LITERATURE REVIEW ON BARRIER EFFECTS, GHOST FISHING, AND ELECTROMAGNETIC FIELDS FOR FLOATING WINDFARMS

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CONTENTS

ABSTRACT **6**
EXECUTIVE SUMMARY **7**
1. INTRODUCTION **10**
  1.1. Offshore wind 10
  1.2. Floating offshore wind 10
  1.3. Equinor projects 11
  1.4. Objectives 11
2. ANIMAL SENSORY SYSTEMS **11**
  2.1. Auditory perception 11
    2.1.1. Echolocation 12
  2.2. Visual perception 12
    2.2.1. Marine mammals 12
    2.2.2. Diving seabirds 13
    2.2.3. Fish 14
    2.2.4. Elasmobranchs 14
  2.3. Mechanoreception 15
3. BARRIER EFFECTS **15**
  3.1. Direct effects of barriers 16
    3.1.1. Marine mammals 16
    3.1.2. Diving seabirds 24
    3.1.3. Fish & elasmobranchs 25
    3.1.4. Invertebrates 25
  3.2. Indirect effects of barriers 26
    3.2.1. Marine mammals 26
    3.2.2. Birds 27
    3.2.3. Fish & elasmobranchs 27
    3.2.4. Invertebrates 27
  3.3. Mitigation options 27
  3.4. Knowledge gaps 28
    3.4.1. Current levels of FOW site use 28
    3.4.2. Spatial scale of effects 29
    3.4.3. Population impacts of habitat exclusion 30
4. ENTANGLEMENT IN GHOST FISHING GEAR **30**
  4.1. Direct effects of entanglement 32
    4.1.1. Marine mammals 32
    4.1.2. Diving seabirds 33
    4.1.3. Fish 34
    4.1.4. Elasmobranchs 34
    4.1.5. Invertebrates 34
  4.2. Indirect effects of entanglement 35
    4.2.1. Pollution 35
    4.2.2. Habitat destruction 36
    4.2.3. Foraging and populations 36
    4.2.4. Social and Economic 37
  4.3. Mitigation options 37
  4.4. Knowledge gaps 38
5. ELECTRO-MAGNETIC FIELDS **39**
  5.1. What are EMFs? 39
    5.1.1. Sources of EMFs 39
  5.2. How do animals detect EMFs? 42
    5.2.1. Marine mammals 43
    5.2.2. Diving seabirds 46
    5.2.3. Turtles 47

5.2.4. Elasmobranchs 47
5.2.5. Fish 48
5.2.6. Invertebrates 49
5.3. Effects of EMFs 50
5.3.1. Marine mammals 67
5.3.2. Diving seabirds 67
5.3.3. Turtles 68
5.3.4. Elasmobranchs 68
5.3.5. Fish 69
5.4. Mitigation options 70
5.5. Knowledge gaps 71
6. CONCLUSIONS 71
7. ACKNOWLEDGEMENTS 72
8. REFERENCES 72

LIST OF FIGURES

Figure 1: Simulation of the scale of a floating windfarm and humpback whale . 17
Figure 2: Tracks of common seals around a windfarm 20
Figure 3: Examples of mysticetes interacting with offshore structures 21
Figure 4: Structures with comparative layouts to floating wind turbines 23
Figure 5: EMF s associated with a) AC and b) DC power cables 41

LIST OF TABLES

Table 1: Studies of parallel structures and impacts on marine mammals 19
Table 2: Electrosense and magnetosense research for cetacean species 44
Table 3: Existing EMF studies from 2022–1988 66

LIST OF ACRONYMS/ABBREVIATIONS/UNITS/TERMS

A	Amp
AC	Alternating Current
ALDFG	Abandoned, Lost or Discarded Fishing Gear
B-field	Magnetic field
ca.	Circa or approximately
dB	DeciBel
E-field	Electric field
EC	European Commission
EIA	Environmental Impact Assessment
EMF	ElectroMagnetic Field
FAO	Food and Agriculture Organisation of the United Nations
F-POD	Full waveform POrpoise Detector
FLO	Fisheries Liaison Officer
FORTUNE	Floating Offshore Wind Turbine Noise
G	Gauss
GG	Ghost Gear
GMF	GeoMagnetic Field
GPS	Global Positioning System
HF	High Frequency
HSE	Health/Safety/Environment
IAR	Independent Assurance Review
iE-field	Induced Electric field
IMO	International Maritime Organisation
IUU	Illegal, Unreported, or Unregulated
JNCC	Joint Nature Conservation Committee
µT	Micro Tesla
m	Metre
MD	Managing Director
MRED	Marine Renewable Energy Device
O&G	Oil & Gas
OSC	Ocean Science Consulting Limited
PAM	Passive Acoustic Monitoring
PCoD	Population Consequences of Disturbance
QC	Quality Control
RL	Received Level
RMS	Root-Mean-Square
ROV	Remotely Operated Vehicle
RV	Research Vessel
SMASS	Scottish Marine Animal Stranding Scheme
T	Tesla
TB	TeraByte
TTS	Temporary Threshold Shift
UK	United Kingdom
UTC	Coordinated Universal Time
UXO	UneXploded Ordnance
V	Volt

ABSTRACT

This document reviews available information relating to barrier effects, entanglement risks from ghost fishing gear, and ElectroMagnetic Fields (EMFs) with regards to marine mammals, diving seabirds, fish, and invertebrates at Floating Offshore Windfarms (FOW). To do this, available information from comparable offshore industries including fixed windfarms, Oil & Gas, aquaculture, *etc.*, is explored, and knowledge gaps identified to steer research efforts in future.

There are currently no first-hand accounts of barrier effects being caused by operational FOWs on marine fauna. Studies from parallel industries indicate that, for odontocetes (toothed whales, dolphins, and porpoises) and pinnipeds (seals, sea lions, and walruses), physical presence of FOWs is unlikely to cause a barrier effect, and if anything, animals may be attracted to FOWs for foraging. Due to a lack of evidence for how mysticetes (baleen whales) interact with anthropogenic structures, there is potential for a behavioural response to physical structures at a FOW. Similarly, diving seabirds, turtles, fish, and elasmobranchs (sharks, skates, and rays) are not considered to be at risk of barrier effects from FOWs. Further evidence is needed regarding marine fauna’s usage of operational FOW sites and how they pass through and between moorings and cables. There is potential for impacts to arise as size of FOWs increases in future, which may be of particular concern for migratory species such as mysticetes.

Direct entanglement with FOW structures is unlikely for marine species due to the size and tension of subsea cables and moorings; however, secondary entanglement, when individuals become trapped in other ropes or derelict fishing gear which is snagged on moorings and cables, presents a higher risk. This is a risk for a variety of taxa from marine mammals, to diving seabirds, turtles, fish, and invertebrates. Direct effects of entanglement include mortality or serious injury; however, individuals that break free from entanglement may suffer respiratory distress or damage to tissues, muscles, or nervous systems. There is a significant knowledge gap on rates of ghost fishing gear snagging on FOW cables and moorings and subsequent rates of animal entanglement.

Electric and magnetic fields produced by subsea cables present a potential stressor to nearby animals. Strength of fields declines with distance from the source. Effects of EMFs on marine species are generally understudied and not well known. Certain taxa, such as sharks, which are known to be receptive to EMF, are likely more impacted by electromagnetic fields produced by subsea cables than species less reliant on detecting EMFs for foraging and navigation.

In summary, impacts of barrier effects and EMF are likely to be minimal for most species. Risk of injury or mortality from entanglement in ghost fishing gear is high for individuals that become entangled; however, given a lack of information on rate of gear snagging on FOW structures and consequently rate of animal entanglement at FOW sites, it is not known if this will pose a significant risk for populations.

EXECUTIVE SUMMARY

Ocean Science Consulting Limited (OSC) was commissioned by Equinor ASA to provide a literature review which assesses available reference materials and data relating to barrier effects, entanglement risks from ghost fishing gear, and ElectroMagnetic Fields (EMFs) with regards to marine mammals, seabirds, fish, and invertebrates at Floating Offshore Windfarms (FOW). Due to a lack of evidence regarding how marine fauna interact with operational FOWs, transferrable information from industries with similar types of anthropogenic structures (*e.g.* vertical structures throughout water column, suspended moorings and anchors, and subsea cables) can be analysed to investigate potential risks from barrier effects, entanglements, and EMFs from FOWs.

Presence of odontocetes and pinnipeds at fixed windfarms and other offshore structures with moorings and cables suspended in the water column indicates that they will not be excluded from FOWs and that no barrier effect will be produced. Seals have been recorded targeting individual wind turbine foundations for foraging, and it is expected that density of marine top predators will increase as moorings/cables accrue communities of biofouling species, which may augment local prey availability. There is a lack of evidence on how mysticetes interact with fixed windfarms and other anthropogenic structures, so it is difficult to predict how they may react. One study has shown that minke whales (*Balaenoptera acutorostrata*) may exhibit behavioural responses to mooring lines, suggesting potential for this to occur in the context of a FOW; however, other evidence suggests that mysticetes may interact with similar offshore structures and a completely exclusive barrier effect is unlikely. Interactions with physical barriers will be within a near-zone scale and will be influenced by how animals perceive the FOW or individual turbines. If vision is used, then it is likely to be only a few tens of metres depending on water clarity and light levels. If animals detect FOW through hearing, then this scale could increase depending on frequencies of noise produced and sensitivity of animals. Low-frequency noise can propagate and be detected over a larger range (*e.g.* 13 km at Hywind Scotland, depending on wind speed), while high-frequency components should attenuate quickly and are unlikely to propagate over large scales. Occurrence of odontocetes and pinnipeds at operational structures that generate a similar acoustic footprint (*e.g.* operational windfarms or O&G structures) suggest this will not act as a barrier to these animals. Mysticetes are more sensitive to lower-frequency noise and are therefore at higher risk; however with few data available on occurrence of mysticetes at offshore windfarms, it is difficult to predict if operational noise will elicit a behavioural avoidance at any distance.

Due to the infancy of this technology, there are no publications currently regarding occurrence of marine mammals at operational FOW site – most reports to date focus on pre/construction phases of FOWs. To de-risk operational decisions, data should be gathered on whether marine mammals pass through or use operational FOW sites, and how they manoeuvre through sites. Surveys and monitoring studies within an operational FOW could be conducted to address this knowledge gap. With most previous research focussing on odontocetes and pinnipeds, there is a need for Further study on how mysticetes interact with offshore windfarms, either floating or fixed. Conducting studies on larger windfarms is also important, as magnitude of effects observed may alter with size of site footprint. Studies of how deep-water species of marine mammal will interact with floating windfarms is also needed, as windfarms to date have been installed in relatively shallow areas; therefore, studies have focussed on coastal, shallow-water species.

No barrier effect from floating windfarms is anticipated for fish, elasmobranchs, or invertebrates, as these species have been observed at offshore structures of similar layouts previously. Preliminary studies at an operational floating windfarm have shown that colonisation of invertebrates is occurring, and fish have been observed in high abundance.

Direct entanglement with installation structures is unlikely for marine species due to the size and tension of subsea cables and moorings; however, secondary entanglement, when individuals are entangled with derelict fishing gear caught on moorings and cables, presents a higher risk. Secondary entanglement is not caused *by* the FOW itself; however, FOWs may make the problem of debris and lost or discarded fishing gear that is already extant in the marine environment more prominent. FOWs are likely to have similar risk of entanglement as other offshore structures; however, as they will be larger and have more cables and moorings than most other types of offshore installation, the risk may be high.

Entanglements with marine litter caught on moorings and cables have a high mortality rate when these incidents occur; however, rate of entanglement with debris or derelict fishing gear, particularly for fixed or floating wind turbines, remains largely unknown. There is an acute knowledge gap on secondary entanglement rates in offshore settings. Direct effects of entanglement often entail mortality or serious injury. Individuals that are able to break free may suffer respiratory distress or damage to tissues, muscles, or nervous systems. Combined, these effects can impact significantly on motility and migratory behaviours and impair reproduction for a wide range of marine taxa.

Indirect effects of derelict fishing gear include localised pollution, destruction of habitat that may alter foraging grounds, broad-scale population impacts due to mortality of adults, and significant human economic costs in terms of clean-up and impacts on fisheries. Several mitigation options are available, including creation of exclusion zones for some fisheries which are at higher risk of entangling gear on FOW structures, regular subsurface inspections of cables and moorings, development of cables that have minimal impacts when lost, and technological developments in monitoring to detect and remove derelict fishing gear.

Overall, several key knowledge gaps exist in relation to how derelict fishing gear and subsequent entanglements impact marine communities. These include detailed snagging risk assessments, identifying prevalence of derelict gear around offshore structures, effects of cumulative biofouling on caught gear, more accurate assessment of entanglement reports, and a better understanding of empirical data on entanglement events involving marine megafauna in offshore contexts. Direct impacts of entanglement will be observed in the near-field; however, animals that break free may disperse considerable distances trailing gear and increase the range of impact. There is also potential scope for pollution from snagged debris to spread on ocean currents.

Electric and magnetic fields produced by subsea cables present a potential stressor to proximate marine species. Electric fields are largely mitigated by industry-standard shielding (though some hypersensitive species will still likely detect these fields when nearby), but magnetic fields persist through shielding. There are numerous sources of EMF in the marine environment, from natural (such as Earth's latent geomagnetic field) to anthropogenic (power cables, marine renewable energy devices, telecommunication cables, *etc.*). Strength of EMF declines with distance from the source; therefore, sessile organisms are more likely to be impacted than motile organisms, though attractive or repellent effects could still lead to impacts on motile organisms.

Effects of EMF on marine species are generally understudied and not well-known. Certain taxa, such as elasmobranchs, which are known to be receptive to EMF, are likely more impacted by EMF produced by subsea cabling than species less reliant on detection of EMF for foraging and navigation. Because sensitivity to EMF of most taxa is poorly understood, there are few studies that assess direct effects of EMF on marine organisms. It is hypothesized that high-impact effects could include navigational miscues for organisms, particularly while undergoing migratory behaviour, reproductive impacts, physiological stress, or detrimental effects on growth or development. There may be greater impacts if FOWs are created in sensitive areas, such as off of turtle nesting beaches. Studies of direct effects are sparse, and impacts/degree of effects are not uniform across taxa, with some studies showing no effect on examined organisms, while others show broad effects (*e.g.* on migratory behaviour). Sensitive marine fauna are likely only to be impacted by EMFs from subsea cables in the near-zone as the strength of the fields decays with distance from the cable, with evidence indicating that EMF can decrease to ambient levels within 20 m (Bochert and Zettler, 2006; Frid *et al.*, 2012; Copping and Hemery, 2020). If multiple cables/developments are situated in close proximity, there is potential for impacts to reach into the medium-zone, due to the lack of 'influence free' space for organisms between the artificial EMFs (Tricas and Gill, 2011).

Very little is known about indirect effects of EMF on marine organisms, such as population-level impacts or longitudinal impacts through time. Current recommendations include establishing baselines of sensitivities of marine organisms, determining which species are most at risk of direct effects, and subsequently examining indirect or broad-scale effects.

Mitigation options include deeper burial of cables, technological developments or cable configurations to reduce EMF strength, and avoidance of cabling in sensitive areas. In general, better understanding of cumulative impacts of EMF is necessary to develop more precise mitigation methods.

Of the stressors covered in this review, least is known about potential impacts of EMF on marine life, primarily due to lack of understanding of EMF-detecting physiology in most organisms and difficulty of studying behavioural modification or stress in response to EMF exposure. What is known is that EMF impacts species differently, and risk is potentially low due to the combination of localised effective range of EMF and the fact that most species are highly motile and are consequently expected to have low exposure.

In conclusion, FOWs are not expected to elicit a barrier effect, except perhaps for baleen whales; however, there is considerable uncertainty in this, as most existing windfarms have not been installed across baleen whale migratory corridors. It is unlikely that FOWs will result in direct entanglement; however, there is significant risk that ghost fishing gear may entangle on FOW moorings and cables and subsequently cause secondary entanglement with marine fauna. Rates of gear snagging on FOW structures must be monitored closely to assess the level of risk. EMFs may be detected by some species, particularly elasmobranchs, but any potential effects will be localised and are unlikely to impact populations significantly.

1. INTRODUCTION

Emissions from anthropogenic activities have been known to exacerbate greenhouse effect on Earth for decades, inducing climate change across the globe (IPCC, 1990). Even with knowledge about impacts of GreenHouse Gases (GHGs), emissions were 12% higher in 2019 than in 2010, and 54% higher than in 1990 (IPCC, 2022). To reduce global GHG emissions, there must be a reduction in fossil fuel use and a transition to low-emission, renewable energy sources (IPCC, 2022). Harvesting renewable energy in the offshore environment has become increasingly common in recent years, with technologies for extracting electricity from wind, tides, and waves developing rapidly.

1.1. Offshore wind

Many countries have implemented legislation to reduce GHG emissions. For example, the United Kingdom's (UK) Climate Change Act aims for net-zero GHG emissions by 2050, Norway plans to reduce emissions by 90–95% by 2050 (IEA, 2022), and South Korea has committed to being carbon neutral by 2050 (Government of South Korea, 2020).

Many offshore sites have stronger and more reliable winds than their onshore counterparts; therefore, significant and increasing investment has gone toward developing Offshore WindFarms, OWFs (Kaldellis and Kapsali, 2013). Currently, total global energy production from offshore wind is over 35 Giga Watts (GW), 92% of which is from Europe and China (GWEC, 2021).

This increasing development poses potential risks of environmental impacts during construction, operation, and decommissioning phases. Consequently, there is a growing body of evidence regarding environmental impacts of these structures, particularly during construction and operational phases (Bailey *et al.*, 2014; Copping and Hemery, 2020). In coming decades, as more structures come to the end of their operational life, there will be a greater focus on environmental impacts of various options for decommissioning, such as leaving structures *in-situ* as artificial reefs (Todd, 2013; Fowler *et al.*, 2018).

1.2. Floating offshore wind

One disadvantage of traditional fixed OWFs is their limitation to shallow waters. All of the UK's current fixed windfarms are located in areas <60-m deep (World Bank, 2019). Another disadvantage is noise produced during the construction process and how this impacts marine fauna, particularly regarding pile-driving methods used to secure monopiles (Tougaard *et al.*, 2009; Bailey *et al.*, 2010; Brandt *et al.*, 2011; Graham *et al.*, 2019). Floating wind technology bypasses the need for piling and thus reduces potential impacts of noise on marine mammals during construction.

The world's first operational Floating Offshore Windfarm (FOW), Hywind Scotland, developed by Equinor, is over 100-m deep, with scope to install floating turbines even deeper elsewhere. For countries with coastlines along steep continental shelves, this technology offers potential to unlock areas previously impracticable for OWFs, leading to greater investment in this technology in recent years.

Very few FOWs are currently in operation, and those that have been installed are quite small (*e.g.* Hywind Scotland is 5 turbines); therefore, little evidence exists of potential effects of these structures, and how these effects will change with increased array sizes is unknown. While knowledge on environmental impacts of FOWs is growing (e.g. Farr *et al.*, 2021; Maxwell *et al.*, 2022), there is still considerable uncertainty about potential effects of this technology on the marine environment.

1.3. Equinor projects

Equinor is a leading developer in the field of floating wind, with the world's first FOW constructed in 2017, Hywind Scotland. In November 2022, Equinor's Hywind Tampen became operational in the Norwegian North Sea. With plans for larger-scale arrays to be developed in Norway and South Korea, there is considerable scope for future research into environmental impacts of floating wind from these sites.

1.4. Objectives

The aim of this review is to assess current state of knowledge on the following topics, as well as highlighting mitigation options and knowledge gaps.

- Barrier effects of offshore windfarms on marine fauna;
- Entanglement risks from ghost fishing gear; and,
- ElectroMagnetic Fields (EMFs).

2. ANIMAL SENSORY SYSTEMS

Before delving into each of the above topics, it is necessary to review how different animal groups sense their environment to understand how they may detect, avoid, or interact with FOW structures. Functions essential to an organism's survival (*e.g.* migration, feeding, reproduction, and predator avoidance) rely on sensory reception (Tricas and Gill, 2011). Low visibility conditions underwater have put strong selective pressure on marine species to develop alternative senses, such as acoustic, olfactory, electroreception, and magnetoreception (Tricas and Gill, 2011).

Auditory and visual perception and mechanoreception relate to how animals may detect barriers or ghost fishing gear and are covered here, while electroreception and magnetoreception are discussed after EMFs are introduced in **Section 5.**

2.1. Auditory perception

Marine mammals, and in particular cetaceans (whales, dolphins, and porpoises), use different sound frequency bands for a number of activities, which include, but are not limited to: communication, navigation, foraging, and a range of activities within the wider social group such as cohesive actions, warnings, and maternal relationships (Southall *et al.*, 2007; André *et al.*, 2010; Erbe *et al.*, 2018; NMFS, 2018; Southall *et al.*, 2019). Odontocetes (*i.e.* toothed whales, dolphins, and porpoises) are considered to be more sensitive to underwater sound (NMFS, 2018; Southall *et al.*, 2019), and also echolocate (see **Section 2.1.1**).

Hearing is an important sensory system to fishes (Popper *et al.*, 2014; Popper and Hawkins, 2019). Sounds can convey information about their environment and species also use sound for communication. Anthropogenic sources of noise, such as piling and explosions, can have effects on fish ranging from direct mortality to behavioural changes (Popper *et al.*, 2014; Popper and Hawkins, 2019).

Marine invertebrates have been shown to use sounds for communication and detect acoustic signals (Popper *et al.*, 2001); however, the extent to how sounds are used by these animals is not well understood. Anthropogenic noise has previously been shown to impact species of marine invertebrates and can have individual and ecosystem wide consequences (Solan *et al.*, 2016; Stenton *et al.*, 2022).

The underwater hearing of seabirds is poorly understood; however, there is growing evidence that they possess hearing capabilities in the water (Larsen *et al.*, 2020; Sørensen *et al.*, 2020).

Underwater noise generated by offshore activities (anthropogenic noise) has capacity to impact marine wildlife. Effects of sounds on marine mammals depend greatly on characteristics of the sound (*e.g.* source level/type of noise), weather conditions, nearby vessels, local sound propagation conditions, and receiver characteristics with regards to sensitivity and bandwidth of hearing.

2.1.1. Echolocation

Odontocetes (i.e. toothed whales, dolphins and porpoises) use echolocation (short bursts of high-frequency noise) to forage for prey, navigate, communicate, and avoid predators in a light-limited environment. Echolocation was first evidenced by Schusterman (1980), by placing suction cups over dolphins' eyes while individuals completed experimental tasks. For example, echolocation allows dolphins to detect objects a few centimetres in diameter up to *ca.* 100 m away (Murchiston, 1980). Once the first click is emitted, an individual can measure distance to the target by timing duration for the echo to return. Clicks can be spaced apart if there is distance between predator and prey, but when the distance closes, the inter-click interval becomes shorter and the rapid succession of clicks, known as a buzz, allows individuals to detect prey movement and attempt prey capture (Martin *et al.*, 2019).

Common bottlenose dolphins *(Tursiops truncatus)* can detect objects over 7 cm in diameter at distances of over 100 m (Au and Snyder, 1980). Additionally, harbour porpoises *(Phocoena phocoena)* have been shown to detect a fisher's gill net at distances of 10s of metres (Nielsen *et al.*, 2012). Materials used for moorings and cables in floating windfarms will be thicker than the fine mesh of a gill net; therefore, these animals are likely to be able to distinguish these structures at greater distances. This would indicate that echolocating animals will be aware of the presence of moorings when approaching a windfarm area and when in close proximity.

2.2. Visual perception

Marine mammals use their visual sense to orient themselves and recognise individuals (Wartzok and Ketten, 1999). Visual cues also play an important role in the ecology of birds and fish (Southwood *et al.*, 2008; Arimto *et al.*, 2011; Bielli *et al.*, 2020).

2.2.1. Marine mammals

Mysticetes (baleen whales) and pinnipeds (seals, sea lions, and fur seals) do not echolocate and instead rely on other senses, such as vision and passive hearing, to detect objects in the water. Environmental factors influence how effective visual detection may be. Decreasing luminance may not significantly impair underwater visual acuity. A study conducted by Schusterman and Balliet (1971, cited in Hanke *et al*., 2009) found that, while low brightness reduced the ability of California sea lion (*Zalophus californianus*) to see in air substantially, no such effect was recorded underwater. It is important to note that turbidity, rather than luminosity, plays a pivotal role in visual detection of objects. Weiffen *et al.* (2006) found that visual acuity of common seals (*Phoca vitulina)* was significantly greater in clear water compared to turbid water.

Some species of marine mammals can identify specific colours from greater distances than others, so colour of objects may impact perception by different species. For example, Kraus *et al.* (2014) determined that red and orange are visible to right whales *(Eubalaena glacialis)* at the longest distances; however, for minke whales *(Balaenoptera acutorostrata),* black and white offer more stark contrast (Kot *et al.*, 2012). Both of these species are thought to perceive predominantly greyscale images (Kot *et al.*, 2012; Kraus *et al.*, 2014). Pinniped visual capabilities and colour spectrum sensitivity are significantly more advanced than those of cetaceans due to their need to see in air.

2.2.2. Diving seabirds

Diving birds in the orders *Procellariiformes* (tube-nosed birds such as fulmars, shearwaters, and petrels), *Suliformes* (gannets and cormorants), and *Charadriiformes* (skuas, larids, and alcids) rely on a host of senses and cues to detect their surrounding environments. Evidence suggests that olfaction aides in long-range detection of prey items (Nevitt *et al.*, 1995; Nevitt, 2008) and it is possible that auditory cues assist in effective near-field prey capture (Hansen *et al.*, 2017), but vision remains the most important sense for seabirds in navigating the marine environment (Darby *et al.*, 2022). Historically, evidence of the importance of underwater vision for diving birds has been difficult to quantify (Haney and Stone, 1988), and to date no studies have demonstrated the ability of diving birds to perceive subsurface structures. More recently; however, behavioural evidence and morphological studies indicate that diving birds do in fact rely on vision for prey capture underwater, which suggests detection capability of underwater obstacles, at least to some extent. Machovsky-Capuska *et al.* (2012) found Australasian gannets *(Morus serrator)* employ visual detection underwater when pursuing prey, and long-tailed ducks *(Clangula hyemalis)* show attraction to LED lights intended as deterrents on gillnets (Cantley *et al.*, 2020). Foraging behaviour and capture success of Procellariforms, Suliformes, and Charadriiforms have been linked to habitat turbidity, further indicating that underwater vision is vital to pelagic and diving birds (Henkel, 2006; Darby *et al.*, 2022). Many seabirds rely on visual cues such as presence of conspecifics (Michel *et al.*, 2022) or fishing vessels and marine mammals (Tremblay *et al.*, 2014) to initiate foraging behaviour, and some clades such as shearwaters nearly exclusively dive during daylight hours (Ronconi *et al.*, 2010), which additionally suggests a reliance on detection through vision.

Morphological facets of waterbirds' eye structures additionally provides evidence that vision is employed underwater to detect objects such as prey and possibly barriers or obstacles (Martin and Prince, 2001). Species that rely solely on visual guidance to capture prey such as King Penguins *(Aptenodytes patagonicus)* have adaptations of thickened/flattened low-powered corneas that reduce the effects of blurriness underwater (Martin, 1999). Numerous similar adaptations can be found across the range of diving birds (Martin and Brooke, 1991; Katzir and Howland, 2003; Nelson, 2006).

As visual detection is critical to diving birds, reductions in underwater visibility pose the greatest threat to foraging individuals. A previous instance of reduced visibility due to a coccolithophore bloom led to a mass mortality event of shearwaters in the Bering Sea (Stockwell *et al.*, 2001), highlighting that increased turbidity in an area may have negative consequences if birds are foraging. Overall, vision is a critical sense for diving birds navigating the subsurface marine environment. Detectability of subsurface structures is unstudied, but it is likely that individuals would be able to detect underwater barriers given their reliance on vision for prey capture.

It is generally understood that seabirds have well-developed detection capabilities for prey, and it is likely that this assists in detection of subsurface structures, though detection of fishing gear such as gillnets is likely more difficult (Martin and Crawford, 2015), as evidenced through high global seabird mortality due to fisheries bycatch (Žydelis *et al.*, 2013). Seabirds, more than other marine species, rely on visual cues, specifically for foraging (Bielli *et al.*, 2020). It is assumed that birds have advanced visual capabilities (Bennett and Théry, 2007) and excellent visual awareness; however, there is growing evidence (*e.g.* collision statistics with land-based anthropogenic structures) this may not be the case for all species (Drewitt and Langston, 2008), and that visual acuity may vary between groups. Cantley *et al.* (2020) suggest that seabird visual capabilities vary across species due to factors such as foraging ecology, visual or non-visual feeding cues, and general conditions of visibility in the natural environment for species such as auklets *(Aethia* spp.*)*, penguins (*Spheniscidae*), and cormorants (*Phalacrocoracidae* spp.).

2.2.3. Fish

Fish vision is a more well-established field of research (Arimto *et al.*, 2011). Most teleost (ray-finned) species have both rod and cone receptor cells, which allow them to visually perceive objects within a wide range of light levels over a diel cycle (Douglas and Hawryshyn, 1990; Arimto *et al.*, 2011). Rod cells have only one pigment and are used for dark-adapted vision, while cone cells may have up to four pigments and are specialised for light-adapted vision (Arimto *et al.*, 2011). At least two types of pigments in the cone cells are required for colour vision, and most fish have three (blue, red, and green), while some shallow-living species also have a fourth UV pigment (Arimto *et al.*, 2011). Some species may retain colour vision in darkness; however, for most species, this ability is reduced in poor lighting (Douglas and Hawryshyn, 1990; Arimto *et al.*, 2011). Similarly, numerous deep-diving species are considered colourblind, as they do not have cone cells at all (Arimto *et al.*, 2011). In lower light intensities, it is more difficult for fish to perceive objects due to the decrease in contrast, which is more extreme in an underwater environment (Douglas and Hawryshyn, 1990). Movement also becomes more difficult to detect in low-light conditions (Arimto *et al.*, 2011).

2.2.4. Elasmobranchs

Research into elasmobranch visual systems extends back over hundreds of years with initial studies published in 1818 (Gruber, 1977). Gruber (1977) acknowledges that elasmobranchs possess the most highly evolved tapetum (eye tissue) throughout the entire animal kingdom and that the evolution of elasmobranch eyes over millions of years differ with species for example some shark species have completely fixed eyelids whilst others possess mobile eyelids. It is apparent that many elasmobranchs maintain a high visual capacity (Gruber, 1977; Litherland *et al.*, 2009; Collin, 2018). This being said, most elasmobranchs tend to be monochromats (Marshall *et al.*, 2015).

2.3. Mechanoreception

Vibrissae, tactile hairs on the face, of pinnipeds also play an important role in detection. They are important for foraging activity and also provide tactile cues for structures in close proximity (Ahl, 1986). They are of even greater importance when these animals are in dark, turbid conditions (Ahl, 1986). Pinnipeds would typically use a combination of both visual and tactile cues to detect physical structures from a floating wind turbine.

3. BARRIER EFFECTS

A barrier effect is when an animal's movement or foraging is restricted due to a natural or anthropogenic obstruction (Bailey, 1970; Merriam *et al.*, 1989; Sparling *et al.*, 2018). A classic example of a barrier effect is construction of roads. Presence of roads can prevent movement of a range of different animal groups, such as mammals, birds, and reptiles (Rico *et al.*, 2007; Jones and Bond, 2010; Andrews *et al.*, 2015). In the aquatic environment, development of hydroelectric dams in Asian freshwater ecosystems has caused habitat fragmentation and a barrier effect for the Indus dolphin (*Platanista gangetica minor*), as dams obstruct their movement along river systems (Braulik *et al.*, 2014).

There is concern that FOWs could constitute a physical barrier that may obstruct marine fauna from passing through. This could be due to mooring lines and cables that are draped through the water column. Scale of potential effect varies depending on how animals may detect the FOW. If detection occurs visually, then scale would be near field; however, if animals respond to the FOW, then scale of potential impact may increase as they move around the site to avoid it. As windfarm arrays grow in the future, distance at which marine fauna may be displaced by a barrier effect could also increase.

Noise generated by turbines, cable strum, or support vessels may create an acoustic barrier that obstructs or deters marine fauna from passing through the area. Acoustic detection of windfarm noise would be at a larger scale of potentially 10s of kilometres. Noise measurement and modelling from Hywind Scotland predicted that noise from the five-turbine array would reach background levels at a distance of 4 km in low wind speeds of 5 m s^{-1}, and 13 km in 13 m s^{-1} winds (Burns, 2022). To experience Temporary Threshold Shift (TTS) to hearing, a porpoise would need to remain within 50 m of a turbine for 24 hours at moderate wind speeds (Burns, 2022), which is highly unlikely. Additional information regarding noise produced by FOWs will be published through the Floating Offshore Wind Turbine Noise (FORTUNE) project, part of the Supergen Offshore Renewable Energy programme, due to be released in early 2023. Results from this project will provide additional evidence for operational noise levels of floating windfarms currently in operation, with the aim to model noise levels of larger arrays in a similar methodology to Tougaard *et al.* (2020), who performed this for fixed windfarms. If windfarms are located in areas with high levels of pre-existing ambient noise, for example near shipping lanes or ports, then the spatial scale at which windfarm noise exceeds ambient noise will be lower than if they are located in areas that had previously experienced little disturbance (Tougaard *et al.*, 2020).

The movement ecology of marine fauna, such as marine mammals, can be complex and will influence the likelihood of encountering an operational FOW. Some species may exhibit high levels of site fidelity and be resident in an area for extended periods. For example, the bottlenose dolphin population inhabiting the Moray Firth, Scotland, has been shown to have select individuals return year after year (Wilson *et al.*, 1999; Cheney *et al.*, 2013). This population of dolphins; however, do not remain in this area permanently, with evidence of individuals being regularly sighted over 100 km along the coast from the Moray Firth in consecutive years (Arso Civil *et al.*, 2019). On a larger scale, some individuals from this population have been recorded to undertake long-distance movements of over 1,000 km (Robinson *et al.*, 2012). This evidence shows how some odontocete species have the capability to travel great distances from their observed home ranges, which creates a greater probability of these animals encountering offshore structures throughout extended movements. A FOW situated near to a resident population of marine mammals will have a greater chance of them interacting with it. A key driver of odontocete distribution is prey availability, which is important to consider regarding density of prey available at an operational windfarm site (Sveegaard *et al.*, 2012).

Pinnipeds spend large quantities of their time on land for resting and breeding; however, offshore foraging trips can vary between hours to multiple days or months and they can cover distances of 10s to 100s of kilometres (McConnell *et al.*, 1999; Le Boeuf *et al.*, 2000; Russell *et al.*, 2016). During these foraging trips, pinnipeds are likely to encounter operational FOWs.

Many mysticete species conduct long-rang migrations between foraging and breeding grounds. For example, humpback whales (*Megaptera novaeangliae)* can migrate thousands of kilometres, even crossing between entire ocean basins (Stone *et al.*, 1990; Pomilla and Rosenbaum, 2005). If a floating windfarm is designated to be developed at a location on a whale's migration route, then there would be a high chance of these animals encountering it.

3.1. Direct effects of barriers

With few examples of operational FOWs globally, there is little evidence of how these arrays may act as barriers to marine fauna. To investigate potential barrier effects of floating windfarms, other offshore developments that possess a similar structure underwater have been reviewed to identify potential impacts and their magnitudes.

3.1.1. Marine mammals

Copping and Grear (2018) simulated encounter risk from moorings and cables of a hypothetical FOW for humpback whales (**Figure 1**). While there were no analytical results from this simulation, its purpose was to communicate scale of the FOW in comparison to behaviour of the humpback whale and highlight a lack of current case studies that are available to research effects of floating wind on marine mammals.

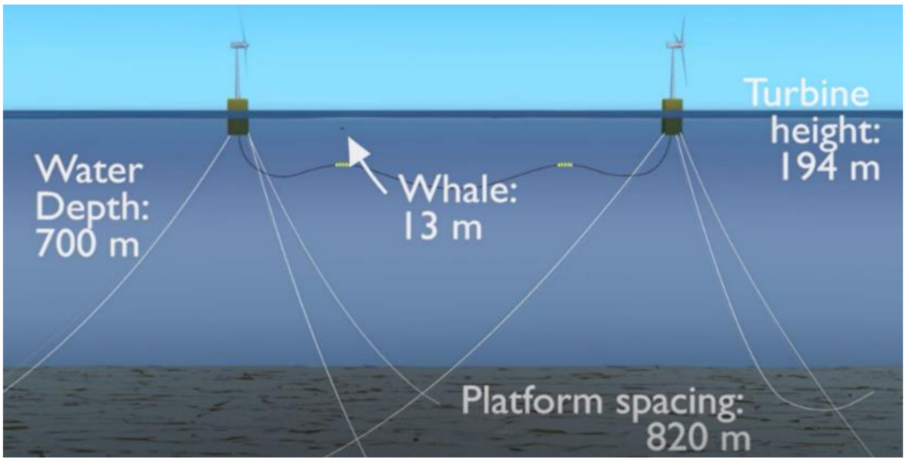

Figure 1: Simulation of the scale of a floating windfarm and humpback whale in 700-m depth. *Source*: Copping and Grear (2018). Link to animation.

The nine-turbine array simulation by Copping and Grear (2018) does not account for increasing scale of large floating arrays in future, which may contain over 100 individual turbines to achieve 1 GW. For example, Equinor is currently developing an 800 MW FOW in South Korea, the Firefly windfarm, which could occupy two 75 km^2 areas. In comparison, the Dutch fixed windfarm, Egmond aan Zee, used by Scheidat *et al.* (2011) to study impacts to harbour porpoises was a total of 26 km^2. While scale of fixed OWFs has increased in recent years, for example the world's largest OWF Hornsea 2 in the North Sea covering an area of 462 km^2, there is potential for FOWs to cover much larger areas than traditional fixed OWFs.

Considering that Hornsea 2 only became operational in August 2022, there is a lack of understanding on the impacts of OWFs of any design, fixed or floating, on such a large scale and whether responses of marine mammals to their operation will scale or be more/less apparent than observed in smaller OWFs.

Direct comparative studies for effects of a variety of industries on marine mammals from are outlined in **Table 1**, with findings from each industry described in more detail below.

Study	**Industry**	**Species (group)**	**Findings**	**Similarities to floating wind**	**Differences to floating wind**
Vallejo *et al.* (2017)	Fixed offshore wind	Harbour porpoise (odontocete)	No difference between porpoise occurrence before and after windfarm operation	Constant low frequency noise, hard structures at surface	Hard structures through water column with lack of moorings
Scheidat *et al.* (2011)	Fixed offshore wind	Harbour porpoise (odontocete)	Greater occurrence of porpoises in windfarm area when operational compared to baseline	Constant low frequency noise, hard structures at surface	Hard structures through water column with lack of moorings
Russell *et al.* (2014)	Fixed offshore wind	Common seal (pinniped)	Seals would use operational windfarm for foraging	Constant low frequency noise, hard structures at surface	Hard structures through water column with lack of moorings
Russell *et al.* (2016)	Fixed offshore wind	Common seal (pinniped)	Seals would pass through operational windfarm to swim out to sea	Constant low frequency noise, hard structures at surface	Hard structures through water column with lack of moorings
Todd *et al.* (2009)	Oil and gas	Harbour porpoise (odontocete)	Porpoises occurring around platform and thought to be foraging around it	Hard structures in water, operational noise	Lack of moorings, single structure
Todd *et al.* (2016)	Oil and gas	Harbour porpoise (odontocete), white-beaked dolphin (odontocete), common seal (pinniped)	Marine mammals observed in the vicinity of platforms while in transit to site	Hard structure in water, floating structure	Lack of moorings, not static structure
Todd *et al.* (2022)	Oil and gas	Harbour porpoise (odontocete)	Porpoise occurrence around operational production platform the same as baseline levels	Hard structures in water, operational noise	Lack of moorings, single structure
Clausen *et al.* (2021)	Oil and gas	Harbour porpoise (odontocete)	Operational noise higher than expected to cause behavioural avoidance yet porpoises still foraging at platform	Hard structures in water, operational noise	Lack of moorings, single structure

Todd *et al.* (2020a)	Oil and gas	Common seal (pinniped), grey seal (pinniped), bottlenose dolphin (odontocete), sperm whale (odontocete)	Species were observed visiting anthropogenic structures offshore. Grey seals were also observed foraging along pipelines	Hard structures in water, operational noise	Lack of moorings, single structure
Markowitz *et al.* (2004)	Aquaculture	Dusky dolphin (odontocete)	Avoidance of area of mussel farms by dolphins	Vertical moorings in water column	Moorings more tightly congested, shallow coastal waters
Pearson *et al.* (2012)	Aquaculture	Dusky dolphin (odontocete)	Mussel farms hindered foraging strategies of dolphins	Vertical moorings in water column	Moorings more tightly congested, shallow coastal waters
Ribeiro *et al.* (2007)	Aquaculture	Chile dolphin (odontocete)	Fine scale area avoidance of mussel farms	Vertical moorings in water column	Moorings more tightly congested, shallow coastal waters
Bonizzoni *et al.* (2014)	Aquaculture	Bottlenose dolphin (odontocete)	Attraction and foraging of dolphins at finfish farms	Moorings present in water	High volumes of fish as attraction, shallow coastal waters
Kot *et al.* (2012)	Fisheries	Minke whale (mysticete)	Minke whales passed through rope fence simulating crab pot lines yet behavioural responses did occur	Vertical moorings in water	Shallow coastal waters
Sparling *et al.* (2018)	Tidal development	Common seal (pinniped)	No barrier effect of seals passing a tidal turbine	Obstruction in water, operational noise	Lack of moorings, single structure, moving turbine blades
Joy *et al.* (2018)	Tidal development	Common seal (pinniped)	Quantified fine scale avoidance when passing around tidal turbine	Obstruction in water, operational noise	Lack of moorings, single structure, moving turbine blades
Onoufriou *et al.* (2021)	Tidal development	Common seal (pinniped)	No barrier effect from array of tidal turbines but fine scale avoidance recorded	Obstruction in water, operational noise	Lack of moorings, moving turbine blades

Table 1: Studies of parallel structures and impacts on marine mammals. *Source*: OSC (2022).

Effects of operational windfarms on odontocete presence has been studied by several groups. Vallejo *et al.* (2017) found no difference between occurrence of harbour porpoises during pre-construction and operational phases of a windfarm in Scotland. Scheidat *et al.* (2011) studied an operational windfarm in the Dutch North Sea and found a greater occurrence of harbour porpoises when the windfarm was operational compared to pre-construction baseline levels. Two possible causes were presented for the observed results; a sheltering effect due to exclusion of vessel traffic, and/or an increase in available food due to a 'reef effect' (Scheidat *et al.*, 2011).

Hard structures provide a substrate upon which larvae settle and develop, which may then lead to increased fish presence, creating an artificial reef (Wilhelmsson *et al.*, 2006; Langhamer *et al.*, 2012; Todd *et al.*, 2020b; Todd *et al.*, 2021; Karlsson *et al.*, 2022). Floating windfarms lack a complete monopile through the water column; however, there are still surfaces viable for settlement on floating turbines, anchors, and cables which could provide an opportunity for artificial reefs to form (Akvaplan-niva, 2021; Karlsson *et al.*, 2022). In addition, floating turbines and associated platforms may act as Fish Aggregation Devices (FAD). A FAD is a floating object that naturally aggregates fish by providing shelter from predators and food availability via settled algae and larvae (Gooding and Magnuson, 1967; Rountree, 1989; Castro *et al.*, 2002). With greater fish presence expected at FOW sites, in addition to a reef effect developed over time, the area within a FOW could prove to be attractive to marine mammal species that could target the location for foraging (Fernandez-Betelu *et al.*, 2022; Todd *et al.*, 2022).

Common seals tagged with GPS loggers have been observed to forage at operational OWFs (**Figure 2**), actively targeting each turbine (Russell *et al.*, 2014). Other pinnipeds have also been observed foraging at anthropogenic structures such as seabed pipelines and cables (Arnould *et al.*, 2015; Todd *et al.*, 2020a).

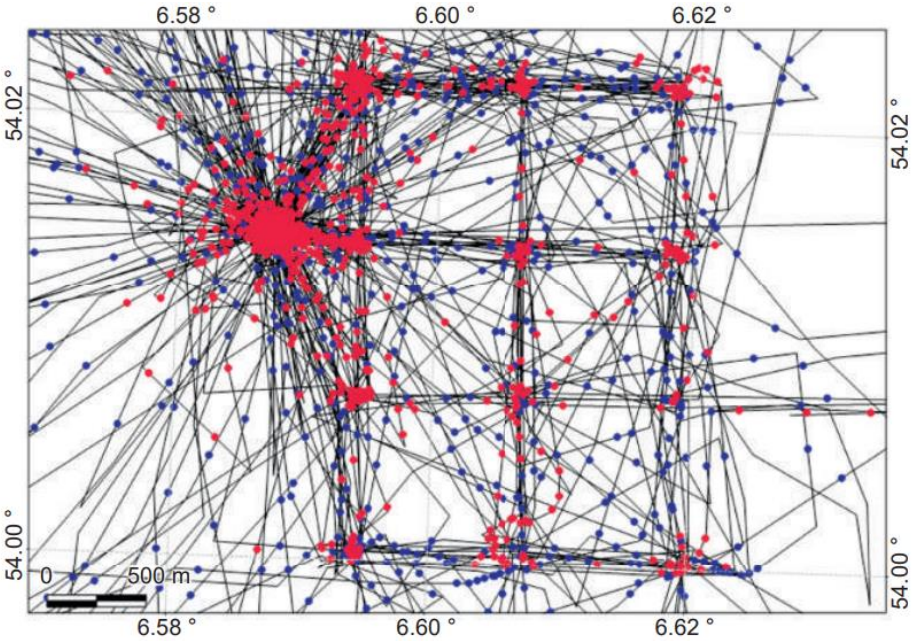

Figure 2: Tracks of common seals around a windfarm. Locations of each turbine and meteorological mast (west) can be see, with red points indicating likely foraging. *Source*: Russell *et al.* (2014).

While short-term avoidance has been shown during piling and other construction activities (Russell *et al.*, 2016; Graham *et al.*, 2017; Graham *et al.*, 2019; Benhemma-Le Gall *et al.*, 2021), there has been no evidence that operational fixed OWFs would act as a barrier to movement for porpoise or seals. Design of FOWs however, differs in that they take up a much greater dynamic space in the water column due to moorings and cables.

There is little evidence about how mysticetes behave around operational windfarms. Video footage was taken of an incidental sighting of a minke whale swimming next to a recently operational windfarm in the Dutch North Sea in 2018 (**Figure 3a**). While this suggests that the animal did not perceive a barrier and was not excluded from the area, conclusions from such an informal sighting cannot be extrapolated to a wider scale.

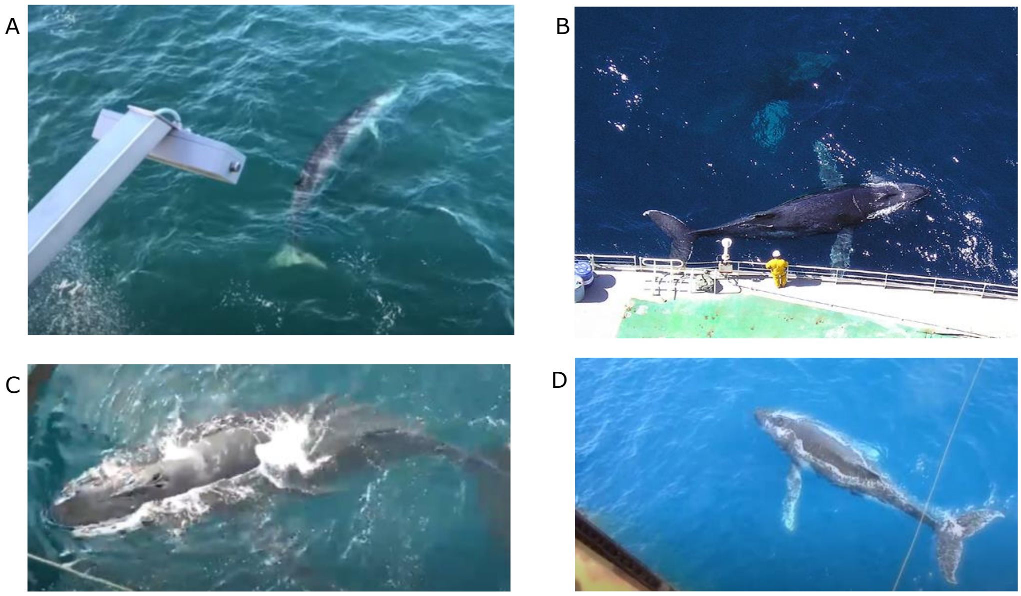

Figure 3: Examples of mysticetes interacting with offshore structures. a) minke whale swimming around a wind turbine at an offshore windfarm in the Dutch North Sea. *Source*: YouTube (2018); b) humpback whales approaching an FPSO in Western Australia which lay in this population's migration route. *Source*: CWR (2012); c) humpback whale swimming underneath an oil platform in India. *Source*: YouTube (2020); and d) humpback whale swimming past a mooring line of an oil production platform. *Source*: YouTube (2017).

In North America, lease acceptance and initial development of offshore windfarms that overlap with distribution of endangered North Atlantic right whales has led to study of these animals' movements and occurrence through planned windfarm areas (Leiter *et al.*, 2017; Quintana-Rizzo *et al.*, 2021). So far, this has only shown evidence of right whale residency before windfarms are constructed, not during operation. As OWFs are developed and data continue to be gathered on right whale interactions, more findings are expected to be published.

In addition to OWFs, marine megafauna have been observed associating with offshore Oil & Gas (O&G) structures (Todd *et al.*, 2016; Delefosse *et al.*, 2018; Todd *et al.*, 2020a), including the North Sea's smallest and most prevalent cetacean, the harbour porpoise (Todd *et al.*, 2009; Clausen *et al.*, 2021; Todd *et al.*, 2022). Todd *et al.* (2009) found that porpoises used the area around and underneath a platform for foraging, and Todd *et al.* (2016) showed that porpoises were detected around floating drilling rigs during transit. In addition, Clausen *et al.*

(2021) measured operational noise levels of an O&G platform and found that although noise levels exceeded those which are thought to elicit behavioural avoidance in harbour porpoises, animals were still present and foraging at the platform. Prevalence of harbour porpoises at platforms is likely due to increased foraging opportunities outweighing aversion due to noise (Clausen *et al.*, 2021; Todd *et al.*, 2022). Other marine mammals including sperm whale (*Physeter macrocephalus*), bottlenose dolphin (*Tursiops truncatus*), grey (*Halichoerus grypus*), and common seal have also been detected around O&G structures (Todd *et al.*, 2020a).

For some species of odontocete at least, O&G structures do not constitute a barrier and can be actively targeted. These examples are primarily for jacket design O&G platforms, which have hard lattice structures spread through the water column, anchoring the platform to the seabed. This design differs from the moorings of a floating windfarm; however, parallels between these examples include a constant operational noise and hard structures upon which organisms could settle or congregate resulting in enhanced foraging opportunities.

In the O&G sector, the most similar designs to a floating wind turbine are those of a tension-leg platform or a Floating Production Storage and Offloading (FPSO) facility (**Figure 4b**). In the literature, there is very little evidence of marine mammals occurring at these types of platforms. This does not necessarily mean these structures exclude marine mammals from the area, simply there is a lack of available evidence of mammals being present. Considering there is no requirement to monitor for presence of marine mammals when the platforms are operational, with the focus for monitoring being during the development and construction periods, this lack of information is not surprising.

Data were gathered by the Centre for Whale Research (CWR) on migrating humpback whales in Western Australia in the mid-2000s. An FPSO was used as a platform for observers to record numbers of whales on their migration. Numerous whales were sighted from the FPSO; however, because distance between animals and platform was not included in the data, it cannot be concluded whether whales approached and passed nearby the structure or if they avoided and circumnavigated the FPSO. There was, however, an anecdotal report of a pair of humpback whales approaching and swimming around the FPSO, which indicates that its presence was not an obstruction (**Figure 3b**). Although an FPSO may have a similar underwater structure to that of a floating wind turbine with mooring and cables, the scale of an operational FOW is considerably larger than a single FPSO, increasing potential for a barrier effect to occur.

Structures from the fishing and aquaculture industries can be used as comparative examples of effects that vertical mooring systems can have on marine mammals. For example, longline mussel farms consist of individual ropes draped through the water column that are laid out in parallel channels (**Figure 4c**). Studies in New Zealand have shown that mussel farms can hinder dusky dolphins' (*Lagenorhynchus obscurus*) specialised foraging strategies, exclude them from foraging within the aquaculture site, and reduce travelling behaviour in proximity to farms (Markowitz *et al.*, 2004; Pearson *et al.*, 2012). Areas close to and within mussel farms have also been shown to cause habitat exclusion of Chilean dolphins, *Cephalorhynchus eutropia* (Ribeiro *et al.*, 2007). This evidence suggests that layout of a mussel farm can cause an obstruction and barrier effect for some odontocetes; however, while possessing vertical ropes, mussel farms are much more congested than a floating windfarm, as a FOW would have much greater distances between individual moorings/cables (**Figure 4a** and **Figure 1**). So, while vertical structures in the water column may cause habitat exclusion in odontocetes, this has been observed in more densely packed arrangements than that of a FOW.

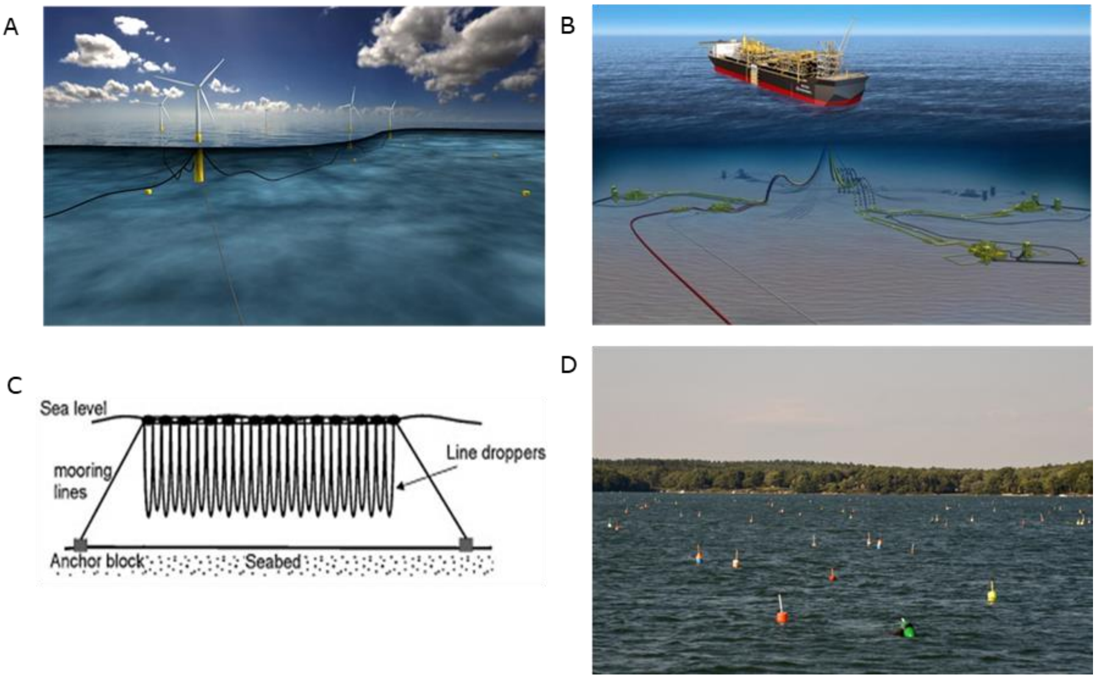

Figure 4: Structures with comparative layouts to floating wind turbines. a) typical floating turbine layout. *Source*: Equinor (2015); b) FPSO facility. *Source*: MODEC; c) longline mussel farms. *Source*: Stevens *et al.* (2008); and d) high density of lobster pots. *Source*: SeaGoingGreen, photographer: Andrew Malone.

Finfish farms, such as for salmon (*Salmonidae* spp.) and seabream (*Sparidae* spp.), can also use mooring lines that anchor cages to the seabed, yet odontocetes can be attracted and feed at these sites (Bonizzoni *et al.*, 2014). Similarly, aquaculture sites do not present a barrier for pinnipeds, with many examples of high levels of depredation (Pemberton, 1989; Güçlüsoy and Savas, 2003; Vilata *et al.*, 2010). The driver for this interaction is prey availability, which appears to override any barrier from moorings, nets, and hard structures.

While reef and FAD effects of a FOW would be unlikely to host fish assemblages akin to those of aquaculture facilities, if there is a greater density of fish within the windfarm, then subsurface moorings are unlikely to elicit a barrier effect. Aquaculture activities are restricted typically to nearshore shallow waters, consequently, effects discussed here may differ, as floating windfarms are typically situated in deeper, offshore waters. In addition, noise generated from an aquaculture facility will vary from operational noise of a floating windfarm, which may alter effects.

Lobster, crab, and whelk pot fisheries use ropes to attach the pots together and typically attach these to a surface marker buoy. A high density of pots in an area would result in numerous moorings present in the water column (**Figure 4d**). Kot *et al.* (2012) simulated crab and whelk fishing ropes in the water column to investigate their effects on minke whale movement. Vertical ropes were suspended in the water column spaced in 15-m intervals and direction and velocity of minke whales' movements was recorded. Behavioural responses to the rope fence were quantified as a reduction in velocity and modifying bearing when passing through or near the ropes (Kot *et al.*, 2012). While there was a behavioural response to ropes, there was no evidence that minke whales would not pass through the rope fence, suggesting no barrier effect. This study demonstrates that minke whales can detect rope structures and avoid physical contact with them, although they must alter their behaviour to do this. These findings indicate that, for vertical moorings in the water column, mysticetes may detect these structures and exhibit a behavioural effect; however, the response may not be on a large enough scale for a complete barrier effect to occur. A similar occurrence has been observed with porpoises in which they are still present even in areas with a high density of ropes from pot fisheries – even in locations when vessels struggle to pass through without becoming entangled (L.D. Williamson, pers. obs.).

Behavioural responses from minke whales were hypothesised to originate from both visual and acoustic cues. While minke whales do not echolocate, moorings in the water can produce noise caused by currents and turbulence (Bassett *et al.*, 2014). Moorings and cables associated with an operational floating windfarm have been recorded to produce various sounds such as 'creaks' and 'pops', correlated with increased wind strength and wave height (Burns, 2022). These sounds could provide acoustic cues for mooring and cable presence; however, further study will be required to understand if these noises elicit any behavioural response, particularly if they cause avoidance.

There has been study into potential barrier effects of tidal turbines to marine mammals, driven by potential risk of collision with moving turbine rotors. Two studies were undertaken on the transit of seals past a tidal turbine in Ireland using telemetry tags. Sparling *et al.* (2018) found that an operational tidal turbine did not cause a barrier effect for tagged common seals. While seals still moved through the channel during turbine operation, there were fine-scale changes in their movement, including a reduction in passage when the turbine was active and an increase in passage distance to turbine during operation. Seals were nearly 70% less likely to use the 200-m area around the turbine when it was active (Joy *et al.*, 2018). This behavioural response was thought to decrease collision risk; however, as the authors discuss, due to the study being undertaken on a single tidal turbine within a narrow channel, results cannot be transferred to other developments, for example with more turbines and in a more open environment.

Onoufriou *et al.* (2021) demonstrated a similar effect on common seals from a multi-turbine array, where a barrier effect was not observed; however, an avoidance response was elicited when the 4 turbines were active. For a FOW, there would be a greater number of moorings and cables attached to the turbines, which would create more obstacles in the water column; however, these would be stationary and pose little risk of collision. These studies highlight potential for further investigation of how animals transit through floating windfarms using telemetry tags to infer movement and site usage and fill knowledge gaps.

3.1.2. Diving seabirds

The topside barrier effects created by offshore windfarms to seabirds has been well documented (Hüppop *et al.*, 2006; Masden *et al.*, 2010; Furness *et al.*, 2013); however, potential impacts of underwater structures has not been studied. Lateral distances travelled while underwater are typically short for diving birds; therefore, assessing absolute barrier effects on subsurface behaviour is not applicable. Though outside the scope of this report, many water bird species use visual cues of conspecific foraging, marine mammal presence, or anthropogenic structures (fishing vessels or offshore platforms) to initiate area-restricted foraging searches (Harrison *et al.*, 1991; Haney *et al.*, 1992; Camphuysen and Webb, 1999; Silverman *et al.*, 2004; see Section 2.1.3). In a fashion similar to attraction to underwater seamounts (Haney *et al.*, 1995), seabird presence may be amplified at FOWs due to a reef effect that encourages foraging by diving birds not deterred from installation areas (see **Section 3.1.1**). There are divergent patterns of general attraction or avoidance to windfarms across species, as the decision to avoid offshore wind installations may be outweighed by increased foraging opportunities if prey species are present (Masden *et al.*, 2010). These conclusions are supported by Dierschke *et al.* (2016), who found attraction of cormorants to OWFs due to presence of loafing areas on platforms, but increased avoidance by divers and gannets. Increased boat traffic to OWFs likely contributes to increased seabird abundance at these sites, particularly for gull species which often follow vessels and have been observed to be attracted to operational windfarms (Vanermen *et al.*, 2015; Dierschke *et al.*, 2016). For birds not deterred by above-water barrier effects of installations, the combined effects of visual cues and attraction of prey to these sites may encourage increased numbers of individuals. There is no evidence to suggest that offshore installations inhibit diving behaviour once birds are present. The reef effect of installations may actually increase diving frequency due to elevated prey abundance and enhanced prey availability at the surface arising from turbulence caused in the wake of turbines (Hunt *et al.*, 1999).

3.1.3. Fish & elasmobranchs

Physical presence of mooring lines from floating turbines are unlikely to cause a barrier to fish movement. As described earlier (**Section 3.1.1**), an operational FOW may provide attractive foraging options for fish through both the reef effect and acting as an FAD. This indicates that physical presence of structures within a FOW will not cause a barrier effect to fish. Similarly, elasmobranchs (*e.g.* sharks, rays, and skates) are unlikely to be affected by the physical presence of mooring lines from floating wind turbines. Species of elasmobranch have been observed at offshore structures and associating with FADs (Robinson *et al.*, 2013; Filmalter *et al.*, 2015; Todd *et al.*, 2020a). In the context of floating wind, these animals could be attracted to the site due to a greater number of fish aggregating there.

Noise has been shown to affect behaviour of fish in a number of different contexts (Mooney *et al.*, 2020); however, noise generated by operational fixed wind turbines does not seem to impact the presence of fish adversely or act as a barrier, as fish have been observed at these sites previously, with individuals demonstrating strong residency to sites (Lindeboom *et al.*, 2011; Stenberg *et al.*, 2015) (Bergström *et al.*, 2013; Reubens *et al.*, 2013). Critically endangered European eel (*Anguilla anguilla*) have been observed to pass through operational windfarms, exhibiting no barrier effect and no avoidance of operational noise (Andersson *et al.*, 2010). If floating windfarms produce a similar acoustic output as fixed windfarms, then it is likely that fish will not be excluded from the area or experience a barrier effect.

3.1.4. Invertebrates

As previously discussed in **Section 3.1.1**, physical presence of floating structures and associated moorings will provide hard surfaces upon which sessile invertebrates may settle (Akvaplan-niva, 2021; Karlsson *et al.*, 2022). This is well documented on anthropogenic structures from other industries, such as O&G platforms (Todd *et al.*, 2018; Todd *et al.*, 2020b; Todd *et al.*, 2021). Settlement of invertebrates within fixed OWFs has also been observed on both monopiles throughout the water column and foundations on the seabed (Andersson and Öhman, 2010). Data from Hywind Scotland show that invertebrates can settle on moorings and turbine structures of a FOW and these will not act as a barrier to invertebrates (Karlsson *et al.*, 2022).

3.2. *Indirect effects of barriers*

If a barrier effect was to be caused by floating windfarms on marine fauna, then their exclusion from the area may have indirect effects on other species that are reliant on them. If local hydrodynamics around a windfarm site were altered, this could impact dispersal or settlement patterns particularly for larval stages of invertebrates and fish through changing species compositions, as has been observed at both fixed offshore windfarms and more recently at Hywind Scotland (Karlsson *et al.*, 2022). This could additionally have knock-on effects for higher trophic levels of fish, as well as mammals and birds.

3.2.1. Marine mammals

Marine mammal distribution is heavily influenced by prey availability (Woodley and Gaskin, 1996; McConnell *et al.*, 1999). Habitat exclusion of prey species through barrier effects would indirectly impact occurrence of marine mammals in an area (Harwood, 2001). There is no observed barrier effect to marine mammal prey species, such as fish and invertebrates, at other similar offshore structures. Consequently, it is unlikely that floating windfarms would indirectly affect marine mammals through exclusion of prey species unless this were to impact larval stages of prey through alteration of currents.

Assessing consequences of anthropogenic disturbance is important to understand long-term impacts of an activity on species, particularly at a wider population level. For pinnipeds, habitat exclusion or alteration can cause changes in their foraging and travelling times. Exclusion of southern elephant seals (*Mirounga leonina*) from preferred foraging habitats was modelled to have negative impacts on individual fitness and cause declines in population size over time (New *et al.*, 2014). If species of marine mammal were excluded from key foraging sites after installation of a FOW, then similar indirect effects could potentially occur across their population. This highlights the importance of surveying windfarm sites before, during and after construction to understand the site’s use by marine fauna. Effective spatial planning could be used to avoid areas of high use by marine species to minimise any impacts.

Dunlop *et al.* (2021) used a Population Consequences of Disturbance (PCoD) framework to model effects of a simulated seismic survey on migration of humpback whales in Australia. Delays in migration for mother-calf pairs due to disturbance were investigated to see if this would have population-level effects. In this scenario, it was predicted that there was low potential for population consequences due to the seismic surveys. A similar approach could be applied in the context of predicting consequences of barrier effects from floating windfarms to migrating marine mammals by modelling how exclusion from an area may affect the population. Braithwaite *et al.* (2015) modelled effects of increasing migration travelling distance and changing the velocity of travel for humpback whales and found this increased overall energy use which could have implications for the growth potential of calves into the future.

3.2.2. Birds

Hydrodynamic features are important influencers of seabird distribution (Scott *et al.*, 2010; Scales *et al.*, 2014). Fixed windfarm structures have been shown to influence vertical mixing, current velocity, and generate turbulent wake at the monopiles (Carpenter *et al.*, 2016; Cazenave *et al.*, 2016; Floeter *et al.*, 2017). As the main cause of hydrodynamic impacts in fixed windfarms originates from the monopile structure and foundations, how FOWs may impact local hydrodynamics is not yet fully understood. If floating windfarms were to have negligible impacts to hydrodynamics within the site, then there should be no indirect impacts to bird species due to a change in hydrodynamic features, for example stratification, frontal zones and turbulent wake.

Prey abundance is also an important predictor in seabird occurrence (de la Cruz *et al.*, 2022). While there is no evidence for a consistent increased fish biomass at FOWs currently, fish species have been observed to aggregate at a FOW site during certain events (Akvaplan-niva, 2021). This would indicate that prey species for seabirds would not experience a barrier effect and there would be no indirect effect to bird species.

3.2.3. Fish & elasmobranchs

As it is unlikely that floating windfarms will create barrier effects to lower trophic levels of fish species and invertebrates then there should be no indirect effects from floating windfarms on fish and elasmobranch presence due to prey exclusion.

3.2.4. Invertebrates

Due to the extra mooring structures of a FOW compared to a bottom fixed windfarm, these structures could influence the fine-scale hydrodynamics of the area, which could indirectly affect recruitment or dispersal of invertebrates into the site or within nearby areas. For example, a change in current velocity or direction due to structures could indirectly influence the number of larvae that can pass through the site.

Study of the recruitment at Hywind Scotland has demonstrated settlement of invertebrates on hard structures, similar to what is experienced in bottom-fixed windfarms (Karlsson *et al.*, 2022). This shows that structures of a FOW would not indirectly influence the surrounding area and act as a barrier to invertebrate settlement.

3.3. Mitigation options

For roads that create a barrier, a typical mitigation strategy is to use wildlife corridors (van der Ree *et al.*, 2007). Fauna passages have been shown to be more successful when a higher number of smaller corridors are used compared to a single large one (Karlson *et al.*, 2017). Gaps in the arrangement of windfarms have potential to act as corridors for birds, although to be effective may need to be on a magnitude of kilometres (Tulp *et al.*, 1999). No studies have investigated how wildlife corridors between anthropogenic structures may support marine fauna in a pelagic environment.

Creating wildlife corridors within a windfarm, would require increased spacing between blocks of turbines, which would increase the overall windfarm footprint.

This would in turn, increase the area affected by noise produced by turbines, vessel traffic for maintenance, and displacement of fisheries and other industries. While wildlife corridors have been hypothesised to aid migrating flying birds, grouping turbines closer together has also been advised as a mitigation practice to reduce topside barrier effects on flying birds (Drewitt and Langston, 2006).

Marine spatial planning is hugely important in its ability to minimise impacts to marine fauna (White *et al.*, 2012). It is important to investigate magnitude, and mitigate potential risks, of a barrier effect from FOWs to marine fauna. Site and species-specific monitoring programmes are required before, during, and after development to understand and scope out potential risks (Maxwell *et al.*, 2022). This includes understanding species' distribution, site importance, and migration data which can be acquired through at-sea or aerial surveys, acoustic monitoring, and/or satellite tracking. Bradbury *et al.* (2014) developed a tool for mapping use of offshore areas by seabirds and estimating their sensitivity to OWFs. This approach requires a huge amount of data and realistically a multi-organisational approach to source the required information; however, once formulated, can be an effective tool in predicting scale of disturbances to different populations of animals.

Telemetry tracking data can be used to understand movement and distribution of marine fauna (Oksanen *et al.*, 2014; Rosenbaum *et al.*, 2014; Isaksson *et al.*, 2021). Pendoley *et al.* (2014) used tracking data from flatback turtles (*Natator depressus*) and archived data of other marine megafauna to demonstrate migratory corridors between marine protected areas. If telemetry studies of species known to pass through a FOW site were conducted, then data could be gathered on areas of highest use for migration to inform marine spatial planning.

As more data are gathered on baseline migration of marine fauna through future FOW sites and their usage of the sites once operational, there will be greater evidence to inform marine spatial planning and show any potential impacts or lack thereof for a barrier effect occurring.

3.4. Knowledge gaps

3.4.1. Current levels of FOW site use

As floating wind is such a novel technology, there are no publications on usage of operational floating windfarm sites by marine mammals. If it can be shown that animals pass through and actively use the site of the floating windfarm, then that would be evidence for a lack of a barrier effect.

While there is more evidence for marine mammals' use of bottom-fixed windfarms, particularly for harbour porpoises and seals, there may be differences in the usage of a floating windfarm, as these designs are typically located further offshore, in deeper water, have differing subsea layouts, and physical presence of moorings and cables will take up more dynamic space throughout the water column. Gaining understanding on how species that are typically found in deeper waters may interact with windfarms is important, as up until now, investigations on effects of offshore windfarms have been limited to species that inhibit shallower waters, which already experience high levels of disturbance from vessel traffic and other industrial operations. Consequently, there has been no study of how deep-water species may interact with offshore windfarms.

It is crucial that mysticete interactions with all windfarm designs are studied further, as currently there is a lack of evidence in the published literature, aside from anecdotal sightings, about how they interact with structures. As mysticetes may be most susceptible to any barrier effects due to their life history traits and long-distance migrations, understanding disturbance from windfarms is needed if mitigation is to be implemented effectively. A huge proportion of research on this topic that has been conducted to date has originated from the North Sea, where there is a relatively low abundance of baleen whales. Also, the most prevalent baleen whale in the North Sea, the minke whale, vocalises at much lower rates than dolphin and porpoise species and their acoustic behaviour is less well understood, meaning acoustic monitoring studies have been less effective at detecting these animals (Risch *et al.*, 2013). This has led to a greater proportion of studies focussing on species such as the harbour porpoise, which is more abundant in the North Sea and employing monitoring techniques that will only detect odontocete species. Dedicated studies on interactions of mysticetes and operational windfarms are urgently required.

Remedies for this knowledge gap include use of telemetry tracking studies of marine mammals that would provide evidence for site usage or avoidance around an operational FOW. This has been a particularly effective approach for pinniped species (Russell *et al.*, 2014; Russell *et al.*, 2016). Acoustic monitoring has been employed in previous studies to monitor occurrence of marine mammals at offshore windfarms (Tougaard *et al.*, 2009; Scheidat *et al.*, 2011); however, by design this approach has been focussed on species of odontocete that echolocate, so careful planning would be needed to incorporate means of monitoring baleen whales. Recent studies have demonstrated acoustic presence of minke whales in the North Sea, which could provide a framework for future monitoring (Risch *et al.*, 2019).

3.4.2. Spatial scale of effects

Changing the scale of anthropogenic structures may modify effects on marine fauna through either amplifying effects already felt, or by crossing a threshold and creating an impact. An example from the aquaculture industry is when, by increasing the number of fish farm sites and consequently organic matter production, the risk of eutrophication in that area increases (Silvert, 1992). Due to so few anthropogenic structures currently operating over such a large spatial scale, there is no evidence to compare and contrast potential effects of increasing the size of a windfarm on marine fauna.

If there are a greater number of turbines in a large-scale array, then any observed effect from their physical presence may be amplified. For example, more turbines in an array would provide more hard substrate for organisms to settle upon and generate a larger reef effect. The current and planned windfarms in the southern North Sea are predicted to provide additional habitat for the equivalent of over 40% of the current common mussel (*Mytilus edulis*) stock in the southern North Sea (Slavik *et al.*, 2019).

Consequently, if there are behavioural responses to the windfarm, then a large-scale array could increase the magnitude of these effects across a greater spatial scale. There is no evidence currently of any behavioural effect, positive or negative, to mysticetes from operational windfarms; therefore, it is uncertain how, or if, larger-scale arrays may alter any potential impacts.

The most effective approach to gather evidence of impacts of large-scale offshore arrays is to conduct surveys at the current large-scale OWFs. Transect surveys and acoustic monitoring could be employed within large-scale windfarm sites, and in control areas, to demonstrate whether marine fauna are present in the site and compare usage patterns with control sites and smaller-scale OWFs.

3.4.3. Population impacts of habitat exclusion

If barrier effects were to occur due to a floating windfarm, then these impacts could be apparent not only at an individual level but could accumulate and generate population-level impacts. For marine mammals, literature shows that habitat exclusion for bottom-fixed windfarms is evident during the construction phase; however, odontocetes and pinnipeds use the site during its operation (Scheidat *et al.*, 2011; Russell *et al.*, 2016; Benhemma-Le Gall *et al.*, 2021). There is no direct evidence of whether this will occur in floating windfarms; therefore, there could be value in modelling a worst-case scenario of complete habitat exclusion for marine fauna and investigating how that may affect wider populations. Frameworks have been developed for this previously, such as the PCoD model, and could be applied to floating windfarms and marine fauna to investigate if population-level effects would be significant. As impacts of operational windfarms are technically unknown currently, it could be important to analyse what could happen on a large scale.

4. ENTANGLEMENT IN GHOST FISHING GEAR

Entanglement of marine fauna directly with cables and moorings associated with FOWs is unlikely due to tension and size of these structures; however, there is considerable risk that other marine debris may snag on cables/moorings with which animals may subsequently become entangled.

Increasing quantities of plastic waste are being released into the marine environment (Hardesty *et al.*, 2021; Ruiz *et al.*, 2022). A significant portion of marine litter includes various types of fishing equipment including gillnets, pots/traps, longlines, and trawl nets (Saez *et al.*, 2021). When referring to this equipment, terms such as 'Derelict Fishing Gear' (NOAA, 2015), Ghost Gear (GG), and 'Abandoned, Lost or Discarded Fishing Gear (ALDFG)' (Richardson *et al.*, 2019) have been developed. The term 'ghost fishing' is used only when fishing equipment has caused an animal mortality (Smolowitz, 1978) as seen in NOAA (2015). GG can be caused by numerous factors including extreme weather events, cost of retrieving gear from the marine environment, Illegal, Unreported, or Unregulated (IUU) fishing practices, vandalism/theft, and broken gear (Macfadyen *et al.*, 2009). GG in recent years has become increasingly common and therefore a prominent concern to organisations such as United Nations Environment Programme (UNEP), Food and Agriculture Organisation of the United Nations (FAO), and International Maritime Organisation (IMO), which have all entered into agreements to tackle the issue on a global scale (Macfadyen *et al.*, 2009).

GG threatens more than 243 marine species worldwide (NOAA, 2015; Thomas *et al.*, 2019; WWF, 2020; Hardesty *et al.*, 2021), and comprises *ca.* 20% of marine litter in the north-east Atlantic (OSPAR, 2021), up to 46% in the Great Pacific Garbage Patch (Lebreton *et al.*, 2018), and over 10% of all marine litter in global oceans (WWF, 2020). There is an estimated 640,000 tonnes of derelict fishing gear left or discarded into oceans annually (WAP, 2022). In the past year, 25,000 nets were recorded lost or discarded in the north-east Atlantic alone (WAP, 2022). WAP

(2022) records around 25,000 ghost nets to be discarded annually in the North-east Atlantic ocean, and in coastal US waters, 870 nets containing more the 32,000 marine animals were lost. Overall, an average of 68.5 ghost nets are lost into the marine environment in the north-east Atlantic every day. Comparatively WWF (2020) records approximately 40,000 gillnets are lost in South Korean waters annually, averaging 109.5 lost each day, and Gjerde (2006) estimates approximately 8 million pieces of marine litter enter the marine environment every single day with GG accounting for 800,000 pieces of litter.

Consoli *et al.* (2018) found the majority of marine litter entangled around benthic habitats was longline fishing reels, similar to Oliveira *et al.* (2015), who also found ALDFG was recovered in the location it was lost. Both studies, as well as Bauer *et al.* (2008), identified rocky habitats with outcrops and densely accumulated sessile species to contain higher quantities of GG due to snagging and damaging of active fishing equipment.

Equinor (2022) recorded a total of 27 incidents of GG becoming tangled on cables and moorings from 2006–2022; however, there is currently a lack of data when considering ALDFG being entangled on structures such as fixed or floating turbines, O&G platforms, and drilling rigs. After an extensive search on entanglements on structures such as O&G platforms and windfarms; it has been determined that there is a severe knowledge gap regarding this topic and there is a need for continued monitoring and reporting in future.

Monitoring GG on structures is important, as it can cause entanglement of marine species, affecting individuals of all sizes from invertebrates and fish up to megafauna including marine mammals, diving seabirds, sharks, rays, and turtles (Macfadyen *et al.*, 2009). Harnois *et al.* (2015) defined entanglement as unintentional restraint or ensnaring of marine species by materials of significant strength and flexibility that originate from manmade equipment. Entanglement within the scope of FOWs is most likely to affect marine megafauna as they swim through areas when ALDFG becomes trapped around mooring lines and cables (ABS Group, 2021). Entanglement of marine species in ALDFG has been observed to cause a variety of effects including both primary entanglement, which affects individuals directly, and secondary entanglement, which affects the wider environment, both marine and terrestrial indirectly, and also the economy (NOAA, 2015; Maxwell *et al.*, 2022). Serious injury or death are widely acknowledged as the most significant effects of entanglement (Laist, 1996; Cox *et al.*, 1998; Cox *et al.*, 2003; Gilardi *et al.*, 2010; Reeves *et al.*, 2013). Hardesty *et al.* (2015) estimated that on average, one abandoned net causes mortality of 500,000 invertebrates, 1,700 fish, and 4 seabirds.

In addition to entanglement on GG that is snagged on moorings and cables, larger marine mammals and sharks (*e.g.* basking sharks, *Cetorhinus maximus*) may become trapped in mooring systems that have either static or dynamic lines attached and also cables (Xodus, 2021). There are a lack of entanglement data within the offshore energy sector and therefore it is difficult to determine how often and severe entanglements are; however, it is believed the highest risk lies within mooring systems that contain mooring lines or cables that free hang in the water column while another section lies on the seabed (Xodus, 2021). Keynes and Crutchfield (2016) suggested highest potential risk within Marine Renewable Energy (MRE) to large baleen whales. Entanglement risk was determined greater and a more significant hazard to a wider range of species including diving seabirds and fish, if any derelict fishing gear was to entangle on a mooring first. Keynes and

Crutchfield (2016) stated that investigations on the risk of entanglement for marine megafauna at floating offshore windfarms are still lacking significantly and further research is required.

Direct impacts of entanglement will be observed in the near-field; however, animals that break free may travel considerable distances trailing gear and increase the range of the gear's impact. There is also potential scope for pollution from snagged debris, such as microplastics, to spread on ocean currents and increase the spatial scale of effects (Andrady, 2011).

4.1. Direct effects of entanglement

Consequences of ALDFG entangling marine species vary depending on type and amount of gear, as well as size and shape of animals (Parton *et al.*, 2019). As mentioned previously, the most prominent direct effects include serious injury or mortality, which are also the most common, especially in larger baleen whales (Laist, 1996; Cox *et al.*, 2003; Gilardi *et al.*, 2010; Reeves *et al.*, 2013); however, other significant effects for all marine species include asphyxiation and respiratory distress, seen commonly in pinnipeds (Hudgins and Sweet, 2016), damage to tissues and muscles causing scarring or more permanent injury to the nerves (Richardson *et al.*, 2019), and significant impacts to the ability to dive, migrate, and potentially reproduce (SEER, 2020).

4.1.1. Marine mammals

Entanglement in fixed fishing gear is a major threat to baleen whales worldwide. At an individual level, entanglement can lead to sudden death through drowning (acute entanglement) or eventual death attributed to inhibited feeding, exhaustion from increased drag, increased stress, weakened immune system, inability to avoid attack by a predator, and trauma or injury such as lesions which could lead to infection, called chronic entanglement (Basran *et al.*, 2019). At a population level, entanglement can have potentially devastating long-term effects, because, as mortality increases, the population declines (Volgenau *et al.*, 1995). Any potential decline is compounded if there is a high frequency of entanglements in juveniles, as it results in decreased recruitment (Knowlton *et al.*, 2012).

Between 2008 and 2020, the Scottish Marine Animal Stranding Scheme (SMASS) documented 47 cetaceans and 28 other animals (including turtles, sharks, and pinnipeds) that stranded and died off the Scottish coast due to entanglement (Brownlow, 2011; SRUC, 2012; Brownlow and Davison, 2013; Brownlow *et al.*, 2014; Brownlow *et al.*, 2015; Brownlow *et al.*, 2016; Brownlow *et al.*, 2017; Brownlow *et al.*, 2018; Davison *et al.*, 2019; Davison and ten Doeschate, 2020).

Saez *et al.* (2021) compiled entanglement records off the Western US coast from 1982–2017. Within this 35-year period, 511 large whale entanglements were reported. Humpback (165 whales) and Grey whales (*Eschrichtius robustus*; 208 whales) were the two most commonly reported species to be entangled. Other species that were recorded included blue whales *(Balaenoptera musculus*; 7*),* fin whales *(Balaenoptera physalus*; 7*)*, minke whales *(Balaenoptera acutorostrata*; 6*)*, killer whales *(Orcinus orca*; 3*)*, sperm whales *(Physeter macrocephalus*; 14), and 19 unidentified whales (Saez *et al.*, 2021). Studies investigating scarring on humpback whales have estimated that more than a quarter of individuals had been entangled at least once in their lifetime (van der Hoop *et al.*, 2017), indicating that animals are often able to free themselves.

Any rope, line, or cable may pose an entanglement risk to a whale; however, inspection of gear recovered from entanglements revealed that end lines, as well as ground lines from fixed fishing gear may contribute significantly to entanglements (Johnson *et al.*, 2005). van der Hoop *et al.* (2016) stated that an entangled whale will often damage or even completely drag gear away, leading to loss to fishermen. It still remains unclear whether this observation discussed by van der Hoop *et al.* (2016), remains true if gear is first snagged on structures before entangling a marine mammal (Keynes and Crutchfield, 2016), as would be the case of gear that snags on a floating turbine. Using a ropeless fishing system decreases the amount of gear prone to snagging on structures and consequently the number of whale entanglements; however, removing the end line attached to a buoy complicates trap retrieval and removes indication of trap location for mariners and enforcement agencies.

Smaller marine mammals such as fur seals and sea lions have been recorded to become entangled in ALDFG rather than larger baleen whales being more at risk mooring lines and cables (Page *et al.*, 2004). Researchers have observed that for smaller marine mammals and other marine species, it is significantly more difficult for them to free themselves from entanglement, causing a higher rate of mortality as a result (Schrey and Vauk, 1987; Duncan *et al.*, 2017).

Overall, it is clear that risk of entanglement from ALDFG to marine mammals is significant and has been repeatedly recorded on a global scale (NOAA, 2015; Thomas *et al.*, 2019; WWF, 2020; WAP, 2022); however, there are still considerable knowledge gaps that need to be addressed to effectively evaluate current status of marine mammal ALDFG entanglements and improve monitoring and mitigation techniques (Benjamins, 2014). Current population-level effects of entanglement are unknown and there is no way to determine if entanglements on fishing nets and line occurred whilst the gear was active or once it had become derelict (Laist, 1997). There is also little information about rate of GG entanglement on FOW structures and subsequent risk of marine mammal entanglement.

4.1.2. Diving seabirds

Despite the generally understood importance of underwater vision and visual accommodation employed by seabirds, certain risks associated with subsurface structures still exist. Similar to with marine mammals, diving birds are unlikely to become entangled directly on mooring lines and subsurface cables; however, they are likely to be trapped in GG that has been caught on moorings and cables (Maxwell *et al.*, 2022). Direct entanglement on mooring/cables is not considered a risk for diving seabirds (Benjamins, 2014) due to their relative size. If nets however become entangled or spread on subsurface FOW structures, there is potential for diving birds to be caught. It is possible that this risk would decrease over time, as biofouling accumulates on GG, which would increase detectability by seabirds (Benjamins, 2014). Entanglement risk will vary by species and numerous other factors, including anthropogenic activity in the surrounding region, foraging behaviour exhibited by diving birds, prey availability, turbidity of water (especially in relation to turbulence caused by operational turbines), and the properties of GG materials (Maxwell *et al.*, 2022). Overall, direct effects of entanglement associated with offshore floating wind installations are likely to be minimal (Harnois *et al.*, 2015); however, confidence in these assessments is low due to a lack of evidence (Maxwell *et al.*, 2022).

4.1.3. Fish

Commercially important fish have been observed in association with sub-sea infrastructure (Jørgensen *et al.*, 2002; Løkkeborg *et al.*, 2002; Soldal *et al.*, 2002; Guerin, 2009; Friedlander *et al.*, 2014; Fujii *et al.*, 2014), many of which are juveniles that preferentially select structurally complex habitats (Sayer *et al.*, 2005), as discussed in **Section 3.1.1**. GG poses a significant threat to fish for decades after originally being discarded or lost into the marine environment, as it can continue to ensnare and kill animals (Thomas *et al.*, 2019). In British Columbia, between 1977 and 1983, Scarsbrook *et al.* (1988) discovered that lost or abandoned traps caught between 7.5%–30% of landings of the sablefish *(Anoplopoma fimbria*) fishery

Overall, commercially valuable pot and trap fishery species seem to be at a higher risk of entanglement than other species (Laist, 1997); however, due to infrequent reports and isolated studies, evidence for magnitude of entanglement is lacking. There is scope for GG that snags on moorings/cables to entangle fish; however, frequency and magnitude of this is unknown and requires future monitoring.

4.1.4. Elasmobranchs

Entanglement risk for elasmobranchs, specifically sharks, in marine debris is still largely understudied. They may be less likely to become entangled than other species, such as marine mammals; however, this may be from lack of research rather than lower susceptibility (Stelfox *et al.*, 2016). Nevertheless, it has been widely accepted for the last three decades that species with long lifespans, late sexual maturity, low fecundity, and slow growth rates are of highest concern for GG mortalities (Kaiser *et al.*, 1996; Laist, 1996; 1997; Donohue *et al.*, 2001; Good *et al.*, 2009; 2010; IWC., 2013). Sharks are also known to be present around offshore structures, sometimes in very high densities (Todd *et al.*, 2020a).

Keynes and Crutchfield (2016) highlighted potential risk of marine megafauna becoming entangled on ghost nets increases if the nets are already attached to mooring lines. Although, there are no known occurrences of this to date. Studies surrounding marine megafauna do reference elasmobranchs as potentially at risk species; however, elasmobranch entanglement in ghost gear is still a largely understudied and requires significant research (Parton *et al.*, 2019).

Risk of entanglement for elasmobranchs is largely understudied, as most studies include marine megafauna collectively (Keynes and Crutchfield, 2016); however, as with marine mammals, severity of risk to individuals is high, whilst effects on populations are still largely unknown (Good *et al.*, 2009; Good *et al.*, 2010; IWC., 2013).

4.1.5. Invertebrates

When considering invertebrate species with artificial infrastructure, the most significant risk offshore installations pose is that of anchors and anchor chains as well as the potential of species being ripped from the seabed from ghost gear and ALDFG (Keynes and Crutchfield, 2016). The most at-risk benthic communities are those in deeper waters where moorings and anchors are placed and where longlines are lost on average >100 m (Consoli *et al.*, 2018)

Breen (1987) investigated the Fraser River Dungeness crab *(Metacarcinus magister)* fishery in British Columbia, which found evidence of lost and abandoned traps estimated to have caught a total of 7.2% of the annual landings. On the east coast of North America in New England, Smolowitz (1978) found 5% of lobster fishery landings were affected by traps. Between 1990 and 1991, the Bristol Bay king crab fishery lost an estimated 31,600 pots, annually if each pot only killed a single crab, losses would equal 93,000 kg (Kruse and Kimker, 1993). These figures; however, only consider traps as GG without considering other types of ALDFG, as lobsters are also known to be trapped in gillnets (Laist, 1996).

Most risk of entanglement to invertebrates occurs in deeper waters around rocky substrate; however, data on benthic species is lacking and therefore it is not possible to determine the extent of risk to these species on a wider scale (Oliveira *et al.*, 2015; Consoli *et al.*, 2018).

4.2. Indirect effects of entanglement

In conjunction with direct effects, ALDFG and GG poses various indirect effects to the marine environment and marine megafauna species. The introduction of such gear to a natural environment can cause effects on both benthic and pelagic species that are not immediately obvious. These effects may also carry over into terrestrial environments and even affect the human population (OECD, 2021).

4.2.1. Pollution

Plastic pollution is referred to by WWF (2020) as being the deadliest type of marine plastic debris that affects up to 66% of marine mammals, 50% of seabirds, and all sea turtle species. In certain areas, such as between California and Hawaii in the Great Pacific Garbage Patch, ghost gear accounts for up to 85% of all plastic (Lebreton *et al.*, 2018; Thomas *et al.*, 2019). Plastic pollution is known to affect marine mammals predominantly through entanglement (Kraus, 2018) and ingestion (de Stephanis *et al.*, 2013; Unger *et al.*, 2016; Alexiadou *et al.*, 2019) but has also been recorded to cause habitat degradation (Gall and Thompson, 2015). Dependent on factors including differing water conditions, UV light and levels of physical abrasion, plastics can endure for up to 600 years in the marine environment (Macfadyen *et al.*, 2009). When plastic degrades to <5 mm, called microplastics, it may be ingested by a variety of taxa (Germanov *et al.*, 2018). Microplastics have been found in all mysticetes, odontocetes, and pinnipeds studied through trophic transfer of ingesting already contaminated prey (Ivar do Sul and Costa, 2013; Au *et al.*, 2017; Nelms *et al.*, 2018). Marine mammals and top predators are particularly susceptible to bioaccumulation and biomagnification of chemical contaminants due to their long lifespans and high trophic level (Nelms *et al.*, 2018). Andrady (2011) found that GG entanglements on benthic habitats exacerbate degradation of marine litter, increasing rate of microplastic production and subsequent uptake by benthic species and communities, allowing for transfer of particles to pollute the ecosystem and species. Laist (1997) concluded entanglement of GG and other marine debris to be a more significant threat to marine megafauna and specifically marine mammals than ingestion of plastics; however, he did note ingestion of derelict gear had been observed and was a risk.

Various pieces of legislation have been implemented to reduce levels of plastic debris and GG in global waters, such as the 1978 International Convention for the Prevention of Pollution from Ships and the 1972 Convention on the Prevention of Marine Pollution by Dumping Wastes and Other Matter (the London Dumping

Convention) (Lentz, 1987). Despite introduction of global and regional legislation, it is still largely ignored with ships, annually estimated to dispose of 6.5 million tonnes of plastic (Clark, 1997).

4.2.2. Habitat destruction

Addition of ALDFG or GG to the marine environment poses threats to habitats and ecosystems in various ways. Entanglement of gear on structures, natural or anthropogenic, can cause nets and ropes to catch on benthic communities and damage or rip them from the seabed (OECD, 2021). Thomas *et al.* (2019) reiterates marine habitats can be impacted both physically through processes such as smothering, abrasion, or shearing, and also through a change to chemical composition. Consequences of physical damage include reduced habitat quality, restricted feeding opportunities or prey quality, and impacts to breeding areas for a multitude of species (Thomas *et al.*, 2019). Rundgren (1992) states that when GG sinks to the seabed, it can smother benthic habitats of both soft and hard substrates and also alter ecosystems chemistry by limiting water flow, which can cause an anoxic mud to form. WWF (2020) also recorded GG damaging vegetation and causing build-up of sediment.

ALDFG such as trawling nets and crab or lobster pots being dragged along the seabed, both in shallow coastal waters and deeper areas, is also a common occurrence that can result in destruction of fragile benthic habitats including coral and associated species (Butterworth *et al.*, 2012). In the Florida Keys, Chiappone *et al.* (2005) identified that hook-and-line fishing gear was the predominant cause of 84% of all visible impacts to benthic species and habitats, primarily sponges and cnidarians. Records show a correlation between GG and sensitive nearshore areas, not only coral reefs but also mangroves, seagrass beds, and macroalgae which are known to act as nursery grounds for a variety of fish and elasmobranch species (WWF, 2020). Such physical and chemical damage to species and habitats from various types of GG consequently decreases their resilience and ability to survive and therefore decrease total biodiversity of the area, it has even been recorded that attempting to remove gear from benthic habitats can further cause damage and destruction to the benthos (OECD, 2021). Consequently, even if GG snags on FOW moorings and cables and does not cause entanglement of animals, it could still drag and impact habitats.

4.2.3. Foraging and populations

Even if an animal survives entanglement, its ability to forage and reproduce may be negatively affected. Depending on severity and duration of entanglement, injuries sustained by GG are likely to cause tissue damage, mobility restrictions, and even infections, which consequently restrict and/or prevent individuals from activities such as foraging, migrating, and even reproducing (Moore *et al.*, 2006; Robbins *et al.*, 2015). WAP (2022) stated that reaction to entanglement from different species is dependent on their behaviour, physiology, and feeding habits. If an animal suffers oral entanglement, its ability to eat is inhibited and can cause starvation to the point of mortality (WAP, 2022). Marine mammals are slow-maturing species with equally slow reproductive rates and low fecundity, producing on average only a single offspring per gestation (Sinclair *et al.*, 2020); consequently, population numbers suffer when juveniles fail to recruit. Ecosystem health is significantly affected by marine megafauna’s inability to foraging, dive, migrate, and/or reproduce effectively (Hardesty *et al.*, 2021).

4.2.4. Social and Economic

Environmental effects of GG on natural habitats are extensive; however, ALDFG also has significant socioeconomic effects on fisheries and wider communities worldwide (Macfadyen *et al.*, 2009; Gilman *et al.*, 2016; Scheld *et al.*, 2016). Such gear results in annual losses of hundreds of millions of dollars worldwide due to lack of tourism and therefore reduced revenue by introduction of invasive species to the marine environment, damage to public health in local communities, and vessel damage (Macfadyen *et al.*, 2009; Vegter *et al.*, 2014). GG already lost or discarded in the marine environment has been known to entangle fishing gear still in use and either cause significant damage or loss, which can be expensive to replace (Thomas *et al.*, 2019; GGGI, 2021). GG snagging during fishing operations can cause secondary costs to vessels in fuel and damages, as well as entanglement of gear in engines can be a risk to safety whilst at sea, and impair navigation ability of vessels (Macfadyen *et al.*, 2009; Thomas *et al.*, 2019).

In certain fisheries, GG starts competing against fishers for their catch; for example, in a Japanese coastal trap fishery of octopus, ghost fishing catch was at least equal to regular fishery catches, and in some cases double the intended catch (Matsuoka *et al.*, 2005). In conjunction with costs to fishers and the marine environment, WAP (2022) considers costs to governments when considering clean-up initiatives, such as beach cleans, removing GG from oceans, and preventative measures. Cost associated with removal initiatives are likely to be smaller than allowing GG to remain in the marine environment. It is estimated that a single derelict gillnet can cause losses of up to US$20,000 worth of Dungeness crab in British Columbia over a span of 10 years, whereas cost to remove that gillnet is $1,258 (WAP, 2022). Direct costs of retrieval of a piece of GG is dependent on various factors including depth at which gear is to be removed, type of gear, and location, but can range up to the tens of thousands (Tscgernij and Larsson, 2003; Brown *et al.*, 2005; Natural Resources Consultants, 2007; Macfadyen *et al.*, 2009). Macfadyen *et al.* (2009) considers social costs together with indirect economic costs of GG as this can include a decrease in incomes in various industries that ultimately create reduced job security. Considering both social and economic effects of GG, MacLennon *et al.* (2021) investigated exact losses to Scottish creel fishers through qualitative questionnaires and discovered the average loss of income to fishers per interaction with GG or incident involving entanglement was £239.69, average costs to individual fishers over 10 years was £518.68 and the total cost to the entire fleet over 10 years amounted to £523,886. Given these estimates, cost to Equinor to remove a piece of GG from turbine moorings or cables is anticipated to be between £100 to £1,000 depending on type, location, depth, *etc*.

4.3. Mitigation options

Most concern for mitigating entanglements focusses on reducing the amount of GG entering the marine environment to start with, or altering the design of fishing gear to make it less dangerous (*e.g.* Macfadyen *et al.*, 2009; NOAA, 2015; Richardson *et al.*, 2019). Neither of these options are directly applicable to Equinor, as they are mitigations that fishers or governments can adopt or mandate, and not directly relevant to FOW operators.

Considering mitigation of indirect entanglement and reducing the amount of GG catching on mooring lines and cables, ABS Group (2021) lists the following three strategies:

1. Creating exclusion zones for fishing around FOW sites,

2. Introducing mandatory regular inspections of FOW sites for presence of, and consequently removal of, any ALDFG; and,
3. Developing mooring lines and cables that, should they be lost or detach from turbines, sink to the seabed rather than floating in the water column further contributing to ALDFG.

Hamilton and Baker (2019) and OPC (2019) recommend using technological solutions to mitigate against ALDFG using underwater cameras to identify when GG entangles in an FOW, Remotely Operated Vehicles (ROVs) for detection and removal of gear without human intervention, and/or human monitoring of mooring and line loads throughout the FOW site. West (2019) indicates that the Kincardine Offshore Windfarm in Scotland has implemented sensors on vessels such as multibeam sonar in conjunction with ROVs to intermittently survey all cables and mooring lines for presence of GG within the FOW site. Recent studies have indicated monitoring techniques for marine mammals that include Side-Scan Sonar (SSS) and ROVs, as well as InfraRed (IR), RADAR, Passive Acoustic Monitoring (PAM), drone, aerial surveys, and animal tagging can be used to monitor entanglements of marine mammals and other marine megafauna and to develop mitigation strategies that are most effective depending on species most likely entangled in certain locations (Brown *et al.*, 2005; Verfuss *et al.*, 2018; Cotter *et al.*, 2019; Hasselman *et al.*, 2020).

4.4. Knowledge gaps

Knowledge and research surrounding ALDFG is increasing, with significantly more stakeholders recognising importance of regulating this form of pollution in the marine environment. Despite increasing interest in ALDFG, there are still considerable knowledge gaps within research worldwide (Benjamins, 2014; NOAA, 2015; Keynes and Crutchfield, 2016; Richardson *et al.*, 2019; Hardesty *et al.*, 2021). There has been widespread acceptance of the need to undertake more in-depth research and conduct studies that increase amounts of data readily available on concentrations, locations and distributions of ghost gear in the marine environment, statistics of ghost gear specifically affecting FOWs and statistics for economic impacts along with mitigation methods for future management (NOAA, 2015).

Regarding FOWs specifically, there is a gap in knowledge surround characteristics and movement of GG around structures. Gaps in shared knowledge among relevant stakeholders such as industry, researchers, and regulators need to be addressed to allow relevant parties a wider picture of the up-to-date findings and mitigation measures (SEER, 2020). Benjamins (2014) provided various research areas that are currently lacking in knowledge and or data, these include:

1. In depth assessments of risks such as snagging;
2. Presence and abundance studies of ALDFG around cables and moorings spanning various offshore industries;
3. Empirical datasets of entanglement events involving marine megafauna surrounding both moorings and vertical structures within the water column;
4. Accuracy of entanglement reports throughout the ever-expanding marine renewable energy industry; and,
5. Effects of increasing biofouling communities on potential increases of ALDFG becoming attached to structures.

Keynes and Crutchfield (2016) refers to a need of all relevant industries to establish understanding of marine mammal behavioural responses to structures such as cables and mooring lines surrounding FOWs whereas Richardson *et al.* (2019), in conjunction with SEER (2020), highlights a need for a database shared across floating and fixed OWF, research, and fishing industries to allow open communication and sharing information as the most significant knowledge gap when tackling GG and marine debris.

5. ELECTRO-MAGNETIC FIELDS

5.1. What are EMFs?

Electromagnetic energy across a broad range of frequencies can be referred to as ElectroMagnetic Fields (EMFs) – from the natural fields of the Earth to cosmic radiation (Tricas and Gill, 2011). Unlike most other measurable environmental variables (*e.g*. temperature, salinity, or pressure), EMFs are vectors, meaning they are directional, which is why a compass needle points north (Tricas and Gill, 2011; Gill *et al.*, 2014). Depending on orientation, this directionality means that vector fields from different sources can either add to one another or cancel each other out (Tricas and Gill, 2011). There are two principal components to EMF – electric fields (E-fields) and magnetic fields (B-fields) (Gill *et al.*, 2014; Copping and Hemery, 2020). At the low frequencies of most EMFs in the marine environment, E- and B-fields are considered independent sources (Tricas and Gill, 2011).

E-fields are produced by a difference in electric potential (voltage) and are measured in Volts per metre (V m^{-1}) (Tricas and Gill, 2011). Induced Electric fields (iE-fields) are created by movement of charges within a B-field (Tricas and Gill, 2011).

Magnetic materials and electric currents are surrounded by B-fields, which are created by the flow of electricity in a conductor or the movement of electrical charges (Tricas and Gill, 2011). Coordinated spins of electrons and nuclei within iron atoms result in magnetic materials or permanent magnets (Tricas and Gill, 2011). B-fields are measured in either Gauss (G) or Tesla (T) (Tricas and Gill, 2011).

5.1.1. Sources of EMFs

In the marine environment, EMFs can be naturally occurring or originate from anthropogenic sources (Tricas and Gill, 2011; Scott *et al.*, 2018; Scott *et al.*, 2020). The most significant naturally occurring EMF is the Earth's GeoMagnetic Field (GMF) (Tricas and Gill, 2011; Scott *et al.*, 2018; Copping and Hemery, 2020; Scott *et al.*, 2020). Strength of the GMF ranges from 30 to 70 μT depending on latitude, with lowest values at the equator and highest at the poles (Tricas and Gill, 2011; Gill *et al.*, 2014). Subterranean dynamics of the Earth's molten core account for the primary field of the GMF, resulting in a dipole-like structure closely aligned with the Earth's geographic poles (Tricas and Gill, 2011; Gill *et al.*, 2014). Magnetic rock in the Earth's crust produces a weaker site-specific component of the field that can have high spatial variability (Skiles, 1985; Tricas and Gill, 2011). A variety of species are thought to use cues from the GMF for large- and small-scale navigation and orientation (Kirschvink, 1997; Tricas and Gill, 2011). Natural E- and B- fields can also be associated with phenomena such as lightning, solar wind, and geological movement, *e.g.* shifting of tectonic plates (Tricas and Gill, 2011; Gill *et al.*, 2014; Copping and Hemery, 2020).

The Lorentz force refers to production of an iE-field by movement of charges through a B-field (Tricas and Gill, 2011). As such, movement of conductive seawater through the GMF as a result of tides and currents creates localised iE-fields (Sanford, 1971; Tricas and Gill, 2011; Copping and Hemery, 2020). In tidal streams, these relatively small iE-fields (generally 0.05–0.5 µV cm^{-1}) can be predictable (Kalmijn, 1982; Tricas and Gill, 2011). Similarly, movement of marine organisms through the GMF (or other B-field) can generate iE-fields within their bodies (Tricas and Gill, 2011).

E-fields are also generated by living organisms directly via, for example, heartbeat, nerve impulses, or ionic exchange (Tricas and Gill, 2011). These bioelectrical fields can be detected by some electro-receptive species and aid them to locate prey or other individuals. Some species (*e.g.* European eels, *Anguilla* spp. and torpedo rays, *Torpedo* spp.) have the ability to produce E-fields of sufficient strength (hundreds of V cm^{-1}) to stun prey or defend against predators (Tricas and Gill, 2011).

Anthropogenic sources of EMFs in the marine environment include Marine Renewable Energy Devices (MREDs), telecommunication cables, power cables, cathodic protection systems on pipelines and ships (including wrecks), and heating of oil and gas pipelines (Tricas and Gill, 2011; Scott *et al.*, 2018; Scott *et al.*, 2020). A number of ferromagnetic sources (*e.g.* shore-based docks and jetties and ship wrecks) may produce local variations in the GMF, similar to those caused by magnetic rock deposits in the Earth's crust (Gill *et al.*, 2005; Tricas and Gill, 2011). Of these, subsea power cables, such as those associated with offshore wind developments, are considered a significant source of EMFs that may affect marine species (Tricas and Gill, 2011; Copping and Hemery, 2020). These cables emit EMFs along their entire length, which propagate perpendicular to the cable axis and decay with distance from source (Copping and Hemery, 2020; Harsanyi *et al.*, 2022).

Power cables can use either Alternating or Direct Current (AC or DC, respectively) AC periodically reverses direction and so has a frequency >0 Hz (Tricas and Gill, 2011; Copping and Hemery, 2020). For cables in North America, the oscillation frequency is usually 60 Hz, while in Europe and Asia it is generally 50 Hz (Tricas and Gill, 2011). In contrast, DC is static, with a frequency of 0 Hz (Tricas and Gill, 2011; Copping and Hemery, 2020). Permanent magnets and DC currents also produce static DC B-fields (Tricas and Gill, 2011). Currently, AC cables are the industry standard for connecting offshore wind turbines and other MREDs; however, DC cables are becoming more common, as more projects are being installed further offshore, due to their suitability for power transmission over longer distances (Tricas and Gill, 2011; Copping and Hemery, 2020; Scott *et al.*, 2020).There are clear differences between EMFs emitted by AC and DC cable systems (Tricas and Gill, 2011).

Different aspects of EMFs associated with AC and DC power cables are illustrated in **Figure 5**. Industry-standard cable shielding has been shown to be effective in preventing E-fields from being emitted into the environment, provided that there are no leaks and the cable is properly grounded, which means that E-fields are unlikely to impact marine organisms (Gill, 2005; Bochert and Zettler, 2006; Tricas and Gill, 2011; Scott *et al.*, 2018; Copping and Hemery, 2020; Scott *et al.*, 2021). B-fields, however, are not contained by the shielding (Gill, 2005; Bochert and Zettler, 2006; Tricas and Gill, 2011; Scott *et al.*, 2018; Copping and Hemery, 2020). As seawater and organisms pass through the B-fields, iE-fields are produced

(De Luca, 2009; Tricas and Gill, 2011; Scott *et al.*, 2018; Copping and Hemery, 2020; Harsanyi *et al.*, 2022). This is dependent on speed and orientation – an organism or current moving perpendicular to the cable B-field will result in the maximum iE-field, whereas parallel movement would not produce any iE-field (Tricas and Gill, 2011). In addition, the out-of-phase B-field emitted by the cores of an AC cable also produce iE-fields in the surrounding seawater that do not occur with a DC cable (Tricas and Gill, 2011; Copping and Hemery, 2020).

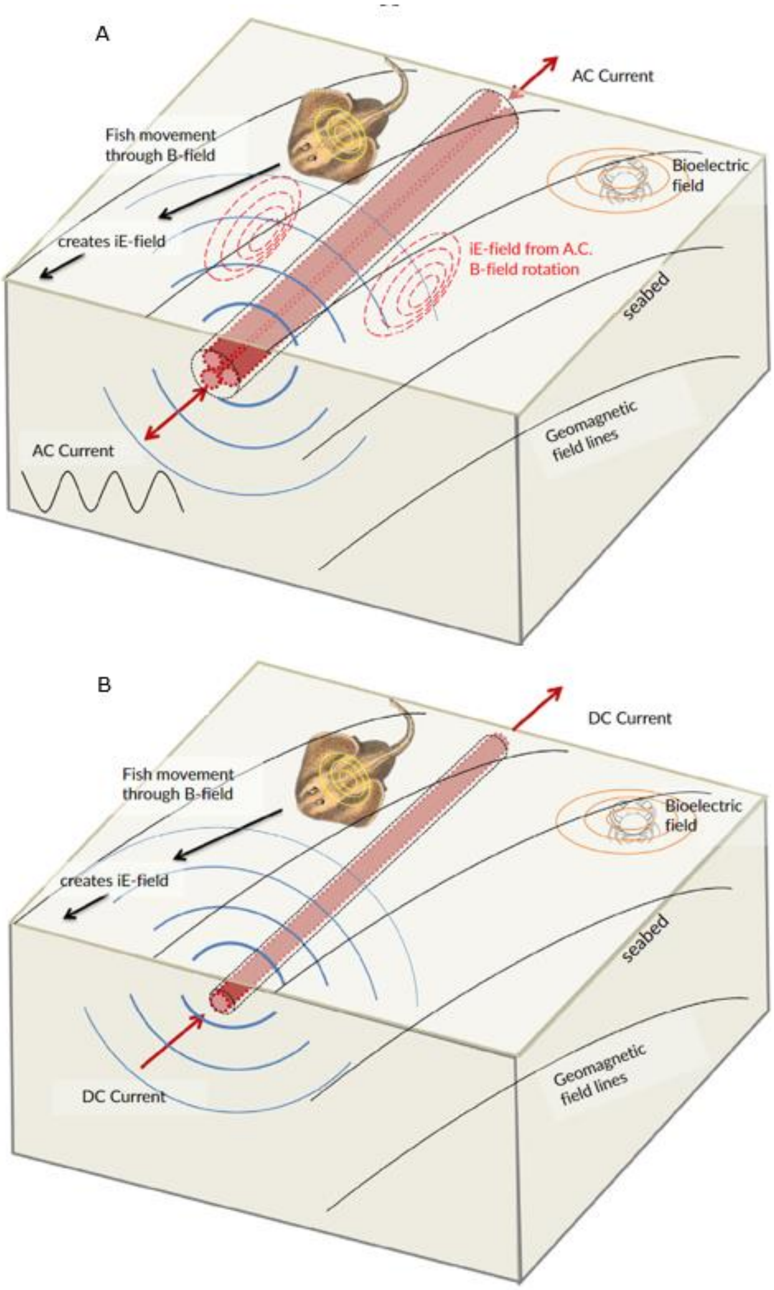

Figure 5: EMF s associated with a) AC and b) DC power cables .GMF in black, bioelectric fields in orange, B-fields in blue, iE-fields induced in fish yellow, and iE-field in surrounding conductive seawater in red. *Source*: Newton *et al.* (2019).

Intensity of EMFs produced will affect degree to which they may impact marine organisms (Copping and Hemery, 2020). Intensity is dependent on type of current

(AC or DC), characteristics of cable (*e.g.* length), power transmitted direction/proximity of other local cables, local GMF, water current speed, and other environmental factors (Bochert and Zettler, 2006; Tricas and Gill, 2011; Taormina *et al.*, 2018; Copping and Hemery, 2020; Scott *et al.*, 2021). Magnetometers can be used to detect and map B-field patterns generated by cable configurations (Tricas and Gill, 2011); however, E-fields are more difficult to measure, particularly at the low intensities associated with MREDs (Copping and Hemery, 2020). This lack of *in situ* data limits the ability to robustly assess the characteristics of EMFs around cables (Centre for Marine and Coastal Studies, 2003; Harsanyi *et al.*, 2022).Mathematical modelling approaches have been combined with the available data to begin to address this knowledge gap (Tricas and Gill, 2011; Copping and Hemery, 2020; Harsanyi *et al.*, 2022). Expected EMF strengths around subsea power cables range up to 8,000 μT (Bochert and Zettler, 2006; Cada *et al.*, 2011; Tricas and Gill, 2011). Bochert and Zettler (2006), for example, modelled a 1,600 A cable and predicted the associated field to have a strength of 3,200 μT at the cable's surface, 320 μT 1 m away from the cable, and 110 μT 4 m away. Modelling is a useful tool, but does have limitations and benefits from being validated by measurement data (Copping and Hemery, 2020).

5.2. How do animals detect EMFs?

If species possess sensory systems with the ability to detect EMFs, they have potential to be impacted by anthropogenic EMFs (Snyder *et al.*, 2019; Copping and Hemery, 2020). Although robust scientific data on organisms' EMF sensory abilities, thresholds, and tolerances are limited, there is behavioural, physiological, and anatomical evidence of EMF detection and use in some marine species (Boles and Lohmann, 2003; Tricas and Gill, 2011; Harsanyi *et al.*, 2022). Interference with these functions, therefore, is a potential risk associated with EMF-producing power cables (Tricas and Gill, 2011).

Taxa for which evidence of EMF detection ability has been reported include marine mammals, sea turtles, birds, fish (particularly elasmobranchs), invertebrates (particularly arthropods, molluscs, and echinoderms), and some microorganisms (Tricas and Gill, 2011). Some species may be able to detect E-fields (electroreceptive), some B-fields (magnetoreceptive), and some both (Newton *et al.*, 2019; Copping and Hemery, 2020). Electroreception is thought to be used for foraging, prey, and predator detection and/or avoidance, social/reproductive behaviours, and magnetoreception may facilitate navigation, homing, and orientation

There are three main proposed mechanisms for magnetorception; biogenic magnetite, electromagnetic induction, and optical pumping (Kirschvink and Gould, 1981; Diebel *et al.*, 2000; Johnsen and Lohmann, 2005; Tricas and Gill, 2011; Ernst and Lohmann, 2016; Copping and Hemery, 2020; Scott *et al.*, 2020). The magnetite detector theory hypothesises that small (<50 μm) magnetite (Fe_3O_4) crystals that have been found in the bodies of some species (Lohmann, 1984; Walker *et al.*, 1997; Shaw *et al.*, 2015) act as transducers for B-fields, aligning with the fields (like an internal compass) and acting on secondary receptors (Johnsen and Lohmann, 2005; Winklhofer and Kirschvink, 2010; Tricas and Gill, 2011; Scott *et al.*, 2020). Electromagnetic induction suggests that electroreceptive species may be able to indirectly obtain directional information about surrounding B-fields based on detections of E-fields by their electrosensory system (Johnsen and Lohmann, 2005; Tricas and Gill, 2011). Optical pumping is a light-dependent mechanism of magnetoreception whereby B-fields induce effects in pigments in an animal's visual system, altering information transmitted by the optical nerve (Johnsen and Lohmann, 2005; Tricas and Gill, 2011).

Differences between probable responses of EMF-sensitive species to AC and DC cables have been predicted by comparing results of modelling studies with animals' sensory capabilities (Tricas and Gill, 2011). B-fields from DC cables are more likely to be detected by receptive species than those from AC cables, particularly by those with biogenic magnetite-based sensory systems (Tricas and Gill, 2011). Differences between potential responses to E-fields from AC and DC cables are less clear (Tricas and Gill, 2011).

5.2.1. Marine mammals

The large size of marine mammals, as well as other logistical constraints, limit feasibility of controlled studies and field trials, particularly for mysticetes (Tricas and Gill, 2011). This means that, where direct data is lacking, reasonable predictions about sensory abilities of marine mammals must be made based on the most closely related species for which more evidence is available or inferred from indirect evidence. Studies to date that have investigated electrosense and magnetosense in cetaceans are listed in **Table 2**.

Common name	**Scientific name**	**Evidence of electrosense**	**Evidence of magnetosense**						
		Czech-Damal *et al.* (2012)	**Kirschvink *et al.* (1986)**	**Kirschvink (1990)**	**Walker *et al.* (1992)**	**Hui (1994)**	**Kremers *et al.* (2014)**	**Zoeger *et al.* (1981)**	**Bauer *et al.* (1985)**
Atlantic spotted dolphin	*Stenella frontalis*			✓					
Atlantic white-sided dolphin	*Lagenorhynchus acutus*			✓					
Beaked whales	Ziphiidae			x					
Bottlenose dolphin	*Tursiops truncatus*		✓	x			✓		✓
Common dolphin	*Delphinus delphis*		✓	✓		x		✓	
Cuvier's beaked whale	*Ziphius cavirostris*								✓
Dall's porpoise	*Phocoenoides dalli*								✓
Dwarf sperm whale	*Kogia sima*			x					
Fin whale	*Balaenoptera physalus*			✓	✓				
Guiana dolphin	*Sotalia guianensis*	✓							
Harbour porpoise	*Phocoena phocoena*			✓					
Humpback whale	*Megaptera novaeangliae*								✓
Long-finned pilot whale	*Globicephala melas*		✓	✓					
Pygmy sperm whale	*Kogia breviceps*		✓	✓					
Risso's dolphin	*Grampus griseus*		x	x					
Short-finned pilot whale	*Globicephala macrorhynchus*		✓	✓					
Sperm whale	*Physeter macrocephalus*		✓	✓					
Striped dolphin	*Stenella coeruleoalba*		✓	✓					

Table 2: Electrosense and magnetosense research for cetacean species. Tick (✓) indicates evidence was found, cross (x) indicates evidence was not found, and a blank space indicates that the species was not included in the study. Species listed alphabetically by common name. *Source*: OSC (2022).

To date, Guiana dolphin (*Sotalia guianensis*) is the only marine mammal for which evidence of electroreception has been found (Tricas and Gill, 2011; Czech-Damal *et al.*, 2012; 2013). Previous to this study, platypus (*Ornithorhynchus anatinus*) was the only known electroreceptive mammal on Earth (Czech-Damal *et al.*, 2012). Behavioural experiments on a captive Guiana dolphin indicated presence of an electrosense with a sensory threshold of 4.6 µV cm^{-1} (Czech-Damal *et al.*, 2012). Histology investigations discovered that hairless vibrissal crypts on the dolphin's rostrum (structures originally associated with mammalian whiskers) served as electroreceptors (Czech-Damal *et al.*, 2012). It is possible that other cetacean species possessing structures derived from the vibrissal system may also have an electrosense (Czech-Damal *et al.*, 2013).

Studies into statistical correlations between cetacean data and local distortions in the GMF caused by geological features have proposed that their results could be explained by magnetic sensitivity in these species (Klinowska, 1985; Kirschvink *et al.*, 1986; 1990; Walker *et al.*, 1992). Cetacean strandings data from both the US (Kirschvink *et al.*, 1986; Kirschvink, 1990) and UK (Klinowska, 1985) were found to be correlated with local geomagnetic variations as small as <0.05 µT. Klinowska (1985) stipulated that these strandings were due to these local magnetic distortions interfering with animals' use of the GMF to navigate, particularly during their long seasonal migrations. Kirschvink *et al.* (1986) found strandings to be correlated with magnetic anomalies for short- (*Globicephala macrorhynchus*) and long-finned (*G. melas*) pilot, sperm (*Physeter macrocephalus*), and pygmy sperm (*Kogia breviceps*) whales, and common (*Delphinus delphis)* and bottlenose dolphins, but found no significant correlations for Risso's dolphin (*Grampus griseus*). Similarly, Kirschvink (1990) also found correlations for short- and long-finned pilot, sperm, and pygmy sperm whales, and common dolphin, as well as fin whale (*Balaenoptera physalus*), and Atlantic white sided (*Lagenorhynchus acutus*), striped (*Stenella coeruleoalba),* and Atlantic spotted dolphins (*S. frontalis*), and harbour porpoise. In addition to Risso's dolphin, Kirschvink (1990) also did not find any significant correlation for dwarf sperm (*K. sima*) and beaked whales (family Ziphiidae), and, in contrast to the previous study, bottlenose dolphin. Walker *et al.* (1992) found a significant correlation between fin whale sightings and geomagnetic variations. These results indicate a potential for magnetoreceptors at least sensitive enough to detect the Earth's GMF across cetacean groups (Tricas and Gill, 2011). Hui (1994) found that common dolphin sightings were not significantly correlated with geomagnetic variation, but were with bottom topography and suggested that, even if this species does use magnetoreception, it may not always be the primary cue for navigation.

Experimental evidence that bottlenose dolphin can discriminate between magnetised and demagnetised stimuli has been demonstrated (Kremers *et al.*, 2014). While this study did indicate that the species could sense B-fields, the sensitivity of this reception was unclear (Kremers *et al.*, 2014; 2016).

Magnetite has been found in the tissues of humpback and Cuvier's beaked (*Ziphius cavirostris*) whales, bottlenose and common dolphins, and Dall's porpoise (*Phocoenoides dalli*), which suggests that a biogenic magnetite mechanism of magnetoreception may be present in cetaceans (Zoeger *et al.*, 1981; Bauer *et al.*, 1985).

While no studies have been conducted to date that provide direct evidence of magnetoreception in pinnipeds (Tricas and Gill, 2011), it is possible that these animals may be able to detect B-fields. Pinnipeds (particularly elephant seal, *Mirounga angustirostris*) have been observed to maintain constant headings over large distances, including making corrections when displaced by currents (Davis *et al.*, 2001; Davis, 2019). Some kind of internal compass responding to the Earth's GMF was thought to be the most plausible explanation for this ability (Davis *et al.*, 2001; Davis, 2019). The question of whether pinniped whiskers may allow them to sense B-fields has been posed, but not addressed in research thus far (Levitt *et al.*, 2021). No evidence of magnetoreception has been found for other carnivora species or for sirenia (Tricas and Gill, 2011; Hanke *et al.*, 2021).

Evidence to date, while limited in scope, does suggest that numerous marine mammal species, particularly cetaceans, are likely to be able to detect relatively low-level B-fields, with the most probable mechanism being biogenic magnetite. Electroreception has only been demonstrated in one marine mammal species, Guiana dolphin.

5.2.2. Diving seabirds

Detection of B-fields by avian species were hypothesized beginning in the early 20th century and first confirmed through a series of studies on European robins in the 1960s and 1970s (Wiltschko and Wiltschko, 1972), showing that caged individuals oriented themselves in the appropriate migratory direction during time periods when free-ranging individuals were migrating. Since then, our understanding of how birds detect and utilise magnetic compass information has progressed and has primarily focused on use of B-fields in orientation for long-distance migration as well as the underlying physiological mechanisms of detection. It is proposed that there is a mix of systems used for long-distance orientation, including using movements of the sun, a stellar compass, and mapping/orientation based on the GMF (Kishkinev and Chernetsov, 2015). It is likely that these three systems are used in combination, but geomagnetic orientation likely plays the most important role, as evidenced by emerging physiological evidence in magnetoreception.

While magnetoreception is well-studied in avian species, electroreception capabilities have not been confirmed, though given industry-standard shielding of underwater cables that mitigates E-fields, this review focuses on magnetic reception (as B-fields persist through shielding). Concerning how birds detect the GMF, there are two theories that are supported by current evidence. First, directional information about B-fields is likely detected through photochemical reactions in the eyes via the protein cryptochrome (Warrant, 2021). Second, intensity of B-fields (giving information on a magnetic 'map', or positional information) is likely sensed through magnetite-based receptors in the upper beak (Wiltschko and Wiltschko, 2019). Combined, these systems help provide locational and directional information (Mouritsen and Ritz, 2005). Birds likely conduct long-distance migrations through this mechanism, aided by sun movements and detection of star positions. Crucially, birds magnetoreception capabilities are sensitive enough to detect the relatively weak GMF. These systems have been studied in a limited number of species (including small passerines and chickens), and notably recently confirmed in one seabird species, Manx shearwater, *Puffinus puffinus* (Wynn *et al.*, 2020).

A survey of current literature found no direct studies on the impact or detection of EMFs on diving birds. Given shared physiology across avian taxa, it is likely that individuals can detect subsea B-fields. Adjacent to subsea cables, where B-fields are strongest, diving birds are unlikely to be able to orient based on strong B-fields without prolonged exposure (>1 hour for chickens) to shift the 'functional window' of detection, that would then allow for orientation based on magnetic information once again (Wiltschko and Wiltschko, 2014). It should be noted that this has been tested for orientation capabilities; as diving species are primarily using eyesight/direct vision to swim underwater, it is highly unlikely that B-fields are informing any sort of navigational behaviour while under the surface for foraging purposes. Thus, while diving birds may detect subsea EMFs, there is little reason to suspect that detection of EMFs would override direct visual detection regarding influencing subsea movements and foraging behaviour. The suspected impact of EMFs on diving birds is low, but the lack of direct study lends low confidence in this assessment.

5.2.3. Turtles

Currently, there is no evidence that sea turtles have the ability to detect E-fields (Tricas and Gill, 2011). It is, however, widely accepted that sea turtles use the Earth's GMF for navigation, migration, and orientation at all life stages, and thus are capable of magnetoreception. Most studies have been conducted on loggerhead turtles (*Caretta caretta*), predominantly hatchlings due to their smaller size, making them more practical to work with (Lohmann, 1991; Light and Salmon, 1993; Lohmann and Lohmann, 1994a; 1994b; Goff *et al.*, 1998; Avens and Lohmann, 2003; Irwin and Lohmann, 2003; Cain *et al.*, 2005; Irwin and Lohmann, 2005). Evidence has suggested that geomagnetic sensitivity of loggerhead turtles likely ranges 0.00469–4,000 μT (Goff *et al.*, 1998; Avens and Lohmann, 2003; Tricas and Gill, 2011). Studies on green turtle (*Chelonia mydas*) have been less conclusive – this species also undertakes long migrations and some experiments point to the GMF as an important navigational cue, but other evidence suggests that other stimuli (*e.g.* wind) may be more significant (Papi *et al.*, 2000; Luschi *et al.*, 2001; Hays *et al.*, 2002; 2003; Lohmann *et al.*, 2004; Luschi *et al.*, 2007; Lohmann *et al.*, 2008a). There is also evidence of use of Earth's GMF by Kemp's ridley (*Lepidochelys kempii*) and leatherback turtles (*Dermochelys coriacea*) (Lohmann and Lohmann, 1993; Putman and Lohmann, 2008). Mechanism behind magnetoreception in sea turtles is not clear due to most studies being observational or behavioural (Tricas and Gill, 2011).

5.2.4. Elasmobranchs

There is strong physiological, behavioural, and anatomical evidence for both electroreception and magnetoreception across elasmobranch species (Collin and Whitehead, 2004; Tricas and Gill, 2011).

Electroreception in elasmobranchs serves a number of purposes, including orientation and navigation (Tricas and Gill, 2011), foraging by sensing bioelectric fields produced by prey organisms (Kalmijn, 1971; 1982; Tricas, 1982; Blonder and Alevizon, 1988; Kajiura and Holland, 2002), location of and social interaction with other individuals, including during reproduction (Tricas *et al.*, 1995), and predator detection and avoidance, particularly during vulnerable early life stages (Sisneros *et al.*, 1998). Detection of physically or biologically generated E-fields through electroreceptors to aid with such functions is known as passive electrolocation (Bullock *et al.*, 2005).

The primary mechanism for electroreception is thought to be via a specialised sensory system called the ampullae of Lorenzini, which is only present in elasmobranchs and holocephali ratfishes (Tricas and Gill, 2011). Less well studied electroreception mechanisms are reported in other fish species and some invertebrates (Tricas and Gill, 2011). The first identification of this sensory system occurred in the 1600s, and, more recently, it has been examined in greater detail (Tricas and Gill, 2011). The sense organs consist of a canal (1-mm in diameter and variable in length), which opens up to the surface via a pore in the skin (Murray, 1974; Tricas and Gill, 2011). The canal contains a conductive gel that responds to external E-fields, transmitting a voltage to the ampullary chamber which stimulates receptor cells and associated neurons (Murray, 1974; Tricas and Gill, 2011).

As it is the voltage difference along the length of the canal that facilitates detection of E-fields, a longer canal results in greater sensitivity (Tricas and Gill, 2011). Some species (*e.g.* chain catshark, *Scyliorhinus retifer*) have been found to be sensitive to a narrow range of electrical stimuli (in line with those emitted by prey), while others (*e.g.* little skate, *Leucoraja erinacea*) are able to detect a broader range (Bellono *et al.*, 2018; Copping and Hemery, 2020). Both physiological and behavioural experiments have provided evidence of sensitivity to very weak E-fields in sea water – as weak as 10 nV cm^{-1} in small-spotted catshark (*S. canicular*) and thornback ray (*Raja clavata*), 5 nV cm^{-1} in round stingray (*Urolophus halleri*) and smooth dogfish (*Mustelus canis*), and <1 nV cm^{-1} in scalloped hammerhead (*Sphyrna lewini*) and sandbar shark (*Carcharhinus plumbeus*) (Kalmijn, 1966; 1982; Kajiura and Holland, 2002; Kajiura and Fitzgerald, 2009).

There is evidence of magnetoreception in elasmobranch species; however, it is unclear whether B-fields are detected directly by a magnetoreceptor, or indirectly via the electrosense through electromagnetic induction (Kalmijn, 1974; 1981; Tricas and Gill, 2011; Siegenthaler *et al.*, 2016; Anderson *et al.*, 2017; Newton and Kajiura, 2017; Richards *et al.*, 2018; Copping and Hemery, 2020). Andrianov *et al.* (1974) found the minimum threshold for magnetoreception in common stingray (*Dasyatis pastinaca*) to be 200 μT sec^{-1}, whereas (Akeov *et al.*, 1976) found it to be 80 μT sec^{-1}. Elasmobranchs may use magnetoreception to solve spatial tasks, orientation, and navigations (Tricas and Gill, 2011; Newton and Kajiura, 2017; Copping and Hemery, 2020).

5.2.5. Fish

There is evidence for electroreception and/or magnetoreception in a variety of non-elasmobranch fishes species – more so for pelagic than demersal species (Tricas and Gill, 2011).

As well as in elasmobranchs, electroreception has been reported in lampreys (Petromyzontiformes), sturgeons (Acipenseriformes), catfish (Siluriformes), and freshwater eels (Anguilliformes) (Bullock *et al.*, 2005; Tricas and Gill, 2011). Electrosensory systems in fish can be either ampullary or tuberous, with sensitivities of <0.1–25 Hz and 50–>2,000 Hz respectively (Collin and Whitehead, 2004; Tricas and Gill, 2011). As discussed in **Section 5.2.4**, elasmobranchs and holocephali ratfishes possess unique electroreceptive systems, the ampullae of Lorenzini (Tricas and Gill, 2011). Tuberous systems have only been found in knifefish (gymnotiformes) and elephantfish (mormyriformes) – both freshwater teleosts (Bullock *et al.*, 2005). Sensitivities of fish electroreceptors have been reported to be as low as 0.1 μV cm^{-1} (Tricas and Gill, 2011)

A few species (*e.g.* aba, *Gymnarchus niloticus*) generate their own E-field which their electroreceptors then detect distortions in (*e.g.* by prey species swimming through) – this process is referred to as active electrolocation (Lissman and Machin, 1958). Another function of this E-field generation is as a weapon to stun prey or deter predators – this ability is also present in some elasmobranchs (Tricas and Gill, 2011).

The main function of electroreception in fish is thought to be prey detection, and it may also be associated with predator detection, socialisation, and reproduction (Tricas and Gill, 2011).

Magnetoreception has been reported in fish including salmon and trout (Salmonidae), tuna (Perciformes), and freshwater eels (Walker, 1984; Nishi and Kawamura, 2005; Tricas and Gill, 2011). Evidence has been found of putative magnetoreceptors in the olfactory system of teleost fish, including in species that lack an electrosense, such as salmon (Walker *et al.*, 1997; Tricas and Gill, 2011). Species that are magnetoreceptive but not electroreceptive must be able to detect B-fields directly, rather than via electromagnetic induction (Tricas and Gill, 2011). Magnetite has been found in the tissues of some fish species, indicating that a biogenic magnetite mechanism of magnetoreception may be likely (Walker, 1984; Mann *et al.*, 1988; Walker *et al.*, 1997; Diebel *et al.*, 2000). Fish species may use magnetoreception for orientation, navigation, migration, and homing using geomagnetic cues (Dittman and Quinn, 1996; Lohmann *et al.*, 2008b).

5.2.6. Invertebrates

There is evidence of electroreception and/or magnetoreception in at least three invertebrate phyla – arthropods, molluscs, and echinoderms (Lohmann, 1984; Lohmann and Willows, 1987; Cameron *et al.*, 1993; Tricas and Gill, 2011).That being said, this evidence is limited to studies on a small number of species (Tricas and Gill, 2011).

Steullet *et al.* (2007) found freshwater crayfish (*Procambarus clarkia*) responded to E-fields, but only at high intensities (>20 mV cm^{-1}). Physiological evidence indicated that E-fields were likely to be stimulating chemo- and mechano-sensory neurons, rather than specialised electroreceptors (Steullet *et al.*, 2007). Evidence of electroreception has also been found for other species of freshwater crayfish (*Cherax destructor* and *C. quadricarinatus*), including detection of low-level E-fields (3 mV cm^{-1}) more comparable with those expected to be produced by subsea cables (Patullo and Macmillan, 2007; 2010). As the majority of studies have been focused on the Earth's GMF (approximately 50 μT), precise sensitivity levels remain unclear (Tricas and Gill, 2011). Studies on electroreception in marine invertebrates are sparce, although it has been speculated that various arthropods, molluscs, and perhaps annelids may possess an electrosense (Bullock, 1999; Tricas and Gill, 2011; Scott *et al.*, 2018; Copping and Hemery, 2020). For invertebrates, an electrosense may serve similar functions as in fish – detection of prey, predators, and other individuals (Tricas and Gill, 2011).

The most studied invertebrate group in terms of magnetoreception is arthropods, in particular decapod crustaceans (Scott *et al.*, 2018; Copping and Hemery, 2020). Spiny lobster (*Panulirus argus*) has been found to be sensitive to B-fields as low as 5 μT and evidence indicates that they make use of Earth's GMF as a directional cue (Lohmann, 1985; 1995; Boles and Lohmann, 2003; Tricas and Gill, 2011). Evidence of magnetoreception has also been found for edible crab (*Cancer pagurus*), European lobster (*Homarus gammarus*), isopod species (*Idotea baltica*), and amphipod sandhopper species (*Talorchestia martensii*) (Ugolini and Pezzani, 1995; Ugolini, 2006; Scott *et al.*, 2018; 2021; Harsanyi *et al.*, 2022).

While the mechanism behind magnetoreception in arthropods in currently unknown, the leading theory is a biogenic magnetite system (Scott *et al.*, 2021). This theory is supported by evidence of magnetite presence in the tissue of some arthropods (Lohmann, 1984; Ernst and Lohmann, 2016). As a crucial element of the olfactory system, antennules are generally considered the primary sensory organ in crustaceans; however, investigations found that they are not likely a significant component of magnetoreception (Woodruff *et al.*, 2012; Scott *et al.*, 2018; 2020).

The main functional roles of magnetorecption in arthropods are thought to include navigation, orientation, and homing via the Earth's GMF (Cain *et al.*, 2005; Lohmann *et al.*, 2007). This could be significant for long seasonal migrations and daily feeding trips in species such as spiny lobster and edible crab, and for orientation relative to the shoreline for species such as marine isopods (Ugolini and Pezzani, 1995; Alerstam, 2003; Cain *et al.*, 2005; Lohmann *et al.*, 2007; Tricas and Gill, 2011). For arthropod species that have not been as well studied, but exhibit similar migratory and homing behaviours to the species above, cautious estimates can be made about their magnetosenory abilities (Tricas and Gill, 2011).

The most studied mollusc in terms of magnetoreception is a nudibranch species (*Tritonia diomedea*), which is known to make use of the Earth's GMF as a cue for navigation (Lohmann and Willows, 1987; 1991; Popescu and Willows, 1999; Willows, 1999; Wang *et al.*, 2003; 2004; Cain *et al.*, 2006). Physiological responses to B-fields (300–700 µT) have been observed in Mediterranean mussel (*Mytilus galloprovincialis*), indicating that they may have some form of magnetoreception (Ottaviani *et al.*, 2002; Malagoli *et al.*, 2003; 2004). Additionally, there is evidence of a magnetosense in dog whelk (*Nassarius* spp.) (Brown *et al.*, 1964).

The mechanism behind magnetoreception in molluscs in unclear. Biogenic magnetite was first discovered in a mollusc (polyplacophore chitons) in 1962 and thought to have the potential to facilitate magnetoreception; however, later analysis in 1979 considered it to be too weakly and randomly magnetised to serve this function (Lowenstam, 1962; Kirschvink and Lowenstam, 1979).

While studies on echinoderm magnetoreception are scarce, exposure to B-fields has been shown to impact echinoderm embryonic development of purple (*Strongylocentrotus purpuratus*) and painted (*Lytechinus pictus*) sea urchins, indicating some degree of sensitivity to these fields (Cameron *et al.*, 1993; Levin and Ernst, 1997).

5.3. Effects of EMFs

To date, much uncertainty surrounds potential ecological impacts of anthropogenic EMFs in the marine environment (Tricas and Gill, 2011). As species across a variety of taxa are thought to use electro- and magnetoreception to support a range of vital life functions, artificial generation of EMFs may cause interference (Tricas and Gill, 2011; Gill *et al.*, 2014; Copping and Hemery, 2020). Electroreception may be involved in detection of prey, predators, and other individuals to facilitate feeding, predator avoidance, and social/reproductive behaviours (Tricas and Gill, 2011). Magnetoreception can support navigation, orientation, and homing in both long-range migrations and short-range movements (Tricas and Gill, 2011).

Interference with these life functions is a risk where an organism's sensory range overlaps with EMF levels produced by cables (Tricas and Gill, 2011). For example, measured E-fields associated with subsea cables have ranged 1 to 100 μV cm^{-1}, which overlaps the bioelectric fields emitted by some prey species. As such, these E-fields may attract predators that use electrosense for prey detection (Kalmijn, 1982; Peters *et al.*, 2007; Copping and Hemery, 2020). Thus far, impacts of E-fields at the levels predicted around subsea cables are understudied (Copping and Hemery, 2020). Studies that have investigated the impacts of EMFs on marine species are listed in **Table 3**.

Study	Field/ Lab	Species covered	Strengths of EMF	AC and/or DC	Description	Findings	Relevance (1–5)
Cresci *et al.* (2022)	Lab	Atlantic haddock (*Melanogrammus aeglefinus*) - larvae	50 – 150 µT	DC	Exposed animals in tanks to EMF produced by Helmholtz coils.	Exposure to EMF decreased swimming speed and acceleration of nonexploratory individuals but had no effect on exploratory individuals.	4
Hutchison *et al.* (2020)	Field	American lobster (*Homarus americanus*); little skate (*Leucoraja erinacea*)	0.023 – 15 µT; 0.00024 – 0.000735 V/m	AC/DC	Animals were placed in mesocosms, which were then placed on top of buried subsea cables *in situ*.	Exposure to EMF increased exploratory/foraging behaviour (more so for skates than lobsters).	5
Taormina *et al.* (2020)	Lab	European lobster (*Homarus gammarus*) - juvenile	Up to 225 µT	AC/DC	Exposed animals in tanks EMF produced by Helmholtz coils.	No effect in time taken for animals to find shelter, or in avoidance/attraction behaviour.	4
Fey *et al.* (2019b)	Lab	Rainbow trout (*Oncorhynchus mykiss*) – eggs/larvae	1 – 10 mT	AC/DC	Exposed eggs in tanks to EMF produced by Helmholtz coils.	Exposure to EMF enhanced yolk-sac absorption rate. Larvae with absorbed yok-sacs by the time of swim-up were less efficient at first feeding. No effect on embryonic or larval mortality, hatching time, larval growth, or time of swim-up.	3
Fey *et al.* (2019a)	Lab	Northern pike (*Esox lucius*) -eggs/larvae	10 mT	AC/DC	Exposed eggs in tanks to EMF produced by Helmholtz coils.	Exposure to EMF brough average hatching time 1 day earlier, decreased yolk size, and increased yolk-sac absorption rate. No effect on hatching success, larvae mortality, size of larvae, and rate of growth.	2

Jakubowska *et al.* (2019)	Lab	Polychaete (*Hediste diversicolor*)	1 mT	None	Exposed animals in tanks to EMF produced by Helmholtz coils.	Exposure to EMF enhanced burrowing activity and reduced ammonia excretion rate. No effect on attraction or avoidance behaviour, or rate for consumption or respiration.	3
Ernst and Lohmann (2018)	Lab	Caribbean spiny lobster (*Panulirus argus*)	703.1 mT	DC	Animals were given the choice of a control den, or a den subjected to EMF.	More animals selected the control den, indicating avoidance behaviour. Lobsters that selected the den exposed to EMF were significantly smaller than those that selected the control den.	3
Richards *et al.* (2018)	Field	Elasmobranchs	2.5 – 22 mT	None	Ferrite magnet bars were attached to the funnel entrances of ocean fish traps.	Incorporation of ferrite magnet bars reduced elasmobranch bycatch (mainly blind shark, *Brachaelurus waddi*), and increased catch of target fish species (snapper, *Pagrus auratus*).	2
Scanlan *et al.* (2018)	Lab	Nonanadromous Atlantic salmon (*Salmo salar*) - juvenile	44.40 – 55.54 µT	DC	Animals were placed in tanks subject to different levels of EMF generated by orthogonally arranged four-coil systems.	Level of EMF affected animals' orientation.	2
Scott *et al.* (2018)	Lab	Edible crab (*Cancer pagurus*)	2.8 and 40 mT	AC	Exposed animals in tanks to EMF produced by Helmholtz coil. Time animals spent inside a shelter exposed to EMF compared to a control shelter was also recorded.	Exposure to EMF disrupted haemolymph L-lactate and D-glucose natural circadian rhythms. Animals were more attracted to the shelter subjected to EMF than the control shelter. No effect on haemocyanin concentration, respiration rate,	4

						activity level, or antennular flicking rate.	
Wyman *et al.* (2018)	Field	Chinook salmon (*Oncorhynchus tshawytscha*) - juvenile	EMF from a 200 kV DC cable, buried (exact field strength variable).	DC	Tracked movement of tagged animals before and after a subsea cable was energised.	No effect on proportion of fish successfully migrating; however, after energisation, higher proportions of fish crossed the cable, and were more likely to be detected south of their normal route.	5
Kantserova *et al.* (2017)	Lab	Crucian carp (*Carassius Carassius*); roach (*Rutilus rutilus*); common carp (*Cyprinus carpio*); great pond snail (*Limnaea stagnalis*); *Daphnia magna*	0 – 51.7 μT	None	Animals were exposed to hypomagnetic conditions (the GMF completely cancelled out) and reversal of the GMF, generated by Helmholtz coils.	Hypomagnetic conditions led to significant decrease in Ca^{2+}-dependent protease (caplain) activity. Reversal of the GMF produced ambiguous results.	1
Kilfoyle *et al.* (2017)	Field	Coral reef fish, representing 151 different species.	0.4 – 559 nT; 204 – 319 μV/m	AC/DC	SCUBA divers conducted visual surveys of fish species at sites surrounding a subsea cable while the power was either on or off.	No effect on reef fish abundance, species richness, or fish reaction.	4
Love *et al.* (2017a)	Field	Dungeness crab (*Metacarcinus magister*); red rock crab (*Cancer productus*).	EMF from 35 kV and 69 kV AC cables (exact field strength not given).	AC/DC	Enclosures were placed over a subsea cable and animals were given the option of traversing the cable to enter a baited trap, or to enter a baited trap away from the cable.	No effect on entry to baited trap. Regardless of cable, Dungeness crab tended to move East and red rock crab tended to move West.	5

Love *et al.* (2017b)	Field	Various fish and invertebrate species, including halfbanded rockfish (*Sebastes semicinctus*), lingcod (*Ophiodon elongatus*), and giant plumose anemone (*Metridium farcimen*).	0-205 µT	AC	Surveys using manned submersibles were conducted along energised and unenergized subsea cables.	Natural habitat community statistically differed from those around both cable types. Total fish densities were significantly higher around both cable types than over the natural habitat. No statistical difference in species composition of fish assemblages along energised and unenergized cables. The densities of four invertebrate species differed significantly between energised and unenergized cables, but not across all depth strata. EMF declined to background levels 1 m from cable.	5
Dunlop *et al.* (2016)	Field	Various fish, including round gib (*Neogobius melanostomus*), alewife (*Alosa harengus*), and American eel (*Anguilla rostrata*).	EMF from 245 kV AC 3-core cable (exact field strength not given)	AC	Electrofishing and acoustic surveys were conducted along transects at varying distances to the cable.	No effect of proximity to cable on fish communities.	4
Kavet *et al.* (2016)	Field	Chinook salmon (*Oncorhynchus tshawytscha*); green sturgeon (*Acipenser medirostris*).	68.5 – 689 nT	N/A	Analysed fish movement behaviour data from previous biotelemetry studies before and after installation and activation of a cable.	Results indicated that salmon may be attracted to the cable after activation but were still able to successfully migrate through the bay. Cable activation increased the time taken for sturgeon outbound migrations, but decreased the time taken for inbound migrations. Again, it did not impact the success of migrations.	4

Love *et al.* (2016)	Field	Various fish, invertebrates, and marine plants, comprising 44 species including kelp perch (*Brachyistius frenatus*), senorita *(Oxyjulis californica*), white seaperch (*Morone americana*), shiner perch (*Cymatogaster aggregata*) rockfishes (), and sanddabs (*Citharichthys sordidus*).	0 – 91.4 µT	AC/DC	Conducted surveys using divers and a manned submersible of fish, invertebrates, and marine plants around energised and unenergised subsea cables.	No differences in community assemblage between energised and unenergised cables. EMF from cables diminished to background levels approximately 1 m away from the cable.	5
Tomanova and Vacha (2016)	Lab	Antarctic amphipod (*Gondogenia antarctica*)	2 – 20 nT	None	Exposed animals to radiofrequency EMF.	Exposure to EMF disorientated amphipod.	2
(Kuhnz *et al.*, 2015)	Field	Various cnidarians, crustaceans, fish, echinoderms	Not recorded	N/A	ROV surveys of faunal assemblage before and after operation of sub sea cable	Cable had no detectable effect on biological assemblages	4
Bevelhimer *et al.* (2015)	Lab	Largemouth bass (*Micropterus salmoides*); pallid sturgeon (*Scaphirhyncus albus*).	Up to 2450 µT	AC/DC	Exposed animals in tanks to EMF produced by coil. Surgically implanted acoustic transmitters gave locations of animals.	No effect on location or activity relative to the location of the coil. EMF diminished to background levels approximately 30 cm from the coil.	3
Formicki *et al.* (2015)	Lab	Trout (*Salmo trutta*) - spermatozoa	1-10 mT	N/A	Trout spermatozoa was exposed to EMF in the lab.	Exposure to EMF prolonged sperm motility and had no effect on fragmentation of genetic material. It also improved	2

						effectiveness of fertilisation and hatching.	
Kuz'mina *et al.* (2015)	Lab	Crucian carp (*Carassius carassius*)	24.2 – 51.7 μT	AC/DC	Exposed animals in tanks to EMF produced by Helmholtz coil.	Exposure to EMF with resonance parameters for calcium ions decreased the proteolytic and amylolytic activities of intestinal enzymes. Exposure to EMF with resonance parameters for potassium ions had almost no effect on the activity of proteinases but decreased amylolytic activity. Inversion of the vertical component of the EMF decreased proteolytic activity of the intestinal mucosa and increased amylolytic activity.	3
Porsmoguer *et al.* (2015)	Field	Blue shark (*Prionace glauca*)	0.464 – 0.885 T	None	Hooks in a longline fishery were equipped with high field strength magnets.	Magnets did not reduce shark catch rates and could have an attractive effect – more so for the larger magnet (0.885 T).	2
Soetaert *et al.* (2015)	Lab	Brown shrimp (*Crangon crangon*); king ragworm (*Alita virens*)	150–200 V/m	AC and DC	Animals were exposed to electric pulses, similar to those used in electric fishing.	Most animals exhibited a tail flip (shrimp) or squirming (ragworm) reaction in response to an electric pulse. No significant increase in mortality or injuries and no irreversible lesions. A significantly higher severity of virus infection in the hepatopancreas on shrimp exposed to 200 V/m.	3
Putman *et al.* (2014)	Lab	juvenile steelhead trout *(Oncorhynchus mykiss)*	52.43 - 52.85 mT	None	Juvenile trout orientation preferences were tested through EMF exposure.	Fish reared in natural magnetic conditions oriented in opposite directions and lead fish to foraging grounds; however, fish	3

						reared in distorted magnetic fields caused random orientation.	
Bevelhimer *et al.* (2013)	Lab	Fathead minnows *(Pimephales promelas)*, redear sunfish *(Lepomis microlophus)*, striped bass *(Morone saxatilis)*, lake sturgeon *(Acipenser fulvescens)* and channel catfish *(Ictalurus punctatus)*	1500 – 165,000 µT	AC/DC	Responses of freshwater fishes to static and variable EMF emitted by hydrokinetic projects.	No effect on fish activity level except for fathead minnow. Redear sunfish and channel catfish showed a change in distributions relative to magnet position, both showing attraction to EMF source.	3
Formicki *et al.* (2013)	Lab	Danube huchen *(Hucho hucho)*	1 – 10 mT	None	Eight sperm motility parameters were tested using CASA. EMF exposure and morphology on spermatozoa also examined.	Static MF had a positive effect on sperm motility parameters which determines fertilisation effectiveness. This study suggests this methods of exposing sperm to MF could be used for short-term storage of sperm.	2
Izyumov and Krylow (2013)	Lab	Roach *(Rutilus rutilus)*	50 – 300 nT	AC	To analyse the biological effects of exposure of eggs and sperms to MS in roach prolarvae at the cytogenetic and organismic levels.	The rate of hatching, survival of embryos, and size and mass parameters of prolarvae varied in experimental and control samples, but no link of this variation with exposure to a magnetic storm has been established.	2
Kantserova *et al.* (2013b)	Lab	Crucian carp (*Carassius carassius* (L.)) and roach *(Rutilus rutilus)*	24.2 – 44.5 µT	None	The in vivo and in vitro effects of weak, low frequency magnetic fields with resonance parameters for calcium ions upon intracellular	the impact of a weak low frequency magnetic field leads to considerable decrease in the activity of calpains in the fish skeletal muscles and brain.	2

					calcium dependent proteinases were studied.		
Kantserova *et al.* (2013a)	Lab	Crucian carp (*Carassius carassius* (L.)) and roach *(Rutilus rutilus)*	0.1 – 60 µT	None	Addressing the effects of weak low frequency magnetic fields on intracellular Ca2+ dependent proteinases from invertebrates and fish.	A significant decrease of calpain activity was recorded in the animals investigated. The physical factor studied also caused partial loss of activity in preparations of Ca2+ dependent proteinases obtained from invertebrates and fish.	2
Woodruff *et al.* (2013)	Lab	Atlantic halibut *(Hippoglossus hippoglossus),* Dungeness crab *(Metacarcinus magister)*, and American lobster *(Homarus americanus)*.	0.2 – 1.2 mT	DC	Investigated environmental issues associated with marine and hydrokinetic energy (MHK) generation.		4
Czech-Damal *et al.* (2012)	Lab	Guiana dolphin *(Sotalia guianensis)*	Up to 9 µV/cm	None	Investigation into hairless vibrissal crypts on the rostrum serving as electroreceptors, as well as observing behavioural response after exposure to different strength electric fields.	Possess a well-innervated ampullary structure similar to other species. Male dolphin sensory detection threshold for EMF is weak (4.6 µV/cm) like that of a platypus. Electroreceptors can evolve from a mechanosensory organ.	1
Hart *et al.* (2012)	Lab	Common carp (*Cyprinus carpio*)	Ambient	None	The alignment of fish in round tanks across Czech Christmas fish markets was observed.	Animals displayed a statistically highly significant spontaneous preference to align their bodies along the North-South axis.	1

Woodruff *et al.* (2012)	Lab	Coho salmon (*Oncorhynchus kisutch*); Atlantic halibut (*Hippoglossus hippoglossus*); California halibut (*Paralicthys californicus*); rainbow trout (*Oncorhynchus mykiss*); Dungeness crab (*Metacarcinus magister*).	0.1-3.0 mT	AC/DC	Exposed animals in tanks to EMF produced by Helmholtz coil.	Minimal effect on development, physiological responses, and behaviour.	4
Fuxjager *et al.* (2011)	Lab	Loggerhead turtles *(Carretta caretta)* hatchlings	44 – 51.1 µT	None	Exposure to several additional magnetic fields existing along or outside of gyre northern boundary.	Hatchlings swam towards migratory routes with fields within the gyre; however, they swam in directions indistinguishable from random with fields outside of the gyre.	3
Kimber *et al.* (2011)	Lab	Small-spotted catshark *(Scyliorhinus canicula)*	5 – 20 nV cm^{-1}	AC/DC	Preferences were studied by behaviourally conditioning individuals to swim through tunnels and exposing them to 2 EMFs simultaneously.	No preference given between artificial and natural EMFs; however, higher preference was given to direct currents, and less so to alternating currents.	3
Krylov (2010)	Lab	*Daphnia magna* - eggs	75 µT	None	Exposed eggs in lab to EMF produced by Helmholtz coil.	Exposure of eggs to EMF increased rate of embryonic development. Adult females developed from exposed eggs demonstrated deteriorated production characteristics in the first brood.	3

Shultz *et al.* (2010)	Lab	Coho salmon (*Onchorhychus kisutch*); California halibut (*Paralicthys californicus*) - larvae; Atlantic halibut (*Hippoglossus hippoglossus*) - larvae; dungeness crab (*Cancer magister*).	0.1-3.0 mT	AC/DC	Exposed animals in tanks to EMF produced by Helmholtz coil.	No effect on behaviour or development.	3
Chebotareva *et al.* (2009)	Lab	Roach *(Rutilus rutilus)*	150 µT	AC	Study life stage most sensitive to EMF during early development and long-term effects.	Earlier hatchling of prelarvae, increase in the morphological diversity of juvenile fish, decrease in body lengths and weights and changes in number of vertebrae in yearlings.	2
Gill *et al.* (2009)	Field	Thornback ray *(Raja clavate),* spurdog *(Squalus acanthias),* small-spotted catshark/lesser-spotted dogfish *(Scyliorhinus canicula)*	0.23 µT – 8 µT	None	Study to determine if electromagnetically (EM) sensitive organisms respond to anthropogenic EMFs of the type and magnitude generated by offshore windfarms	Evidence that benthic, elasmobranch species studied can respond to the presence of EMF of type and intensity associated with sub-sea cables. Not predictable and responses seem to be species specific, individuals more likely to respond by focussing movement within the EMF zone. Thornback rays more likely to move around EMF zone, some catshark individuals also.	5
Hellinger and Hoffman (2009)	Lab	Rainbow trout *(Oncorhynchus mykiss)*	0 – 0.085 T	None	Demonstrate the role of the trigeminal system in the perception process of different magnetic field parameters by heartbeat conditioning	Inactivation of the ophthalmic branch by local anaesthesia of the magnetic field by abolishing the conditioned response (CR). Experiments with 90° direction shifts showed normal	2

						conditioning. Experiments under red light and darkness had CR occurring also.	
Barry *et al.* (2008)	Field	Variety of benthic megafauna, comprising 116 species, including sea pen (*Funiculina* sp.), sea star (*Rathbunaster californicus*), and urchin (*Allocentrotus fragilis*).	Cable was not energised.	None	ROV was used to survey area around a cable.	No significant effect on distribution or abundances of benthic megafaunal communities; although longnose skate (*Raja rhina*) was more abundant along sections where cable was suspended over topography.	1
Marcotte and Lowe (2008)	Lab	Scalloped hammerhead (*Sphyrna lewin*) and leopard sharks (*Triakis semifasciata*) - juvenile	Up to 33.96 V/m	DC	Animals were exposed to an electrical deterrent (strong, DC electrical field) and baited with a food odour source.	A mean voltage threshold of 4.16 Vm (hammerhead) and 4.30 V/m (leopard) provoked a head twitch behaviour. A threshold of 5.54 V/m elicited a shimmy behaviour response in hammerheads. A threshold of 18.50 V/m (hammerhead) and 9.64 V/m (leopard) prompted a retreat behavioural response.	2
Westerberg and Lagenfelt (2008)	Field	European eel (*Anguilla anguilla*)	5 µT	AC	Acoustic tags were used to study the effect of a subsea cable on migrating eel.	Eel swimming speed was lower around the cable.	5
Bochart and Zettler (2006)	Lab	North sea prawns *(Crangon crangon* and *Palaemon squilla)*	0.02 – 3.2 mT	AC and DC	Observations in a closed flow-through system under similar external conditions.	No significant differences between AC and DC.	4
Polet *et al.* (2005)	Lab	Brown shrimp (*Crangon crangon*) and other demersal	Up to 25 V/m	AC	Brown shrimp and common bycatch species were exposed	Shrimp reacted strongly to the pulses (*e.g.* startle response) and other species did not. No effect on mortality.	2

		species, including flatfish.			to electric pulses used in electrical fishing.		
Formicki *et al.* (2004b)	Field	Perch (*Perca fluviatilis*), pike (*Esox lucius*), roach (*Rutilus rutilus*), rudd (*Scardinius erythrophthalmus*), bleak (*Alburnus alburnas*), bream (*Abramis brama*), ruffe (*Gymnocephalus cernua*), *eel* (*Anguilla anguilla*)	0.1 mT	None	Summary The effects of magnetic fields generated by ferritic magnets and mounted in entrances to fyke nets were studied in 1999–2002.	Differences in magnet placement had no significant importance on the number of fish entering the nets.	2
Formicki *et al.* (2004a)	Lab	Trout (*Salmo trutta* L.) larvae and fry	0.15 – 4.2 mT	DC	Effects of a constant magnetic field on the swimming direction of trout larvae and fry were investigated using chambers equipped with magnets as well as magnet-free chambers placed at the entrance.	The experiments showed a close relationship between the direction selected by the larvae and fry and the presence or absence of ferritic magnets generating a constant magnetic field.	2
Nishi *et al.* (2004)	Lab	Japanese eel (*Anguilla japonica*)	12,663 – 192,473 nT	DC	Magneto sensitivity of the Japanese eel, *Anguilla japonica*, was examined by conditioning and electrocardiography.	Japanese eel are magneto sensitive whether they are at sea, in the river or in the farm.	3
Winnicki *et al.* (2004)	Lab	Northern pike (*Esox lucius* L.)	4 – 15 mT	DC and AC	Looking for a material basis of the directional responses of adults by trying to find their	No effect was observed.	2

					rational explanation in the embryogenesis.		
Boles and Lohmann (2003)	Field	Caribbean spiny lobster (*Panulirus argus*)	Ambient	None	A series of three tests were conducted to determine if spiny lobster were capable of true navigation, by using magnetic cues at test sites rather than information gained on an outward journey.	Spiny lobster are capable of determining position as well as direction solely using magnetic cues, fulfilling the requirements of true navigation.	1
Gill and Taylor (2001)	Lab	Dogfish (*Scyliorhinus canicular*)	1000 µV/cm	None	Literature review of EMF effects from sub sea cables and study of dogfish response to an EMF similar to a offshore windfarm cable	A highly variable avoidance response by individual dogfish to the electric field which had a low probability of occurring	4
Skauli *et al.* (2000)	Lab	Zebrafish (*Danio rerio*)	1000 µT	AC	Zebrafish embryos in eggs were exposed to a strong magnetic field and compared to controls to see if hatching was delayed or effected.	Results suggest that exposure to the experimental magnetic field delayed hatching of eggs (dependent on timing of exposure) but did not cause deformities.	2
Formicki and Winnicki (1998)	Lab	Trout *(Salmo trutta)*, rainbow trout *(Oncorhynchus mykiss)*, pike *(Esox lucius)* and carp *(Cyprinus carpio)* hatchlings and larvae	0.5 – 13 mT	None	Studying the influence of magnetic fields on embryonic development, on circulatory locomotion in embryos and larvae, and on orientation in embryos.	Embryos of trout and rainbow trout exhibited orientation preferences both in the geomagnetic field and in the artificially generated field superimposed on the natural field. Magnetic fields of lower values (1-5 mT), exerted more evident positive influence on the	2

						embryonic and larval development of the fishes than the fields of higher values.	
Formicki *et al.* (1997)	Lab	Trout *(Salmo trutta* L.) and rainbow trout *(Oncorhynchus mykiss)*	0.5 – 1 mT	None	Studying whether embryos of trout and rainbow trout, developing inside eggs, do orient themselves in the natural and artificial magnetic fields.	There is a relationship between the responses and the magnetic field value as shown by responses to the natural and stronger artificial fields.	2
Walker *et al.* (1997)	Lab	Rainbow trout *(Oncorhynchus mykiss)*	-25 – 75 µT	None	A description of the key components of a magnetic sense underpinning this navigational ability in a single species, the rainbow trout.	Presence of both behavioural and electrophysiological responses to magnetic intensity in trout and there is a close association between magnetically responsive nerve and the candidate magnetoreceptor cells.	1
Yano *et al.* (1997)	Field	Chum salmon *(Oncorhynchus keta)*	0.6 mT	AC	To investigate the role of magnetic compass orientation in oceanic migrating chum salmon, Oncorhynchus keta.	There was no observable effect on the horizontal and vertical movements of the salmon when the magnetic field was modified; However, it was noted that salmon slowed their swimming speed significantly before changing direction.	3
Winnicki *et al.* (1993)	Lab	Trout (*Salmo trutta* L.) eggs	200 – 250 mT	None	Studying the effect of steady magnetic fields on water absorption of eggs of trout.	Eggs exposed to the magnetic field absorbed water much slower than control eggs.	1
Formicki *et al.* (1991)	Lab	Trout (*Salmo trutta* L.)	200 – 250 mT	None	Trout eggs were fertilized with spermatozoa which had been exposed for 4	5 hr exposure of spermatozoa to 200 mT magnetic field increased significant percentage of successfully fertilised eggs. 4 hr	1

					hours to the effect of a steady magnetic field of 200 mT and 250 mT and for 5 hours to 200 mT	exposure of 250 mT had no noticeable change.	
Tesch *et al.* (1991)	Field	Silver eels *(Anguilla anguilla L.)*	None	None	16 silver eels tagged with pressure sensing ultrasonic transmitters were released for tracking studies in the Central Baltic Sea.	Eels preferred to swim above the thermocline, in a mean depth of 7 to 11 m at night, and 4 m deeper during daylight. Dives of short duration were observed.	1
Chew and Brown (1989)	Lab	Rainbow trout *(Salmo gairdneri)*		None	To establish whether nonanadromous salmonid forms are capable of using geomagnetic cues in spatial behaviour.	Fish in normal EMFs showed preferred orientations. Other groups tested in null EMFs were statistically indistinguishable from randomness.	1
Souza *et al.* (1988)	Lab	Freshwater American eels *(Anguilla rostrata)*	-0.1 – 0.1 mT	None	Locations of freshwater yellow eels were videotaped during six-day intervals while the animals were being subjected to normal and experimental magnetic fields.	Preferred direction with -0.05 and -0.1 mT fields were southeast. In a 0 mT, there was a preference for north and under earth's EMF there was a preference for northeast to north to northwest.	2

Table 3: Existing EMF studies from 2022–1988 indicating responses from organisms to EMFs generated by subsea cables. Studies listed chronologically from most recent, then alphabetically by first author within each year. Relevance of studies was analysed and subsequently rated 1–5 (5 being most relevant, 1 being least relevant) according to the following criteria: 5 - A field study on an energised subsea power cable. Completely relevant to the question, without any major caveats; 4 - One significant caveat, or several minor ones. For example, freshwater, rather than marine, a lab study but still at EMF intensities relevant to subsea power cable, *etc.*; 3 - three significant caveats; 2 - more irrelevant than relevant with many significant caveats; examples include studies that use EMFs at strengths far in excess of those expected around subsea cables, but still show animal responses to EMF; 1 - Barely relevant. For example, a non-energised cable. *Source*: OSC (2022).

The strength of EMFs decays with distance from the source. Evidence has indicated that EMF can be expected to decrease to ambient levels within 20 m of a subsea power cable, thus only sensitive marine fauna in the near-zone are likely to be impacted (Bochert and Zettler, 2006; Frid *et al.*, 2012; Copping and Hemery, 2020). There is, however, the potential for effects to be wider-reaching (*i.e.* into the medium-zone), if multiple cables/developments are situated in close proximity, meaning that animals are not afforded sufficient 'influence free' space between artificial EMFs (Tricas and Gill, 2011).

5.3.1. Marine mammals

With the exception of Guiana dolphin, there is no evidence for electroreception in marine mammals (Czech-Damal *et al.*, 2012). There is, however, evidence of magnetoreception in a range of cetacean species (*e.g.* humpback whale, bottlenose dolphin, harbour porpoise); therefore the B-field component of EMFs poses much greater risk of impact than the E-field (Bauer *et al.*, 1985; Kirschvink *et al.*, 1986; Kirschvink, 1990; Kremers *et al.*, 2014). As described in **Section 5.2.1**, many cetacean species (and potentially some pinniped species) use the Earth's GMF to navigate, particularly during long migrations, which means there is the potential for anthropogenic EMFs to interfere with their navigational cues (Kirschvink *et al.*, 1986; Davis, 2019). Modelling approaches have indicated that bottlenose dolphin could potentially detect the B-field from a subsea cable up to 50 m away when directly above the cable, which could cause it to alter its direction of travel; however, the animal would only need to move a matter of metres away from the cable to no longer detect the artificial B-field and would most likely be able to correct its orientation (Tricas and Gill, 2011). The high mobility of most cetaceans means that they are unlikely to remain under the influence of EMFs generated by a subsea cable for any prolonged period of time, and so impacts are expected to be minimal (Tricas and Gill, 2011). The risk becomes greater in the event that an individual encounters multiple cables along its migratory route, meaning that they are afforded fewer 'influence-free' spaces where they can accurately navigate (Tricas and Gill, 2011). As magnetoreception in other marine mammal groups (carnivora) remains understudied, it is difficult to make meaningful predictions about how they may be impacted by EMFs (Tricas and Gill, 2011; Hanke *et al.*, 2021); however, risk from EMFs associated with FOWs is considered to be minimal.

5.3.2. Diving seabirds

Direct effects of EMFs generated by subsea cables on diving birds is likely limited, but understudied. A review of effects of EMF generated by land-based power lines showed that adverse effects can be present for wild birds, with a number of caveats (Fernie and Reynolds, 2005). The primary risk for birds with prolonged exposure to EMF (such as raptors breeding on EMF generating structures, for example) is reduced breeding success, though hindered song development in passerines, changes in egg sizes and development, suppressed melatonin concentrations, oxidative stress, elevated immune responses, and premature aging are all suggested as possible adverse outcomes. Notably, reduced breeding success and other adverse effects were only present in caged/aviary-based experiments, and these effects were not detected in wild birds (Fernie and Reynolds, 2005).

In a review of possible effects of wave energy installations on marine species, Lin and Yu (2012) suggest that decreased fertility could be a possible negative effect of underwater EMF produced by subsea cables; however, no studies have been conducted on impacts of EMF on diving birds. Given that EMF levels fall to approximately background levels of the GMF at a distance of 20 m from subsea cables (Frid *et al.*, 2012), and that diving (foraging) birds are unlikely to be located next to EMF producing subsea cables for a significant amount of time, it is highly unlikely that adverse effects would be present from subsea cable EMF.

5.3.3. Turtles

While there is no evidence of electroreception in sea turtles, they do use cues from the Earth's GMF (Lohmann, 1991; Light and Salmon, 1993; Lohmann and Lohmann, 1994a; 1994b; Goff *et al.*, 1998; Avens and Lohmann, 2003; Irwin and Lohmann, 2003; Cain *et al.*, 2005; Irwin and Lohmann, 2005; Tricas and Gill, 2011). Hatchlings rely on magnetoreception in order to travel towards the sea and navigate away from their natal beach (Goff *et al.*, 1998; Irwin and Lohmann, 2003). It is also thought that hatchlings imprint on the magnetic signature of their birth place, allowing them to return to the nesting beaches as adults (Lohmann *et al.*, 2008b; Putman and Lohmann, 2008). As such, impacts of EMFs emitted from a subsea cable in sensitive locations could be high, so laying cables near nesting sites should be avoided (Tricas and Gill, 2011). Risk to open-ocean migrating adults and juveniles is lower, as while they do make use of the GMF, they also rely on other cues such as light and wave motion (Lohmann and Lohmann, 1996; Papi *et al.*, 2000; Luschi *et al.*, 2001; Avens and Lohmann, 2003; Hays *et al.*, 2003). Consequently, as long as a FOW is not near a nesting beach, potential impact of EMFs is considered to be low.

5.3.4. Elasmobranchs

The primary concern for effects of EMF on elasmobranchs is impacts to feeding, predator/conspecific detection, and navigation (Tricas and Gill, 2011). While prolonged exposure to EMF is known to potentially affect development and physiology of other groups (Woodruff *et al.*, 2012), no direct studies have been conducted to demonstrate these adverse effects for elasmobranchs, and thus direct effects of EMF on elasmobranchs remains uncertain.

Indirect effects concerning predator/prey interactions, avoidance behaviours, and navigation are better studied. Elamobranchs can detect very low E-field – from 0.005 μV cm^{-1} (Taormina et al., 2018), thus despite strong industry-standard shielding of subsea cables, it is understood that these species will sense and be respond to cabling E-fields (Cliff and Dudley, 1992; Yano *et al.*, 2000). Notably, a recent field study conducted by Hutchison and colleagues in 2018 showed that little skates (*Leucoraia erinacea*) exhibited strong behavioural responses to variable power in a subsea cable (Hutchison *et al.*, 2018). This behavioural difference was strong enough to have biological relevance for the species and consequently have adverse implications. In this instance, the EMF did not constitute a barrier effect, but rather imparted differences in motility such as longer distances travelled and larger turns during swimming behaviour. Such behavioural changes could translate to interrupted foraging patterns, detection of prey/conspecifics, or increased energy expenditure with negative consequences for overall body condition.

For wild and highly motile elasmobranchs, the effects of exposure to cable EMF on behavioural responses and population-level impacts is not well understood. Current studies have investigated single exposures to EMF in discrete time periods rather than repeated and multiple exposures over time, and responses will likely be determined by a number of factors, including species distribution (both broad spatial ranges and vertically within the water column), distribution of cabling (affecting encounter rate with EMF), migratory patterns, and near-cable behaviour (Tricas and Gill, 2011). Additionally, it is expected that there would be sex- and age-specific differences for individuals. Again, the primary risk of EMF for elasmobranchs is directional/navigational miscues. For species that migrate for the purposes of reproduction, disruptions in migratory patterns due to encounters with cable EMF may have population impacts, though there have been no studies confirming this potential risk (Westerberg and Lagenfelt, 2008 investigated EMF impacts on European eel and did not find evidence of population-level impacts, additionally noting that no impacts have been shown concerning physiology, development, or survival for these taxa).

Several impacts and risks of E-fields on navigation, behaviour, and population-level impacts have been conjectured for elasmobranchs, but the dearth of studies (especially those examining cumulative effects on repeated exposure to EMF through space and time) lends high uncertainty to these hypothesized impacts.

5.3.5. Fish

Copping *et al.* (2021) provides the most recent review of EMF impacts on fish species and provides a survey of current knowledge of how EMF potentially directly impacts fish species, citing laboratory studies that demonstrated changes in development/growth (earlier hatch dates for whitefish and vendace, Brysiewicz *et al.*, 2017; smaller yolk sacs and faster absorption in Northern pike, Fey *et al.*, 2019a; yolk sac absorption rate in rainbow trout, Fey *et al.*, 2019b) and physiological effects (decreased enzyme activity in crucian carp, Kuz'mina *et al.*, 2015; changes in intracellular ions in carp species, Kantserova *et al.*, 2017; nuclear abnormalities for rainbow trout, Stankevičiūtė *et al.*, 2019). Relevant studies have primarily been conducted on freshwater species. It is possible that similar direct effects on physiology and growth are present for marine species due to shared physiology, but this has yet to be confirmed. A major knowledge gap identified by Copping *et al.* (2021) is the need to confirm which marine and diadromous species are sensitive to EMF and if EMF sensitive species react to cable signatures in the wild. Formicki *et al.* (2004b) suggest a number of freshwater species are electroreceptive. Newton *et al.* (2019) provides a review that highlights uncertainty surrounding the ability of marine teleost fish to respond to EMF. Overall, the risk of direct impacts of EMF on fish development and physiology may be low for certain taxa, as pelagic species will have low encounter rates with EMF fields. Coastal and demersal species potentially have a higher risk of detrimental effects, though there is a lack of study to confirm sensitivity to EMF of most marine fish species. Furthermore, while physiology supporting detection of magnetic fields (i.e. ferromagnetic material in bone structure) has been found in several species of marine fish (Öhman *et al.*, 2007), no behavioural studies have been conducted to confirm is these taxa are reactive to EMF.

Mesocosm field studies have been implemented to assess indirect impacts on fish species regarding behavioural modification and navigational impacts. Like elasmobranchs, other fish taxa are believed to have the capability to detect EMF (Kirschvink and Neeson, 1997; Tricas and New, 1997), and thus there is the potential for indirect effects through impacts on navigational cues and behavioural modification. Impacts from the few studies of behavioural modification that have been conducted appear to be low. Salmon migration was found to be mostly unchanged (Wyman *et al.*, 2018), as was green sturgeon migration (Kavet *et al.*, 2016). Broadly, there is little evidence that shows indirect effects on fish species due to EMF exposure, but impacts remain understudied, particularly in the case of examining species which have more pelagic distributions and thus limited exposure to subsea cabling.

Similar to elasmobranchs, there is a lack of study estimating the cumulative effects of EMF exposure on other fish taxa. Again, it is hypothesised that population level impacts could be present for fish exposed to subsea cable EMF, but uncertainty in this regard is high.

5.4. Mitigation options

The current uncertainty surrounding the potential environmental impacts of EMFs from subsea cables makes it difficult to assess the degree to which mitigation measures should be required (Tricas and Gill, 2011; Copping and Hemery, 2020). Should they prove necessary, there are a number of solutions – some of which have the added benefit of providing the cable with additional protection, and so can be implemented without significant additional cost. This is advantageous as additional cost is often an obstacle in getting environmental mitigation measures approved of by developers (Tricas and Gill, 2011).

Current industry-standard cable insulation or sheathing have been shown to be successful in preventing the emission of E-fields directly (Gill *et al.*, 2005; Scott *et al.*, 2021). Sheathing (along with increasing the permeability and conductivity of the sheaths) can sometimes reduce the level of B-field emitted to an extent; however, there is not as of yet a standard form of insulation that can completely prevent B-field leakage, or therefore, the generation of iE-fields (Gill *et al.*, 2005; Tricas and Gill, 2011; Scott *et al.*, 2021)

B-field generation is likely to be most significantly affected by cable design and voltage. For the same power delivered, higher voltage cables produce lower strength B-fields than lower voltage cables, and, for the same voltage, AC cables produce lower strength B-fields than DC cables (Tricas and Gill, 2011). Other technical design standards, such as helically twisted there-conductor cables, may be effective in reducing EMF emissions (Petterson and Schönborg, 1997; Copping and Hemery, 2020)

Several adaptations to cable configuration can reduce the strength of EMFs produced. For example, placing cables close together can allow the B-field vectors from each cable to cancel each other out (Tricas and Gill, 2011). Considering the orientation of a cable relative to the local GMF can also determine the strength of the combined field as, depending on direction, the effect of the two fields can be additive or cancel each other out (Tricas and Gill, 2011). This may be more difficult for some projects as the most desirable cable route is usually the most direct path between the asset and land (this is advantageous because it minimises both costs and seabed disturbance). This kind of cost/benefit assessment will need to be conducted on an individual project-specific basis. The unique combination of turbine size, distance from shore, shoreline configuration, local wind and seabed characteristics, and cable requirements, along with considerations for potential impacts of EMFs and other environmental factors will inform the optimal layout of a wind project (Tricas and Gill, 2011).

Burial of cables increases the distance between the cable and most demersal and benthic species and so reduces their exposure to the greatest strengths of EMFs produced. Nevertheless, it is not a truly effective mitigation measure as it does not stop EMFs from being emitted into the environment (Copping and Hemery, 2020). It is also not always practical, particularly in the case of FOWs where the cables themselves must be suspended in the water column.

Avoidance is generally considered the most effective mitigation strategy and, certainly until further research provides more conclusive results on the risks exposure to EMFs pose to marine life, it is recommended that subsea power cables avoid particularly sensitive sites, such as turtle nesting beaches (Tricas and Gill, 2011).

Future plans for mitigation could be improved by monitoring and measuring actual E-fields and B-fields surrounding cables with mitigation measures implemented once they are powered. These measurements would be useful for validating modelling conducted during the permitting stage and in assessing actual effectiveness of the mitigation strategy (Tricas and Gill, 2011).

5.5. Knowledge gaps

Significant data and knowledge gaps are present concerning impacts of EMF, largely due to difficulties in studying pelagic species interactions and encounters with EMF, as well as a lack of study on which species are receptive or sensitive to EMF. Copping *et al.* (2021) highlight key knowledge gaps in relation to understanding potential risks of EMF on marine species. These include measurements and estimates of power emittance from cables to estimate exposure to marine species, baseline studies to determine which diadromous and marine fish are actually receptive of or sensitive to electromagnetic fields, and estimates of cumulative effects of EMF (through repeated exposure through time and space) and how those effects may have negative outcomes on affected species.

Significant data gaps exist in parallel to knowledge gaps of research questions. As suggested by Taormina *et al.* (2018), there is very little understanding of sensitivity to EMF thresholds for nearly all marine species (notably including marine mammals, crustaceans, and most pelagic species), and what data we do have is only available for a small number of taxa. Addressing data gaps in which species are sensitive to EMF would be the first step in better understanding how EMF may directly impact species of concern. Indirect effects, such as possible population-wide impacts, could only be addressed after establishing the baseline knowledge.

Similarly, cumulative impacts of repeated exposures and combinatory impacts of other anthropogenic stressors (such as pollution or sediment perturbation) with EMF have yet to be addressed. This represents another knowledge gap that could have significant implications for the overall effect of EMF on species of concern.

6. CONCLUSIONS

In conclusion, FOWs are not expected to elicit a barrier effect, except perhaps for baleen whales; however, there is considerable uncertainty in this, as most existing windfarms have not been installed across baleen whale migratory corridors. It is unlikely that FOWs will result in direct entanglement; however, there is significant risk that ghost fishing gear may entangle on FOW moorings and cables and subsequently cause secondary entanglement with marine fauna. Rates of gear snagging on FOW structures must be monitored closely to assess level of risk. EMFs may be detected by some species, particularly elasmobranchs, but any potential effects will be localised and unlikely to impact populations significantly; however, there may be greater impacts if FOWs are created in sensitive areas, such as adjacent to turtle nesting beaches. Significant knowledge gaps remain surrounding all three subject areas covered in this review and substantial research is required to gain a deeper understanding of impacts and the current status of marine megafauna's habitat use at FOW sites.

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8. REFERENCES

ABS Group (2021): Floating offshore wind turbine development assessment. *OCS Study BOEM 2021-030*. Arlington, VA. 311 pp.

Ahl, A.S. (1986): The role of vibrissae in behavior: a status review. *Veterinary Research Communications* **10**, 245-268.

Akeov, G.N., Ilyinsky, O.B., and Zadan, P.M. (1976): Responses of electroreceptors (ampullae of Lorenzini) of skates to electric and magnetic fields. *Journal of Comparative Physiology* **106**, 127-136.

Akvaplan-niva (2021): Glider study at Hywind Scotland. *Report: 2021 62861.01 for Equinor Energy AS*. 46 pp.

Alerstam, T. (2003): The lobster navigators. *Nature* **421**, 27-28.

Alexiadou, P., Foskolos, I., and Frantzis, A. (2019): Ingestion of macroplastics by odontocetes of the Greek Seas, Eastern Mediterranean: Often deadly! *Marine Pollution Bulletin* **146**, 67-75.

Anderson, J.M., Clegg, T.M., Véras, L.V.M.V.Q., and Holland, K.N. (2017): Insight into shark magnetic field perception from empirical observations. *Scientific Reports* **7**, 11042.

Andersson, M., H.,, and Öhman, M., C. (2010): Fish and sessile assemblages associated with wind-turbine constructions in the Baltic Sea. *Marine and Freshwater Research* **61**, 642-650.

Andersson, M.H., Lagenfelt, I., and Sigray, P. (2010): Do ocean-based wind farms alter the migration pattern in the endangered European silver eel (*Anguilla anguilla)* due to noise disturbance? 2nd International Conference on the effects of noise on aquatic marine life on 15-20th August, Cork, pp. 6.

Andrady, A.L. (2011): Microplastics in the marine environment *Marine Pollution Bulletin* **62**, 10.

André, M., van der Schaar, M., Zaugg, S., Houégnigan, L., Sánchez, A., Mas, A., and Castell, J.V. (2010): Real-time monitoring of noise in cetacean acoustic niches. 2nd International Conference on the effects of noise on aquatic marine life on 15-20th August, Cork, pp. 7.

Andrews, K.M., Langen, T.A., and Struijk, R.P.J.H. (2015): Reptiles: overlooked but often at risk from roads: *Handbook of Road Ecology*. pp. 271-280.

Andrianov, G.N., Brown, H.R., and Ilyinsky, O.B. (1974): Responses of central neurons to electrical and magnetic stimuli of the ampullae of Lorenzini in the Black Sea skate. *Journal of Comparative Physiology* **93**, 287-299.

Arimto, T., Glass, C.W., and Zhang, X. (2011): Fish vision and its role in fish capture: *Behavior of marine fishes: capture processes and conservation challenges*. John Wiley & Sons.

Arnould, J.P., Monk, J., Ierodiaconou, D., Hindell, M.A., Semmens, J., Hoskins, A.J., Costa, D.P., Abernathy, K., and Marshall, G.J. (2015): Use of anthropogenic sea floor structures by Australian fur seals: potential positive ecological impacts of marine industrial development? *PLoS ONE* **10**, e0130581.

Arso Civil, M., Quick, N.J., Cheney, B., Pirotta, E., Thompson, P.M., and Hammond, P.S. (2019): Changing distribution of the east coast of Scotland bottlenose dolphin population and the challenges of area-based management. *Aquatic Conservation: Marine and Freshwater Ecosystems* **29**, 178-196.

Au, S.Y., Lee, C.M., Weinstein, J.E., van den Hurk, P., and Klaine, S.J. (2017): Trophic transfer of microplastics in aquatic ecosystems: identifying critical research needs. *Integrated Environmental Assessment and Management* **13**, 5.

Au, W.W., and Snyder, K.J. (1980): Long-range detection in open waters by an echolocating Atlantic Bottlenose dolphin (*Tursiops truncatus*). *The Journal of the Acoustical Society of America* **68**, 1077-1084.

Avens, L., and Lohmann, K.J. (2003): Use of multiple orientation cues by juveile loggerhead sea turtles *Caretta caretta*. *Journal of Experimental Biology* **206**, 4317-4325.

Bailey, A.W. (1970): Barrier effect of the shrub *Elaeagnus commutata* on grazing cattle and forage production in central Alberta. *Journal of Range Management* **23**.

Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G., and Thompson, P.M. (2010): Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. *Marine Pollution Bulletin* **60**, 888-897.

Bailey, H., Brookes, K.L., and Thompson, P.M. (2014): Assessing environmental impacts of offshore wind farms: lessons learned and recommendations for the future. *Aquatic Biosystems* **10**, 1-13.

Barry, J.P., Kuhnz, L., Buck, K., Lovera, C., and Whaling, P.J. (2008): Potential impacts of the MARS cable on the seabed and benthic faunal assemblages. Monterey Bay Aquarium Research Institute.

Basran, C.J., Bertulli, C.G., Cecchetti, A., Rasmussen, M.H., Whittaker, M., and Robbins, J. (2019): First estimates of entanglement rate of humpback whales *Megaptera novaeangliae* observed in coastal Icelandic waters. *Endangered Species Research* **38**, 67-77.

Bassett, C., Thomson, J., Dahl, P., H.,, and Polagye, B. (2014): Flow-noise and turbulence in two tidal channels. *The Journal of the Acoustical Society of America* **135**, 1764-1774.

Bauer, G.B., Fuller, M., Perry, A., Dunn, J.R., and Zoeger, J. (1985): Magnetoreception and biomineralization of magnetite in cetaceans. In J. L. Kirschvink, D. S. Jones, and B. J. MacFadden (Eds): *Magnetite biomineralization and magnetoreception in organisms*, Vol. 5. Springer, pp. 489-507.

Bauer, L.J., Kendall, M.S., and Jeffrey, C.F.G. (2008): Incidence of marine debris and its relationships with benthic features in Gray's reef National Marine Sanctuary, Southeast USA. *Marine Pollution Bulletin* **56**, 12.

Bellono, N.W., Leitch, D.B., and Julius, D. (2018): Molecular tuning of electroreception in sharks and skates. *Nature* **558**, 122-126.

Benhemma-Le Gall, A., Graham, I.M., Merchant, N.D., and Thompson, P.M. (2021): Broad-scale responses of harbor porpoises to pile-driving and vessel activities during offshore windfarm construction. *Frontiers in Marine Science* **8**.

Benjamins, S., Harnoise, V., Smith, H. C. M., Johanning, L., Greenhill, L., Carter, C., Wilson, B. (2014): Understanding the potential for marine megafauna entanglement risk from renewable marine energy developments. Scottish Natural Heritage Commissioned Report No 791, Perth, Scotland. 95 pp.

Bennett, A.T.D., and Théry, M. (2007): Avian color vision and coloration: multidisciplinary evolutionary biology. *The American Naturalist* **169**.

Bergström, L., Sundqvist, F., and Bergström, U. (2013): Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community. *Marine Ecology Progress Series* **485**, 199-210.

Bevelhimer, M.S., Cada, G.F., Fortner, A.M., Schweizer, P.E., and Riemer, K.P. (2013): Laboratory studies of the short-term responses of freshwater fish to electromagnetic fields. *Transactions of the American Fisheries Society* **142**, 12.

Bevelhimer, M.S., Cada, G.F., and Scherelis, C. (2015): Effects of electromagnetic fields on behavior of largemouth bass and pallid sturgeon in an experimental pond setting. Oak Ridge National Laboratory, US Department of Energy.

Bielli, A., Alfaro-Shigueto, J., Doherty, P.D., Godley, B.J., Ortiz, C., Pasara, A., Wang, J.H., and Mangel, J.C. (2020): An illuminating idea to reduce bycatch in the Peruvian small-scale gillnet fishery. *Biological Conservation* **241**.

Blonder, B.I., and Alevizon, W.S. (1988): Discrimination and electroreception in the stingray *Dasyatis sabina*. *Copeia* **1**, 33-36.

Bochart, R., and Zettler, M.L. (2006): Effect of electromagnetic fields on marine organisms *Offshore Wind Energy*. Springer, Berline, Hedeilberg, Be, pp. 12.

Bochert, R., and Zettler, M.L. (2006): Effect of electromagnetic fields on marine organisms. In J. Köller, J. Köppel, and W. Peters (Eds): *Offshore Wind Energy*. Springer, Berlin.

Boles, L.C., and Lohmann, K.J. (2003): True navigation and magnetic maps in spiny lobsters. *Nature* **421**, 60.

Bonizzoni, S., Furey, N.B., Pirotta, E., Valavanis, V.D., Würsig, B., and Bearzi, G. (2014): Fish farming and its appeal to common bottlenose dolphins: modelling habitat use in a Mediterranean embayment. *Aquatic Conservation: Marine and Freshwater Ecosystems* **24**, 696-711.

Bradbury, G., Trinder, M., Furness, B., Banks, A.N., Caldow, R.W., and Hume, D. (2014): Mapping seabird sensitivity to offshore wind farms. *PLoS ONE* **9**, e106366.

Braithwaite, J.E., Meeuwig, J.J., and Hipsey, M.R. (2015): Optimal migration energetics of humpback whales and the implications of disturbance. *Conservation physiology* **3**, cov001-cov001.

Brandt, M.J., Diederichs, A., Betke, K., and Nehls, G. (2011): Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. *Marine Ecology Progress Series* **421**, 205-216.

Braulik, G.T., Arshad, M., Noureen, U., and Northridge, S.P. (2014): Habitat fragmentation and species extirpation in freshwater ecosystems; causes of range decline of the Indus river dolphin (*Platanista gangetica minor*). *PLoS ONE* **9**, e101657.

Breen, P.A. (1987): Mortality of dungeness crabs caused by lost traps in the Fraser River estuary, British Columbia. *North American Journal of Fisheries Management* **7**, 7.

Brown, F.A.J., Barnwell, F.H., and Webb, H.M. (1964): Adaptation of the magnetoreceptive mechanism of mud-snails to geomagnetic strength. *The Biological Bulletin* **127**, 221-231.

Brown, J., Macfadyen, G., Huntington, T., Magnus, J., and Tumilty, J. (2005): Ghost fishing by lost fishing gear. *Final Report: DG FISH/2004/20*. to DG Fisheries and Maritime Affairs of the European Commission, London, UK. 151 pp.

Brownlow, A. (2011): Annual final report: 1 January April 2008 to 31 December March 2011. *Final Report*. Scottish Marine Animal Stranding Scheme, Inverness, Scotland. 58 pp.

Brownlow, A., and Davison, N. (2013): Annual report 2013: 1 January to 31 December 2013. *Final Report*. Scottish Marine Animal Stranding Scheme, Inverness, Scotland. 72 pp.

Brownlow, A., Davison, N., and ten Doeschate, M. (2014): Annual report 2014: 1 January to 31 December 2014. *Final Report*. Scottish Marine Animal Stranding Scheme, Inverness, Scotland. 96 pp.

Brownlow, A., Davison, N., and ten Doeschate, M. (2015): Annual report 2015: 1 January to 31 December 2015. *Final Report*. Scottish Marine Animal Stranding Scheme, Inverness, Scotland. 127 pp.

Brownlow, A., Davison, N., and ten Doeschate, M. (2016): Annual report 2016: 1 January to 31 December 2016. *Final Report*. Scottish Marine Animal Stranding Scheme, Inverness, Scotland. 122 pp.

Brownlow, A., Davison, N., and ten Doeschate, M. (2017): Annual report 2017: 1 January to 31 December 2017. *Final Report*. Scottish Marine Animal Stranding Scheme Inverness, Scotland. 119 pp.

Brownlow, A., Davison, N., and ten Doeschate, M. (2018): Annual report 2018: 1 January to 31 December 2018. *Final Report*. Scottish Marine Animal Stranding Scheme, Inverness, Scotland. 94 pp.

Brysiewicz, A., Formicki, K., Tański, A., and Wesołowski, P. (2017): Magnetic field effect on melanophores of the European whitefish *Coregonus lavaretus* (Linnaeus, 1758) and vendace *Coregonus albula* (Linnaeus, 1758) (Salmonidae) during early embryogenesis. *The European Zoological Journal* **84**, 49-60.

Bullock, T.H. (1999): The future of research on electroreception and electrocommunication. *Journal of Experimental Biology* **202**, 1455-1458.

Bullock, T.H., Hopkinds, C.D., Popper, A.N., and Fay, R.R. (2005): *Electroreception*. Springer.

Burns, R.D.J., S.B. Martin, M.A. Wood, C.C. Wilson, C.E. Lumsden, and F. Pace (2022): Hywind Scotland floating offshore wind farm: sound source charactierisation of operational floating turbines. *Document 02521, Version 3.0 FINAL*. Technical report by JASCO Applied Sciences for Equinor Energy AS.

Butterworth, A., Clegg, I., and Bass, C. (2012): Marine debris: a global picture of the impact on animal welfare and of animal-focused solutions. World Society for the Protection of Animals, London. 79 pp.

Cada, G.F., Bevelhimer, M.S., Riemer, K.P., and Turner, J.W. (2011): Effects on freshwater organisms of magnetic fields associated with hydrokinetic turbines. Oak Ridge National Laboratory.

Cain, S.D., Boles, L.C., Wang, J.H., and Lohmann, K.J. (2005): Magnetic orientation in marine turtles, lobsters, and molluscs: concepts and conundrums. *Integrative and Comparative Biology* **45**, 539-546.

Cain, S.D., Wang, J.H., and Lohmann, K.J. (2006): Immunochemical and electrophyiological analyses of magnetically responsive neurons in the mollusc *Tritonia diomedea*. *Journal of Comparative Physiology* **192**, 235-245.

Cameron, I.L., Hardman, W.E., Winters, W.D., Zimmerman, S., and Zimmerman, A.M. (1993): Enviornmental magnetic fields: influences on early embryogenesis. *Journal of Cellular Biochemistry* **51**, 417-425.

Camphuysen, C., and Webb, A. (1999): Multi-species feeding associations in North Sea seabirds: jointly exploiting a patchy environment. *Ardea* **87**, 177-198.

Cantley, J.C., Bond, A.L., Wells-Berlin, A.M., Crawford, R., Martin, G.R., Rouxel, Y., Peregoy, S., McGrew, K., and Portugal, S.J. (2020): Ineffectiveness of light emitting diodes as underwater deterrents for long-tailed ducks, *Clangula hyemalis*. *Global Ecology and Conservation* **23**, 12.

Carpenter, J.R., Merckelbach, L., Callies, U., Clark, S., Gaslikova, L., and Baschek, B. (2016): Potential impacts of offshore wind farms on North Sea stratification. *PLoS ONE* **11**, e0160830.

Castro, J.J., Santiago, J.A., and Santana-Ortega, A.T. (2002): A general theory on fish aggregation to floating objects: An alternative to the meeting point hypothesis. *Reviews in Fish Biology and Fisheries* **11**, 255-277.

Cazenave, P.W., Torres, R., and Allen, J.I. (2016): Unstructured grid modelling of offshore wind farm impacts on seasonally stratified shelf seas. *Progress in Oceanography* **145**, 25-41.

Centre for Marine and Coastal Studies (2003): A baseline assessment of electromagnetic fields generated by offshore windfarm cables. *COWIE Report EMF 01-2022 66*. University of Liverpool.

Chebotareva, Y.V., Izyumov, Y.G., and Krylow, V.V. (2009): The effect of an alternating electromagnetic field upon early development in roach *(Rutilus rutilus: Cyprinidae, Cypriniformes)*. *Journal of Ichthyology* **45**, 8.

Cheney, B., Thompson, P.M., Ingram, S.N., Hammond, P.S., Stevick, P.T., Durban, J.W., Culloch, R.M., Elwen, S.H., Mandleberg, L., Janik, V.M., Quick, N.J., Islas-Villanueva, V., Robinson, K.P., Costa, M., Eisfeld, S.M., Walters, A., Phillips, C., Weir, C.R., Evans, P.G.H., Anderwald, P., Reid, R.J., Reid, J.B., and Wilson, B. (2013): Integrating multiple data sources to assess the distribution and abundance of bottlenose dolphins *Tursiops truncatus* in Scottish waters. *Mammal Review* **43**, 71-88.

Chew, G.L., and Brown, G.E. (1989): Orientation of rainbow trout *(Salmo gairdneri)* in normal and null magnetic fields. *Canadian Journal of Zoology* **67**, 3.

Chiappone, M., Dienes, H., DSwanson, D.W., and Miller, S.L. (2005): Impacts of lost fishing gear on coral reef sessile invertebrates in the Florida Keys national marine sanctuary *Biological Conservation* **121**, 10.

Clark, R.B. (1997): *Marine pollution*. Oxford: Clarendon Press, New York, USA.

Clausen, K.T., Teilmann, J., Wisniewska, D.M., Balle, J.D., Delefosse, M., and van Beest, F.M. (2021): Echolocation activity of harbour porpoises, *Phocoena phocoena*, shows seasonal artificial reef attraction despite elevated noise levels close to oil and gas platforms. *Ecological Solutions and Evidence* **2**, e12055.

Cliff, G., and Dudley, S.F. (1992): Protection against shark attack in South Africa, 1952-90. *Marine and Freshwater Research* **43**, 263-272.

Collin, S.P., and Whitehead, D. (2004): The functional roles of passive electroreception in non-electric fishes. *Animal Biology* **54**, 1-25.

Collin, S.P. (2018): Scene through the eyes of an apex predator: a comparative analysis of the shark visual system. *Clinical and Experimental Optometry* **101**, 17.

Consoli, P., Andaloro, F., Altobelli, C., Battaglia, P., Campagnuolo, S., Canese, S., Castriota, L., Cillari, T., Falautano, M., Peda, C., Perzia, P., Sinopoli, M., Vivona, P., Scotti, G., Esposito, V., Galgani, F., and Romeo, T. (2018): Marine litter in an EBSA (Ecologically or Biologically Significant Area) of the central Mediterranean Sea: abundance, composition, impact on benthic species and basis for monitoring entanglement *Environmental Pollution* **236**, 11.

Copping, A., and Grear, M. (2018): Humpback whale encounter with offshore wind mooring lines and inter-array cables. Bureau of Ocean Energy Management. 34 pp.

Copping, A.E., and Hemery, L.G. (2020): OES-Environmental 2020 state of the science report: environmental effects of marine renewable energy development around the world. Ocean Energy Systems (OES).

Copping, A.E., Hemery, L.G., Viehman, H., Seitz, A.C., Staines, G.J., and Hasselman, D.J. (2021): Are fish in danger? A review of environmental effects of marine renewable energy on fishes. *Biological Conservation* **262**.

Cotter, E., Murphy, P., Bassett, C., Williamson, B., and Polagye, B. (2019): Acoustic characterization of sensors used for marine environmental monitoring. *Marine Pollution Bulletin* **144**, 205-215.

Cox, T.M., Read, A.J., Barco, S., Evans, J., Gannon, D.P., Koopman, H.N., McLellan, W.A., Murray, K., Nicolas, J., Pabst, D.A., Potter, C.W., Swingle, W.M., Thayer, V.G., Touhey, K.M., and Westgate, A.J. (1998): Documenting the bycatch of harbor porpoises, *Phocoena phocoena*, in coastal gillnet fisheries from stranded carcasses. *Fishery Bulletin* **96**, 727-734.

Cox, T.M., Read, A.J., Swanner, D., Urian, K., and Waples, D. (2003): Behavioral responses of bottlenose dolphins, *Tursiops truncatus*, to gillnets and acoustic alarms. *Biological Conservation* **115**, 203-212.

Cresci, A., Durif, C.M.F., Larsen, T., Bjelland, R., Skiftesvik, A.B., and Bowman, H.I. (2022): Magnetic fields produced by subsea high-voltage direct current cables reduce swimming activity of haddock larvae *Melangrammus aeglefinus*. *PNAS Nexus* **1**.

CWR (2012): Griffin Venture whale monitoring project.

Czech-Damal, N.U., Liebschner, A., Miersch, L., Klauer, G., Hanke, F.D., Marshall, C., Dehnhardt, G., and Hanke, W. (2012): Electroreception in the Guiana dolphin (*Sotalia guianesnsis*). *Proceedings Of The Royal Society B* **279**, 663-668.

Czech-Damal, N.U., Dehnhardt, G., Manger, P., and Hanke, W. (2013): Passive electroreception in aquatic animals. *Journal of Experimental Biology* **199**, 555-563.

Darby, J., Clairbaux, M., Bennison, A., Quinn, J.L., and Jessopp, M.J. (2022): Underwater visibility constrains the foraging behaviour of a diving pelagic seabird. *Proceedings of the Royal Society B: Biological Sciences* **289**, 20220862.

Davis, R.W., Fuiman, L.A., Williams, T.M., and Le Boeuf, B.J. (2001): Three-dimensional movement and swimming activity of a northern elephant seal. *Comparative Biochemistry and Physiology Part A* **129**, 759-770.

Davis, R.W. (2019): *Marine mammals: adaptations for an aquatic life*. Springer International Publishing, Cham.

Davison, N., ten Doeschate, M., and Brownlow, A. (2019): Annual report 2019: 1 January to 31 December 2019. *Final Report*. Scottish Marine Animal Stranding Scheme, Inverness, Scotland. 96 pp.

Davison, N., and ten Doeschate, M. (2020): Annual report 2020: 1 January to 31 December 2020 *Final Report*. Scottish Marine Animal Stranding Scheme Inverness, Scotland. 87 pp.

De Luca, R. (2009): Lorentz force on sodium and chlorine ions in a salt water solution flow under a transverse magnetic field. *European Journal of Physics* **30**, 459-466.

de Stephanis, R., Giménez, J., Carpinelli, E., Gutierrez-Exposito, C., and Cañadas, A. (2013): As main meal for sperm whales: plastics debris. *Marine Pollution Bulletin* **69**, 206-214.

de la Cruz, A., Ramos, F., Tornero, J., Rincón, M.M., Jiménez, M.P., and Arroyo, G.M. (2022): Seabird distribution is better predicted by abundance of prey than oceanography. A case study in the Gulf of Cadiz (SW, Iberian Peninsula). *ICES Journal of Marine Science* **79**, 204-217.

Delefosse, M., Rahbek, M.L., Roesen, L., and Clausen, K.T. (2018): Marine mammal sightings around oil and gas installations in the central North Sea. *Journal of the Marine Biological Association of the United Kingdom* **98**, 993-1001.

Diebel, C.E., Proksch, R., Green, C.R., Neilson, P., and Walker, M.M. (2000): Magnetite defines a vertebrate magnetoreceptor. *Nature* **406**, 299-302.

Dierschke, V., Furness, R.W., and Garthe, S. (2016): Seabirds and offshore wind farms in European waters: avoidance and attraction. *Biological Conservation* **202**, 59-68.

Dittman, A.H., and Quinn, T.P. (1996): Homing in Pacific salmon: mechanisms and ecological basis. *Journal of Experimental Biology* **199**, 83-91.

Donohue, M.J., Boland, R.C., Sramek, C.M., and Antonelis, G.A. (2001): Derelict fishing gear in the Northwestern Hawaiian Islands: diving surveys and debris removal in 1999 confirm threat to coral reef ecosystems *Marine Pollution Bulletin* **42**, 12.

Douglas, R.H., and Hawryshyn, C.W. (1990): Behavioural studies of fish vision: an analysis of visual capabilities: *The visual system of fish*. Springer Dordrecht, pp. 373-418.

Drewitt, A., and Langston, R.H.W. (2008): Collison effects of wind-power generators and other obstacles on birds. *New York Academy of Sciences* **1134**, 34.

Drewitt, A.L., and Langston, R.H.W. (2006): Assessing the impacts of wind farms on birds. *Ibis* **148**, 29-42.

Duncan, E.M., Botterell, Z.L.R., Broderick, A.C., Galloway, T.S., Lindeque, P.K., Nuno, A., and Godley, B.J. (2017): A global review of marine turtle entanglement in anthropogenic debris: a baseline for further action. *Endangered Species Research* **34**, 19.

Dunlop, E.S., Reid, S.M., and Murrant, M. (2016): Limited influence of a wind power project submarine cable on a Laurentian Great Lakes fish community. *Journal of Applied Ichthyology* **32**, 18-31.

Dunlop, R.A., Braithwaite, J., Mortensen, L.O., and Harris, C.M. (2021): Assessing population-level effects of anthropogenic disturbance on a marine mammal population. *Frontiers in Marine Science* **8**.

Equinor (2022): Synergi registrations fishing gear 2006_2022. Equinor, Denmark. 12 pp.

Erbe, C., Dunlop, R., and Dolman, S. (2018): Effects of noise on marine mammals. In H. Slabbekoorn, R. J. Dooling, A. N. Popper, and R. R. Fay (Eds): *Effects of anthropogenic noise on animals*. Springer New York, New York, NY, pp. 277-309.

Ernst, D.A., and Lohmann, K.J. (2016): Effect of magnetic pulses on Caribbean spiny lobsters: implications for magnetoreception. *Journal of Experimental Biology* **219**, 1827-1832.

Ernst, D.A., and Lohmann, K.J. (2018): Size-dependent avoidance of a strong magnetic anomaly in Carribbean spiny lobsters. *Journal of Experimental Biology* **221**.

Farr, H., Ruttenberg, B., Walter, R.K., Wang, Y.-H., and White, C. (2021): Potential environmental effects of deepwater floating offshore wind energy facilities. *Ocean and Coastal Management*.

Fernandez-Betelu, O., Graham, I.M., and Thompson, P.M. (2022): Reef effect of offshore structures on the occurrence and foraging activity of harbour porpoises. *Frontiers in Marine Science* **9**.

Fernie, K.J., and Reynolds, S.J. (2005): The effects of electromagnetic fields from power lines on avian reproductive biology and physiology: a review. *Journal of toxicology and environmental health, part b* **8**, 127-140.

Fey, D.P., Greszkiewicz, M., Otremba, Z., and Andrulewicz, E. (2019a): Effect of static magnetic field on the hatching success, growth, mortality, and yolk-sac absorption of larval Northern pike *Esox lucius*. *Science of the Total Environment* **647**, 1239-1244.

Fey, D.P., Jakubowska, M., Greszkiewicz, M., Andrulewicz, E., Otremba, Z., and Urban-Malinga, B. (2019b): Are magnetic and electromagnetic fields of anthropogenic origin potential threats to early life stages of fish? *Aquatic Toxicology* **209**, 150-158.

Filmalter, J., Cowley, P., Forget, F., and Dagorn, L. (2015): Fine-scale 3-dimensional movement behaviour of silky sharks *Carcharhinus falciformis* associated with fish aggregating devices (FADs). *Marine Ecology Progress Series* **539**, 207-223.

Floeter, J., van Beusekom, J.E.E., Auch, D., Callies, U., Carpenter, J., Dudeck, T., Eberle, S., Eckhardt, A., Gloe, D., Hänselmann, K., Hufnagl, M., Janßen, S., Lenhart, H., Möller, K.O., North, R.P., Pohlmann, T., Riethmüller, R., Schulz, S., Spreizenbarth, S., Temming, A., Walter, B., Zielinski, O., and Möllmann, C. (2017): Pelagic effects of offshore wind farm foundations in the stratified North Sea. *Progress in Oceanography* **156**, 154-173.

Formicki, K., Sadowski, M., Winnicki, A., and Mongialo, Z. (1991): Effects of fertilising sea trout (Salmo trutta L.) eggs with spermatozoa exposed to a magnetic field. *Acta Ichthyologica Et Piscatoria* **21**, 6.

Formicki, K., Bonislawska, M., and Jasinski, M. (1997): Spatial orientation of trout (Salmo trutta L.) and rainbow trout (Oncorhynchud mykiss walb.) embroys in natural and artificial magnetic fields *Acta Ichthyologica Et Piscatoria* **27**, 13.

Formicki, K., and Winnicki, A. (1998): Reactions of fish embryos and larvae to constant magnetic fields. *Italian Journal of Zoology* **65**, 5.

Formicki, K., Sadowski, M., Tanski, A., Korzelecka-Orkisz, A., and Winnicki, A. (2004a): Behaviour of trout (Salmo trutta L.) larvae and fry in a constant magnetic field *Journal of Applied Ichthyology* **20**, 5.

Formicki, K., Tański, A., Sadowski, M., and Winnicki, A. (2004b): Effects of magnetic fields on fyke net performance. *Journal of Applied Ichthyology* **20**, 402-406.

Formicki, K., Szulc, J., Tanski, A., Korzelecka-Orkisz, A., Witkowski, A., and Kwiatkowski, P. (2013): The effect of static magentic field on Danube huchen, *Hucho hucho* (L.) sperm motility parameters. *Archives of Polish Fisheries* **21**, 9.

Formicki, K., Szulc, J., Korzelecka-Orkisz, A., Tański, A., Kurzydłowski, J.K., Grzonka, J., and Kwiatkowski, P. (2015): The effect of a magnetic field on trout (*Salmo trutta* Linnaeus, 1758) sperm motility parameters and fertilisation rate. *Journal of Applied Ichthyology* **31**, 136-146.

Fowler, A.M., Jørgensen, A.-M., Svendsen, J.C., Macreadie, P.I., Jones, D.O., Boon, A.R., Booth, D.J., Brabant, R., Callahan, E., Claisse, J.T., Dahlgren, T.G., Degraer, S., Dokken, Q.R., Gill, A.B., Johns, D.G., Leewis, R.J., Lindeboom, H.J., Linden, O., May, R., Murk, A.J., Ottersen, G., Schroeder, D.M., Shastri, S.M., Teilmann, J., Todd, V.L.G., Van Hoey, G., Vanaverbeke, J., and Coolen, J.W. (2018): Environmental benefits of leaving offshore infrastructure in the ocean. *Frontiers in Ecology and the Environment* **16**, 571-578.

Frid, C., Andonegi, E., Depestele, J., Judd, A., Rihan, D., Rogers, S.I., and Kenchington, E. (2012): The environmental interactions of tidal and wave energy generation devices. *Environmental Impact Assessment Review* **32**, 133-139.

Friedlander, A.M., Ballesteros, E., Fay, M., and Sala, E. (2014): Marine communities on oil platforms in Gabon, West Africa: high biodiversity oases in a low biodiversity environment. *PLoS ONE* **9**, e103709.

Fujii, T., Walls, A., and Horsfield, M. (2014): Is there a net benefit from offshore structures? SPE International Conference on Health, Safety, and Environment, pp. 9.

Furness, R.W., Wade, H.M., and Masden, E.A. (2013): Assessing vulnerability of marine bird populations to offshore wind farms. *Journal of Environmental Management* **119**, 56-66.

Fuxjager, M.J., Eastwood, B.S., and Lohmann, K.J. (2011): Orientation of hatchling loggerhead sea turtles to regional magnetic fields along a transoceanic migratory pathway. *The Journal of Experimental Biology* **214**, 5.

Gall, S.C., and Thompson, R.C. (2015): The impact of debris on marine life. *Marine Pollution Bulletin* **92**, 10.

Germanov, E.S., Marshall, A.D., Bejder, L., Fossi, M.C., and Loneragan, N.R. (2018): Microplastics: no small problem for filter-feeding megafauna. *Trends in ecology & evolution* **33**, 6.

GGGI (2021): The impacts of fishing gear as a source of marine plastic pollution: A Global Ghost Gear Initiative (GGGI) information paper to support negotiations in preparation for UNEA 5.2. *UNEA 5.2*. Ocean Conservancy London. 8 pp.

Gilardi, K.V.K., Carlson-Bremer, D., June, J.A., Antonelis, K., Broadhurst, G., and Cowan, T. (2010): Marine species mortality in derelict fishing nets in Puget Sound, WA and the cost/benefits of derelict net removal. *Marine Pollution Bulletin* **60**, 7.

Gill, A.B., and Taylor, H. (2001): The potential effects of electromagnetic fields generated by cabling between ofshore wind turbines upon elasmobranch fishes. Applied Ecology Research Group, University of Liverpool.

Gill, A.B. (2005): Offshore renewable energy: ecological implications of generating electricity in the coastal zone. *Journal of Applied Ecology* **42**, 605-615.

Gill, A.B., Gloyne-Phillips, I., Neal, K.J., and Kimber, J.A. (2005): COWRIE 1.5 Electromagnetic fields review: The potential effects of electromagnetic fields generated by sub-sea power cables associated with offshore wind farm developments on electrically and magnetically sensitive marine organisms – a review. FINAL REPORT. Cranfield University & Centre for Marine and Coastal Studies Ltd., Bedfordshire & Birkenhead, UK. 128 pp.

Gill, A.B., Huang, Y., Gloyne-Philips, I., Metcalfe, J., Quayle, V., Spencer, J., and Wearmouth, V. (2009): EMF-sensitive fish response to EM emissions from sub-sea electricity cables of the type used by the offshore renewable energy industry. *COWRIE 2.0 EMF Final Report*. COWRIE Ltd, Liverpool, UK.

Gill, A.B., Gloyne-Philips, I., Kimber, J., and Sigray, P. (2014): Marine renewable energy, ElectroMagnetic (EM) fields and EM-sensitive animals: *Marine renewable energy technology and environmental interactions*. Springer, pp. 61-79.

Gilman, E., Chopin, F., Suuronen, P., and Kuemlangan, B. (2016): Methods to estimate ghost fishing mortality, and the status of regional monitoring and management *FAO Fisheries and Aquaculture Technical Paper No. 600*. Food and Agriculture Organisation of the United Nations, Rome, Italy. 96 pp.

Gjerde, K.M. (2006): Ecosystems and biodiversity in deep waters and high seas. *UNEP Regional Seas Report and Studies No. 178*. UNEP Switzerland. 60 pp.

Goff, M., Salmon, M., and Lohmann, K.J. (1998): Hatchling sea turtles use surface waves to establish a magnetic compass direction. *Animal Behaviour* **55**, 69-77.

Good, T.P., June, J.A., Etnier, M.A., and Broadhurst, G. (2009): Ghosts of the Salish Sea: threats to marine birds in Puget Sounf and the Northwest straits from derelict fishing gear. *Marine Ornithology* **37**, 10.

Good, T.P., June, J.A., Etnier, M.A., and Broadhurst, G. (2010): Derelict fishing nets in Puget Sound and the Northwest stratis: patterns and threats to marine fauna. *Marine Pollution Bulletin* **60**, 12.

Gooding, R.M., and Magnuson, J.J. (1967): Ecological significance of a drifting object to pelagic fishes. *Pacific Science* **21**, 486-497.

Government of South Korea (2020): Towards a sustainable and green society. The Government of the Republic of Korea, Republic of Korea. 131 pp.

Graham, I.M., Pirotta, E., Merchant, N.D., Farcas, A., Barton, T.R., Cheney, B., Hastie, G.D., and Thompson, P.M. (2017): Responses of bottlenose dolphins and harbor porpoises to impact and vibration piling noise during harbor construction. *Ecosphere* **8**, e01793.

Graham, I.M., Merchant, N.D., Farcas, A., Barton, T.R., Cheney, B., Bono, S., and Thompson, P.M. (2019): Harbour porpoise responses to pile-driving diminish over time. *Royal Society Open Science* **6**, 190335.

Gruber, S.H. (1977): The visual system of sharks: adaptations and capability. *The Journal of American Zoology* **17**, 18.

Güçlüsoy, H., and Savas, Y. (2003): Interaction between monk seals *Monachus monachus* (Hermann, 1779) and marine fish farms in the Turkish Aegean and management of the problem. *Aquaculture Research* **34**, 777-783.

Guerin, A.J. (2009): Marine communities of North Sea offshore platforms, and the use of stable isotopes to explore artificial reef food webs: *School of Ocean & Earth Sciences*, Vol. PhD thesis. University of Southampton, pp. 226.

GWEC (2021): Global wind report 2021.

Hamilton, S., and Baker, G.B. (2019): Technical mitigation to reduce marine mammal bycatch and entanglement in commercial fishing gear: lessons learnt and future directions. *Reviews in Fish Biology and Fisheries*, 1-25.

Haney, J., Haury, L., Mullineaux, L., and Fey, C. (1995): Sea-bird aggregation at a deep North Pacific seamount. *Marine Biology* **123**, 1-9.

Haney, J.C., and Stone, A. (1988): Seabird foraging tactics and water clarity: are plunge divers really in the clear? *Mar. Ecol. Prog. Ser* **49**, 1-9.

Haney, J.C., Fristrup, K.M., and Lee, D.S. (1992): Geometry of visual recruitment by seabirds to ephemeral foraging flocks. *Ornis Scandinavica*, 49-62.

Hanke, F.D., Reichmuth, C., and Cook, P. (2021): The sensory world of otariids. In C. Camapagna, and R. Harcourt (Eds): *Ethology and behavioral ecology of otariids and the odobenid*. Springer, pp. 305-321.

Hansen, K.A., Maxwell, A., Siebert, U., Larsen, O.N., and Wahlberg, M. (2017): Great cormorants (*Phalacrocorax carbo*) can detect auditory cues while diving. *The Science of Nature* **104**, 1-7.

Hardesty, B.D., Good, T.P., and Wilcox, C. (2015): Novel methods, new results and science-based solutions to tackle marine debris impacts on wildlife. *Ocean & Coastal Management* **115**, 6.

Hardesty, B.D., Roman, L., Duke, N.C., Mackenzie, J.R., and Wilcox, C. (2021): Abandoned, lost and discarded fishing gear 'ghost nets' are increasing through time in Northern Australia. *Marine Pollution Bulletin* **173**, 10.

Harnois, V., Benjamins, S., Smith, H.C.M., and Johanning, L. (2015): Assessment of entanglement risk to marine megafauna due to offshore renewable energy mooring systems. *International Journal of Marine Energy*, 33.

Harrison, N.M., Whitehouse, M.J., Heinemann, D., Prince, P.A., Hunt Jr, G.L., and Veit, R.R. (1991): Observations of multispecies seabird flocks around South Georgia. *The Auk* **108**, 801-810.

Harsanyi, P., Scott, K., Easton, B.A.A., de la Cruz Ortiz, G., Chapman, E.C.N., Piper, A.J.R., Rochas, C.M.V., and Lyndon, A.R. (2022): The effect of anthropogenic ElectroMagnetic Fields (EMF) on the early development of two commercially important crustaceans, European lobster, (*Homarus gammarus* (L.) and edible crab *Cancer pagurus* (L.). *Journal of Marine Science and Engineering* **10**.

Hart, V., Kusta, T., Nemec, P., Blahova, V., Jezek, M., Novakova, P., Begall, S., Cerveny, J., Hanzal, V., Malkemper, E.P., Stipek, K., Vole, C., and Burda, H. (2012): Magentic alignment in carps: evidence from the Czech christmas fish market *PLoS ONE* **7**, 7.

Harwood, J. (2001): Marine mammals and their environment in the twenty-first century. *Journal of Mammalogy* **82**, 630-640.

Hasselman, D.J., Barclay, D.R., Cavagnaro, R.J., Chandler, C., Cotter, E., Gillespie, D.M., Hastie, G.D., Horne, J.K., Joslin, J., Long, C., McGarry, L.P., Mueller, R.P., Sparling, C.E., and Williamson, B.J. (2020): Chapter 10 supplementary material: environmental monitoring technologies and techniques for detecting interactions of marine animals with turbines. Ocean Energy Systems.

Hays, G.C., Broderick, A.C., Godley, B.J., Lovell, P., Martin, C., McConnell, B.J., and Richardson, S. (2002): Biphasal long-distance migration in green turtles. *Animal Behaviour* **64**, 895-898.

Hays, G.C., Åkesson, S., Godley, B.J., Papi, F., and Luschi, P. (2003): Island-finding ability of marine turtles. *Proceedings Of The Royal Society B* **270**.

Hellinger, J., and Hoffman, K.-P. (2009): Magnetic field perception in the rainbow trout *(Oncorynhus mykiss)*: magnetite mediated, light dependent or both? *Journal of Comparative Physiology* **198**, 13.

Henkel, L.A. (2006): Effect of water clarity on the distribution of marine birds in nearshore waters of Monterey Bay, California. *Journal of Field Ornithology* **77**, 151-156.

Hudgins, J., and Sweet, M.J. (2016): A review of ghost gear entanglement amongst marine mammals, reptiles and elasmobranchs. *Marine Pollution Bulletin*, 13.

Hui, C.A. (1994): Lack of association between magnetic patterns and the distribution of free-ranging dolphins. *Journal of Mammology* **75**, 399-405.

Hunt, G.L., Mehlum, F., Russell, R.W., Irons, D., Decker, B., and Becker, P.H. (1999): Physical processes, prey abundance, and the foraging ecology of seabirds. Proc. 22nd International Ornithological Congress. Durban.

Hüppop, O., jochen dierschke, Klaus-Michael Exo, Elvira Fredrich, and Reinhold Hill (2006): Bird migration studies and potential collision risk with offshore wind turbines. *Ibis* **48**, 90-109.

Hutchison, Z., Sigray, P., He, H., Gill, A., King, J., and Gibson, C. (2018): Electromagnetic Field (EMF) impacts on elasmobranch (shark, rays, and skates) and American lobster movement and migration from direct current cables. *Sterling (VA): US Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM* **3**, 2018.

Hutchison, Z.L., Gill, A.B., Sigray, P., He, H., and King, J.W. (2020): Anthropogenic electromagnetic fields (EMF) influence the behaviour of bottom-dwelling marine species. *Scientific Reports* **10**.

IEA (2022): Norway 2022 energy policy review. International Energy Agency Norway. 147 pp.

IPCC (1990): Policymakers summary. In J. Houghton, T.,, G. Jenkins, J.,, and J. Ephraums, J. (Eds): *Climate change: the IPCC scientific assessment*. Cambridge University Press, UK.

IPCC (2022): Summary for policymakers. In P. Shukla, R.,, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R.

Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley (Eds): *Climate change 2022: mitigation of climate change. Contribution of Working Group III to the sixth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

Irwin, W.P., and Lohmann, K.J. (2003): Magnet-induced disorientation in hatchling loggerhead sea turtles. *Journal of Experimental Biology* **206**, 497-501.

Irwin, W.P., and Lohmann, K.J. (2005): Disruption of magnetic orientation in hatchling loggerhead sea turtles by pulsed magnetic fields. *Journal of Comparative Physiology A* **191**, 475-480.

Isaksson, N., Cleasby, I.R., Owen, E., Williamson, B.J., Houghton, J.D., Wilson, J., and Masden, E.A. (2021): The use of animal-borne biologging and telemetry data to quantify spatial overlap of wildlife with marine renewables. *Journal of Marine Science and Engineering* **9**, 263.

Ivar do Sul, J.A., and Costa, M.F. (2013): The present and future of microplastic pollution in the marine environment *Environmental Pollution*, 13.

IWC. (2013): Report of the 2013 IWC scientific committee workshop on marine debris *SC/65a/Rep06*. International Whaling Commission, Falmouth, MA, USA. 39 pp.

Izyumov, Y.G., and Krylow, V.V. (2013): Bastomere mitosis, hatching, survival rate, and size paramters of prolarvae in the roach *Rutilus rutilus* following exposure of effs and sperm to main phase of a strong magnetic storm. *Journal of Ichthyology* **55**, 6.

Jakubowska, M., Urban-Malinga, B., Otremba, Z., and Andrulewicz, E. (2019): Effect of low frequency electromagnetic field on the behavior and bioenergetics of the polychete *Hediste diversicolor*. *Marine Environmental Research* **150**.

Johnsen, S., and Lohmann, K.J. (2005): The physics and neurobiology of magnetorecption. *Nature Reviews Neuroscience* **6**, 703-712.

Johnson, A., Salvador, G., Kenney, J., Robbins, J., Kraus, S., Landry, S., and Clapham, P. (2005): Fishing gear involved in entanglements of right and humpback whales. *Marine Mammal Science* **21**, 635-645.

Jones, D.N., and Bond, A.R.F. (2010): Road barrier effect on small birds removed by vegetated overpass in South East Queensland. *Ecological Management & Restoration* **11**, 65-67.

Jørgensen, T., Løkkeborg, S., and Soldal, A.V. (2002): Residence of fish in the vicinity of a decommissioned oil platform in the North Sea. *ICES Journal of Marine Science* **59**, S288-S293.

Joy, R., Wood, J.D., Sparling, C.E., Tollit, D.J., Copping, A.E., and McConnell, B.J. (2018): Empirical measures of harbor seal behavior and avoidance of an operational tidal turbine. *Marine Pollution Bulletin* **136**, 92-106.

Kaiser, M.J., Bullimore, B., Newman, P., Lock, K., and S., G. (1996): Catches in 'ghost fishing' set nets. *Marine Ecology Progress Series* **145**, 6.

Kajiura, S.M., and Holland, K.N. (2002): Electroreception in juvenile scalloped hammerhead and sandbar sharks. *Journal of Experimental Biology* **205**, 3609-3621.

Kajiura, S.M., and Fitzgerald, T.P. (2009): Response of juvenile scalloped hammerhead sharks to electric stimuli. *Zoology* **112**, 241-250.

Kaldellis, J.K., and Kapsali, M. (2013): Shifting towards offshore wind energy — recent activity and future development. *Energy Policy* **53**, 136-148.

Kalmijn, A.J. (1966): Electro-perception in sharks and rays. *Nature* **212**, 1232-1233.

Kalmijn, A.J. (1971): The electric sense of sharks and rays. *Journal of Experimental Biology* **55**, 371-383.

Kalmijn, A.J. (1974): The detection of electric fields from inanimate and animate sources other than electric organs: *Electroreceptors and other specialized receptors in lower vertebrates*. Springer, pp. 147-200.

Kalmijn, A.J. (1981): Biophysics of geomagnetic field detection. *IEEE Transactions on magnetics* **17**, 1113-1124.

Kalmijn, A.J. (1982): Electric and magnetic field detection in elasmobranch fishes. *Science* **218**, 916-918.

Kantserova, N.P., Ushakova, N.V., Krylow, V.V., Lysenko, L.A., and Nemova, N.N. (2013a): Modulation of Ca2+ dependent protease activity in fish and invertebrates by weak low-frequency mangnetic fields. *Russian Jounral of Bioorganic Chemistry* **39**, 5.

Kantserova, N.P., Ushakova, N.V., Krylow, V.V., Lysenko, L.A., and Nemova, N.N. (2013b): The effect of weak low frequency magnetic fields on the intracellular calcium-dependent proteinases of fish. *Biology Bulletin* **40**, 4.

Kantserova, N.P., Krylov, V.V., Lysenko, L.A., Ushakova, N.V., and Nemova, N.N. (2017): Effects of hypomagnetic conditions and reversed geomagnetic field on calcium-dependent proteases of invertebrates and fish. *Izvestiya, Atmospheric and Oceanic Physics* **53**, 719-723.

Karlson, M., Seiler, A., and Mörtberg, U. (2017): The effect of fauna passages and landscape characteristics on barrier mitigation success. *Ecological Engineering* **105**, 211-220.

Karlsson, R., Tivefälth, M., Duranović, I., Martinsson, S., Kjølhamar, A., and Murvoll, K.M. (2022): Artificial hard-substrate colonisation in the offshore Hywind Scotland Pilot Park. *Wind Energ. Sci.* **7**, 801-814.

Katzir, G., and Howland, H.C. (2003): Corneal power and underwater accommodation in great cormorants (*Phalacrocorax carbo sinensis*). *Journal of Experimental Biology* **206**, 833-841.

Kavet, R., Wyman, M., Klimley, A., and Vergara, X. (2016): Assessment of potential impact of electromagnetic fields from undersea cable on migratory fish behavior. *Electric Power Research Institute (EPRI) for the US Department of Energy and US Department of the Interior, Bureau of Ocean Energy Management*.

Keynes, S., and Crutchfield, Z. (2016): Environmental and consenting barriers to developing floating offshore wind farms including innovative solutions Natural Environment Research Council Swindon, UK. 50 pp.

Kilfoyle, A.K., Jermain, R.F., Dhanak, M.R., Huston, J.P., and Spieler, R.E. (2017): Effects of EMF emissions from undersea electric cables on coral reef fish. *Bioelectric Magnetics* **39**, 35-52.

Kimber, J.A., Bellamy, P.H., Sims, D.W., and Gill, A.B. (2011): The ability of a benthic elasmobranch to discriminate between biological and artificial electric fields. *Marine Biology* **158**, 9.

Kirschvink, J., and Neeson, M. (1997): Magnetite as a testable physical mechanism for non-sensory EMF biological effects: ELF to microwaves. Proceedings of the 2nd World Congress for Electricity and Magnetism in Biology and Medicine, Bologna, Italy, pp. 48.

Kirschvink, J.L., and Lowenstam, H.A. (1979): Mineralization and magnetization of chiton teeth: paleomagnetic, sedimentologic, and biologic implications of organis magnetite. *Earth and Planetary Science Letters* **44**, 193-204.

Kirschvink, J.L., and Gould, J.L. (1981): Biogenic magetite as a basis for magnetic field detection in animals. *Biosystems* **13**, 181-201.

Kirschvink, J.L., Dizon, A.E., and Westphal, J.A. (1986): Evidence from strandings for geomagnetic sensitivity in cetaceans. *Journal of Experimental Biology* **120**, 1-24.

Kirschvink, J.L. (1990): Geomagnetic sensitivity in cetaceans: an update with live stranding records in the United States. In J. A. Thomas, and A. Kastelein (Eds): *Sensory Abilities of Cetaceans*. Springer.

Kirschvink, J.L. (1997): Homing in on vertebrates. *Nature* **390**, 339-340.

Kishkinev, D., and Chernetsov, N. (2015): Magnetoreception systems in birds: a review of current research. *Biology Bulletin Reviews* **5**, 46-62.

Klinowska, M. (1985): Cetacean live stranging sites relate to geomagnetic topography. *Aquatic Mammals* **1**, 27 - 32.

Knowlton, A.R., Hamilton, P.K., Marx, M.K., Pettis, H.M., and Kraus, S.D. (2012): Monitoring North Atlantic right whale *Eubalaena glacialis* entanglement rates: a 30 yr retrospective. *Marine Ecology Progress Series* **466**, 293-302.

Kot, B.W., Sears, R., Anis, A., Nowacek, D.P., Gedamke, J., and Marshall, C.D. (2012): Behavioural responses of minke whales (*Balaenoptera acutorostrata*) to experimental fishing gear in a coastal environment. *Journal of Experimental Marine Biology and Ecology* **413**, 13-20.

Kraus, S., Fasick, J., Werner, T., and McFarron, P. (2014): Enhancing the visibility of fishing ropes to reduce right whale entanglements. *Bycatch Reduction Engineering Program 1*, 67-75.

Kraus, S.D. (2018): *Entanglement of whales in fishing gear*. Academic Press, USA.

Kremers, D., Marulanda, J.L., Hausberger, M., and Lemasson, A. (2014): Behavioural evidence of magnetoreception in dolphins: detection of experimental magnetic fields. *Naturwissenschaften* **101**, 907-911.

Kremers, D., A., C., Schaal, B., Campagna, S., Trabalon, M., Böye, M., Hausberger, M., and Lemasson, A. (2016): Sensory perception in cetaceans: part i - current knowledge about dolphin senses as a representative species. *Frontiers in Ecology and Evolution* **4**.

Kruse, G.H., and Kimker, A. (1993): Degradable escape mechanisms for pot gear: a summary report to the Alaska board of fisheries *Regional Information Report No. 5J93-01*. Alaska Department of Fish & Game Juneau, Alaska. 29 pp.

Krylov, V.V. (2010): Effects of electromagnetic fields on parthenogenic eggs of *Daphnia magna* Straus. *Ecotoxicology and Environmental Safety* **73**, 62-66.

Kuhnz, L., A.,, Buck, K., Lovera, C., Whaling, P., J.,, and Barry, J., P. (2015): Potential impacts of the Monterey accelerated research system (MARS) cable on the seabed and benthic faunal assemblages. Monterey Bay Aquarium Research Institute.

Kuz'mina, V., Ushakova, N., and Krylov, V. (2015): The effect of magnetic fields on the activity of proteinases and glycosidases in the intestine of the crucian carp Carassius carassius. *Biology Bulletin* **42**, 61-66.

Laist, D.W. (1996): Marine debris entanglement and ghost fishing: a cryptic and significant type of bycatch?: *Solving Bycatch: Considerations for Today and Tomorrow*. Seattle pp. 8.

Laist, D.W. (1997): Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. In J. M. Coe, and D. B. Rogers (Eds): *Marine debris: sources, impacts, and solutions*. Springer, New York, USA, pp. 99-139.

Langhamer, O., Vicinanza, D., Azzellino, A., Kofoed, J.P., and Conley, D. (2012): Artificial reef effect in relation to offshore renewable energy conversion: state of the art. *The Scientific World Journal* **2012**.

Larsen, O.N., Wahlberg, M., and Christensen-Dalsgaard, J. (2020): Amphibious hearing in a diving bird, the great cormorant (*Phalacrocorax carbo sinensis*). *Journal of Experimental Biology* **223**, jeb217265.

Le Boeuf, B.J., Crocker, D.E., Costa, D.P., Blackwell, S.B., Webb, P.M., and Houser, D.S. (2000): Foraging ecology of Northern elephant seals. *Ecological Monographs* **70**, 353-382.

Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitkin, J., Marthouse, R., Hajbane, S., Cunsolo, S., Schwarz, A., Levivier, A., Noble, K., Debeljak, P., Maral, H., Schoeneich-Argent, R., Brambini, R., and Reisser, J. (2018): Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. *Scientific Reports* **8**, 15.

Leiter, S.M., Stone, K.M., Thompson, J.L., Accardo, C.M., Wikgren, B.C., Zani, M.A., Cole, T.V.N., Kenney, R.D., Mayo, C.A., and Kraus, S.D. (2017): North Atlantic right whale *Eubalaena glacialis* occurrence in offshore wind energy areas near Massachusetts and Rhode Island, USA. *Endangered Species Research* **34**, 45-59.

Lentz, S.A. (1987): Plastics in the marine environment: legal approaches for international action *Marine Pollution Bulletin* **18**, 5.

Levin, M., and Ernst, S.G. (1997): Applied DC magnetic fields cause alterations in the time of cells divisions and development abnormalities in early sea urchin embryos. *Bioelectromagnetics* **18**, 255-263.

Levitt, B.B., Lai, H.C., and Manville, A.M.I. (2021): Effects of non-ionizing electromagnetic fields on flora and fauna, part 2 impacts: how species interact with natural and man-made EMF. *Reviews on Environmental Health*.

Light, P., and Salmon, M. (1993): Geomagnetic orientation of loggerhead sea turtles: evidence for an inlination compass. *Journal of Experimental Biology* **182**, 1-10.

Lin, L., and Yu, H. (2012): Offshore wave energy generation devices: impacts on ocean bio-environment. *Acta Ecologica Sinica* **32**, 117-122.

Lindeboom, H.J., Kouwenhoven, H.J., Bergman, M.J.N., Bouma, S., Brasseur, S., Daan, R., Fijn, R.C., de Haan, D., Dirksen, S., van Hal, R., Hille Ris Lambers, R., ter Hofstede, R., Krijgsveld, K.L., Leopold, M., and Scheidat, M. (2011): Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environmental Research Letters* **6**, 035101.

Lissman, H.W., and Machin, K.E. (1958): The mechanism of object location in *Gymnarchus niloticus* and similar fish. *Journal of Experimental Biology* **35**, 451-486.

Litherland, L., Collin, S.P., and Fritsches, K.A. (2009): Visual optics and ecomorphology of the growing shark eye: a comparison between deep and shallow water species. *The Journal of Experimental Biology* **212**, 13.

Lohmann, K.J. (1984): Magnetic remanence in the western Atlantic spiny lobster, *Panulirus argus*. *Journal of Experimental Biology* **113**.

Lohmann, K.J. (1985): Geomagnetic field detection by the western Atlantic spiny lobster, *Panulirus argus*. *Marine Behaviour and Physiology* **12**, 1-7.

Lohmann, K.J., and Willows, A.O.D. (1987): Lunar-modulated geomagnetic orientation by a marine mollusk. *Science* **235**, 331-334.

Lohmann, K.J. (1991): Magnetic orientation by hatchling loggerhead sea turtles (*Caretta caretta*). *Journal of Experimental Biology* **155**, 37-49.

Lohmann, K.J., and Willows, A.O.D. (1991): An identifiable molluscan neuron responds to changes in Earth-strength magnetic fields. *Journal of Experimental Biology* **161**, 1-24.

Lohmann, K.J., and Lohmann, C.M.E. (1993): A light-independent magnetic compass in the leatherback sea turtle. *The Biological Bulletin* **185**, 149-151.

Lohmann, K.J., and Lohmann, C.M.F. (1994a): Detection of magnetic inclination angle by sea turtles: a possible mechanism for determining latitude. *Journal of Experimental Biology* **194**, 23-32.

Lohmann, K.J., and Lohmann, C.M.F. (1994b): Aquisition of magnetic directional preference in hatchling loggerhead sea turtles. *Journal of Experimental Biology* **190**, 1-8.

Lohmann, K.J., Pentcheff, N.D., Nevitt, G.A., Stetten, G.D., Zimmer-Faust, R.K., Jarrard, H.E., and Boles, L.C. (1995): Magnetic orientation of spiny lobsters in the ocean: experiments with undersea coil systems. *Journal of Experimental Biology* **198**, 2041-2048.

Lohmann, K.J., and Lohmann, C.M.F. (1996): Orientation and open-sea navigation in sea turtles. *Journal of Experimental Biology* **199**, 73-81.

Lohmann, K.J., Lohmann, C.M.E., Ehrhart, L.M., Bagley, D.A., and Swing, T. (2004): Geomagnetic map used in sea-turtle navigation. *Nature* **428**, 909-910.

Lohmann, K.J., Lohmann, C.M.E., and Putman, N.F. (2007): Magnetic maps in animals: nature's GPS. *Journal of Experimental Biology* **210**, 3697-3705.

Lohmann, K.J., Luschi, P., and Hays, G.C. (2008a): Goal navigation and island-finding in sea turtles. *Journal of Experimental Marie Biology and Ecology* **356**, 83-95.

Lohmann, K.J., Putman, N.F., and Lohmann, C.M.E. (2008b): Geomagnetic imprinting: a unifying hypothesis of long-distance natal homing in salmon and sea turtles. *Proceedings of the National Academy of Sciences of the United States of America* **105**, 19096-19101.

Løkkeborg, S., Humborstad, O.B., Jørgensen, T., and Soldal, A.V. (2002): Spatio-temporal variations in gillnet catch rates in the vicinity of North Sea oil platforms. *ICES Journal of Marine Science* **59**, S294-S299.

Love, M.S., Nishimoto, M.M., Clark, S., and Bull, A.S. (2016): Renewable energy in situ power cable observations. Marine Science Institute, University of California, BOEM Cooperative Agreement No. M11AC00008.

Love, M.S., Nishimoto, M.M., Clark, S., McCrea, M., and Bull, A.S. (2017a): Assessing potential impacts of energized submarine power cables on crab harvests. *Continental Shelf Research* **151**, 23-29.

Love, M.S., Nishimoto, M.M., Snook, L., Schroeder, D.M., and Bull, A.S. (2017b): A comparison of fishes and invertebrates living in the vicinity of energized and unenergized submarine power cables and natural sea floor off southern California, USA. *Journal of Renewable Energy*.

Lowenstam, H.A. (1962): Magnetite in denticle capping in recent chitons (polyplacophora). *Geological Society of America Bulletin* **73**, 435-438.

Luschi, P., Åkesson, S., Broderick, A.C., Glen, F., Godley, B.J., Papi, F., and Hays, G.C. (2001): Testing the navigational abilities of ocean migrants: displacement experiments on green sea turtles (*Chelonia mydas*). *Behavioral Ecology and Sociobiology* **50**, 528-534.

Luschi, P., Benhamou, S., Girard, C., Ciccione, S., Roos, D., Sudre, J., and Benvenuti, S. (2007): Marine turtles use geomagnetic cues during open-sea homing. *Current Biology* **17**, 126-133.

Macfadyen, G., Huntington, T., and Cappell, R. (2009): Abandoned, lost or otherwise discarded fishing gear. United Nations Environment Programme, Rome. 139 pp.

Machovsky-Capuska, G.E., Howland, H.C., Raubenheimer, D., Vaughn-Hirshorn, R., Würsig, B., Hauber, M.E., and Katzir, G. (2012): Visual accommodation and active pursuit of prey underwater in a plunge-diving bird: the Australasian gannet. *Proceedings of the Royal Society B: Biological Sciences* **279**, 4118-4125.

MacLennon, E., Hartny-Mills, L., Read, F.L., Dolman, S.J., Philp, A., Dearing, K.E., Jarvis, D., and Brownlow, A.C. (2021): NatureScot research report 1268 - Scottish Entanglement Alliance (SEA) - understanding the scale and impacts of marine animal entanglement in the Scottish creel fishery. *NatureScot Research Report 1268*. NatureScot, Edinburgh. 79 pp.

Malagoli, D., Gobba, F., and Ottaviani, E. (2003): Effects of 50-Hz magnetic fields on the signalling pathways of fMLP-induced shape changes in invertebrate immunocytes: the activation of an alternative "stress pathway". *Biochimica et Biophysica Acta* **1620**, 185-190.

Malagoli, D., Lusvardi, M., Gobba, F., and Ottaviani, E. (2004): 50 Hz magnetic fields activate mussel immunocyte p38 MAP kinase and induce HSP70 and 90. *Comparative Biochemistry and Physiology Part C* **137**, 75-79.

Mann, S., Sparks, N.H.C., Walker, M.M., and Kirschvink, J.L. (1988): Ultrastructure, morphology and organization of biogenic magnetite from sockeye salmon, *Oncorhynchus nerka*: implications for magnetoreception. *Journal of Experimental Biology* **140**, 35-49.

Marcotte, M.M., and Lowe, C.G. (2008): Behavioral responses of two species of sharks to pulsed, direct current electrical fields: testing a potential shark deterrent. *Marine Technology Society Journal* **42**, 53-61.

Markowitz, T.M., Harlin, A.D., Würsig, B., and McFadden, C.J. (2004): Dusky dolphin foraging habitat: overlap with aquaculture in New Zealand. *Aquatic Conservation: Marine and Freshwater Ecosystems* **14**, 133-149.

Marshall, J., Carleton, K.L., and Cronin, T. (2015): Colour vision in marine organisms *Current Opinion in Neurobiology* **34**, 9.

Martin, G.R., and Brooke, M.d.L. (1991): The eye of a procellariiform seabird, the Manx shearwater, *Puffinus puffinus*: visual fields and optical structure. *Brain, Behavior and Evolution* **37**, 65-78.

Martin, G.R. (1999): Eye structure and foraging in King Penguins *Aptenodytes patagonicus*. *Ibis* **141**, 444-450.

Martin, G.R., and Prince, P.A. (2001): Visual fields and foraging in Procellariiform seabirds: sensory aspects of dietary segregation. *Brain, Behavior and Evolution* **57**, 33-38.

Martin, G.R., and Crawford, R. (2015): Reducing bycatch in gillnets: a sensory ecology perspective. *Global Ecology and Conservation* **3**, 28-50.

Martin, M., Elwen, S., Kassanjee, R., and Gridley, T. (2019): To buzz or burst-pulse? The functional role of Heaviside's dolphin, *Cephalorhynchus heavisidii*, rapidly pulsed signals. *Animal Behaviour*, 1-12.

Masden, E.A., Haydon, D.T., Fox, A.D., and Furness, R.W. (2010): Barriers to movement: modelling energetic costs of avoiding marine wind farms amongst breeding seabirds. *Marine Pollution Bulletin* **60**, 1085-1091.

Matsuoka, T., Nakashima, T., and Nagsawa, N. (2005): Review of ghost-fishing; scientific approaches to evaluation and solutions. *Fisheries Science* **71**, 12.

Maxwell, S.M., Kershaw, F., Locke, C.C., Conners, M.G., Dawson, C., Aylesworth, S., Loomis, R., and Johnson, A.F. (2022): Potential impacts of floating wind turbine technology for marine species and habitats. *Journal of Environmental Management* **307**, 114577.

McConnell, B.J., Fedak, M.A., Lovell, P., and Hammond, P.S. (1999): Movements and foraging areas of grey seals in the North Sea. *Journal of Applied Ecology* **36**, 573-590.

Merriam, G., Kozakiewicz, M., Tsuchiya, E., and Hawley, K. (1989): Barriers as boundaries for metapopulations and demes of *Peromyscus leucopus* in farm landscapes. *Landscape Ecology* **2**, 227 - 235.

Michel, L., Cianchetti-Benedetti, M., Catoni, C., and Dell'Omo, G. (2022): How shearwaters prey. New insights in foraging behaviour and marine foraging associations using bird-borne video cameras. *Marine Biology* **169**, 1-11.

Mooney, T., A., , Andersson, M., H.,, and Stanley, J. (2020): Acoutic impacts of offshore wind energy on fishery resources: an evolving source and varied effects across a wind farm's lifetime. *Oceanography* **33**, 82-95.

Moore, M.J., Bogomolni, A., Bowman, R., Hamilton, P.K., Harry, C.T., Knowlton, A.R., Landry, S., Rotstein, D.S., and Touhey, K. (2006): Fatally entagled right whales can die extremely slowly *OCEANS 2006*. Boston, MA, pp. 4.

Mouritsen, H., and Ritz, T. (2005): Magnetoreception and its use in bird navigation. *Current Opinion in Neurobiology* **15**, 406-414.

Murchiston, A.E. (1980): Detection range and range resolution of echolocating bottlenose porpoise (*Tursiops truncatus*). In R. G. Busnel, and J. F. Fish (Eds): *Animal Sonar Systems*. Plenum, New York, pp. 43-70.

Murray, R.W. (1974): The ampullae of Lorenzini. In A. Fessard (Ed.): *Electroreceptors and other specialized receptors in lower vertebrates*. Springer.

Natural Resources Consultants, I. (2007): A cost-benefit analysis of derelict fishing gear removal in Puget Sound, Washington The Northwest Straits Foundation WA, USA. 16 pp.

Nelms, S.E., Galloway, T.S., Godley, B.J., Jarvis, D.S., and Lindeque, P.K. (2018): Investigating microplastic trophic transfer in marine top predators. *Environmental Pollution* **238**, 999-1007.

Nelson, J.B. (2006): *Pelicans, cormorants, and their relatives: Pelecanidae, Sulidae, Phalacrocoracidae, Anhingidae, Fregatidae, Phaethontidae*. OUP Oxford.

Nevitt, G.A., Veit, R.R., and Kareiva, P. (1995): Dimethyl sulphide as a foraging cue for Antarctic procellariiform seabirds. *Nature* **376**, 680-682.

Nevitt, G.A. (2008): Sensory ecology on the high seas: the odor world of the procellariiform seabirds. *Journal of Experimental Biology* **211**, 1706-1713.

New, L.F., Clark, J.S., Costa, D.P., Fleishman, E., Hindell, M.A., Klanjšček, T., Lusseau, D., Kraus, S., McMahon, C.R., Robinson, P.W., Schick, R.S., Schwarz, L.K., Simmons, S.E., Thomas, L., Tyack, P., and Harwood, J. (2014): Using short-term measures of behaviour to estimate long-term fitness of southern elephant seals. *Marine Ecology Progress Series* **496**, 99-108.

Newton, K.C., and Kajiura, S.M. (2017): Magnetic field discrimination, learning, and memory in the yellow stingray (*Urobatis jamaicensis*). *Animal Cognition* **20**, 603-614.

Newton, K.C., Gill, A.B., and Kajiura, S.M. (2019): Electroreception in marine fishes: chondrichthyans. *Journal of Fish Biology* **95**, 135-154.

Nielsen, T.P., Wahlberg, M., Heikkila, S., Jensen, M., Sabinsky, P., and Dabelsteen, T. (2012): Swimming patterns of wild harbour porpoises *Phocoena phocoena* show detection and avoidance of gillnets at very long ranges. *Marine Ecology Progress Series* **453**, 241-248.

Nishi, T., Kawamura, G., and Matsumoto, K. (2004): Magnetic sense in the Japanese, Anguilla japonica, as determined by conditioning and electrocardiography. *The Journal of Experimental Biology* **207**, 6.

Nishi, T., and Kawamura, G. (2005): *Aguilla japonica* is already magnetosensitive at the glass eel phase. *Journal of Fish Biology* **67**, 1213-1224.

NMFS (2018): 2018 Revisions to: Technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing (Version 2.0): underwater thresholds for onset of permanent and temporary threshold shifts. *NOAA Technical Memorandum NMFS-OPR-59*. National Marine Fisheries Service, U.S. Department of Commerce, and National Oceanic and Atmospheric Administration, Silver Springs, Maryland. 167 pp.

NOAA, m.d.p. (2015): Report on the impacts of "ghost fishing" via derelict fishing gear. National Oceanic and Atmospheric Association, Silver Spring, MD. 25 pp.

OECD (2021): A background report prepared for the 2021 G7 Presidency of the United Kingdom *Policy Paper No. 25*. Organisation for Economic Co-operation and Development United Kingdom. 60 pp.

Öhman, M.C., Sigray, P., and Westerberg, H. (2007): Offshore windmills and the effects of electromagnetic fields on fish. *AMBIO: A Journal of the Human Environment* **36**, 630-633, 4.

Oksanen, S.M., Ahola, M.P., Lehtonen, E., and Kunnasranta, M. (2014): Using movement data of Baltic grey seals to examine foraging-site fidelity: implications for seal-fishery conflict mitigation. *Marine Ecology Progress Series* **507**, 297-308.

Oliveira, F., Monteiro, P., Bentes, L., Henriques, N.S., Aguilar, R., and Goncalves, J.M.S. (2015): Marine litter in the upper Sao Vicente submarine canyon (SW Portugal): abundance, distribution, composition and fauna interactions. *Marine Pollution Bulletin* **97**, 7.

Onoufriou, J., Russell, D.J.F., Thompson, D., Moss, S.E., and Hastie, G.D. (2021): Quantifying the effects of tidal turbine array operations on the distribution of marine mammals: implications for collision risk. *Renewable Energy*.

OPC (2019): Strategy for protecting whales and sea turtles & ensuring thriving fisheries: reducing the risk of entanglement in California fishing gear California Ocean Protection Council, CA, USA. 23 pp.

OSPAR (2021): The second OSPAR regional action plan on marine litter. *OSPAR Publication 2022/891 RAP ML 2*. OSPAR Commission, London, UK. 11 pp.

Ottaviani, E., Malagoli, D., Ferrari, A., Taglizucchi, D., Conte, A., and Gobba, F. (2002): 50 Hz magnetic fields of varying flux intensity affect cell shape changes in invertebrate immunocytes: the role of potassium ion channels. *Bioelectromagnetics* **23**, 292-297.

Page, B., McKenzie, J., McIntosh, R., Baylis, A., Morrissey, A., Calvert, N., Haase, T., Berris, M., Dowie, D., Shaughnessy, P.D., and Goldsworthy, S.D. (2004): Entanglement of Australian sea lions and New Zealand fur seals in lost fishing gear and other marine debris before and after government and industry attempts to reduce the problem *Marine Pollution Bulletin* **49**, 10.

Papi, F., Åkesson, S., Capogrossi, S., and Hays, G.C. (2000): Open-sea migration of magnetically disturbed sea turtles. *Journal of Experimental Biology* **203**, 3435-3443.

Parton, J.K., Galloway, T.S., and Godley, B.J. (2019): Global review of shark and ray entanglement in anthropogenic marine debris *Endangered Species Research* **39**, 19.

Patullo, B.W., and Macmillan, D.L. (2007): Crayfish respond to electrical fields. *Current Biology* **17**, 83-84.

Patullo, B.W., and Macmillan, D.L. (2010): Making sense of electrical sense in crayfish. *Journal of Experimental Biology* **213**, 651-657.

Pearson, H.C., Vaughn-Hirshorn, R.L., Srinivasan, M., and Würsig, B. (2012): Avoidance of mussel farms by dusky dolphins (*Lagenorhynchus obscurus*) in New Zealand. *New Zealand Journal of Marine and Freshwater Research* **46**, 567-574.

Pemberton, D. (1989): The interaction between seals and fish farms in Tasmania, Hobart. Department of Lands, Parks and Wildlife, Tasmania. Unpublished report. 96. pp.

Pendoley, K.L., Schofield, G., Whittock, P.A., Ierodiaconou, D., and Hays, G.C. (2014): Protected species use of a coastal marine migratory corridor connecting marine protected areas. *Marine Biology*, 1-12.

Peters, R.C., Eeuwes, L.B., and Bretschneider, F. (2007): On the electrodetection threshold of aquatic vertebrates with ampullary or mucous gland electroreceptor organs. *Biological Reviews* **82**, 361-373.

Petterson, P., and Schönborg, N. (1997): Reduction of power system magnetic field by configuration twist. *IEEE Transactions on Power Delivery* **12**, 1678-1683.

Polet, H., Delanghe, F., and Verschoore, R. (2005): On electrical fishing for brown shrimp (*Crangon crangon*) I. laboratory experiments. *Fisheries Research* **72**, 1-12.

Pomilla, C., and Rosenbaum, H.C. (2005): Against the current: an inter-oceanic whale migration event. *Biology Letters* **1**, 476-479.

Popescu, I.R., and Willows, A.O.D. (1999): Sources of magnetic sensory input to identified neurons active during crawling in the marine mollusc *Tritonia diomedea*. *Journal of Experimental Biology* **202**, 3029-3026.

Popper, A.N., Salmon, M., and Horch, K.W. (2001): Acoustic detection and communication by decapod crustaceans. *Journal of Comparative Physiology* **187**, 83-89.

Popper, A.N., Hawkins, A.D., Fay, R.R., Mann, D.A., Bartol, S., Carlson, T.J., Coombs, S., Ellison, W.T., Gentry, R.L., and Halvorsen, M.B. (2014): *ASA S3/SC1.4 TR-2014 Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report Prepared by ANSI-Accredited Standards Committee S3/SC1 and Registered with ANSI*. Springer.

Popper, A.N., and Hawkins, A.D. (2019): An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishes. *Journal of Fish Biology* **94**, 692-713.

Porsmoguer, S.B., Bănaru, D., Boudouresque, C.F., Dekeyser, I., and Almarcha, C. (2015): Hooks equipped with magnets can increase catches of blue shark (*Prionace glauca*) by longline fishery. *Fisheries Research* **172**, 345-351.

Putman, N.F., and Lohmann, K.J. (2008): Compatibility of magnetic imprinting and secular variation. *Current Biology* **18**.

Putman, N.F., Meinke, A.M., and Noakes, D.L.G. (2014): Rearing in a distorted magnetic field disrupts the 'map sense' of juvenile steelhead trout *Biology Letters* **10**, 5.

Quintana-Rizzo, E., Leiter, S., Cole, T.V.N., Hagbloom, M.N., Knowlton, A.R., Nagelkirk, P., O′ Brien, O., Khan, C.B., Henry, A.G., Duley, P.A., Crowe, L.M., Mayo, C.A., and Kraus, S.D. (2021): Residency, demographics, and movement patterns of North Atlantic right whales *Eubalaena glacialis* in an offshore wind energy development area in southern New England, USA. *Endangered Species Research* **45**, 251-268.

Reeves, R.R., McClellan, K., and Werner, T.B. (2013): Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. *Endangered Species Research* **20**, 71-97.

Reubens, J.T., Pasotti, F., Degraer, S., and Vincx, M. (2013): Residency, site fidelity and habitat use of Atlantic cod (*Gadus morhua*) at an offshore wind farm using acoustic telemetry. *Marine Environmental Research* **90**, 128-35.

Ribeiro, S., Viddi, F.A., Cordeiro, J.L., and Freitas, T.R.O. (2007): Fine-scale habitat selection of Chilean dolphins (*Cephalorhynchus eutropia*): interactions with aquaculture activities in southern Chiloé Island, Chile. *Journal of the Marine Biological Association of the United Kingdom* **87**, 119-128.

Richards, R.J., Raoult, V., Powter, D.M., and Gaston, T.F. (2018): Permanent magnets reduce bycatch of benthic sharks in an ocean trap fishery. *Fisheries Research* **208**, 16-21.

Richardson, K., Asmutis-Silviab, R., Drinkwinc, J., Gilardid, K.V.K., Giskese, I., Jonesf, G., O'Brieng, K., Pragnell-Raaschh, H., Ludwigi, L., Antonelisc, K., Barcoj, S., Henryk, A., Knowltonl, A., Landryi, S., Mattilai, D., MacDonaldd, K., Moorem, M., Morgann, J., Robbinsi, J., van der Hoopm, J., and Hogan, E. (2019): Building evidence around ghost gear: global trends and analysis for sustainable solutions at scale. *Marine Pollution Bulletin* **138**, 8.

Rico, A., Kindlmann, P., and Sedláček, F. (2007): Barrier effects of roads on movements of small mammals. *Folia Ecologica* **56**, 1-12.

Risch, D., Clark, C.W., Dugan, P.J., Popescu, M., Siebert, U., and Van Parijs, S.M. (2013): Minke whale acoustic behavior and multi-year seasonal and diel vocalisation patterns in Massachusetts Bay, USA. *Marine Ecology Progress Series* **489**, 279-295.

Risch, D., Wilson, S.C., Hoogerwerf, M., van Geel, N.C.F., Edwards, E.W.J., and Brookes, K.L. (2019): Seasonal and diel acoustic presence of North Atlantic minke whales in the North Sea. *Scientific Reports* **9**, 3571.

Robbins, J., Knowlton, A.R., and Landry, S. (2015): Apparent survival of North Atlantic right whales after entanglement in fishing gear. *Biological Conservation* **191**, 7.

Robinson, D.P., Jaidah, M.Y., Jabado, R.W., Lee-Brooks, K., Nour El-Din, N.M., Malki, A.A.A., Elmeer, K., McCormick, P.A., Henderson, A.C., Pierce, S.J., and Ormond, R.F.G. (2013): Whale Sharks, *Rhincodon typus*, aggregate around offshore platforms in Qatari waters of the Arabian Gulf to feed on fish spawn. *PLoS ONE* **8**, e58255.

Robinson, K.P., O'Brien, J.M., Berrow, S.D., Cheney, B., Costa, M., Eisfeld, S.M., Haberlin, D., Mandelberg, L., O'Donovan, M., Oudejans, M.G., Ryan, C., Stevick, P.T., Thompson, P.M., and Whooley, P. (2012): Discrete or not so discrete: Long distance movements by coastal bottlenose dolphins in UK and Irish waters. *Journal of Cetacean Research and Management* **12**, 365-371.

Ronconi, R.A., Ryan, P.G., and Ropert-Coudert, Y. (2010): Diving of great shearwaters (*Puffinus gravis*) in cold and warm water regions of the South Atlantic Ocean. *PLoS ONE* **5**, e15508.

Rosenbaum, H.C., Maxwell, S.M., Kershaw, F., and Mate, B. (2014): Long-range movement of humpback whales and their overlap with anthropogenic activity in the South Atlantic Ocean. *Conservation Biology* **28**, 604-615.

Rountree, R.A. (1989): Association of fishes with fish aggregation devices: effects of structure size on fish abundance. *Bulletin of Marine Science* **44**, 960-972.

Ruiz, I., Absacal, A.J., Basurko, O.C., and Rubio, A. (2022): Modelling the distribution of fishing-related floating marine litter within the Bay of Biscay and its marine protected areas. *Environmental Pollution* **292**, 14.

Rundgren, C.D. (1992): Aspects of pollution in False Bay, South Africa (with special reference to subtidal pollution)): *Department of Biological Sciences* Vol. Master of Science University of Cape Town, South Africa, pp. 235.

Russell, D.J., Hastie, G.D., Thompson, D., Janik, V.M., Hammond, P.S., Scott-Hayward, L.A., Matthiopoulos, J., Jones, E.L., and McConnell, B.J. (2016): Avoidance of wind farms by harbour seals is limited to pile driving activities. *Journal of Applied Ecology* **53**, 1642-1652.

Russell, D.J.F., Brasseur, S.M.J.M., Thompson, D., Hastie, G.D., Janik, V.M., Aarts, G., McClintock, B.T., Matthiopoulos, J., Moss, S.E.W., and McConnell, B. (2014): Marine mammals trace anthropogenic structures at sea. *Current Biology* **24**, R638-R639.

Saez, L., Lawson, D., and DeAngelis, M. (2021): Large whale entanglements off the U.S. West Coast, from 1982-2017. *NMFS-OPR-63A*. National Oceanic and Atmospheric Association Silver Spring, MD. 50 pp.

Sanford, T.B. (1971): Motionally induced electric and magnetic fields in the sea. *Journal of Geophysical Research* **76**, 3476-3492.

Sayer, M., Magill, S., Pitcher, T., Morissette, L., and Ainsworth, C. (2005): Simulation-based investigations of fishery changes as affected by the scale and design of artificial habitats. *Journal of Fish Biology* **67**, 218-243.

Scales, K.L., Miller, P.I., Hawkes, L.A., Ingram, S.N., Sims, D.W., and Votier, S.C. (2014): On the front line: frontal zones as priority at-sea conservation areas for mobile marine vertebrates. *Journal of Applied Ecology* **51**, 1575-1583.

Scanlan, M.M., Putman, N.F., Pollock, A.M., and Noakes, D.L.G. (2018): Magnetic map in nonanadromous Atlantic salmon. *Proceedings of the National Academy of Sciences of the United States of America* **115**, 10995-10999.

Scarsbrook, J.R., McFarlane, G.A., and Shaw, W. (1988): Effectiveness of experimental escape mechanisms in Sablefish traps. *North American Journal of Fisheries Management* **8**, 4.

Scheidat, M., Tougaard, J., Brasseur, S., Carstensen, J., van Polanen Petel, T., Teilmann, J., and Reijnders, P. (2011): Harbour porpoises (*Phocoena phocoena*) and wind farms: a case study in the Dutch North Sea. *Environmental Research Letters* **6**, 025102.

Scheld, A.M., Bilkovic, D.M., and Havens, K.J. (2016): The dilemma of derelict gear. *Scientific Reports* **6**, 7.

Schrey, E., and Vauk, G.J.M. (1987): Records of entangled gannets *(Sula bassana)* at Helgoland, German Bight *Marine Pollution Bulletin* **18**, 3.

Schusterman, R.J., and Balliet, R.F. (1971): Aerial and underwater visual acuity in the California sea lion (*Zalophus californianus*) as a function of luminance. *Annals of the New York Academy of Sciences* **188**, 37.

Schusterman, R.J. (1980): Behavioural methodology in echolocation by marine animals. In R. G. Busnel, and J. F. Fish (Eds): *Animal Sonar Systems*. Plenum, New York, pp. 11-41.

Scott, B.E., Sharples, J., Ross, O.N., Wang, J., Pierce, G.J., and Camphuysen, C.J. (2010): Sub-surface hotspots in shallow seas: fine-scale limited locations of top predator foraging habitat indicated by tidal mixing and sub-surface chlorophyll. *Marine Ecology Progress Series* **408**, 207-226.

Scott, K., Harsanyi, P., and Lyndon, A. (2018): Understanding the effects of electromagnetic field emissions from Marine Renewable Energy Devices (MREDs) on the commercially important edible crab, *Cancer pagurus* (L.). *Marine Pollution Bulletin* **131**, 580-588.

Scott, K., Piper, A.J.R., Chapman, E.C.N., and Rochas, C.M.V. (2020): Review of the effects of underwater soud, vibration and electromagnetic fields on crustaceans - Seafish report. St Abbs Marine Station.

Scott, K., Harsanyi, P., Easton, B.A.A., Piper, A.J.R., Rochas, C.M.V., and Lyndon, A.R. (2021): Exposure to ElectroMagnetic Fields (EMF) from submarine power cables can trigger strength-dependent behavioural and physiological responses in edible crab, *Cancer pagurus* (L.). *Journal of Marine Science and Engineering* **9**.

SEER (2020): Risk to marine life from marine debris & floating offshore wind cable systems. U.S. Offshore Wind Synthesis of Environmental Effects Research, USA. 7 pp.

Shaw, J., Boyd, A., House, M., Woodward, R., Mathes, F., Cowin, G., Saunders, M., and Baer, B. (2015): Magnetic particle-mediated magnetoreception. *Journal of the Royal Society Interface* **12**.

Shultz, I.R., Woodruff, D.L., Marshall, K.E., Pratt, W.J., and Roesijadi, G. (2010): Effects of electromagnetic fields on fish and invertebrates - task 2.1.3: effects on aquatic organisms fiscal year 2010 progress report. Pacific Northwest Laboratory.

Siegenthaler, A., Niemantsverdriet, P.R.W., Laterveer, M., and Heitkönig, I.M.A. (2016): Averse responses of captive sandbar sharks *Carcharhinus plumbeus* to strong magnetic fields. *Journal of Fish Biology* **89**, 1603-1611.

Silverman, E.D., Veit, R.R., and Nevitt, G.A. (2004): Nearest neighbors as foraging cues: information transfer in a patchy environment. *Marine Ecology Progress Series* **277**, 25-36.

Silvert, W. (1992): Assessing environmental impacts of finfish aquaculture in marine waters. *Aquaculture* **107**, 67-79.

Sinclair, R.R., Sparling, C.E., and Harwood, J. (2020): Review of demographic parameters and sensitivity analysis to inform inputs and outputs of population consequences of disturbance assessments for marine mammals *No 14*. Marine Scotland Edinburgh. 78 pp.

Sisneros, J.A., Tricas, T.C., and Luer, C.A. (1998): Response properties and biological function of the skate electrosensory system during ontogeny. *Journal of Comparative Physiology A* **183**, 87-99.

Skauli, K.S., Reitan, J.B., and Walther, B.T. (2000): Hatching in zebrafish (*Danio rerio*) embryos exposed to a 50 Hz magnetic field. *Bioelectromagnetics: Journal of the Bioelectromagnetics Society, The Society for Physical Regulation in Biology and Medicine, The European Bioelectromagnetics Association* **21**, 407-410.

Skiles, D.D. (1985): The geomagnetic field - its nature, history, and biological relevance: *Magnetite Biomineralization and Magnetoreception in Organisms*. pp. 43-102.

Slavik, K., Lemmen, C., Zhang, W., Kerimoglu, O., Klingbeil, K., and Wirtz, K.W. (2019): The large-scale impact of offshore wind farm structures on pelagic primary productivity in the southern North Sea. *Hydrobiologia* **845**, 35-53.

Smolowitz, R.J. (1978): Lobster, *Homarus americanus*, trap design and ghost fishing. *MFR paper 1306*. Northwest Fisheries Centre, Woods Hole, MA. 8 pp.

Snyder, D.B., Bailey, W.H., Palmquist, K., Cotts, B.R.T., and Olsen, K.R. (2019): Evaluation of potential EMF effects on fish species of commericial or recreational fishing importance in southern New England. *OCS Study BOEM 2019-049*. U.S. Department of the Interior, Bureau of Ocean Energy Management.

Soetaert, M., Chiers, K., Duchateau, L., Polet, H., and Verschueren, B. (2015): Determining the safety range of electrical pulses for two benthic invertebrates: brown shrimp (*Crangon crangon* L.) and ragworm (*Alitta virens* S.). *ICES Journal of Marine Science* **72**, 973-980.

Solan, M., Hauton, C., Godbold, J.A., Wood, C.L., Leighton, T.G., and White, P. (2016): Anthropogenic sources of underwater sound can modify how sediment-dwelling invertebrates mediate ecosystem properties. *Scientific Reports* **6**, 20540.

Soldal, A.V., Svellingen, I., Jørgensen, T., and Løkkeborg, S. (2002): Rigs-to-reefs in the North Sea: hydroacoustic quantification of fish in the vicinity of a "semi-cold" platform. *ICES Journal of Marine Science* **59**, S281-S287.

Sørensen, K., Neumann, C., Dähne, M., Hansen, K.A., and Wahlberg, M. (2020): Gentoo penguins (*Pygoscelis papua*) react to underwater sounds. *Royal Society Open Science* **7**, 191988.

Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene, C.R., Kastak, D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, J.A., and Tyack, P.L. (2007): Marine mammal noise exposure criteria, initial scientific recommendations. *Aquatic Mammals* **33**, 411-414.

Southall, B.L., Finneran, J.J., Reichmuth, C., Nachtigall, P.E., Ketten, D.R., Bowles, A.E., Ellison, W.T., Nowacek, D.P., and Tyack, P.L. (2019): Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects. *Aquatic Mammals* **45**, 125-232.

Southwood, A., Fritsches, K., Brill, R., and Swimmer, Y. (2008): Sound, chemical, and light detection in sea turtles and pelagic fishes: sensory-based approaches to bycatch reduction in longline fisheries. *Endangered Species Research* **5**, 225-238.

Souza, J.J., Poluhowich, J.J., and Guerra, R.J. (1988): Orientation responses of american eels, *Anguilla rostrata*, to varying magnetic fields. *Comparative Biochemistry and Physiology Part A; Physiology* **90**, 5.

Sparling, C., Lonergan, M., and McConnell, B. (2018): Harbour seals (*Phoca vitulina*) around an operational tidal turbine in Strangford Narrows: no barrier effect but small changes in transit behaviour. *Aquatic Conservation: Marine and Freshwater Ecosystems* **28**, 194-204.

SRUC, W.U. (2012): Annual report 2012: 1 January to 31 December 2012. *Final Report*. Scottish Marine Animal Stranding Scheme, Inverness, Scotland. 61 pp.

Stankevičiūtė, M., Jakubowska, M., Pažusienė, J., Makaras, T., Otremba, Z., Urban-Malinga, B., Fey, D.P., Greszkiewicz, M., Sauliutė, G., Baršienė, J., and Andrulewicz, E. (2019): Genotoxic and cytotoxic effects of 50 Hz 1 mT electromagnetic field on larval rainbow trout (*Oncorhynchus mykiss*), Baltic clam (*Limecola balthica*) and common ragworm (*Hediste diversicolor*). *Aquatic Toxicology* **208**, 109-117.

Stelfox, M., Hudgins, J., and Sweet, M.J. (2016): A review of ghost gear entanglement amongst marine mammals, reptiles and elasmobranchs *Marine Pollution Bulletin* **111**, 12.

Stenberg, C., Støttrup, J., Deurs, M.v., Berg, C.W., Dinesen, G.E., Mosegaard, H., Grome, T., and Leonhard, S. (2015): Long-term effects of an offshore wind farm in the North Sea on fish communities. *Marine Ecology Progress Series* **528**, 257-265.

Stenton, C.A., Bolger, E.L., Michenot, M., Dodd, J.A., Wale, M.A., Briers, R.A., Hartl, M.G.J., and Diele, K. (2022): Effects of pile driving sound playbacks and cadmium co-exposure on the early life stage development of the Norway lobster, *Nephrops norvegicus*. *Marine Pollution Bulletin* **179**, 113667.

Steullet, P., Edwards, D.H., and Derby, C.D. (2007): An electric sense in crayfish? *Biological Bulletin* **213**, 16-20.

Stevens, C., Plew, D., Hartstein, N., and Fredriksson, D. (2008): The physics of open-water shellfish aquaculture. *Aquacultural Engineering* **38**, 145-160.

Stockwell, D.A., Whitledge, T.E., Zeeman, S.I., Coyle, K.O., Napp, J.M., Brodeur, R.D., Pinchuk, A.I., and Hunt Jr, G.L. (2001): Anomalous conditions in the south-eastern Bering Sea, 1997: nutrients, phytoplankton and zooplankton. *Fisheries Oceanography* **10**, 99-116.

Stone, G., Florez-Gonzalez, L., and Katona, S. (1990): Whale migration record. *Nature* **346**, 705-705.

Sveegaard, S., Andreasen, H., Mouritsen, K.N., Jeppesen, J.P., Teilmann, J., and Kinze, C.C. (2012): Correlation between the seasonal distribution of harbour porpoises and their prey in the Sound, Baltic Sea. *Marine Biology* **159**, 1029-1037.

Taormina, B., Bald, J., Want, A., Thouzeau, G., Lejart, M., Desroy, N., and Carlier, A. (2018): A review of potential impacts of submarine power cables on the marine environment: knowledge gaps, recommendations and future directions. *Renewable and Sustainable Energy Reviews* **96**, 380-391.

Taormina, B., Di Poi, C., Agnalt, A.-L., Carlier, A., Desroy, N., Escobar-Lux, R.H., D'eu, J.-F., Freytet, F., and Durif, C.M.F. (2020): Impact of magnetic field generated by AC/DC submarine power cables on the behavior of juvenile European lobster (*Homarus gammarus*). *Aquatic Toxicology*.

Tesch, F.W., Westerberg, H., and Karlsson, L. (1991): Tracking studies on migrating silver eels in the central Baltic. *Meeresforsch* **33**, 14.

Thomas, K., Dorey, C., and Obaidullah, F. (2019): Ghost gear: the abandoned fishing nets haunting our oceans. *S02641*. GreenPeace Germany Germany 20 pp.

Todd, V.L.G., Pearse, W.D., Tregenza, N.C., and Todd, I.B. (2009): Diel echolocation activity of harbour porpoises (*Phocoena phocoena*) around North Sea offshore gas installations. *ICES Journal of Marine Science* **66**, 734-745.

Todd, V.L.G. (2013): Rigs - to decommission or not to decommission? *Marine Scientist* **43**, 22-25.

Todd, V.L.G., Warley, J.C., and Todd, I.B. (2016): Meals on wheels? A decade of megafaunal visual and real-time Passive Acoustic Monitoring detections from on-tow and stationary offshore oil and gas rigs and platforms in the North and Irish Seas. *PLoS ONE* **11**, 25.

Todd, V.L.G., Lavallin, E.W., and Macreadie, P.I. (2018): Quantitative analysis of fish and invertebrate assemblage dynamics in association with a North Sea oil and gas installation complex. *Marine Environmental Research* **142**, 69-79.

Todd, V.L.G., Lazar, L., Williamson, L.D., Peters, I., Cox, S.E., Todd, I.B., Macreadie, P.I., and McLean, D.L. (2020a): Underwater visual records of marine megafauna around offshore anthropogenic structures. *Frontiers in Marine Science* **7**, 230.

Todd, V.L.G., Williamson, L.D., Cox, S.E., Todd, I.B., and Macreadie, P.I. (2020b): Characterising the first wave of fish and invertebrate colonisation on a new offshore petroleum platform. *ICES Journal of Marine Science* **77**, 1127-1136.

Todd, V.L.G., Susini, I., Williamson, L.D., Todd, I.B., McLean, D.L., and Macreadie, P.I. (2021): Characterising the second wave of fish and invertebrate colonisation and production potential of an offshore petroleum platform. *ICES Journal of Marine Science* **78**, 1131–1145.

Todd, V.L.G., Williamson, L.D., Couto, A., Todd, I.B., and Clapham, P.J. (2022): Effect of a new offshore gas platform on harbor porpoise in the Dogger Bank. *Marine Mammal Science* **38**, 1609-1622.

Tomanova, K., and Vacha, M. (2016): The magnetic orientation of the Antarctic amphipod *Gondogeneia antarctia* is cancelled out by very weak radiofrequency fields. *Journal of Experimental Biology* **219**, 1717-1724.

Tougaard, J., Carstensen, J., Teilmann, J., Skov, H., and Rasmussen, P. (2009): Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (*Phocoena phocoena* (L.)). *The Journal of the Acoustical Society of America* **126**, 11-14.

Tougaard, J., Hermannsen, L., and Madsen, P.T. (2020): How loud is the underwater noise from operating offshore wind turbines? *The Journal of the Acoustical Society of America* **148**, 2885-2893.

Tremblay, Y., Thiebault, A., Mullers, R., and Pistorius, P. (2014): Bird-borne video-cameras show that seabird movement patterns relate to previously unrevealed proximate environment, not prey. *PLoS ONE* **9**, e88424.

Tricas, T., and New, J. (1997): Sensitivity and response dynamics of elasmobranch electrosensory primary afferent neurons to near threshold fields. *Journal of Comparative Physiology A* **182**, 89-101.

Tricas, T., and Gill, A.B. (2011): Effects of EMFs from undersea power cables on elasmobranchs and other marine species. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Regulation, and Enforcement, Camarillo, California.

Tricas, T.C. (1982): Bioelectric-mediated predation by swell sharks, *Cephaloscyllium ventriosum*. *Copeia* **4**, 948-952.

Tricas, T.C., Michael, S.W., and Sisneros, J.A. (1995): Electrosensory optimization to conspecific phasic signals for mating. *Neuroscience Letters* **202**, 129-132.

Tscgernij, V., and Larsson, P.-O. (2003): Ghost fishing by lost cod gill nets in the Baltic Sea. *Fisheries Research* **64**, 12.

Tulp, I., Schekkerman, H., Larsen, J., van der Winden, J., van de Haterd, R., van Horssen, P., Dirksen, S., and Spaans, A. (1999): Nocturnal flight activity of sea ducks near the windfarm Tunø Knob in the Kattegat. Bureau Waardenburg bv.

Ugolini, A., and Pezzani, A. (1995): Magnetic compass and learning of the Y-axis (sea-land) direction in the marine isopod *Idotea baltica baltica*. *Animal Behaviour* **50**, 295-300.

Ugolini, A. (2006): Equatorial sandhoppers use body scans to detect the earth's magnetic field. *Journal of Comparative Physiology* **192**, 45-49.

Unger, B., Bravo Rebolledo, E.L., Deaville, R., Grone, A., Ijsseldijk, L.L., Leopold, M.F., Siebert, U., Spitz, J., Wohlsein, P., and Herr, H. (2016): Large amounts of marine debris found in sperm whales stranded along the North Sea coast in early 2016. *Marine Pollution Bulletin* **112**, 8.

Vallejo, G.C., Grellier, K., Nelson, E.J., McGregor, R.M., Canning, S.J., Caryl, F.M., and McLean, N. (2017): Responses of two marine top predators to an offshore wind farm. *Ecology and Evolution* **7**, 8698-8708.

van der Hoop, J., Corkeron, P., and Moore, M. (2017): Entanglement is a costly life-history stage in large whales. *Ecology and Evolution* **7**, 92-106.

van der Hoop, J.M., Corkeron, P., Kenney, J., Landry, S., Morin, D., Smith, J., and Moore, M.J. (2016): Drag from fishing gear entangling North Atlantic right whales. *Marine Mammal Science* **32**, 619-642.

van der Ree, R., Grift, E., V.,, Gulle, N., Holland, K., Mata, C., and Suarez, F. (2007): Overcoming the barrier effects of roads - how effective are mitigation strategies? 2007 International conference on ecology and transportation, Raleigh, NC, pp. 423-431.

Vanermen, N., Onkelinx, T., Courtens, W., Verstraete, H., and Stienen, E.W. (2015): Seabird avoidance and attraction at an offshore wind farm in the Belgian part of the North Sea. *Hydrobiologia* **756**, 51-61.

Vegter, A.C., Barletta, M., Beck, C., Borrero, J., Burton, H., Campbell, M.L., Costa, M.F., Eriksen, M., Eriksson, C., Estrades, A., Gilardi, K.V.K., Hardesty, B.D., Ivar do Sul, J.A., Lavers, J.L., Lazar, B., Lebreton, L., Nichols, W.J., Ribic, C.A., Ryan, P.G., Schuyler, Q.A., Smith, S.D.A., Takada, H., Townsend, K.A., Wabnitz, C.C.C., Wilcox, C., Young, L.C., and Hamann, M. (2014): Global research priorities to mitigate plastic pollution impacts on marine wildlife *Endangered Species Research* **25**, 23.

Verfuss, U.K., Gillespie, D., Gordon, J., Marques, T.A., Miller, B., Plunkett, R., Theriault, J.A., Tollit, D.J., Zitterbart, D.P., Hubert, P., and Thomas, L. (2018): Comparing methods suitable for monitoring marine mammals in low visibility conditions during seismic surveys. *Marine Pollution Bulletin* **126**, 1-18.

Vilata, J., Oliva, D., and Sepúlveda, M. (2010): The predation of farmed salmon by South American sea lions (*Otaria flavescens*) in southern Chile. *ICES Journal of Marine Science* **67**, 475-482.

Volgenau, L., Kraus, S.D., and Lien, J. (1995): The impact of entanglements on two substocks of the western North Atlantic humpback whale, *Megaptera novaeangliae*. *Canadian Journal of Zoology* **73**, 1689-1698.

Walker, M.M. (1984): Learned magnetic field discrimination in yellowfin tuna, *Thunnus albacares*. *Journal of Comparative Physiology* **155**, 673-679.

Walker, M.M., Kirschvink, J.L., Ahmed, G., and Dizon, A.E. (1992): Evidence that fin whales respond to the geomagnetic field during migration. *Journal of Experimental Biology* **171**, 67-78.

Walker, M.M., Diebel, C.E., Haugh, C.V., Pankhurst, P.M., Montgomery, J.C., and Green, C.R. (1997): Structure and function of the vertebrate magnetic sense. *Nature* **390**, 371-376.

Wang, J.H., Cain, S.D., and Lohmann, K.J. (2003): Identification of magnetically responsive neurons in the marine mollusc *Tritonia diomedea*. *Journal of Experimental Biology* **206**, 381-388.

Wang, J.H., Cain, S.D., and Lohmann, K.J. (2004): Identifiable neurons inhibited by Earth-strength magnetic stimuli in the mollusc *Tritonia diomedea*. *Journal of Experimental Biology* **207**, 1043-1049.

WAP (2022): How ghost fishing gear is endangering our sea life World Animal Protection, London. 33 pp.

Warrant, E.J. (2021): Unravelling the enigma of bird magnetoreception. Nature Publishing Group.

Wartzok, D., and Ketten, D.R. (1999): Marine mammal sensory systems. In J. Reynolds, and S. Rommel (Eds): *Biology of marine mammals*. Smithsonian Institution Press, pp. 117-175.

Weiffen, M., Möller, B., Mauck, B., and Dehnhardt, G. (2006): Effect of water turbidity on the visual acuity of harbor seals (*Phoca vitulina*). *Vision Research* **46**, 1777-1783.

West, A. (2019): Project environmental monitoring plan: Kincardine offshore windfarm project. *KOWL-PL-0004-005*. Kincardine Offshore Windfarm Project Scotland 25 pp.

Westerberg, H., and Lagenfelt, I. (2008): Sub-sea power cables and the migration behaviour of the European eel. *Fisheries Management and Ecology* **15**, 369-375.

White, C., Halpern, B.S., and Kappel, C.V. (2012): Ecosystem service tradeoff analysis reveals the value of marine spatial planning for multiple ocean uses. *Proceedings of the National Academy of Sciences* **109**, 4696-4701.

Wilhelmsson, D., Malm, T., and Öhman, M.C. (2006): The influence of offshore windpower on demersal fish. *ICES Journal of Marine Science* **63**, 775-784.

Willows, A.O.D. (1999): Shoreward orientation involving geomagnetic cues in the nudibranch mollusc *Tritonia diomedea*. *Marine and Freshwater Behaviour and Physiology* **32**, 181-192.

Wilson, B., Hammond, P.S., and Thompson, P.M. (1999): Estimating size and assessing trends in a coastal bottlenose dolphin population. *Ecological Applications* **9**, 288-300.

Wiltschko, R., and Wiltschko, W. (2014): Sensing magnetic directions in birds: radical pair processes involving cryptochrome. *Biosensors* **4**, 221-242.

Wiltschko, R., and Wiltschko, W. (2019): Magnetoreception in birds. *Journal of the Royal Society Interface* **16**, 20190295.

Wiltschko, W., and Wiltschko, R. (1972): Magnetic compass of European robins. *Science* **176**, 62-64.

Winklhofer, M., and Kirschvink, J.L. (2010): A quantitative assessment of torque-transducer models for magnetoreception. *Journal of the Royal Society Interface* **7**, 273-289.

Winnicki, A., Formicki, K., and Sobocinski, A. (1993): Water uptake by trout (Salmo trutta L.) eggs exposed after acitivation to magnetic fields *Acta Ichthyologica Et Piscatoria* **22**, 7.

Winnicki, A., Korzelecka-Orkisz, A., Sobocinski, A., Tanski, A., and Formicki, K. (2004): Effects of the magnetic field on different forms of embryonic locomotor activity of northern pike (*Esox lucious* L.). *Journal of Applied Ichthyology* **34**, 11.

Woodley, T.H., and Gaskin, D.E. (1996): Environmental characteristics of North Atlantic right and fin whale habitat in the lower Bay of Fundy, Canada. *Canadian Journal of Zoology* **74**, 75-84.

Woodruff, D.L., Schultz, I.R., Marshall, K.E., Ward, J.A., and Cullinan, V.I. (2012): Effects of electromagnetic fields on fish and invertebrates - task 2.1.3: effects on aquatic organisms fiscal year 2011 progress report. Pacific Northwest National Laboratory.

Woodruff, D.L., Schultz, I.R., Marshall, K.E., Ward, J.A., and Cullinan, V.I. (2013): Effects of electromagnetic fields on fish and invertebrates - task 2.1.3: effects on aquatic organisms fiscal year 2012 progress report. Pacific Northwest National Laboratory.

World Bank (2019): Expanding offshore wind to emerging markets World Bank Group, Washington, D.C. 44 pp.

WWF (2020): The most deadly form of marine plastic debris World Wildlife Fund For Nature Gland, Switzerland 64 pp.

Wyman, M.T., Peter Klimley, A., Battleson, R.D., Agosta, T.V., Chapman, E.D., Haverkamp, P.J., Pagel, M.D., and Kavet, R. (2018): Behavioral responses by migrating juvenile salmonids to a subsea high-voltage DC power cable. *Marine Biology* **165**, 1-15.

Wynn, J., Padget, O., Mouritsen, H., Perrins, C., and Guilford, T. (2020): Natal imprinting to the Earth's magnetic field in a pelagic seabird. *Current Biology* **30**, 2869-2873.e2.

Xodus, G. (2021): Pentland floating offshore wind farm EIA scoping report. *A-100671-S00-REPT-001*. Xodus Group, Orkney, Scotland 353 pp.

Yano, A., Ogura, M., Sato, A., Sakaki, Y., Shimizu, Y., Baba, N., and Nagasawa, K. (1997): Effect of modified magnetic fieldd on the ocean migration of maturing chum salmon *(Oncorhynchus keta)*. *Marine Biology* **129**, 8.

Yano, K., Mori, H., Minamikawa, K., Ueno, S., Uchida, S., Nagai, K., Toda, M., and Masuda, M. (2000): Behavioral response of sharks to electric stimulation. *Bulletin of Seikai Bational Fisheries Research Institute* **78**, 13-30.

YouTube (2017): Humpback whale playing under an oil rig in Australia.

YouTube (2018): Whales love wind.

YouTube (2020): Whale spotted near ONGC Mumbai offshore plant.

Zoeger, J., Dunn, J.R., and Fuller, M. (1981): Magnetic material in the head of the common pacific dolphin. *Science* **213**, 892-894.

Žydelis, R., Small, C., and French, G. (2013): The incidental catch of seabirds in gillnet fisheries: a global review. *Biological Conservation* **162**, 76-88.