fisheries and Aquaculture Science)*. Available at: https://www.cefas.co.uk/premiam/ (Accessed: 6 October 2022).

Rainer Engelhardt, F. (1983) ‘Petroleum effects on marine mammals’, *Aquatic Toxicology*, 4(3), pp. 199–217. Available at: https://doi.org/10.1016/0166-445X(83)90018-8.

Ridoux, V. *et al.* (2004) ‘The impact of the “Erika” oil spill on pelagic and coastal marine mammals: Combining demographic, ecological, trace metals and biomarker evidences’, *http://dx.doi.org/10.1051/alr:2004031*, 17. Available at: https://doi.org/10.1051/alr:2004031.

Roughneen, S. (2022) *Cod and salmon prices leap in first quarter as doubts about Russian exports grow*, *The Grocer*. Available at: https://www.thegrocer.co.uk/commodities/cod-and-salmon-prices-leap-in-first-quarter-as-doubts-about-russian-exports-grow/666459.article (Accessed: 5 October 2022).

Ruberg, E.J., Elliott, J.E. and Williams, T.D. (2021) ‘Review of petroleum toxicity and identifying common endpoints for future research on diluted bitumen toxicity in marine mammals’, *Ecotoxicology*, 30(4), pp. 537–551. Available at: https://doi.org/10.1007/s10646-021-02373-x.

Schwacke, L.H. *et al.* (2014) ‘Health of Common Bottlenose Dolphins (Tursiops truncatus) in Barataria Bay, Louisiana, Following the Deepwater Horizon Oil Spill’, *Environmental Science & Technology*, 48(1), pp. 93–103. Available at: https://doi.org/10.1021/es403610f.

Scottish Government (2021a) *UK dolphin and porpoise conservation strategy: high level strategy*. Available at: http://www.gov.scot/publications/uk-dolphin-porpoise-conservation-strategy-high-level-report/pages/3/ (Accessed: 24 October 2022).

Scottish Government (2021b) ‘UK Dolphin and Porpoise Conservation Strategy: Technical Report’, p. 115.

Silva, M., Etnoyer, P.J. and MacDonald, I.R. (2016) ‘Coral injuries observed at Mesophotic Reefs after the Deepwater Horizon oil discharge’, *Deep Sea Research Part II: Topical Studies in Oceanography*, 129, pp. 96–107. Available at: https://doi.org/10.1016/j.dsr2.2015.05.013.

Smith, C.R. *et al.* (2017) ‘Slow recovery of Barataria Bay dolphin health following the Deepwater Horizon oil spill (2013-2014), with evidence of persistent lung disease and impaired stress response’, *Endangered Species Research*, 33, pp. 127–142. Available at: https://doi.org/10.3354/esr00778.

Sørensen, L. *et al.* (2017) ‘Oil droplet fouling and differential toxicokinetics of polycyclic aromatic hydrocarbons in embryos of Atlantic haddock and cod’, *PLOS ONE*, 12(7), p. e0180048. Available at: https://doi.org/10.1371/journal.pone.0180048.

Sørhus, E. *et al.* (2015) ‘Unexpected Interaction with Dispersed Crude Oil Droplets Drives Severe Toxicity in Atlantic Haddock Embryos’, *PLOS ONE*, 10(4), p. e0124376. Available at: https://doi.org/10.1371/journal.pone.0124376.

Sørhus, E. *et al.* (2021) ‘Untangling mechanisms of crude oil toxicity: Linking gene expression, morphology and PAHs at two developmental stages in a cold-water fish’, *Science of The Total Environment*, 757, p. 143896. Available at: https://doi.org/10.1016/j.scitotenv.2020.143896.

de Soysa, T.Y. *et al.* (2012) ‘Macondo crude oil from the Deepwater Horizon oil spill disrupts specific developmental processes during zebrafish embryogenesis’, *BMC Biology*, 10(1), p. 40. Available at: https://doi.org/10.1186/1741-7007-10-40.

Stagg, R.M. *et al.* (2009) ‘Effects of polycyclic aromatic hydrocarbons on expression of cyp1a in salmon (Salmo salar) following experimental exposure and after the Braer oil spill’, *Environmental Toxicology and Chemistry*, 19(11), pp. 2797–2805. Available at: https://doi.org/10.1002/etc.5620191126.

Stephenson, S. and Johnson, Andrew.F. (2021) *Shifting gears: achieving climate smart fisheries.* Published by WWF, RSPB and Marine Conservation Society. Available at: https://www.wwf.org.uk/sites/default/files/2021-08/Pact\_Media\_WWF\_Climate\_Smart\_Fisheries\_Report\_2021\_Aug\_16\_V2.pdf.

Stévenne, C. (2018) ‘The response of a boreal deep-sea sponge holobiont to an acute crude oil exposure: a mesocosm experiment’, p. 78.

Stieglitz, J.D. *et al.* (2016) ‘Impacts of Deepwater Horizon crude oil exposure on adult mahi-mahi (Coryphaena hippurus) swim performance’, *Environmental Toxicology and Chemistry*, 35(10), pp. 2613–2622. Available at: https://doi.org/10.1002/etc.3436.

Suchanek, T.H. (1993) ‘Oil Impacts on Marine Invertebrate Populations and Communities1’, *American Zoologist*, 33(6), pp. 510–523. Available at: Stieglitz.

Takeshita, R. *et al.* (2017) ‘The Deepwater Horizon oil spill marine mammal injury assessment’, *Endangered Species Research*, 33, pp. 95–106. Available at: https://doi.org/10.3354/esr00808.

Tarasoff, F.J. *et al.* (1972) ‘Locomotory patterns and external morphology of the river otter, sea otter, and harp seal (Mammalia)’, *Canadian Journal of Zoology*, 50(7), pp. 915–929. Available at: https://doi.org/10.1139/z72-124.

Uberoi, E. *et al.* (2021) *UK Fisheries Statistics*. House of Commons Library. Available at: https://researchbriefings.files.parliament.uk/documents/SN02788/SN02788.pdf.

UK Parliament (2020) ‘PUBLIC NOTICE - THE OFFSHORE OIL AND GAS EXPLORATION, PRODUCTION, UNLOADING AND STORAGE (ENVIRONMENTAL IMPACT ASSESSMENT) REGULATIONS 2020 (the 2020 Regulations) -Rosebank Field Development’. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\_data/file/1097881/Rosebank\_Field\_Development\_Public\_Notice.pdf.

Varanasi, U. *et al.* (1989) ‘Formation and persistence of benzo[a]pyrene-diolepoxide-DNA adducts in liver of English sole (Parophrys vetulus)’, *Chemico-Biological Interactions*, 69(2), pp. 203–216. Available at: https://doi.org/10.1016/0009-2797(89)90078-1.

Venn-Watson, S. *et al.* (2015) ‘Adrenal Gland and Lung Lesions in Gulf of Mexico Common Bottlenose Dolphins (Tursiops truncatus) Found Dead following the Deepwater Horizon Oil Spill’, *PLOS ONE*, 10(5), p. e0126538. Available at: https://doi.org/10.1371/journal.pone.0126538.

Watts, R. (2020) *BP slapped with small fine for UK oil spill | Upstream Online*, *Upstream Online | Latest oil and gas news*. Available at: https://www.upstreamonline.com/environment/bp-slapped-with-small-fine-for-uk-oil-spill/2-1-849091 (Accessed: 7 October 2022).

Weinnig, A.M. *et al.* (2020) ‘Cold-water coral (Lophelia pertusa) response to multiple stressors: High temperature affects recovery from short-term pollution exposure’, *Scientific Reports*, 10(1), p. 1768. Available at: https://doi.org/10.1038/s41598-020-58556-9.

Werth, A.J., Blakeney, S.M. and Cothren, A.I. (2019) ‘Oil adsorption does not structurally or functionally alter whale baleen’, *Royal Society Open Science*, 6(5), p. 182194. Available at: https://doi.org/10.1098/rsos.182194.

White, H.K. *et al.* (2012) ‘Impact of the Deepwater Horizon oil spill on a deep-water coral community in the Gulf of Mexico’, *Proceedings of the National Academy of Sciences*, 109(50), pp. 20303–20308. Available at: https://doi.org/10.1073/pnas.1118029109.

Wright, S.K. *et al.* (2022) ‘Oil Spills in the Arctic’, in M. Tryland (ed.) *Arctic One Health: Challenges for Northern Animals and People*. Cham: Springer International Publishing, pp. 159–192. Available at: https://doi.org/10.1007/978-3-030-87853-5\_7.

# Follow-up research ideas

* Blue carbon contribution of priority offshore UK species linked to the impacts of oil spills. E.g. how much carbon are they estimated to sequester in their lifetime, how many offspring will they have that will contribute to carbon sequestration, and how will oil spills cut this short/ impact carbon uptake?