**Direct impacts of oil and gas development: Seismic and other geophysical survey techniques**

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By

MarFishEco Fisheries Consultants Ltd

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# Executive summary

Seismic air gun sound, used to locate oil and gas deposits, is a major source of anthropogenic sound in the ocean – generating sound impulses typically over 230 decibels (dB). Surveys can cover hundreds or thousands of square kilometres and take weeks or months to complete.

This review assesses the evidence for impacts of seismic and other geophysical survey techniques on marine life, including priority species and wider ecosystem impacts. Key findings are:

**Marine mammals**

* Marine mammals are acoustically sensitive, relying on sound for key life functions (e.g. communication and orientation). Seismic air gun sound impacts communication, causing hearing damage (temporary threshold shifts) and masking biologically significant sounds.
* Cetaceans consistently show avoidance in response to seismic sound, which may cause pods to move away from key habitats such as foraging grounds or alter their migration routes. Altered diving patterns have also been observed.
* The evidence strongly indicates that harbour porpoise are particularly sensitive to seismic sound, exhibiting avoidance behaviours and also reductions in echolocation and buzzing (used in foraging).
* Humpback whale pods have also been observed to avoid seismic sound, affecting their migration patterns, with pods containing resting cows exhibiting responses at a distance of 7-12 kilometres from a seismic air gun source.

**Fish and shellfish**

* There is a high degree of variability in how different species of fish and shellfish detect and respond to sound, with some taxa only sensitive to the particle motion element of sound (and not sound pressure).
* General impacts of seismic sound include damage to hearing, stress, and behavioural responses such as startle responses and changes in swimming.
* Atlantic cod exhibit signs of stress (e.g. reduced heart rate) in response to seismic sound, with chronic exposure having the potential to negatively impact stocks due to reduced embryo quantity and quality. Behavioural responses, which could lead to reduced catch rates, have also been observed.
* Other commercial fish, including blue whiting, haddock and saithe, have also been found to respond behaviourally to seismic sound, often showing an avoidance response which could reduce catch rates.
* Crustaceans are most likely to respond to particle motion, with a large range in sensitivities. General impacts of seismic sound include hearing damage (due to statocyst damage), organ and/or tissue damage, stress and behavioural changes.
* Cephalopods have also been found to be severely impacted by seismic sound, with acute morphological impacts resulting from exposure, which could be a cause of strandings.

**Wider ecosystem impacts**

* Zooplankton abundance has been found to drop significantly following seismic air gun exposure, with 64% declines of all species sampled (primarily copepods) found within one hour of exposure and a 100% mortality rate of larval krill within 1.2 km of the seismic air gun source.
* Mussel beds could also be impacted by seismic sound exposure, with *Mytilus edulis* exhibiting valve closure in response to particle motion, which is likely to impact the overall fitness of individuals and mussel beds.
* Impacts on zooplankton and key habitats such as mussel beds could lead to significant knock-on consequences for the wider ecosystem, with population-level implications for species of commercial and conservation concern.

**The cumulative footprint of impact**

* Seismic surveys, due to their large spatial and temporal scale, are likely to have chronic impacts on individuals which are not fully understood. Population-level implications have also not been studied.
* Seismic sound should be considered in combination with other anthropogenic sounds in the ocean, such as vessel noise. Cumulative impacts could have serious effects on the health of marine ecosystems.

In general, there is a lack of research into the effects of seismic sound on marine life. Many studies are laboratory experiments, which limits extrapolation to wild populations. The chronic and population-level consequences of impacts are not understood, including the long-term effects of sublethal impacts (such as stress).

Despite this, there is clear evidence of the severe impacts of seismic sound on many marine species. Alternatives to seismic surveys, such as marine vibroseis and electromagnetic surveys, do exist. These technologies are potentially lower impact, but more research is required to understand their environmental implications.

There are significant challenges surrounding the licencing and permitting of seismic sound surveys. Guidelines are given for mitigating the impacts of seismic air gun sound on some species (primarily cetaceans), and many impacts are noted. However, guidelines are voluntary, and mitigation advice is unclear in many cases.

# Key statistics

* “During seismic surveying, reef fish abundance declined by 78%.” (Paxton *et al.*, 2017) – study of reef fish in the Caribbean – distance = 100m from source sound.
* “Air gun sounds were recorded almost 4,000 km away from the survey vessel.” (Nieukirk *et al.*, 2012) – study of acoustics properties of oil and gas survey vessels in the mid-Atlantic.
* “Density of fish was clearly lower within the shooting area, with increasing abundance at distance from the seismic shooting.” (Slotte *et al.*, 2004) – acoustic mapping of pelagic fish distribution and abundance in relation to a seismic shooting area off the Norwegian coast.
* “Findings suggest that the majority of fish species are sensitive to changes in the soundscape, and species responses may have extreme and negative fitness consequences.” (Cox *et al.*, 2018) – a meta-analysis on the effect of aquatic noise on fish behaviour and physiology.
* “Exposure to sound can result in behavioural responses that alter how species mediate ecosystem processes” (Solan *et al.*, 2016) – a study on how anthropogenic sound can modify how sediment-dwelling invertebrates mediate ecosystem properties.
* “Scallop larvae exposed to playbacks of seismic pulses showed significant developmental delays and 46% developed body abnormalities compared to none in the control.” (de Soto *et al.*, 2013) – study of anthropogenic noise impacts on marine larvae.
* “Exposure to air guns signals caused morphological damage to the statocyst of spiny rock lobsters, which can, in turn, impair complex reflexes.” (Day *et al.*, 2019) – study of seismic air gun exposure on lobster mechanosensory organs.
* “Given the extensive spatial scale for serious impacts on plankton observed, combined with the repeat and sustained nature of many seismic surveys in a comparatively small spatial area, it is highly probable that significant depletion or modification of plankton community is occurring on the scale of 3D seismic surveys undertaken.” (McCauley *et al.*, 2017) – study of seismic air gun operation impacts on zooplankton.

# Main content

## Introduction to seismic sound

Seismic air gun sound, used to locate oil and gas deposits, is a major source of anthropogenic sound in the ocean. Intense sound impulses, typically over 230 decibels (dB) root mean square (RMS), are used (Nowacek *et al.*, 2015), equivalent to more than twice the sound level of an ambulance siren. These sound waves consist of two components which can impact marine life: sound pressure and particle motion.

The vast majority of seismic air gun surveys are three-dimensional (3D), often covering hundreds or thousands of square kilometres (km2) and taking weeks or months to complete (McCauley *et al.*, 2017). The impact of these intense sound impulses can be far-reaching – with one study by Nieukirk *et al.*, (2012) recording seismic air gun sounds almost 4,000 km away from the survey vessel.

## Marine mammals

### Introduction

Marine mammals, including cetaceans (dolphins, whales and porpoise) and pinnipeds (seals), are protected species in the UK (JNCC, 2022). Marine mammals are acoustically sensitive (Gordon *et al.*, 2003), relying on acoustic signalling for key life functions, such as communication, orientation, and locating prey (Kavanagh *et al.*, 2019).

The dominant frequencies of seismic air gun sound overlap with those of the communication signals of whales (Kavanagh *et al.*, 2019), raising concerns about the impacts on individuals and populations. A review by Gordon *et al.*, (2003) explored the effects of seismic sound on marine mammals. Impacts included:

* **Physical and physiological impacts,** e.g. hearing damage (including temporary threshold shifts (TTS)), stress bio-indicators
* **Perceptual impacts,** e.g., masking of biologically significant sounds
* **Behavioural impacts,** e.g., sound avoidance, altered dive and respiratory patterns, disruption of foraging
* **Indirect impacts,** e.g., reduced availability of prey

### Harbour porpoise (*Phocoena phocoena*)

Several studies have investigated the impact of seismic survey air gun sounds on the harbour porpoise (*Phocoena phocoena*) in the North Sea and Moray Firth, Scotland. Sound avoidance (aversive behaviour) responses have been found at multiple scales – from the immediate area (Lucke *et al.*, 2009) to several kilometres (km) away from a seismic source (Ward, 2010; Thompson *et al.*, 2013; Pirotta *et al.*, 2014; Sarnocińska *et al.*, 2020).

In addition to these sound avoidance responses, a study by Pirotta *et al.*, (2014) based in Scottish waters found a 15% reduction in buzzing behaviour (high-repetition click trains used in prey capture) within a seismic survey impact area (up to 25 km away from the sound source). A more recent study by Sarnocińska *et al.*, (2020) in the Danish North Sea found a reduction in echolocation between 8 and 12 km from a 3D seismic survey source – with could indicate temporary displacement (sound avoidance) and/or a change in echolocation behaviour.

Thompson *et al.*, (2013) also found sound avoidance behaviours over 5-10 km ranges in groups of harbour porpoise throughout a 2,000 km2 two-dimensional (2D) seismic survey area in the North Sea, with animals being detected again in the area within a few hours of the seismic vessel passing.

Reductions in buzzing and echolocation could disrupt harbour porpoise foraging and social activities (Ward, 2010; Pirotta *et al.*, 2014; Sarnocińska *et al.*, 2020), with unknown long-term effects on individuals and populations. The high metabolic rates of these animals mean they have limited ability to cope with prolonged starvation (Pirotta *et al.*, 2014). Harbour porpoise have been identified by OSPAR as threatened and/or declining and are considered to be in need of priority protection (OSPAR Commission, 2008).

### Humpback whale (*Megaptera novaeangliae*).

Similarly, multiple studies in Australia have found avoidance responses to seismic sound in humpback whales (*Megaptera novaeangliae*). Again, the potential long-term effects of these aversive behaviours on individuals and populations are unknown.

A study by Dunlop *et al.*, (2017) did not find any evidence that humpback whales were under significant additional stress during seismic air gun exposure. However, groups of migrating humpback whales did respond to a full seismic array by changing their movement patterns (migrating southwards below typical speeds due to deviance off their normal course).

In 2018, Dunlop *et al.* further investigated sound avoidance responses in humpback whales and found that whale groups were most likely to show an avoidance response within 4 km of the seismic air gun source. Furthermore, McCauley *et al.*, (2000) found that humpback whales would take manoeuvres to ensure a seismic vessel would not pass closer than 3-4 km.

Pods containing resting cows have been shown to be more sensitive to seismic sound, exhibiting an avoidance response at 7–12 km from a seismic air gun source (McCauley *et al.*, 2000). Though displacements appeared to be short in time, the authors noted that displacement by a continuously operating seismic vessel in a key habitat (such as a resting and/or foraging area) could have profound and serious effects on individuals and populations.

### Bottlenose dolphin (*Tursiops truncatus*)

In bottlenose dolphins (*Tursiops truncatus*), an increase in aldosterone and a decrease in monocytes (stress bio-indicators) have been observed in response to a single seismic air gun exposure (Romano *et al.*, 2004). Of seven deceased bottlenose dolphins studied after a stranding event in the USA, four (57%) had significant hearing deficits, although this cannot be definitely linked to seismic survey sounds (Mann *et al.*, 2010).

### Fin whale (*Balaenoptera physalus*)

Fin whales (*Balaenoptera physalus*) (the most commonly sighted baleen whale in the Kavanagh *et al.*, (2019) study) in the northeast Atlantic have been found to move away from seismic air gun array sources for an extended time beyond the period of seismic activity (Castellote, Clark and Lammers, 2012).

### Sperm whale (*Physeter macrocephalus*)

Madsen *et al.* have studied the impacts of seismic sound on sperm whales (*Physeter macrocephalus*) in Mexico, finding that sperm whales took avoidance manoeuvrers to reduce exposure to seismic sound and could be impacted more than 10 km away from the seismic source (Madsen *et al.*, 2006).

However, this response is variable – in the more recent study investigating male sperm whales, no observable avoidance was seen in male sperm whales during exposures to a maximum of 146 dB from a seismic vessel more than 20 km away (Madsen *et al.*, 2015). This is in contrast to findings outlined by Gordon *et al.*, (2003), suggesting that sperm whales could respond behaviourally to a source hundreds of kilometres away.

### Minke whale (*Balaenoptera acutorostrata*)

Very little is known about the impacts of seismic sound on minke whales, a common cetacean in UK waters. No dedicated studies were found; however, the most recent analysis of marine mammal observer data by Stone *et al.*, (2017) (see below) revealed some previously unknown responses (Stone, 2003).

Significant reductions in detection rates occurred when large air gun arrays were firing, and significantly more pods were observed to avoid or travel away from the vessel when air guns were firing (compared to when they were not) (Stone *et al.*, 2017). This is similar to findings by Moulton and Holst (2010), who observed localised avoidance in response to seismic sound in minke whales in the northwest Atlantic.

### General trends (UK cetaceans)

Some studies have used UK marine mammal observer sightings data to investigate general and species-specific trends:

Stone, (2003) analysed 1,652 sightings of marine mammals during 201 seismic surveys in UK waters and some adjacent areas between 1998 and 2000 and found that the observation rate for all whale species consistently declined during active seismic air gun surveys. Some of the most common behavioural reactions recorded by marine mammal observers were fleeing, a change in swimming direction, and a change in diving.

In 2017, Stone *et al.* analysed 13 years of marine mammal observer data (9,073 sightings) from 1994-2010. Again, a significant reduction in detection rates of multiple species of whales, dolphins, and porpoise was evident when large air gun arrays were active. When small air gun arrays were active, sightings of sperm whales and harbour porpoise were significantly lower, indicating that these species may be more sensitive to seismic sound.

Kavanagh *et al.*, (2019) then modelled the impacts of seismic surveys on cetaceans across a large marine ecosystem covering >880,000 km2 off the Irish coast using UK sightings data. An 88% decrease in baleen whale sightings and a 53% decrease in toothed whale sightings were predicted during active seismic surveys.

### Pinnipeds

Very few studies have specifically investigated the impact of seismic sound on the UK’s seal species (the harbour seal, *Phoca vitulina;* and grey seal, *Halichoerus grypus*). Gordon *et al.*, (2003) reviewed the findings of available studies, with some evidence of fright responses and aversive behaviour (sound avoidance) in harbour seals and a change from foraging to transiting behaviour with some seals hauling out (possible sound avoidance) in grey seals.

For both species, these behaviours were observed to be short-term, but the authors noted that effects could be longer-term and more extreme during commercial seismic surveys. In 2017 a study by Stone *et al.* 2017 found a decrease in grey seal sightings during active large (commercial) seismic air gun surveys. The potential chronic impacts of exposure to seismic air gun sound on UK seal species are unknown.

### Marine Mammals: Summary

There is a general agreement among the research that marine mammals show aversive behaviour (avoidance) towards seismic survey air gun sounds. In addition, physical and physiological, perceptual, and indirect impacts have been found (Gordon *et al.*, 2003).

These impacts have the potential to impact the abilities of marine mammals to find food, navigate, locate mates, avoid predators, and migrate. This could cause chronic stress, leading to reduced viability, mortality and strandings (e.g. Mann *et al.*, 2010). However, there is a significant lack of research into these potential chronic effects and the wider consequences of seismic sound impacts on marine mammals.

Table 1. Table shows the varying impacts of oil and gas seismic surveys on priority marine mammal species at distance from the source. Sound exposure level (SEL) is shown in brackets, p-p =peak pressure.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | **Distance from source** | | | | | |
|  |  | **Impact** | **At source** | **10's m** | **100's m** | **1km** | **10's km** | **100'km** |
| **Species** | *Harbour porpoise* | **Behavioural:** Sound avoidance | >174 dB ([Lucke](https://asa.scitation.org/doi/10.1121/1.3117443) *[et al.,](https://asa.scitation.org/doi/10.1121/1.3117443)* [2009](https://asa.scitation.org/doi/10.1121/1.3117443)) | >174 dB ([Lucke](https://asa.scitation.org/doi/10.1121/1.3117443) *[et al.,](https://asa.scitation.org/doi/10.1121/1.3117443)* [2009](https://asa.scitation.org/doi/10.1121/1.3117443)) |  | 145-155 dB ([Sarnocinska](https://www.frontiersin.org/articles/10.3389/fmars.2019.00824/full) *[et al.](https://www.frontiersin.org/articles/10.3389/fmars.2019.00824/full)*[, 2020](https://www.frontiersin.org/articles/10.3389/fmars.2019.00824/full); [Thompson *et al.,* 2013](https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.807.3664&rep=rep1&type=pdf); [Ward *et al.,* 2010](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/851549/2D_Seismic_Survey_in_the_Moray_Firth_-_Review_of_noise_impact_studies_and_Re-assessment_of_Acoustic_Impacts.pdf)) | 145-155 dB ([Sarnocinska](https://www.frontiersin.org/articles/10.3389/fmars.2019.00824/full) *[et al.](https://www.frontiersin.org/articles/10.3389/fmars.2019.00824/full)*[, 2020](https://www.frontiersin.org/articles/10.3389/fmars.2019.00824/full); [Thompson *et al.,* 2013](https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.807.3664&rep=rep1&type=pdf); [Ward *et al.,* 2010](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/851549/2D_Seismic_Survey_in_the_Moray_Firth_-_Review_of_noise_impact_studies_and_Re-assessment_of_Acoustic_Impacts.pdf)) |  |
| **Behavioural:**  Reduced buzzing | 145-165 dB ([Pirotta](https://royalsocietypublishing.org/doi/10.1098/rsbl.2013.1090) *[et al.,](https://royalsocietypublishing.org/doi/10.1098/rsbl.2013.1090)* [2014](https://royalsocietypublishing.org/doi/10.1098/rsbl.2013.1090)) | 145-165 dB ([Pirotta](https://royalsocietypublishing.org/doi/10.1098/rsbl.2013.1090) *[et al.,](https://royalsocietypublishing.org/doi/10.1098/rsbl.2013.1090)* [2014](https://royalsocietypublishing.org/doi/10.1098/rsbl.2013.1090)) | 145-165 dB ([Pirotta](https://royalsocietypublishing.org/doi/10.1098/rsbl.2013.1090) *[et al.,](https://royalsocietypublishing.org/doi/10.1098/rsbl.2013.1090)* [2014](https://royalsocietypublishing.org/doi/10.1098/rsbl.2013.1090)) | 145-165 dB ([Pirotta](https://royalsocietypublishing.org/doi/10.1098/rsbl.2013.1090) *[et al.,](https://royalsocietypublishing.org/doi/10.1098/rsbl.2013.1090)* [2014](https://royalsocietypublishing.org/doi/10.1098/rsbl.2013.1090)) | 145-165 dB ([Pirotta](https://royalsocietypublishing.org/doi/10.1098/rsbl.2013.1090) *[et al.,](https://royalsocietypublishing.org/doi/10.1098/rsbl.2013.1090)* [2014](https://royalsocietypublishing.org/doi/10.1098/rsbl.2013.1090)) |  |
| **Behavioural:** Decreased echolocation |  |  |  | 140-155 dB ([Sarnocinska](https://www.frontiersin.org/articles/10.3389/fmars.2019.00824/full) *[et al.,](https://www.frontiersin.org/articles/10.3389/fmars.2019.00824/full)* [2020](https://www.frontiersin.org/articles/10.3389/fmars.2019.00824/full)), | 140-155 dB ([Sarnocinska](https://www.frontiersin.org/articles/10.3389/fmars.2019.00824/full) *[et al.,](https://www.frontiersin.org/articles/10.3389/fmars.2019.00824/full)* [2020](https://www.frontiersin.org/articles/10.3389/fmars.2019.00824/full)), |  |
| *Humpback whale* | **Behavioural:** Sound avoidance |  |  | >130 dB ([Dunlop *et al.*, 2017](https://royalsocietypublishing.org/doi/10.1098/rspb.2017.1901), [Dunlop *et al.*, 2018](https://www.sciencedirect.com/science/article/abs/pii/S0025326X18304077)) | >130 dB ([Dunlop *et al.*, 2017](https://royalsocietypublishing.org/doi/10.1098/rspb.2017.1901), [Dunlop *et al.*, 2018](https://www.sciencedirect.com/science/article/abs/pii/S0025326X18304077))**,** 182 dB p-p ([McCauley *et al.*, 2000](https://www.publish.csiro.au/AJ/AJ99048)) | 182 dB p-p ([McCauley *et al.*, 2000](https://www.publish.csiro.au/AJ/AJ99048)) |  |
| *Bottlenose dolphin* | **Physiological:** Stress bio-indicators | 198-226 dB p-p ([Romano *et al.*, 2004](https://www.researchgate.net/publication/255588954_Anthropogenic_sound_and_marine_mammal_health_Measures_of_the_nervous_and_immune_systems_before_and_after_intense_sound_exposure)) | 198-226 dB p-p ([Romano *et al.*, 2004](https://www.researchgate.net/publication/255588954_Anthropogenic_sound_and_marine_mammal_health_Measures_of_the_nervous_and_immune_systems_before_and_after_intense_sound_exposure)) |  |  |  |  |
| *Fin whale* | **Behavioural:** Sound avoidance |  |  | 13-15 dB increase in background noise due to seismic survey  ([Castellote](https://www.sciencedirect.com/science/article/abs/pii/S0006320711004848) *[et al.](https://www.sciencedirect.com/science/article/abs/pii/S0006320711004848)*[, 2012](https://www.sciencedirect.com/science/article/abs/pii/S0006320711004848)) | 13-15 dB increase in background noise due to seismic survey  ([Castellote](https://www.sciencedirect.com/science/article/abs/pii/S0006320711004848) *[et al.](https://www.sciencedirect.com/science/article/abs/pii/S0006320711004848)*[, 2012](https://www.sciencedirect.com/science/article/abs/pii/S0006320711004848)) |  |  |
| *Sperm whale* | **Behavioural:** Sound avoidance |  |  |  | 146 dB ([Madsen *et al.*, 2005](https://www.researchgate.net/publication/6727580_Quantitative_measures_of_air-gun_pulses_recorded_on_sperm_whales_Physeter_macrocephalus_using_acoustic_tags_during_controlled_exposure_experiments)) | 146 dB ([Madsen *et al.*, 2005](https://www.researchgate.net/publication/6727580_Quantitative_measures_of_air-gun_pulses_recorded_on_sperm_whales_Physeter_macrocephalus_using_acoustic_tags_during_controlled_exposure_experiments)) |  |

## Fish

### Introduction

Bony fish (teleosts) sense sound using their main auditory organs, the otolithic organs of the inner ear (Popper *et al.*, 2014), which they use to sense the particle motion component of a sound wave (Popper and Fay, 2011). Some, but not all, fish can also detect the sound pressure component using gas-filled (swim) bladders (Popper *et al.*, 2014; Slabbekoorn *et al.*, 2019).

There is substantial variation between fish species in how they sense sound, resulting in differences in hearing sensitivities and sound pressure thresholds (Popper and Hastings, 2009; Popper and Fay, 2011; Popper *et al.*, 2014; Carroll *et al.*, 2017). This is likely to mean that there is high variability in how different species are impacted by seismic sound.

However, of the hundreds of species of fish that inhabit UK waters, the potential impacts of seismic sound have been studied on very few. A review by Carroll *et al.*, (2017) reviewed the impacts of seismic sound on fish, which included:

* **Physical impacts,** e.g. hearing damage (including TTS) due to damage to the otolith/inner ear and/or swim bladder
* **Physiological impacts,** e.g. stress bio-indicators
* **Behavioural impacts,** e.g. startle/alarm responses, sound avoidance, other changes in swimming, foraging, communication
* **Catch effects,** e.g. changes in catch rates/abundance

### Atlantic cod (*Gadus morhua*).

Two recent studies have investigated the impact of seismic air gun sound on Atlantic cod (*Gadus morhua*). Atlantic cod is one of the UK’s key commercial demersal species, with 13,000 tonnes of cod landed by UK vessels in 2021 at a total value of £37,025,000 – the second-highest value for any demersal species (Marine Management Organisation, 2021). Cod have been identified by OSPAR as threatened and/or declining and are considered to be in need of priority protection (OSPAR Commission, 2008).

A study by Davidsen *et al.*, (2019), found that free-swimming Atlantic cod in the North Sea (Norway) exhibited reduced heart rate (a stress bio-indicator) in response to the particle motion component of sound from a seismic air gun and changed both swimming depth and horizontal position more frequently during seismic sound exposure. Quick recovery and potential habituation to the sound were shown. A stress response to general anthropogenic noise in Atlantic cod has also been found by Sierra-Flores *et al.*, (2015), with chronic noise exposure negatively impacting the quantity and quality of viable embryos produced.

In 2021, van der Knaap *et al.* investigated the effects of a full-scale (commercial) seismic survey on the behaviour of free-swimming Atlantic cod, finding that cod reduced their activity during exposure and left the area more quickly than expected two days to two weeks post-seismic survey. Diurnal activity cycles were also disrupted, particularly during periods when cod are known to feed actively. The potential for these effects to lead to population-level consequences is noted by the authors.

However, there is very limited knowledge of the potential effects of these impacts on fisheries. One study by Engås and Løkkeborg, (2002) found that longline catch rates of Atlantic cod significantly declined during and for at least five days following a seismic survey.

### Blue whiting (*Micromesistius poutassou*)

In 2021, the total landings of blue whiting (*Micromesistius poutassou*) by UK vessels were over 73,000 tonnes at a value of £16,765,000 (Marine Management Organisation, 2021). Very little is known about the impacts of seismic sound on these key commercial species.

A study by Slotte *et al.*, (2004) found that blue whiting dived away from a seismic air gun source during shooting by a depth of 10 metres (m) and would not return until the seismic activity had stopped. A lower density of fish was seen within the shooting area, with abundance increasing with distance from the seismic vessel.

### Haddock (*Melanogrammus aeglefinus*)

Over 25,000 tonnes of haddock (*Melanogrammus aeglefinus*) were landed by UK vessels in 2021, with a value of £35,534,000 – the highest landings for any demersal species (Marine Management Organisation, 2021). Almost nothing is known about the impacts of seismic sound on haddock, despite the potential effect on these fisheries.

In 2012, Løkkeborg *et al.* found that longline catch rates of haddock in a Norwegian fishing ground fell by 25% as a seismic survey vessel approached (but never entered the fishing area). A reduction in the stomach contents of caught fish was observed, which indicates a potential change in foraging behaviour (impaired feeding) in fish due to seismic sound. A stronger response by larger haddock was also indicated by a decrease in the mean length of haddock at the end of the seismic survey period.

### Herring (*Clupea harengus*)

Herring (*Clupea harengus*) comprised both the second-highest landings (over 77,000 tonnes), and second-highest total value (£46,036,000) of any pelagic species by UK vessels in 2021 (Marine Management Organisation, 2021). Again, very little is known about the impacts of seismic sound on this key commercial species.

A study by Pena, Handegard and Ona, (2013) found unexpected results – no changes in swimming speed, direction, or school size were detected in herring in response to a seismic survey (at a distance of 2-27 km). It is noted that this could be due to a strong motivation for feeding, the lack of suddenness of the air gun sound, and/or increased tolerance to the sound. The study used fisheries sonar to monitor responses, which may not pick up any fine-scale behavioural changes.

### Monkfish (*Lophius piscatorius*)

Monks or anglers (multiple species) comprised the highest total value (£56,640,000) demersal fish landed by UK vessels in 2021, with almost 20,000 tonnes landed (Marine Management Organisation, 2021). Despite this value, there have again been almost no studies investigating the potential impacts of seismic sound on these fish.

One study by Payne, Coady and White, (2009) did investigate the effects of seismic sound on developing monkfish (*Lophius americanus*) eggs and found no differences in survival compared to a control. However, sublethal effects were not considered, and larvae were only observed for 72 hours post-exposure.

### Saithe (*Pollachius virens*)

Over 10,000 tonnes of saithe (*Pollachius virens*) were landed by UK vessels in 2021, with a total value of £9,768,000. Three studies have investigated the impact of seismic sound on saithe in the North Sea / UK waters.

Davidsen *et al.*, (2019) found that saithe exhibited changes to swimming during seismic sound exposure, showing more frequent changes in depth and horizontal position. This could indicate a flight response to seismic sound. The fish also became more dispersed, which could increase their predation risk. In contrast, a study by Wardle *et al.*, (2001) found virtually no response to seismic air gun sounds in saithe other than a transient startle response.

Acoustic mapping by Løkkeborg *et al.*, (2012) revealed that saithe moved away from a seismic survey area during shooting, leading to an observed (but not statistically significant) decline in gillnet catches. There was also a falling trend in the mean length of saithe caught, indicating that larger fish were more likely to move out of the area.

### Whiting (*Merlangius merlangus*)

Over 13,000 tonnes of whiting (*Merlangius merlangus*) were landed by UK vessels in 2021 at a total value of £17,556,000 (Marine Management Organisation, 2021). The impacts of seismic surveys on this species in the UK are unknown.

There are concerning reports, however, of a 99.5% reduction in catch rates of whiting during a six-month-long seismic survey in Australia (Energy News Bulletin, 2020). It must be noted that the data has not been formally published or peer-reviewed.

### Other UK commercial species

In addition to the key commercial species (>1,000 tonnes landed by UK vessels in 2021) detailed above, several studies have found impacts of exposure to seismic air gun sounds on other UK commercial species.

European seabass (*Dicentrarchus labrax*) have been found to show initial elevated ventilation rates (a stress bio-indicator) in response to playbacks of seismic air gun sound. The response weakened with repeated exposure over time, indicating increased tolerance and/or a shift in hearing threshold (Radford *et al.*, 2016).

Catches of Greenland halibut (*Reinhardtius hippoglossoides*) have been shown to be impacted by seismic air gun shooting in the vicinity of a fishing ground. In the Løkkeborg *et al.*, (2012) study, gillnet catch rates increased (likely due to an increase in swimming activity, making the fish more vulnerable to capture), and longline catch rates fell by 16% (likely due to decreased foraging behaviour leading to reduced catchability by baited hooks).

In the same study by Løkkeborg *et al.*, (2012), gillnet catches of redfish (*Sebastes norvegicus*) were found to increase. Again, this is likely due to a change in swimming behaviour, making the fish more vulnerable to capture.

Finally, Hassel *et al.*, (2003, 2004) investigated the impacts of seismic sound on the lesser sandeel (*Ammodytes marinus*). Although sandeels represent a very small proportion of the UK’s fish landings, they play important roles in the marine food chain as a food source for birds, marine mammals and other fish. Findings included a startle response in reaction to seismic air gun sound and a temporary decline in catch rates.

### Potential impact on spawning grounds

Very little is known about the potential impacts of seismic sound on fish larvae and the consequent implications on fish spawning grounds and stocks. Carroll *et al.* identified this lack of research in their 2017 review, highlighting that certain species (such as flounders/soles/flatfishes) may be more susceptible to underwater sound during their early life stages due to their swim bladders (which are lost on settlement as juveniles).

In Norway, an evidence-based approach to management has been taken, and the impacts of seismic sound on fish larvae have been investigated, with models showing that adult fish can move away from air gun sounds, whereas larvae cannot. This has resulted in precautionary advice to protect important areas for spawning and migration by not allowing seismic surveys to take place in these areas during certain periods (e.g. during March for species such as cod, saithe, and herring) (Sivle *et al.*, 2021).

### Elasmobranchs

Most of the work investigating the impacts of seismic sound on fish has focused on the bony fish (teleosts). Very little effort has been focused on the potential impacts on elasmobranchs (sharks, rays and skates) – many of which are threatened and endangered species.

Previous research has assessed the hearing range of elasmobranchs compared to teleosts, with findings suggesting a relatively narrow hearing range and poor sensitivity (Casper, Halvorsen and Popper, 2012). However, research on the particle motion element of sound (of particular relevance to elasmobranchs) has been limited (Mickle and Higgs, 2021). Some work has indicated that sharks may show aversive reactions or change their foraging behaviour in response to loud sounds (such as those produced by seismic air guns). More research is required to better understand the potential impacts of seismic sound on these animals.

### Fish: Summary

There is a general lack of research into the impacts of seismic sound on fish, particularly key UK commercial species (such as hake, ling, plaice and mackerel). Some studies that have taken place have been in response to concerns raised by fishing communities. There is also a lack of knowledge of chronic and wider impacts. For example, of 168 Faroese fishers (targeting cod, whiting, European plaice, lemon sole, saithe, halibut, and others) who had experienced seismic activity during fishing, 75% reported negative effects on catch rate both immediately and in the days following due to these activities (í Jákupsstovu, Olsen and Zachariassen, 2001). However, it seems the impact on fisheries is variable, depending on species-specific responses and gear types (Løkkeborg *et al.*, 2012).

Most studies have overlooked the sensitivity of fish to particle motion rather than sound pressure (Hawkins and Popper, 2017). They have not investigated sub-lethal effects (such as potential masking of natural sound cues (Carroll *et al.*, 2017)), chronic stress effects on growth (Slabbekoorn *et al.*, 2019)) or broader scale impacts. The cumulative effects of multiple sources of anthropogenic noise should also be considered (Cox *et al.*, 2018).

It is clear from the research that has taken place that seismic air gun sound can have significant impacts on fish behaviour (startle responses, changes in foraging), cause increases in stress and hearing thresholds, and lead to changes in catch rates.

Table 2. Table shows the varying impacts of oil and gas seismic surveys on UK commercial fish species at distance from the source. Sound exposure level (SEL) is shown in brackets, p-p =peak pressure.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | |  | **Distance from source** | | | | | |
| **Impact type** | **At source** | **10's m** | **100's m** | **1’s km** | **10's km** | **100's km** |
| **Key UK commercial species** | *Atlantic cod* | **Catch effect:** Longline catch rate decline |  |  | ([Engås and Løkkeborg, 2002](https://www.researchgate.net/publication/233202660_Effects_of_seismic_shooting_and_vessel-generated_noise_on_fish_behaviour_and_catch_rates)) | ([Engås and Løkkeborg, 2002](https://www.researchgate.net/publication/233202660_Effects_of_seismic_shooting_and_vessel-generated_noise_on_fish_behaviour_and_catch_rates)) |  |  |
| **Physiological:** Stress bio-indicators | 121-163 dB ([Davidsen](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001) *[et al.](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001)*[, 2019](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001)) | 121 -163 dB ([Davidsen](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001) *[et al.](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001)*[, 2019](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001)) |  |  |  |  |
| **Behavioural:** Change in swimming | 121-163 dB ([Davidsen](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001) *[et al.](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001)*[, 2019](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001)) | 121-163 dB ([Davidsen](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001) *[et al.](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001)*[, 2019](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001)) | 186 dB ([van der Knaap *et al.*, 2021](https://www.sciencedirect.com/science/article/pii/S0960982221001159#!)) | 186 dB ([van der Knaap *et al.*, 2021](https://www.sciencedirect.com/science/article/pii/S0960982221001159#!)) |  |  |
| **Behavioural:** Change in foraging |  |  | 186 dB ([van der Knaap *et al.*, 2021](https://www.sciencedirect.com/science/article/pii/S0960982221001159#!)) | 186 dB ([van der Knaap *et al.*, 2021](https://www.sciencedirect.com/science/article/pii/S0960982221001159#!)) |  |  |
| *Blue whiting* | **Behavioural:** Change in swimming |  |  |  | 189-197 dB ([Slotte](https://www.pge.com/includes/docs/pdfs/shared/edusafety/systemworks/dcpp/slotte_et_al_2004_acoustic_mapping_of_pelagic_fish_distribution_and_abundance_in_relation_to_seismic_shooting_off_norwegian_coast.pdf) *[et al.](https://www.pge.com/includes/docs/pdfs/shared/edusafety/systemworks/dcpp/slotte_et_al_2004_acoustic_mapping_of_pelagic_fish_distribution_and_abundance_in_relation_to_seismic_shooting_off_norwegian_coast.pdf)*[, 2004](https://www.pge.com/includes/docs/pdfs/shared/edusafety/systemworks/dcpp/slotte_et_al_2004_acoustic_mapping_of_pelagic_fish_distribution_and_abundance_in_relation_to_seismic_shooting_off_norwegian_coast.pdf)) | 189-197 dB ([Slotte](https://www.pge.com/includes/docs/pdfs/shared/edusafety/systemworks/dcpp/slotte_et_al_2004_acoustic_mapping_of_pelagic_fish_distribution_and_abundance_in_relation_to_seismic_shooting_off_norwegian_coast.pdf) *[et al.](https://www.pge.com/includes/docs/pdfs/shared/edusafety/systemworks/dcpp/slotte_et_al_2004_acoustic_mapping_of_pelagic_fish_distribution_and_abundance_in_relation_to_seismic_shooting_off_norwegian_coast.pdf)*[, 2004](https://www.pge.com/includes/docs/pdfs/shared/edusafety/systemworks/dcpp/slotte_et_al_2004_acoustic_mapping_of_pelagic_fish_distribution_and_abundance_in_relation_to_seismic_shooting_off_norwegian_coast.pdf)) |  |
| *Haddock* | **Catch effect:** Longline catch rate decline |  |  |  | 140-170 dB ([Lokkeborg](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download) *[et al.](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)*[, 2012](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)) | 140-170 dB ([Lokkeborg](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download) *[et al.](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)*[, 2012](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)) |  |
| *Saithe* | **Behavioural:** Change in swimming | 121-163 dB ([Davidsen](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001) *[et al.](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001)*[, 2019](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001)) | 121-163 dB ([Davidsen](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001) *[et al.](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001)*[, 2019](https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2598001)) |  |  |  |  |
| **Catch effect:** Gillnet catch rate decline |  |  |  | 140-170 dB ([Lokkeborg](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download) *[et al.](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)*[, 2012](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)) | 140-170 dB ([Lokkeborg](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download) *[et al.](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)*[, 2012](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)) |  |
| **Other UK commercial species** | *European seabass* | **Physiological:** Stress bio-indicators | 131-146 dB ([Radford *et al.*, 2016](https://onlinelibrary.wiley.com/doi/epdf/10.1111/gcb.13352?src=getftr)) |  |  |  |  |  |
| *Greenland halibut* | **Catch effect:** Gillnet catch rate increase |  |  |  | 140-170 dB ([Lokkeborg](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download) *[et al.](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)*[, 2012](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)) | 140-170 dB ([Lokkeborg](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download) *[et al.](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)*[, 2012](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)) |  |
| **Catch effect:** Longline catch rate decline |  |  |  | 140-170 dB ([Lokkeborg](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download) *[et al.](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)*[, 2012](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)) | 140-170 dB ([Lokkeborg](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download) *[et al.](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)*[, 2012](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)) |  |
| *Redfish* | **Catch effect:** Gillnet catch rate increase |  |  |  | 140-170 dB ([Lokkeborg](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download) *[et al.](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)*[, 2012](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)) | 140-170 dB ([Lokkeborg](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download) *[et al.](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)*[, 2012](https://www.researchgate.net/publication/237176145_Sounds_from_seismic_air_guns_Gear-and_speciesspecific_effects_on_catch_rates_and_fish_distribution/link/54294b910cf2e4ce940c9b13/download)) |  |
| *Lesser sandeel* | **Behavioural:** Change in swimming |  | 221 dB ([Hassel *et al.*, 2003](https://www.iqoe.org/library/15972)) | 221 dB ([Hassel *et al.*, 2003](https://www.iqoe.org/library/15972)) | 221 dB ([Hassel *et al.*, 2003](https://www.iqoe.org/library/15972)) | 221 dB ([Hassel *et al.*, 2003](https://www.iqoe.org/library/15972)) |  |
| **Catch effect:** Catch rate decline |  |  | 256 dB ([Hassel *et al.*, 2004](https://watermark.silverchair.com/61-7-1165.pdf?token=AQECAHi208BE49Ooan9kkhW_Ercy7Dm3ZL_9Cf3qfKAc485ysgAAAtYwggLSBgkqhkiG9w0BBwagggLDMIICvwIBADCCArgGCSqGSIb3DQEHATAeBglghkgBZQMEAS4wEQQMf1WwC7K9nv2VDRgzAgEQgIICidMNNmdiMCoSAKuQLCHQx7dFQAKDUeX7XwChEoImADbQnYINUFNP1Blcm0RpSb1spuGJ6ZeYIW-9x-m-7j3-R5_vHlGis-wfS8Qdbct8HYY8aaSBd0DR4bIUrao2B4wTaMOmSoeYAIlHfgyoaf2hmvMwH8sgqZ0AVHkcjcR2nnD2c7N2R4C4yeh1PbOnD7w2E2-ETyu_yVS7nL6TA0wR2MwOe72vHVj0jojUJGkGmPve4OQxO8h0uDi3ZXtuOsclb0hiZ00MMwIEG6nk7ctz_JIbH4a5BIoZaPhaC-n7YZM7bWsQWZ3CIxLU6ewhi9sB4J4EuEoHFBx1XlY51YUfAogVFJLHBhh1OC_F1uaANSFA_w_w_CBFiHakiKCQyaqAi_rLKKIBFDWzLg6yuYMY4N09FnABvcFUoUGnQrQotMjnIPQGxncp1R3lfi_7fclj53RMBEjr5cc-dH8B4zSylxkydmLcTwSufwYw1V6XdLDydZOWvKCPtwfQO9Hu7RUAmTPmwq7hsnwqf2buodETExWYxwZtG2eXi_z--mGH8kkfiipeJ8StDC9wowtwXVwF5gVlnfYqwsifwZXNGNpoAwLiuhvAiT9cl0gl63kZFYp0cFybxmDAQ0vb108KiIq-gI9-ROqOstQeZYrBXjIVZgRG7o8JMyR2zLyTa0w88sXFdXTpr_WQzLY7Ju3AukG00hulTPGwVxacTmV81qVNKtfTP5Z5JoBspv-v0jCelhb3RLrljeS53mWGleIOP-5sDc87GJU5c12lIkuGCtCl0P1xCMpTbOx63Nq3LNYpv0qsJ80Fft23dKj3nzU3tCdEy_bPufDcr35wtNeSvqyPNwRThZe9NP-xQHU)) | 256 dB ([Hassel *et al.*, 2004](https://watermark.silverchair.com/61-7-1165.pdf?token=AQECAHi208BE49Ooan9kkhW_Ercy7Dm3ZL_9Cf3qfKAc485ysgAAAtYwggLSBgkqhkiG9w0BBwagggLDMIICvwIBADCCArgGCSqGSIb3DQEHATAeBglghkgBZQMEAS4wEQQMf1WwC7K9nv2VDRgzAgEQgIICidMNNmdiMCoSAKuQLCHQx7dFQAKDUeX7XwChEoImADbQnYINUFNP1Blcm0RpSb1spuGJ6ZeYIW-9x-m-7j3-R5_vHlGis-wfS8Qdbct8HYY8aaSBd0DR4bIUrao2B4wTaMOmSoeYAIlHfgyoaf2hmvMwH8sgqZ0AVHkcjcR2nnD2c7N2R4C4yeh1PbOnD7w2E2-ETyu_yVS7nL6TA0wR2MwOe72vHVj0jojUJGkGmPve4OQxO8h0uDi3ZXtuOsclb0hiZ00MMwIEG6nk7ctz_JIbH4a5BIoZaPhaC-n7YZM7bWsQWZ3CIxLU6ewhi9sB4J4EuEoHFBx1XlY51YUfAogVFJLHBhh1OC_F1uaANSFA_w_w_CBFiHakiKCQyaqAi_rLKKIBFDWzLg6yuYMY4N09FnABvcFUoUGnQrQotMjnIPQGxncp1R3lfi_7fclj53RMBEjr5cc-dH8B4zSylxkydmLcTwSufwYw1V6XdLDydZOWvKCPtwfQO9Hu7RUAmTPmwq7hsnwqf2buodETExWYxwZtG2eXi_z--mGH8kkfiipeJ8StDC9wowtwXVwF5gVlnfYqwsifwZXNGNpoAwLiuhvAiT9cl0gl63kZFYp0cFybxmDAQ0vb108KiIq-gI9-ROqOstQeZYrBXjIVZgRG7o8JMyR2zLyTa0w88sXFdXTpr_WQzLY7Ju3AukG00hulTPGwVxacTmV81qVNKtfTP5Z5JoBspv-v0jCelhb3RLrljeS53mWGleIOP-5sDc87GJU5c12lIkuGCtCl0P1xCMpTbOx63Nq3LNYpv0qsJ80Fft23dKj3nzU3tCdEy_bPufDcr35wtNeSvqyPNwRThZe9NP-xQHU)) |  |  |

## Shellfish (including molluscs)

### Introduction

The element of seismic sound waves which is most likely to be detected by crustaceans and cephalopods is particle motion – with many species having a sac-like structure (statocyst) and epidermal hair cells, which allows them to detect this element of sound (Kaifu, Akamatsu and Segawa, 2008; Roberts *et al.*, 2016; Carroll *et al.*, 2017; Scott *et al.*, 2020).

Different species have different hearing sensitivities (Carroll *et al.*, 2017), which could be a cause of differing conclusions about the impacts of seismic surveys on shellfish (Morris *et al.*, 2020). In a review by Carroll *et al.*, (2017), the impacts identified were:

* **Physical impacts,** e.g. hearing damage due to damage to the statocyst/hair cells, organ and/or tissue damage
* **Physiological impacts,** e.g. stress bio-indicators, changes to metamorphosis
* **Behavioural impacts,** e.g. sound avoidance, changes to bioturbation or other behaviours such as foraging and reproduction
* **Catch effects,** e.g. changes in catch rates/abundance

In late 2021, the UK’s Animal Welfare (Sentience) Bill was extended to recognise lobsters, octopus and crabs, as well as all other decapod crustaceans and cephalopod molluscs as sentient beings.

### Crabs

Over 28,000 tonnes were landed by UK vessels in 2021, with a total value of £69,971,000 (Marine Management Organisation, 2021). Despite the high total value of crab fisheries, very little research has been done on the impacts of seismic sound on UK species.

A study by Roberts *et al.*, (2016) found that the hermit crab (*Pagurus bernhardus*) exhibited behavioural changes (such as antennae flicks) in response to particle motion, showing that seismic sound has the potential to impact this common species.

Other studies have investigated the impact of seismic sound on a non-UK species,the snow crab (*Chionoecetes opilio*) in Canada. Field studies have been carried out in response to concerns raised by commercial fishers. Results have been mixed – higher mortality and delayed development of embryos have been observed (Christian *et al.*, 2003), as well as a change in expression in transcripts involved in the inflammatory response and other processes, which are potential stress-bioindicators (Hall *et al.*, 2021). However, no long-term changes in catch rate have been observed in snow crab fisheries which have been exposed to seismic sound (Morris *et al.*, 2020).

### Cuttlefish (*Sepia officinalis*)

Over 2,600 tonnes of the common cuttlefish (*Sepia officinalis*) were landed by UK vessels in 2021, with a total value of £7,314,000 (Marine Management Organisation, 2021). This species is of increasing fisheries importance in the UK.

A few studies investigating the effects of seismic sound on cuttlefish have revealed multiple impacts. Both Solé *et al.*, (2017) and André *et al.*, (2011) found evidence for damage to cuttlefish statocysts following seismic sound exposure. Samson *et al.*, (2014) observed behavioural responses such as inking and jetting in response to sound. Solé *et al.*, (2019) performed a proteomic analysis of cuttlefish statocysts before and after sound exposure, found changes in 37 proteins, many of which were stress related.

### Lobsters

Lobsters are of high value in the UK, with the 3,250 tonnes landed by UK vessels in 2021 reaching a total value of £51,985,000 (Marine Management Organisation, 2021). However, there is a complete lack of research into the impacts of seismic sound on UK lobster species (such as the European or common lobster, *Homarus gammarus*).

Knowledge of potential impacts comes primarily from research into the spiny rock lobster (*Jasus edwardsii)*, found in Australia and New Zealand. Multiple sub-lethal effects as a result of seismic air gun exposure have been found, such as statocyst damage (Day *et al.*, 2016a; Day *et al.*, 2016b; Day *et al.*, 2019) and disruption to reflexes such as righting and tail extension, which could impact key behaviours such as escaping from predators (Day, Robert D McCauley, *et al.*, 2016). Fitzgibbon *et al.*, (2017) also studied the spiny lobster, finding that seismic air gun exposure may suppress immunological capacity and nutritional condition.

A study by Payne *et al.*, (2007) on another lobster species, *Homarus americanus*, found a possible reduction in calcium (a stress bio-indicator), as well as sub-lethal effects on feeding seen weeks to months following exposure to a seismic survey.

Limited to no recovery from these sub-lethal effects has been shown up to one year following exposure (Day *et al.*, 2019). However, whether seismic air gun exposure has any long-term effects on catch rates remains unknown (Parry and Gason, 2006). Further studies are also required on the effects on lobster larvae, which could affect recruitment (Day, Robert D. McCauley, *et al.*, 2016).

### Mussels

In 2021, 403 tonnes of mussels were landed by UK vessels, with a total value of £605,000 (Marine Management Organisation, 2021). In addition to this commercial value, mussels provide essential ecosystem services in marine systems. However, very little is known about the impacts of seismic sound on mussels.

A study by Roberts *et al.*, (2015) observed behavioural changes in mussels (*Mytilus edulis*) in response to particle motion, including valve closure, which is likely to impact the overall fitness of individuals and mussel beds. This could have wider commercial and ecosystem implications. *Mytilus edulis* beds have been identified by OSPAR as a threatened and/or declining habitat and are considered to be in need of priority protection (OSPAR Commission, 2008).

### Octopus

Octopus are of commercial importance in European waters, with a recent increase in UK octopus landings and a significant increase in value. One study conducted experiments on common octopus (*Octopus vulgaris*) following strandings in the northwest Mediterranean which coincided with seismic surveys. Freshly caught individuals (landed in Spain) were exposed to 157 dB sound impulses. The study found acute morphological effects such as neuron swelling and hair cell loss and damage (André *et al.*, 2011).

Two further studies have investigated particle motion detection in *Octopus (ocellatus)* in Japan, finding suppressed respiratory activity (a stress-bioindicator) at frequencies between 50-283 hertz (Hz), indicating that sound plays an important role for octopuses, for example, in predator detection (Kaifu, Segawa and Tsuchiya, 2007; Kaifu, Akamatsu and Segawa, 2008).

### Scallops

Over 32,000 tonnes of scallops were landed by UK vessels in 2021, with a total value of £53,687,000 (Marine Management Organisation, 2021). Numerous studies have investigated the effects of seismic sound on scallops, with contradictory results.

Significantly increased mortality, as well as disruptions to behaviour and reflexes, and other sub-lethal effects (such as altered haemolymph biochemistry and osmoregulation capacity), have been found in the commercial scallop *Pecten fumatus* following seismic air gun exposure (Day, McCauley, *et al.*, 2016; Day *et al.*, 2017). Malformations and developmental delays due to exposure to seismic air guns have also been found in *Pecten novaezelandiae* (de Soto *et al.*, 2013).

Parry *et al.*, (2002) investigated impacts on the strength of the adductor muscle in adult scallops, in response to concerns raised by commercial fishers. No effects on mortality were observed up to 17 days following the seismic survey. Other studies have also found no changes to scallop mortality and catch rates in the months following seismic exposure (Harrington, McAllister and Semmens, 2010; Przeslawski *et al.*, 2018). However, sub-lethal effects, which may have longer-term consequences on catch rates, could not be excluded.

### Shrimp

In 2021, 764 tonnes of shrimps and prawns were landed by UK vessels, with a total value of £2,029,000 (Marine Management Organisation, 2021). The impact of seismic sound on UK shrimps and prawns is unknown.

One study by Andriguetto-Filho *et al.*, (2005) suggests that Brazilian shrimp stocks may be resilient to disturbance by seismic air guns. Bottom trawl yields of the southern brown shrimp (*Farfantepenaeus subtilis*) and southern white shrimp (*Litopenaeus schmitti*) were measured before and after a seismic air gun array, and no significant deleterious impact on shrimp yields was found.

### Squid

In 2021, 2,365 tonnes of squid were landed by UK vessels, with a total value of £8,137,000 (Marine Management Organisation, 2021). Several studies have found acute morphological effects of seismic sound on squid.

Lesions, hair cell loss and statocyst damage, and neuron swelling have been observed following exposure in the European squid (*Loligo vulgaris*) and shortfin squid (*Illex coindetii*) (André *et al.*, 2011; Solé *et al.*, 2013). Animals stopped moving and feeding following exposure, with worsening effects (including mortality) over time.

Guerra, González and Rocha, (2004) found tissue, statolith, and organ damage in giant squid (*Architeuthis dux*) following seismic surveys, which was likely the cause of death. Of the 146 reported specimens, 43% had been stranded in the northeastern Atlantic. In 2016, the first sightings of a dead giant squid observed from a seismic vessel was made by marine mammal observers. Although the animal was not examined, the cause of death was presumed to be seismic sound (Leite *et al.*, 2016).

### Shellfish: Summary

There is a clear body of evidence showing multiple impacts of seismic sound on shellfish, from behavioural effects to acute morphological effects leading to significantly increased mortality. Many studies show sub-lethal effects, which often worsen over the short-term. However, there is a lack of research into the long-term consequences of such effects and how these could affect stocks. For example, the malformation in scallop larvae and developmental delays found by de Soto *et al.*, (2013), and impacts on escape behaviours in lobsters found by (Day, Robert D McCauley, *et al.*, 2016), could have knock-on effects on the fishing industry and wider ecosystem.

Furthermore, studies have primarily been restricted to studying effects at source or within tens of metres. In the wild, shellfish could be affected over much larger distances and are likely to be exposed to multiple stressors (Scott *et al.*, 2020). Further work is required to understand impacts over larger scales.

Often, sediment-dwelling invertebrates (such as lobsters and clams) play important roles in mediating their ecosystems, such as nutrient cycling. Therefore, any sub-lethal effects which impact animals’ abilities to carry out these crucial roles could pose a significant risk to populations and ecosystems and must be considered (Solan *et al.*, 2016). No research was uncovered on the impacts of seismic sound on bivalves of conservation importance in UK waters, such as ocean quahog or horse mussel reefs.

Table 3. Table shows the varying impacts of oil and gas seismic surveys on shellfish (crustacean and cephalopod) species at distance from the source. Sound exposure level (SEL) is shown in brackets, p-p =peak pressure.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | | **Distance from source** | | | |
|  | | **Impact type** | **At source** | **10's m** | **100's m** |
| **Crustaceans** | *Crabs (snow crab)* | **Physical:** Mortality, delayed development | 197-237 p-p ([Christian *et al.*, 2003](https://www.pge.com/includes/docs/pdfs/shared/edusafety/systemworks/dcpp/christian_et_al_2003_effect_of_seismic_energy_on_snow_crab.pdf)) | 197-237 p-p ([Christian *et al.*, 2003](https://www.pge.com/includes/docs/pdfs/shared/edusafety/systemworks/dcpp/christian_et_al_2003_effect_of_seismic_energy_on_snow_crab.pdf)) | 197-237 p-p ([Christian *et al.*, 2003](https://www.pge.com/includes/docs/pdfs/shared/edusafety/systemworks/dcpp/christian_et_al_2003_effect_of_seismic_energy_on_snow_crab.pdf)) |
| **Physiological:** Stress bio-indicators |  | 229 ([Hall *et al.*, 2021](https://www.sciencedirect.com/science/article/pii/S0165783620303118)) | 229 ([Hall *et al.*, 2021](https://www.sciencedirect.com/science/article/pii/S0165783620303118)) |
| *Lobsters (Homarus americanus, Jasus edwardsii)* | **Physiological:** Stress bio-indicators | 202-227 ([Payne *et al.*, 2007](https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.516.5711&rep=rep1&type=pdf)) | 191-213 ([Day *et al.*, 2016](https://www.frdc.com.au/sites/default/files/products/2012-008-DLD.pdf)) | 191-213 ([Day *et al.*, 2016](https://www.frdc.com.au/sites/default/files/products/2012-008-DLD.pdf)), (Fitzgibbon *et al.*, 2017) |
| **Physical:** Sub-lethal effects inc. statocyst damage | 202-227 ([Payne *et al.*, 2007](https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.516.5711&rep=rep1&type=pdf)) | 191-213 ([Day *et al.*, 2016](https://www.frdc.com.au/sites/default/files/products/2012-008-DLD.pdf)) | 191-213 ([Day *et al.*, 2016](https://www.frdc.com.au/sites/default/files/products/2012-008-DLD.pdf)), (Fitzgibbon *et al.*, 2017) |
| **Catch effects:** Short-term changes to catch rates |  | ([Parry and Gason, 2006](https://www.researchgate.net/publication/222690737_The_effect_of_seismic_surveys_on_catch_rates_of_rock_lobsters_in_western_Victoria_Australia)) | ([Parry and Gason, 2006](https://www.researchgate.net/publication/222690737_The_effect_of_seismic_surveys_on_catch_rates_of_rock_lobsters_in_western_Victoria_Australia)) |
| *Mussels* | **Behavioural:** Valve closure | 0.01-1ms2 particle motion ([Roberts *et al.*, 2015](https://www.int-res.com/articles/meps2015/538/m538p185.pdf)) |  |  |
| *Scallops (Pecten fumatus, Pecten novaezelandiae)* | **Physical:** Increased mortality, malformations | 161-165 ([de Soto *et al.*, 2013](https://www.nature.com/articles/srep02831)) | 189-213 p-p ([Day et al., 2016](https://www.frdc.com.au/sites/default/files/products/2012-008-DLD.pdf), [2017](https://www.pnas.org/doi/abs/10.1073/pnas.1700564114)) | 189-213 p-p ([Day et al., 2016](https://www.frdc.com.au/sites/default/files/products/2012-008-DLD.pdf), [2017](https://www.pnas.org/doi/abs/10.1073/pnas.1700564114)) |
| **Behavioural:** Changes to reflexes |  | 189-213 p-p ([Day et al., 2016](https://www.frdc.com.au/sites/default/files/products/2012-008-DLD.pdf), [2017](https://www.pnas.org/doi/abs/10.1073/pnas.1700564114)) | 189-213 p-p ([Day et al., 2016](https://www.frdc.com.au/sites/default/files/products/2012-008-DLD.pdf), [2017](https://www.pnas.org/doi/abs/10.1073/pnas.1700564114)) |
| **Physiological:** Stress bio-indicators |  | 189-213 p-p ([Day et al., 2016](https://www.frdc.com.au/sites/default/files/products/2012-008-DLD.pdf), [2017](https://www.pnas.org/doi/abs/10.1073/pnas.1700564114)) | 189-213 p-p ([Day et al., 2016](https://www.frdc.com.au/sites/default/files/products/2012-008-DLD.pdf), [2017](https://www.pnas.org/doi/abs/10.1073/pnas.1700564114)) |
| **Cephalopods** | *Cuttlefish* | **Behavioural:** Inking and jetting | 140 ([Samson *et al.*, 2014](https://journals.biologists.com/jeb/article/217/24/4347/12993/Graded-behavioral-responses-and-habituation-to)) |  |  |
| **Physical:** Statocyst damage | 157-175 ([Andre *et al.,* 2011](https://www.esa.org/pdfs/Andre.pdf); [Sole *et al.*, 2019](https://www.nature.com/articles/s41598-019-45646-6)), 139-142 ([Sole *et al.*, 2017](https://www.nature.com/articles/srep45899)) | 139-142 ([Sole *et al.*, 2017](https://www.nature.com/articles/srep45899)) |  |
| **Physiological:** Stress bio-indicators | 157-175 ([Sole *et al.*, 2019](https://www.nature.com/articles/s41598-019-45646-6)) |  |  |
| *Octopuses (Octopus vulgaris, Octopus ocellatus)* | **Physical:** Lethal effects | 157-175 ([Andre *et al.*, 2011](https://www.esa.org/pdfs/Andre.pdf)) |  |  |
| **Behavioural**: Suppressed respiration | 120 ([Kaifu](https://www.jstage.jst.go.jp/article/jmasj/34/4/34_4_266/_pdf) *[et al.](https://www.jstage.jst.go.jp/article/jmasj/34/4/34_4_266/_pdf)*[, 2007](https://www.jstage.jst.go.jp/article/jmasj/34/4/34_4_266/_pdf), [2008](https://link.springer.com/article/10.1111/j.1444-2906.2008.01589.x)) |  |  |
| *Squid (European, shortfin)* | **Physical:** Sub-lethal effects inc. statocyst damage | 157-175 ([Andre *et al.*, 2011](https://www.esa.org/pdfs/Andre.pdf), [Sole *et al.*, 2013](https://www.sciencedirect.com/science/article/abs/pii/S0967064512001877)) |  |  |

## Zooplankton and the wider ecosystem

### Introduction

Most zooplankton species have external sensory hairs with mechanosensory systems, which are likely to be extremely sensitive (McCauley *et al.*, 2017). Nevertheless, the potential impact of seismic sound on zooplankton and the wider ecosystem has not been investigated in-depth. Up until recently, very few studies have investigated the short-term effects of seismic air gun exposure on zooplankton. At the same time, there appears to be a total lack of studies on potential long-term effects. Furthermore, no studies appear to have taken place within UK waters.

### Zooplankton

In 2017, a study by McCauley *et al.* was the first large-scale field experiment on the impact of seismic activity on zooplankton. It was found that seismic air gun exposure significantly decreased the abundance of zooplankton (primarily copepods) by 64% within one hour. A two- to threefold increase in dead adult and larval zooplankton was seen (from 19% natural mortality to 45% during seismic exposure), and all larval krill were killed after seismic air gun passage, and no adult krill were present. These impacts were observed throughout the assessed range of 1.2 km. Krill (adult and larval) perform key biogeochemical roles (Cavan *et al.*, 2019) and form the main diet for most marine predators (many marine mammals and fish) – any decline to krill biomass could have significant ecological consequences.

Following the results of the McCauley *et al.*, (2017) study, a study by Richardson, Matear and Lenton, (2017) scaled up the findings to a commercial seismic survey covering an area of 80km by 36km and 300-800 m deep. Over the 35-day survey, zooplankton biomass declined by 22% within the survey area, with impacts extending 15 km (14% decline) and 150 km (2% decline) outside of the survey region. Recovery of zooplankton biomass could take days to months.

Fields *et al.*, (2019) studied the impacts of seismic air gun blasts on *Calanus* copepods (a key food source for commercially important fish). They found some immediate and delayed mortality in copepods >5 m and 10 m away from the seismic source, but this was less than 30% and diminished with distance from the source.

Most recently, Palm *et al.*, (2022) sampled zooplankton throughout a 70 m depth range as a seismic survey vessel passed (up to 16 km away) in the Norwegian North Sea to study immediate and delayed mortality. The results are being finalised.

### Zooplankton: Summary

Any impacts on zooplankton due to seismic sound have the potential to cause potentially serious knock-on consequences for the ocean ecosystem, negatively impacting function and productivity (McCauley *et al.*, 2017). For example, declines in krill biomass could have severe consequences for populations of species of conservation and commercial importance.

Given the spatial and temporal scale of seismic surveys, particularly 3D surveys, it is likely that significant impacts on zooplankton communities are taking place.

Table 4. Table shows the varying impacts of oil and gas seismic surveys on zooplankton at distance from the source. Sound exposure level (SEL) is shown in brackets, p-p =peak pressure.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | **Distance from source** | | | | | |
| **Impact type** | **At source** | **10's m** | **100's m** | **1km** | **10's km** | **100'km** |
| **Zooplankton** | *Larval krill* | **Physical:** Increased mortality |  | 156 ([McCauley *et al.*, 2017](https://www.nature.com/articles/s41559-017-0195)) | 156 ([McCauley *et al.*, 2017](https://www.nature.com/articles/s41559-017-0195)); ([Richardson *et al.*, 2017](https://publications.csiro.au/rpr/pub?pid=csiro:EP175084)) | 156 ([McCauley *et al.*, 2017](https://www.nature.com/articles/s41559-017-0195)); ([Richardson *et al.*, 2017](https://publications.csiro.au/rpr/pub?pid=csiro:EP175084)) | ([Richardson *et al.*, 2017](https://publications.csiro.au/rpr/pub?pid=csiro:EP175084)) | ([Richardson *et al.*, 2017](https://publications.csiro.au/rpr/pub?pid=csiro:EP175084)) |
| *Copepods (Acartia* *tranteri*, *Oithona* spp., *Calanus finmarchicus*, *Clausocalanus* spp., *Paracalanus* spp.) | **Physical:** Increased mortality | 183-221 p-p ([Fields *et al.*, 2019](https://academic.oup.com/icesjms/article/76/7/2033/5543877?login=false)) | 156 ([McCauley *et al.*, 2017](https://www.nature.com/articles/s41559-017-0195)); 183-221 p-p ([Fields et al., 2019](https://academic.oup.com/icesjms/article/76/7/2033/5543877?login=false)) | 156 ([McCauley *et al.*, 2017](https://www.nature.com/articles/s41559-017-0195)); ([Richardson *et al.*, 2017](https://publications.csiro.au/rpr/pub?pid=csiro:EP175084)) | 156 ([McCauley *et al.*, 2017](https://www.nature.com/articles/s41559-017-0195)); ([Richardson *et al.*, 2017](https://publications.csiro.au/rpr/pub?pid=csiro:EP175084)) | ([Richardson *et al.*, 2017](https://publications.csiro.au/rpr/pub?pid=csiro:EP175084)) | ([Richardson *et al.*, 2017](https://publications.csiro.au/rpr/pub?pid=csiro:EP175084)) |
| **Physiological:** Gene change | 183-221 p-p ([Fields *et al.*, 2019](https://academic.oup.com/icesjms/article/76/7/2033/5543877?login=false)) | 183-221 p-p ([Fields *et al.*, 2019](https://academic.oup.com/icesjms/article/76/7/2033/5543877?login=false)) |  |  |  |  |
| *Other zooplankton spp.* | **Physical:** Increased mortality |  | 156 ([McCauley *et al.*, 2017](https://www.nature.com/articles/s41559-017-0195)) | 156 ([McCauley *et al.*, 2017](https://www.nature.com/articles/s41559-017-0195)); ([Richardson *et al.*, 2017](https://publications.csiro.au/rpr/pub?pid=csiro:EP175084)) | 156 ([McCauley *et al.*, 2017](https://www.nature.com/articles/s41559-017-0195)); ([Richardson *et al.*, 2017](https://publications.csiro.au/rpr/pub?pid=csiro:EP175084)) | ([Richardson *et al.*, 2017](https://publications.csiro.au/rpr/pub?pid=csiro:EP175084)) | ([Richardson *et al.*, 2017](https://publications.csiro.au/rpr/pub?pid=csiro:EP175084)) |

## Does the Oil and Gas Industry’s monitoring, reporting and licencing account for these known impacts of seismic sound?

### Overview

The Offshore Energy SEA 4 (OESEA 4) focuses on population- and species-level effects and mentions - but does not focus on - individual mortality or sub-lethal effects. The OESEA 4 tends not to fully acknowledge the distances (up to 10’s and 100’s of kms) at which seismic sound may have impacts on marine mammals and other species.

Control and mitigation measures are primarily focused on ensuring compliance with the Habitats Directive, whereby it is an offence to deliberately injure or disturb wild animals of any species listed on Annex IVa of the Habitats Directive. This list does not include the vast majority of marine animals (fish and invertebrates), with the exception of cetaceans.

Within the guidance, marine mammals are the focus despite realistically being a small proportion of the biomass of marine animals affected by seismic sound. Many effects are acknowledged but dismissed as being short-lived and/or not at the population level, with little to no mitigation guidance given for most species. The mitigation measures that are detailed in the OESEA 4 are voluntary, and there is a lack of incentives to ensure compliance with these.

### Marine mammals

The recommendations for mitigating impacts on marine mammals consistently focus on population-level consequences rather than individual or sub-lethal effects.

The noise exposure criteria for causing permanent threshold shifts in hearing (PTS) provided by Southall *et al.* are the most commonly used (recommended) in the UK. These are updated based on the available evidence. The sound levels presented in the Offshore Energy SEA 4 are shown below, in comparison to the evidence found for impacts (not necessarily injury, e.g. PTS) in the literature detailed within the marine mammal section. JNCC requires these thresholds and functional hearing groups to be used in any marine mammal noise assessment.

Using the exposure criteria presented below may lead to other impacts (e.g. sound avoidance, which may lead to population-level consequences) to be dismissed, as these impacts are often found at lower thresholds than those detailed by Southall *et al.* as causing onset of PTS.

Table 5. Marine mammal injury criteria most commonly used (recommended) in the UK, compared to the evidence (for any impacts) presented in Table 1 of this report.

|  |  |  |  |
| --- | --- | --- | --- |
| Marine mammal injury criteria ((Southall *et al.*, 2007) | | | Evidence from Table 1 – findings from literature for all impacts |
| Functional hearing group | **Dual-criteria** | **PTS Onset – Impulsive noise** |
| Low-frequency cetaceans (e.g. humpback whale, fin whale) | Peak sound pressure level (p-p) | 219 | 182 (Humpback whale, McCauley *et al.*, 2000) |
| Sound exposure level (SEL) | 183 | 130 (Humpback whale, Dunlop *et al.*, 2017, 2018) |
| High-frequency cetaceans (e.g. bottlenose dolphin, sperm whale) | Peak sound pressure level (p-p) | 230 | 198 (Bottlenose dolphin, (Romano *et al.*, 2004) |
| Sound exposure level (SEL) | 185 | 146 (Sperm whale, (Madsen *et al.*, 2006) |
| Very high-frequency cetaceans (e.g. harbour porpoise) | Peak sound pressure level (p-p) | 202 | ND |
| Sound exposure level (SEL) | 155 | 140 (Harbour porpoise, Sarnocińska *et al.*, 2020) |
| Pinnipeds in water | Peak sound pressure level (p-p) | 218 | ND |
| Sound exposure level (SEL) | 185 | ND |

The main focus for control and mitigation is to ensure compliance with the Habitats Directive, which states that it is an offence to deliberately injure or disturb wild animals, including all cetaceans, particularly where disturbance is likely to impair breeding, rearing, hibernation and migration or to affect significantly the local distribution or abundance of the species to which they belong.

Specific guidelines to avoid or minimise the risk of killing, injuring or disturbing cetaceans have been prepared by JNCC. Marine mammal management units (MUs) for the seven most common cetacean species in UK waters have been agreed (JNCC, 2015), which gives an indication of the spatial scales at which impacts of plans and projects need to be assessed.

Table 6. The table compares the impacts of seismic surveys on priority shellfish/ mollusc species uncovered in scientific literature with its inclusion in oil and gas monitoring and licencing reporting. The left column states the impact uncovered in scientific literature, the middle column states if the impact is mentioned in oil and gas reporting (etc), and the right column states the reason why/notes.

|  |  |  |
| --- | --- | --- |
| Peer review evidence | Oil and gas monitoring, licence reporting etc. | Notes / reason |
| Harbour porpoises are particularly sensitive to seismic sound, exhibiting sound avoidance, reduced buzzing, and decreased echolocation at distances 10’s km away from the air gun source. | Recommended Effective Deterrence Ranges for harbour porpoise is 12 km. | Based on peer-reviewed literature, but only recommended. |
| Multiple additional cetacean species have been shown to exhibit sound avoidance and stress bio-indicators, as well as injury (e.g. hearing threshold shifts) at distances from close range to 10’s km from the air gun source. | Judges that underwater sound generated during seismic operations have the potential to cause injury within a limited range (tens to hundreds of metres). However, this may not be the case – not precautionary enough? | Assessment of risk relies on exposure thresholds. |
| Avoidance responses in marine mammals could impact the abilities of animals to find food, locate mates, avoid predators, and to migrate. | Mentioned (small behavioural reactions) but not acted on. | Assumed to be insignificant due to the “short-term” nature of seismic surveys. |
| Other marine mammals (such as seals) are likely to be sensitive to seismic sound. | Regional Seas with key areas of marine mammal sensitivity have been identified, but it is not clear whether these areas must be avoided. | No specific wording to say how these key areas of marine mammal sensitivity should be addressed. |
| Indirect impacts on marine mammals include impacts on food availability. | Mentioned but not acted on. | Assumed to be insignificant due to the “short-term” nature of seismic surveys. |
| Cumulative impacts of seismic sound in combination with other anthropogenic noise, or over a longer term, could cause greater population-level consequences. | Acknowledges this but states that current understanding is that, in combination, noise generated from planned activities are highly unlikely to result in a population level effect. | Assumes that acoustic disturbance equates to the loss of foraging opportunities through avoidance, leading to long-term population consequences. |

Primary mitigation measures for marine mammals include:

* In planning, choice of location and timing can be key to minimise risk, especially with respect to migration, breeding, calving or pupping.
* During the operational stage, the main mitigation measure recommended is to monitor for the presence of marine mammals before the start of operations and only allow operations to commence if animals are not present.
* The second key mitigation measure is to induce an avoidance response by animals, using a so-called ‘soft-start’.

The main points of concern regarding marine mammals that have been raised (detailed in the OESEA 4) are:

* Over-reliance on the soft-start procedure, which may not be effective (especially considering that marine mammal observers are not always effective, e.g. at night or in high sea states), and introduces additional noise.
* A lack of shut-down operations if a marine mammal is observed entering the mitigation zone.
* The focus is on mitigating the risk of injury rather than disturbance.

### Fish, shellfish and zooplankton

The OESEA 4 details criteria for responses in fish to the amount of sound received above the hearing threshold, with above 110 dB as the tolerance limit of sound (unbearably loud). Above 130 dB the possibility of traumatic hearing damage from a single event is stated.

However, there are limitations with this approach, including the lack of acknowledgement of the particle motion element of sound, which most fish are sensitive to. Guidance for sound exposure published by Popper *et al.*, (2014) has classified fish into different groups based on their hearing abilities and thresholds, considering potential effects from different sound sources.

For invertebrates (including shellfish and zooplankton), the sensitivity to sound is downplayed. No clear guidance is given on the mitigation of any potential impacts of seismic sound on fish and invertebrates.

The OESEA 4 also mentions that alternatives to seismic surveys, such as marine vibroseis, are being developed in order to reduce the potential impacts.

Table 7. The table compares the impacts of seismic surveys on priority shellfish/ mollusc species uncovered in the scientific literature with its inclusion in oil and gas monitoring, and licencing reporting. The left column states the impact uncovered in scientific literature, the middle column states if the impact is mentioned in oil and gas reporting (etc) and the right column states the reason why/notes.

|  |  |  |
| --- | --- | --- |
| Peer review evidence | Oil and gas monitoring, licence reporting etc. | Notes / reason |
| Physical impacts including mortality and serious injury in fish from seismic sound. | Mentioned, but states that results are limited and highly variable. | The available evidence should be taken into account and the precautionary principle employed. |
| Behavioural impacts such as changes in swimming and foraging in fishes – sub-lethal effects which could lead to ecosystem and commercial consequences. | Mentions that avoidance reactions in fish have been observed. | Consequences not mentioned. |
| Stress bio-indicators, other physiological impacts (e.g. TTS) on fish – could have individual and population-level effects. | Somewhat acknowledged, states that results are highly variable. | Results clearly show multiple sub-lethal effects across species. |
| Changes to catch rates of commercial fish species – fisheries industry consequence. | Mentions that seismic air gun shooting can result in reduced trawl and longline catches of several species. | No clear advise given to minimise impacts on fisheries. |
| Physical impacts such as increased mortality and developmental delays in crustaceans | States that studies are too few to reach conclusions. | No clear mitigation guidance given. |
| Damage to shellfish statocysts, stress-bioindicators – unknown consequences on stocks | States that studies are too few to reach conclusions. | No clear mitigation guidance given. |
| Behavioural impacts on mussels – valve closure. Could affect mussel beds, with commercial and ecosystem implications. | Mentioned. | No clear mitigation guidance given. |
| Physical impacts on cephalopods – lethal damage, potentially leading to strandings. Also sub-lethal effects such as suppressed respiration and other stress bio-indicators. | Mentioned. | No clear mitigation guidance given. |
| Behavioural impacts on cephalopods such as inking and jetting, stress. | Mentioned. | No clear mitigation guidance given. |
| Declines to zooplankton biomass / increased mortality potentially over large spatial scales with unknown knock-on ecosystem (and commercial) consequences. | States planktonic invertebrates are considered less susceptible to acute trauma and behavioural disturbance resulting from noise and vibration, and that data are very limited. | Recent studies on seismic sound impacts on zooplankton are not mentioned. |

## Other geophysical surveys

### Introduction

Alternatives to seismic surveys for oil and gas exploration do exist – for example, marine vibroseis, microseismic monitoring, fibre optics, and electromagnetic surveys. These technologies are often considered more environmentally safe than seismic air guns. However, currently published research investigating the impacts of these methods is incredibly limited.

Lower impact seismic and other geophysical survey techniques (such as multi-beam and side-scan sonars and magnetometers) are also used in offshore wind site characterisation surveys. Furthermore, floating turbines reduce the noise-associated impacts on marine life due to the lack of pile driving required (as opposed to fixed turbines) (Maxwell *et al.*, 2022).

### Electromagnetic surveys

One alternative is electromagnetic (EM) surveys, which generate electromagnetic fields to map oil and gas deposits. These fields can be detected by many marine mammals and may affect behaviour such as prey detection and predator avoidance, but the potential consequences of EM surveys on marine life are unknown (Nyqvist *et al.*, 2020).

Nyqvist *et al.*, (2020) reviewed the use, and potential effects of EM surveys for oil and gas exploration on marine mammal behaviour. Findings suggest that the effects of EM surveys on marine life likely depend on the strength and direction of the fields, duration of exposure, and detection capabilities of the animal. For example, elasmobranchs which are sensitive to electromagnetic fields and use this sense for navigation, e.g. the bonnethead shark (Keller *et al.*, 2021), may be particularly susceptible to EM surveys.

In theory, effects could be either physical, in the form of injuries or mortality, or behavioural, with relatively small disruptions potentially causing misorientation. This could have knock-on consequences on important and time-restricted movements such as finding protection from predation or foraging areas (Nyqvist *et al.*, 2020). However, both electric and magnetic fields attenuate quickly, and exposure is short in duration as the source is continually moved around. This could mean that any impacts of EM surveys are short-lived and spatially limited.

### Marine vibroseis surveys

Another alternative to seismic air gun surveys is marine vibroseis (MV). MV systems produce acoustic signals through volume displacement of water using a vibrating plate or shell. Generally, lower acoustic pressure is produced compared to air guns, but longer-duration signals must be used (Matthews *et al.*, 2021).

Matthews *et al.*, (2021)modelled the potential effects of sounds produced by marine vibroseis surveys compared to seismic air guns on marine mammals. In the modelled scenarios, MV surveys were found to have a lower potential to cause the onset of permanent or temporary threshold shift in marine mammals or to cause mortality and injury in fish and other animals.

*Table 5. From Matthews et al., (2021) showing the mean number of marine mammals expected to be exposed to sound levels (SEL) at or above injury thresholds. Scenarios 2 and 3 are based in shallow water in the North Sea.*

Table

Description automatically generated

### Exploratory drilling

It is also worth noting that following surveying, exploratory drilling is carried out. Exploratory drilling is another element of oil and gas exploration which has potentially severe impacts on marine life. For example, Currie and Isaacs, (2004) found that the abundances of benthic species decreased by 71 to 88% at a well-head site immediately after exploratory drilling Santos *et al.*, (2009) also found measurable effects on community structure within 500 metres of an exploratory drilling well.

See Work Package 2, Direct impacts of oil and gas development: Drilling and other operational impacts, for further information regarding the impacts of drilling for oil and gas on marine species and habitats.

## General impacts of underwater noise

Anthropogenic noise in the ocean, to which seismic sound is a major contributor, is gaining increased recognition as an important global conservation issue with a transboundary and cumulative nature (Chou *et al.*, 2021).

Data indicate several reasons for concern about the negative impacts of anthropogenic noise on numerous marine species, which include habitat displacement, disruption of biologically important behaviours, masking of communication signals, chronic stress, and potential auditory damage (Nowacek *et al.*, 2015). In 2018, Cox *et al*. published a paper entitled “Sound the alarm: A meta-analysis on the effect of aquatic noise on fish behaviour and physiology”. Their findings showed that it is likely that most fish species are sensitive to changes in the aquatic soundscapes, with responses potentially having extreme and negative fitness consequences. The most predominant responses occurred within foraging ability, predation risk, and reproductive success.

# Conclusion

There is clear evidence for multi-taxa impacts of seismic sound, from zooplankton to marine mammals, at scales from the immediate area surrounding the seismic air gun source to tens and even potentially hundreds of kilometres away. It is also clear that some of these impacts are acute, including significantly increased mortality of some species following exposure to seismic sound (generally at close range).

Many studies over the previous decades have investigated the impacts of seismic sound on marine life. Although generalisations are difficult to make due to issues surrounding study methodologies and a lack of uncaged field research, the results cannot be ignored. Seismic sound has a multitude of severe impacts on marine life, including priority species such as humpback whales and harbour porpoise, and key UK commercial fish and shellfish species.

In highly-mobile marine mammals, impacts tend to be behavioural – for example, animals exhibit aversive behaviour in response to seismic sound, moving out of the area. Hearing threshold shifts have also been observed. These impacts, particularly when considered together, have the potential to seriously detriment both individuals and populations of highly sensitive marine mammals.

In fish, sub-lethal impacts (such as stress, changes in swimming and foraging), as well as changes to catch rates, have been observed in numerous key UK commercial species, including Atlantic cod, blue whiting, haddock, and saithe. Together these four species alone contributed almost £1 billion to the UK economy in 2021 (total value of landings by UK vessels, (Marine Management Organisation, 2021).

Even fewer studies investigate seismic sound's impacts on UK shellfish species, particularly crustaceans. However, the international work that has been carried out gives a glimpse of the potentially severe consequences of seismic surveys on these animals. At close ranges, both crustaceans and cephalopods exhibit stress bio-indicators and behavioural changes (such as valve closure in mussels or inking/jetting in cuttlefish and squid) in response to seismic air gun sound. In addition, developmental delays/malformations and mortality have been observed in crustaceans, and potentially lethal damage to statocysts, hair cells and neurons in cephalopods.

The impacts of seismic sound on zooplankton are only beginning to be understood. The few studies that have taken place indicate significant increases in mortality/declines in biomass in the immediate vicinity and kilometres away from the seismic source. This has the potential to cause serious knock-on ecosystem-wide consequences.

This report discusses only the “knowns” based on available literature. However, there are many unknowns. The chronic and cumulative impacts for the species described throughout are often not investigated, and for most UK marine species, the impacts of seismic sound are not known at all. Much more research is required into the impacts of this major source of anthropogenic sound in the ocean.

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# Personal communications/interviews

Table 5. Contact details of specialists who could provide further information on specific species impacted by oil and gas development, seismic surveys and other geophysical survey techniques.

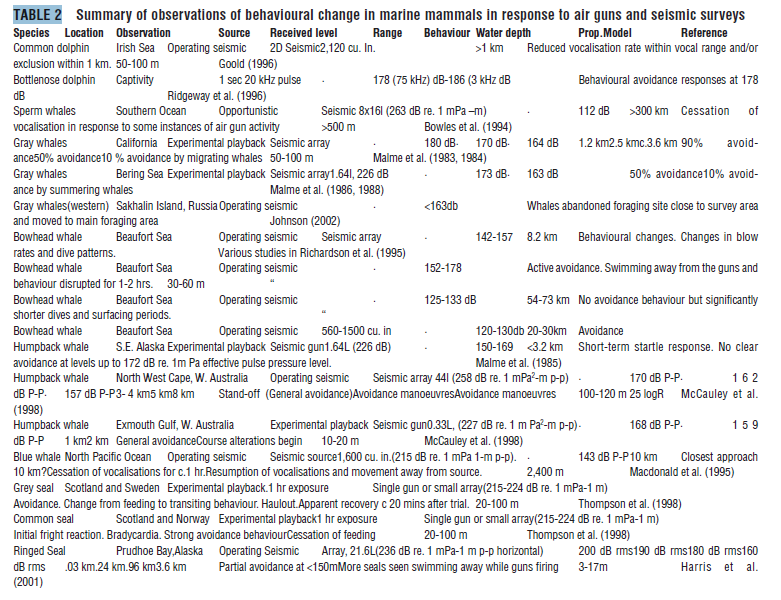
|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Organisation** | **Specialist area** | **Contact details** |
| Unknown | Fishwell Consulting | Commercial fisheries – carried out study on whiting mentioned in fish section, with drastic results (not published) | <https://www.fishwell.com.au/contact/> |
| Anne Christine Utne Palm | Havforskningsinstituttet | Zooplankton – carried out recent study with results being finalised currently. | [anne.christine.utne.palm@hi.no](mailto:anne.christine.utne.palm@hi.no) |

# Key challenges

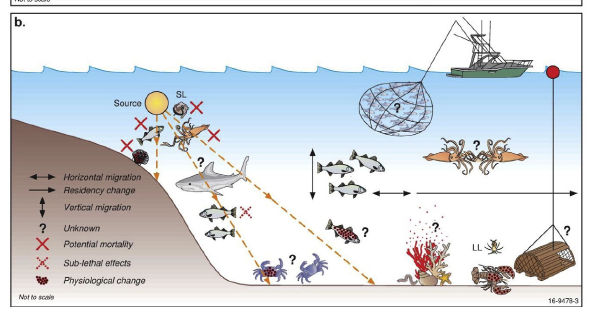
* General lack of research, especially into key commercial fish and shellfish species in the UK.
* The majority of studies are laboratory experiments, making extrapolation difficult due to methodological issues and sometimes unrealistic sound exposure levels.
* Limited research into sub-lethal effects over time and effects over large spatial scales (e.g. most laboratory experiments are limited to the immediate vicinity).
* Few assessments on the effects of chronic exposure to seismic sound and/or the cumulative effects of multiple sources of anthropogenic sound.
* There is very limited information available on the recoverability of species.
* Results can be contradictory with some finding no impacts of seismic sound, which may be due to differences in experimental design, environmental differences, species-specific differences, etc.
* There is a lack of studies into the particle motion element of sound waves, despite the sensitivity of many animals to this element (and sometimes only this element). Most studies are focused on sound pressure.
* Much of the research available is over 10 years old.
* There is a complete lack of research into the potential effects of other geophysical survey techniques.

# Infographic ideas

* Marine mammals: an updated version of table 2 from Gordon *et al.*, (2003) in infographic form – looking at behavioural and other responses of marine mammals to seismic sound (including by the received sound exposure level and distance). Could also tailor this to the most commonly observed marine mammal species in the UK using data from Stone *et al.*, (2017).



* Fish and shellfish: an updated version of figure 2 from Carroll *et al.*, (2017) in infographic form – showing various species and the types of impact found at different distances from source and SELs.



* Zooplankton: Infographic displaying data from McCauley *et al.*, (2017) and Richardson, Matear and Lenton, (2017) showing zooplankton mortality/biomass declines at different distances from source (up to 150 km).

# Follow up research ideas

* Could look at current and proposed seismic survey areas and if/how they overlap with fishing areas, see if there is any overlap with important targeted fisheries for species where impacts of seismic sound have been found (e.g. scallops, cephalopods, Atlantic cod, etc.). Also overlap with spawning areas and the potential knock-on consequences for fisheries.
* Looking at the scale of seismic surveys in the UK and modelling impacts (e.g. as done by Richardson *et al.* (2017)) – could investigate potential population-level impacts and knock-on consequences of e.g. drops in zooplankton biomass.