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Review article

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Assessing, monitoring and mitigating the effects of offshore wind farms on biodiversity

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Abstract

Offshore wind farms (OWFs) are integral to the global shift towards renewable energy, yet they introduce complex challenges for marine biodiversity. OWF development affects a range of species – including fish, invertebrates, seabirds and marine mammals – through noise pollution, habitat alteration, physical barriers and potential entanglement. Conversely, turbine structures can act as artificial reefs and fish refuges, enhancing local biodiversity. This Review synthesizes current knowledge of OWF impacts across their life cycle – from construction to decommissioning – highlighting both direct and indirect ecological effects, including food web changes and displacement of fisheries. The Review discusses assessment, monitoring and mitigation strategies, and emphasizes the need for more coordinated international approaches, particularly in the areas of data sharing, cumulative impact assessments and long-term ecological monitoring. Differences in governance, regulation, data collection and mitigation strategies across countries or regions lead to varying biodiversity outcomes at OWFs. We outline priority steps that could be taken to improve assessment and monitoring across regional and international scales, including the use of emerging technologies, adaptive management, the development of more sophisticated models and decision-support tools, and the establishment of regionally tailored ecosystem monitoring programmes to better understand the impacts of OWF energy developments on biodiversity.

Sections

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Key points

- Offshore wind farms affect marine life in complex ways, creating both risks (including noise, disturbance and habitat loss) and benefits (including new habitat for some species).
- Turbine structures can support marine biodiversity by acting as artificial reefs, attracting fish, invertebrates and algae — although this effect varies by design and location.
- Noise from construction is a major concern, especially for marine mammals and fish, but new technologies and better planning can reduce harmful impacts.
- Floating wind farms and decommissioning remain poorly studied, meaning their full effects on biodiversity are still uncertain and need more attention.
- Current monitoring and impact assessments are inconsistent across countries, making it hard to understand long-term or large-scale effects on ecosystems.
- Stronger collaboration, shared data and smarter tools — including sensors, modelling and DNA-based monitoring — are needed to guide nature-positive offshore wind development.

Introduction

Offshore wind farms (OWFs) are a growing source of clean, renewable energy that have a substantial role in the global transition away from fossil fuels. Global installations of large-scale OWFs are expected to increase from a level of 117 GW in 2023 to at least 320 GW of capacity by 2030 (ref. 1). Expansion is occurring across 158 countries, with the largest potential for future capacity growth identified in Europe (495 GW), Asia (292 GW) and the Americas (200 GW) (Fig. 1). Oceania (99 GW) and Africa (1.5 GW) have the lowest number of OWF projects under construction or in development. As part of this development, 15% of new offshore wind energy installations by 2050 are anticipated to feature floating foundations rather than fixed-bottoms[2]. Floating OWFs will open new possibilities for wind power locations, especially in areas of deeper water, where winds are stronger and more consistent[3].

With the rapid expansion of OWFs, many regulators, stakeholders and researchers are increasingly expressing concerns about the potential impacts on the marine environment. OWF projects can affect the marine environment in different ways, either positively or negatively, or sometimes not at all[4]. OWF structures can elevate underwater noise, change electromagnetic fields and disrupt waterways, leading (in some cases) to vessel collisions, displacement of populations and shifts in food webs[5,6]. However, OWFs can introduce new habitat, creating 'artificial reefs' that support a variety of marine life, including invertebrates, shellfish and local fish populations[7]. Despite substantial progress in rigorously measuring global biodiversity effects and impacts from OWFs (Box 1), major taxonomic and geographic knowledge gaps remain and there are still considerable uncertainties about the assessment of impacts resulting from cumulative OWF pressures[8]. Current evidence must be synthesized to identify information gaps and guide targeted data collection as OWFs expand into new regions.

Following global agreements to protect oceans (for example, the UN Ocean Decade, Sustainable Development Goal 14 (Life Below Water), the UN High Seas Treaty and the Convention on Biological Diversity (CBD) Global Biodiversity Framework targets), the offshore wind sector is increasingly identifying ways to make projects more 'biodiversity-positive'. For example, regulations on noise control during drilling processes increasingly reflect nature-positive approaches to OWF development, such as using noise mitigation technologies to protect marine life during construction[9]. Mitigation of effects in the OWF industry are guided globally by a well-established hierarchy[10], with four components: avoidance; minimization; mitigation or restoration; and offsetting or compensation of biodiversity impacts. In this mitigation framework, negative biodiversity impacts that cannot be avoided or minimized can be moderated by environmental gains to produce net neutral or net positive outcomes for affected populations and ecosystems[10,11]. However, taking a net neutral or net positive approach requires that the impacts on the marine environment are adequately quantified[12].

In this Review, we summarize the range of effects of OWFs on species and ecosystems. We discuss how effects vary across fixed-bottom and floating OWFs, and across life-cycle phases (including construction, operation and decommissioning), highlighting existing evidence and important knowledge gaps. After explaining the different approaches to assessing, mitigating and monitoring impacts, we suggest future assessment, monitoring and mitigation directions that could help to enhance biodiversity while simultaneously accelerating the deployment of OWFs, in line with targets needed to meet global climate change and net zero targets.

Evidence of biodiversity effects

Several methods have been used to determine how OWFs affect the environment and biodiversity (Box 1). The main types of effects that have been described in prior literature[4,13–15] are discussed in detail in this section. Impacts that occur during the construction and operation stages are primarily attributed to the direct presence of the structure (including ancillary structures such as cables and substations) and noise disturbance from vessel activity, whereas effects during decommissioning involve planning, transporting and managing the removal of the turbines and can also include noise disturbance depending on the removal methods used. Because very few full-scale commercial OWFs have been fully decommissioned, evidence for the impacts of decommissioning on biodiversity is rare[16].

Species abundance, biomass and diversity

During the construction and operational phase of OWFs, turbine structures and wind wakes alter local hydrodynamics, affecting nutrient distribution, water column mixing and light penetration. These changes can influence primary production, which in turn affects phytoplankton biomass and community composition near turbines, potentially altering broader ecosystem dynamics[17]. For example, projected local changes in annual primary production of up to 10%, meaning both increases and decreases of up to 10% in phytoplankton biomass, have been modelled[18] in North Sea areas influenced by operational OWF wind wakes. These effects reflect a spatially heterogeneous pattern of phytoplankton response where some OWFs can boost phytoplankton productivity whereas others suppress it, depending on local hydrographic conditions, bathymetry and nutrient availability.

Once operational, the submerged parts of fixed offshore wind turbines together with their associated scour protection (protective

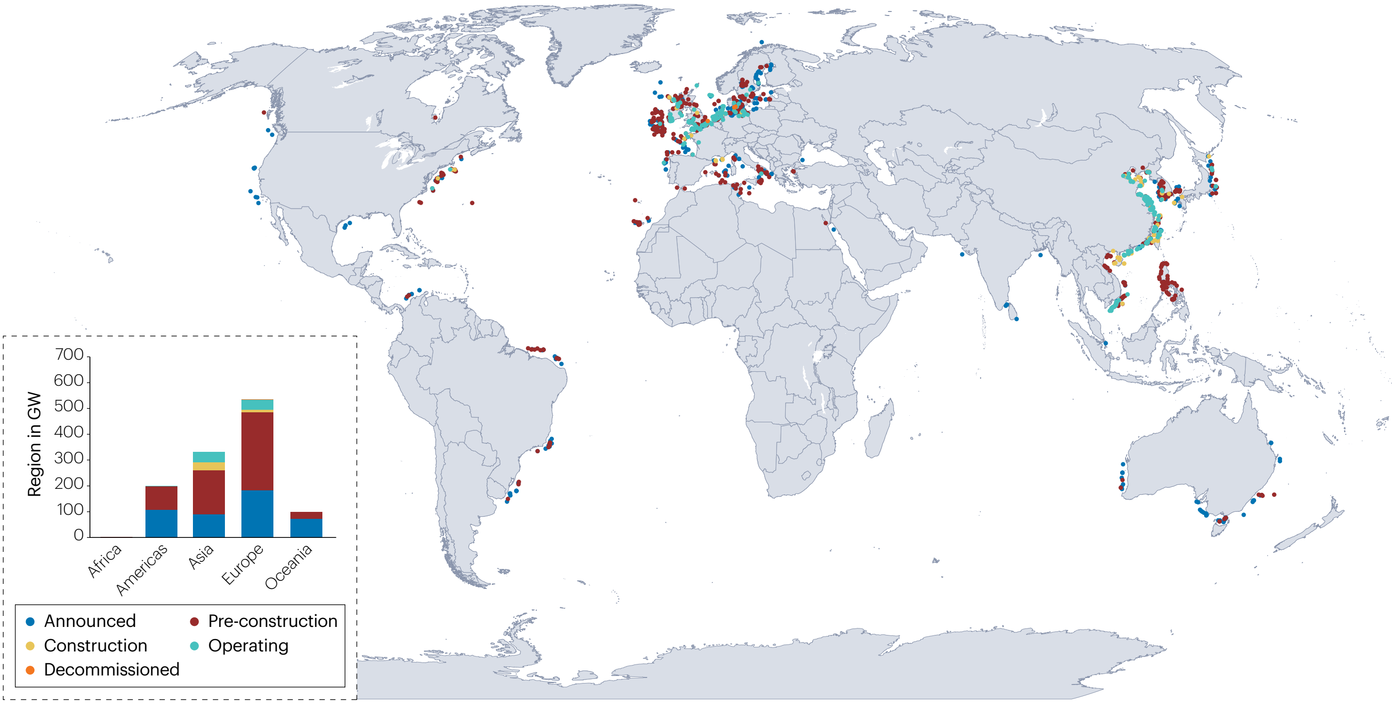


Fig. 1 | Global spatial distribution of offshore wind farm projects in different stages of development. 'Announced' projects have been publicly reported but have not yet received permits or sought land, material or financing (dark blue). 'Pre-construction' projects are actively moving forward in seeking governmental approvals, land rights, financing and conducting environmental and/or social impact assessments (red). 'Construction' projects have initiated the installation of equipment (yellow). 'Operating' projects have achieved commercial operation (teal). 'Decommissioned' projects have been dismantled (orange). Inset shows offshore wind farm (OWF) capacity by installation type (GW) and by region. Data derived from the Global Energy Monitor's Global Wind Power Tracker (https://globalenergymonitor.org/projects/global-wind-power-tracker), June 2024 release.

structures placed around turbine foundations to prevent seabed erosion caused by water currents) can act as an artificial reef, providing new habitats for marine life (Fig. 2). Evidence from the literature suggests these artificial structures can lead to increases not only in species abundance[19,20] and biomass[21] but also in species richness[22] and community diversity[23], with various species of fish, invertebrates (for example, mussels, crabs and lobsters) and algae colonizing these structures[24,25]. However, the extent and magnitude of the positive impact depend on the structure's design materials, its biogeographical location, and how quickly and effectively existing marine species can colonize the OWF[7]. For example, turbine foundations made of rough concrete or rock-armoured scour protection tend to support greater colonization by benthic invertebrates and algae than smoother steel monopiles, owing to enhanced microhabitat availability and substrate complexity[26]. Additionally, colonization speed and ecological outcomes could also be influenced by proximity to natural reefs or larval source areas, which act as propagule supply zones, accelerating succession and boosting early-stage biodiversity[27]. Although the structures of fixed and floating OWFs are different, they create similar artificial reef effects. For example, surveys of invertebrates and algae on the Hywind Scotland floating OWF show overall similarities with the colonization of midwater and surface structures of other fixed OWF structures[28] and the mooring lines and floating substructures have been found to attract fish, jellyfish and cephalopods[29].

Because fishing is typically restricted or prohibited within OWF installations, these areas can also provide a sanctuary area for fish and can act as marine refuges where fish populations increase in abundance and size. Over time, fish populations can increase locally and eventually supplement populations further away from the installations. Studies of fish distributions before and after installation of OWFs demonstrate that some demersal fish species such as Atlantic cod (*Gadus morhua*) aggregate near the new hard structures[30,31], whereas several species of flounder (including the Gulf Stream flounder, *Citharichthys arctifrons*) show no net increase in the local population[32,33].

One potentially negative outcome of these artificial reef effects is the recruitment of non-native species, some of which are invasive[25,34,35]. Examples of non-native species found on or near OWFs include the Pacific oyster (*Crassostrea gigas*), barnacles (*Elminius modestus* and *Megabalanus coccopoma*), the amphipod (*Jassa marmorata*), the Asian crab (*Hemigrapsus sanguineus*), skeleton shrimp (*Caprella mutica*) and the common or moon jellyfish (*Aurelia aurita*). Although the potential for OWFs to facilitate the spread of non-native species is an important future consideration, more research is needed to quantify the extent of this impact and develop mitigation strategies, including routine ecological monitoring, and rapid response protocols to prevent establishment and further spread.

The degree of artificial reef effects at the decommissioning stage of OWFs is still uncertain and probably depends on the way the structure is decommissioned[36]. When structures such as scour protection and foundations are retained, they continue to provide essential habitats for marine species, preserving the artificial reef effect and supporting biodiversity, including benthic organisms and small fish. Partial removal of the structures could also preserve local epibenthic

Box 1 | Methods to measure offshore wind farm effects on biodiversity

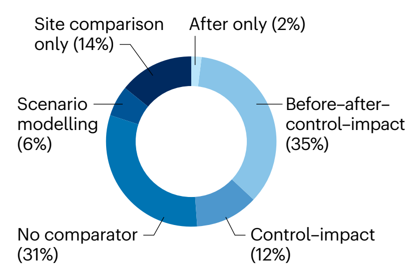
A range of empirical and modelling methods have been used to assess the impacts of offshore wind farms (OWFs) on biodiversity; their relative use within the 154 studies discussed in this Review are shown in the figure.

The most common designs are 'control–impact' representing 12% of studies and 'before–after–control–impact' (BACI) representing 35%. In control–impact designs, ecological conditions at the impact site are compared with one or more unaffected control sites, usually during the same period[96,141]. BACI designs build on this by incorporating both spatial and temporal comparisons, assessing conditions at both impact and control sites before and after construction[134,168]. These approaches are generally considered the most robust for detecting change because they account for natural variability and help to attribute observed effects directly to OWF development rather than to unrelated environmental fluctuations. By contrast, site comparison-only and after-only approaches are considerably less reliable in the context of OWF impact assessments. Site comparison-only studies[19,151] (14%) typically compare conditions at the OWF site with a reference site selected a posteriori, without baseline or control data, whereas after-only studies[169] (2%) assess ecological conditions at multiple time points following OWF construction but lack any data from before the development. Additionally, many studies (31%) do not compare impacts with a suitable control area unaffected by OWF construction and operation[170,171] (categorized as 'no comparator' in the figure); these approaches are disadvantageous in robustly identifying biodiversity impacts.

Despite the clear advantages of BACI and control–impact designs, they are not always implemented for a number of reasons including the absence of pre-construction (baseline) data, difficulty identifying suitable control sites with comparable environmental characteristics, and the cost and logistical demands of long-term monitoring. Time constraints within permitting processes or limited regulatory requirements might also discourage their use, especially in emerging OWF markets. Regionally, BACI designs are more commonly applied in Northern Europe (specifically the UK, Germany and Denmark), where robust regulatory frameworks support best-practice ecological monitoring.

These empirical study designs use a combination of observation types to identify impacts during construction and operational phases (Table 2). Importantly, none of the empirical studies in this Review has repeated long-term measurements of the physical and biological environment surrounding the OWF over the structure's lifespan of approximately 25–30 years. Therefore, given the rarity of long-term empirical datasets, scenario models that simulate the potential effects of OWFs on marine ecosystems are also important tools, representing 6% of current studies. Scenario modelling helps researchers to predict long-term ecological impacts, such as potential shifts in biodiversity, species distribution and food webs[76,145]. It can also help to assess how OWF activities could affect the resilience of marine ecosystems over time.

Moving forward, the adoption of BACI designs, alongside scenario modelling and the more recently proposed before–after–gradient method[145,172] (sampling ecological conditions before and after OWF construction along a spatial gradient extending outwards from the turbines), is encouraged for improving the comparability, credibility and ecological value of OWF impact assessments.



benthic communities (including mussels, barnacles and crabs), although effects vary depending on the structure type, location and species present[37]. By contrast, complete removal of all infrastructure eliminates the artificial habitat, potentially resulting in a loss of existing biodiversity, especially for species that rely on these hard substrates for shelter and feeding. However, despite compelling case studies of reef formation on operational and decommissioned OWF structures, a systematic review and meta-analysis concluded that the available evidence is insufficient to demonstrate clear, long-term ecological gains from decommissioning OWFs as artificial reefs[36].

Species behaviour

During construction and operation, multiple aspects of OWFs — underwater noise, physical barriers and electromagnetic fields — can cause behavioural changes in marine species and flying terrestrial vertebrates (birds and bats) (Fig. 2).

Underwater noise. The magnitude of underwater noise production varies across life-cycle stages (resulting from different activities) and differs slightly between fixed and floating OWFs. During the construction phase of fixed OWFs, seismic surveys and pile-driving (forcing a pile into sediment, typically used to secure the foundations of offshore wind turbines) generate underwater noise levels often exceeding 200 dB at the source[38]. During operation, fixed OWFs also produce continuous low-frequency noise — typically 120–150 dB — from turbine movement and vessel traffic. Increased vessel traffic and removing foundations and cables during decommissioning can produce noise pollution in the range of 140–200 dB, comparable with the construction phase[39]. Although floating OWF construction does not require pile-driving, underwater noise impacts can also occur for floating OWF developments from activities such as cable laying and anchor installation, and from mooring lines, which may also generate impulsive sounds when tension is released, adding to acoustic disturbance. However, substantially fewer industry data are available for noise emissions from floating OWFs compared with bottom-fixed OWFs.

This magnitude of sound production is far above the behavioural response thresholds for many taxa; for example, hearing-specialist fish (with enhanced auditory structures) respond at thresholds from 55 to 83 dB and hearing generalists (with less sensitive hearing) from 78 to 150 dB[40]. Noise from OWFs can cause stress and behavioural changes in fish and invertebrates, affecting their ability to detect predators and prey[41] and reducing their overall survival and reproduction capabilities[42]. In crustaceans, noise exposure has been linked to reduced egg development, growth and reproductive rates, or changes in haemolymph biogeochemistry[43]. Scallops have also responded negatively to pile-driving noise, showing reduced gonadal growth and lower egg quality and a shortened pelagic larval phase[44]. Pile-driving noise can disrupt marine mammals' communication, navigation and foraging. For example, harbour porpoises (*Phocoena phocoena*), which rely on echolocation with detection thresholds around 90–100 dB[45], have exhibited behavioural disturbances such as displacement from important habitats and disruption of foraging activity in response to underwater pile-driving noise[46]. However, although construction noise from fixed OWFs can cause behavioural disturbances in harbour seals (*Phoca vitulina*) and harbour porpoises (*P. phocoena*), the lower-frequency noise during operation typically does not reach levels high enough to cause harm or mask acoustic communication[47,48].

Understanding the acoustic behavioural impacts of floating OWFs on marine life, including fish, crustaceans and other sensitive species, requires further research to define acceptable exposure thresholds[49,50]. Although some of these data gaps can be addressed through controlled laboratory experiments before floating OWF deployment, resource constraints limit the breadth of species tested. In such cases, prioritizing representative species from functionally or ecologically similar groups to fixed OWFs offers a pragmatic solution for assessing potential impacts.

Physical barriers. Operational fixed and floating OWFs can also act as physical barriers that obstruct the regular movements and behaviours of birds, bats, fish and marine mammals, through multiple mechanisms. The first type of obstruction is a barrier or avoidance effect in which the wind farm creates an obstacle to regular

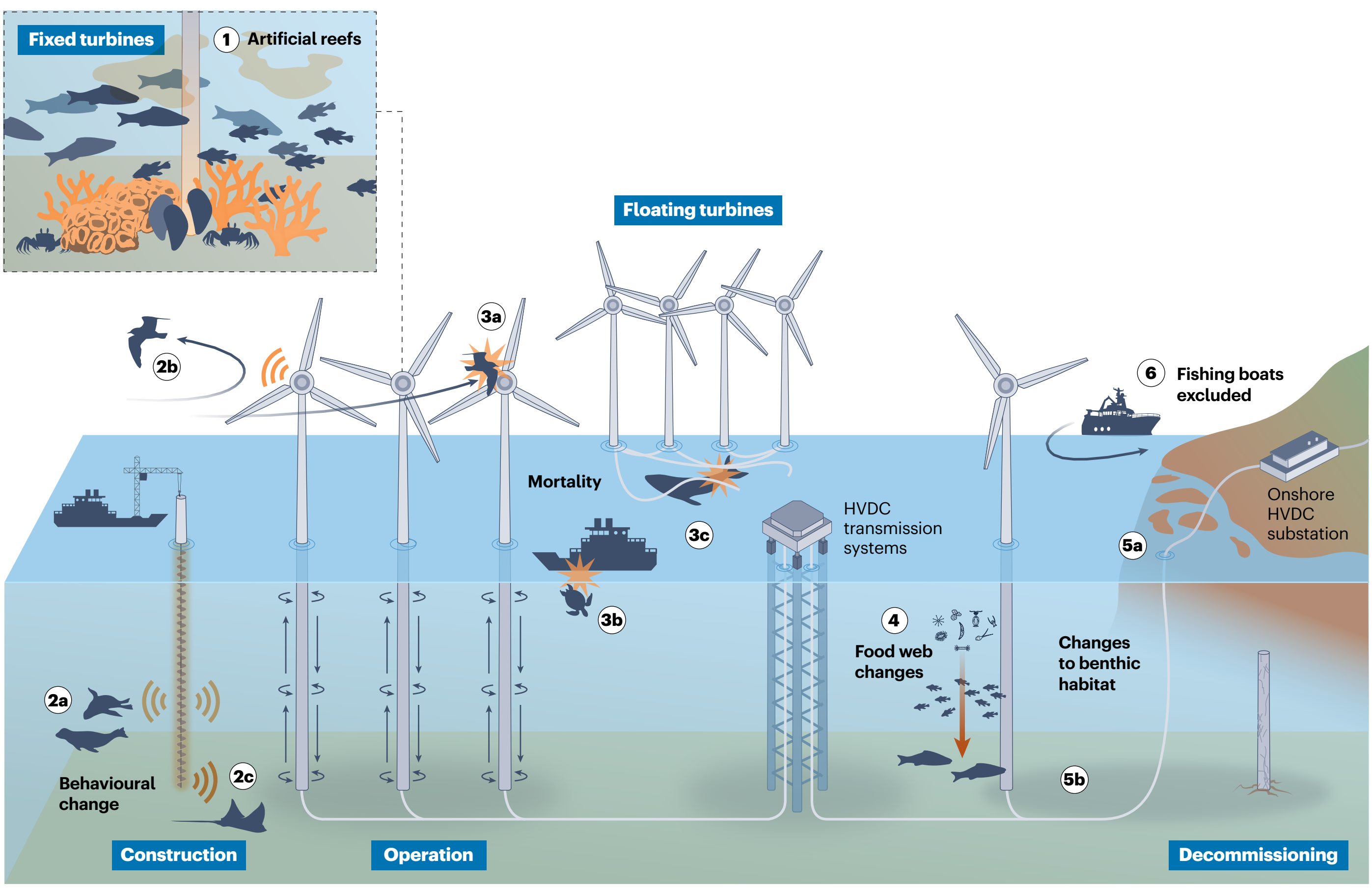


Fig. 2 | Six ways that offshore wind farms affect species and marine ecosystems. The abundance, biomass and diversity of some groups (such as benthic invertebrates and fish) can increase as turbines create artificial reef habitats (1). Turbines elicit multiple changes in species behaviour; noise pollution can deter species such as marine mammals (2a), physical barriers cause birds to avoid offshore wind farm (OWF) areas (2b) and electromagnetic fields might alter behaviour (2c). Mortality occurs through collision with turbines (3a), collision with construction vessels (3b) or entanglement with floating vessel cables (3c). The artificial reef effect (shown in (1)) and enhanced vertical mixing can cause food web alterations, such as an attraction of fish to OWF areas (4). OWF construction and (potentially) decommissioning can harm benthic habitats in both coastal areas (through high voltage direct current (HVDC) cable installation and removal) (5a) and on the seafloor at the base of fixed turbines (5b). Line fisheries are prohibited from entering OWF areas during construction and bottom trawling is prohibited during operation; this displacement of fisheries could have a range of potential indirect effects on local and regional fish communities (6).

movements to and from breeding colonies or feeding activities[51]. For example, sandwich terns (*Thalasseus sandvicensis*) and loons (divers, family Gaviidae) tend to avoid OWFs, with avoidance rates increasing with turbine density[52,53]. Such avoidance effects are generally more pronounced in flying vertebrates, such as birds and bats, which often alter flight paths to circumvent wind farms, potentially increasing energy expenditure and disrupting migration or foraging routes. By contrast, marine species such as large migratory mammals (large porpoises or seals) either show no clear avoidance response or are attracted to OWFs[54]. The second type of obstruction is an effective loss of habitat by excluding individuals from areas they would normally inhabit, further affecting their behaviours and population[51]. For example, some seabird species reduce or abandon foraging and breeding grounds near operational OWFs, resulting in decreased local abundance[55].

During decommissioning, full removal of turbines, foundations and cables eliminates the physical barriers created by OWFs, thereby restoring free movement for mobile species and removing potential displacement effects[56]. To date, specific behavioural responses of birds, marine mammals, fish and invertebrates to decommissioning have not been observed, highlighting a critical knowledge gap for future impact assessments.

Electromagnetic fields. Export and inter-array cables from both fixed and floating OWFs emit electromagnetic fields. Magnetic fields with a strength of ~50 μT (considered a relatively strong magnetic field) have been observed near transmission cables immediately adjacent to OWFs[57].

Electromagnetic fields can affect the behaviour and navigation of certain fish and invertebrate species[58], but the species response to electromagnetic fields near OWFs has been tested in very few species. Electromagnetic fields comparable with those observed at OWFs have elicited subtle exploratory and sheltering responses in American lobster (*Homarus americanus*)[59] and increases in foraging behaviour in little skates (*Leucoraja erinacea*)[59]. These observations come from in situ enclosure experiments, demonstrating real-world responses to electromagnetic fields emitted by OWF cables.

Currently, no research papers have examined the combined effects of OWF-associated noise and electromagnetic fields on biodiversity, despite the likelihood of simultaneous or sequential exposure during cable laying, pile-driving and maintenance operations.

Mortality

During the construction phase of OWFs, vessel movements during surveying and installation activities have caused collisions with marine mammals, turtles and fish[60,61] (Fig. 2). More than 30 marine mammal species and at least 5 sea turtle species have been shown to be vulnerable to such vessel strikes[62]. Modelled estimates indicate that encounter rates between large whales and OWF construction vessels can range from 0.5 to 4 per month per wind farm during peak activity[63]. Despite existing mitigation measures such as vessel speed limits, challenges in monitoring and enforcing compliance mean that mortality risks of collisions remain high[64]. Species that have been found to avoid OWFs (seals and porpoises[65,66]) might be less vulnerable to mortality from direct collisions with vessels[65,66].

During operation, the rotating blades of the wind turbines add another source of collision risk, particularly for seabirds and, to a lesser extent, bats[67]. Although bat fatalities are common at onshore wind farms[68], to date no bat fatalities have been documented at offshore wind projects even though bats have been reported occasionally to visit OWFs while migrating across the Baltic Sea in Europe[69]. The probability of collision is determined, in part, by structure properties such as turbine heights, blade lengths, tip speeds and blade appearances to birds[70]. Some species, including the Eurasian curlew (*Numenius arquata arquata*)[71], black-tailed gulls (*Larus crassirostris*) and slaty-backed gulls (*Larus schistisagus*)[72], also experience particularly high risk of collision with OWFs owing to a combination of ecological and behavioural factors. These species typically fly at altitudes that coincide with turbine rotor-swept zones (approximately 20–150 m above sea level), increasing their vulnerability to strikes[72]. Moreover, they often engage in foraging or migratory flights through regions with dense OWF development, such as the North Sea, Sea of Japan and parts of the East China Sea. In Japan, collision risk models projected potential annual fatalities of more than 250 black-tailed gulls under certain turbine layouts of OWFs located within 15 km of breeding colonies and within 5 km of harbours[72]. Data on the factors influencing the collision risk for bird and bat fatalities, however, are sparse and often based on theoretical estimates of collision risk via models or using different field-based techniques, including radar, GPS tagging, thermal imaging, and visual or acoustic observations.

In operational floating OWFs, another source of wildlife mortality is entanglement with cables. Ocean currents, wind and waves continuously move the mooring and inter-array cables of floating OWFs that — relative to the static platforms of fixed OWFs — increase the risk that marine mammals such as whales will become entangled[49]. In addition to this 'primary' entanglement, 'secondary' entanglement can also occur when marine debris such as fishing gear becomes entangled in lines or cables, leading to further entanglements of animals[49]. Although there are currently no confirmed cases of whales or other marine mammals becoming directly or indirectly entangled in OWF components such as mooring lines or dynamic cables, modelling studies and risk assessments suggest that such events are plausible and likely to increase as OWF expansion continues into deeper waters[73].

Little is known about species mortality during decommissioning, but the risk of collision with vessels should be comparable with the risk during construction given similar rates of marine traffic[74]. The entanglement risk should decrease if cables and mooring systems are successfully removed, particularly for floating OWFs. However, if parts of the infrastructure are left in situ, residual entanglement hazards could persist, especially in areas where marine debris is common.

Food web alterations

The presence of OWFs can alter local food webs in several ways. Construction-related activities such as pile-driving, increased vessel traffic and sediment disturbance from seabed preparations have been shown to disrupt prey–predator relationships for species such as the little tern (*Sternula albifrons*), by reducing prey abundance and decreasing foraging success[75].

By contrast, during the operational phase, the colonization of submerged structures by suspension feeders such as mussels and barnacles can enhance habitat complexity and increase habitat and food availability for higher trophic levels such as fish, birds and marine mammals. However, this trophic enhancement is often spatially limited to the immediate vicinity of turbine foundations. It can also coincide with broader reductions in regional productivity[25]. Model results in the North Sea of Europe indicate that blue mussel (*Mytilus edulis*) colonization of OWFs induces extensive ecological change through filtration of organic matter (including phytoplankton and zooplankton) from the water that can reduce regional annual primary productivity by 8%[76]. This demonstrates that whereas localized food availability may increase near turbines, OWFs can simultaneously redistribute and even suppress broader ecosystem productivity[77].

OWFs also influence ecosystem processes such as nutrient cycling and vertical mixing of the water column, which in turn affect marine life, including birds and fish. Enhanced vertical mixing has been shown to attract fish to OWFs during the operational phase, where they find more abundant resources (Fig. 2). Large-scale OWFs can reduce the magnitude or frequency of local wind stress, potentially suppressing or enhancing upwelling intensity around the OWF and altering nutrient availability in the affected area[78]. Such disruptions could have cascading impacts on trophic dynamics, from phytoplankton assemblages to higher-order consumers, including commercially important fish stocks and marine megafauna[79]. These food web effects remain to be tested.

Moreover, physical interactions between turbine foundations and ambient flow during operation are likely to influence larval transport processes. For instance, models suggest that these monopile–fluid interactions could substantially alter offshore scallop larval dispersal patterns[80], with potential consequences for recruitment and population connectivity.

Floating OWFs could lead to different patterns of biofouling community development and associated food web interactions compared with fixed structures because they are moored in deeper waters, often far from the coast, in less disturbed and more oligotrophic (nutrient-poor) environments. Floating OWFs might connect pelagic and benthic ecosystems in novel ways: by introducing hard substrate into water columns that previously lacked it, they provide novel feeding grounds for pelagic predators and pathways for vertical energy transfer[81]. Furthermore, the mobility of the structures (from wave and current action) could make the spatial extent of ecological influence more dynamic and less predictable compared with fixed installations. The implications for larval transport, nutrient cycling and trophic dynamics in these offshore zones remain an emerging area of research, but early indications suggest that floating OWFs could substantially reshape offshore food webs by attracting new assemblages of species and modifying predator–prey interactions in previously undisturbed habitats[29].

As OWFs become decommissioned, the removal of turbine structures could lead to the sudden loss of artificial reef habitats, potentially displacing colonizing species and disrupting local food webs that became dependent on the habitat and foraging opportunities provided[82]. This structural loss could decrease biodiversity and alter predator–prey dynamics, especially for species that rely on biofouling communities for sustenance. The removal of offshore structures without accounting for their function as stepping-stone habitats might also disrupt ecological connectivity[83] and hinder the recovery of species with limited dispersal capacities, such as sessile invertebrates or reef-associated fish, which rely on these artificial substrates to maintain population linkages across otherwise fragmented habitats.

Benthic habitat alterations

Loss of seabed habitat during the installation of turbine foundations and substructures is a primary concern for fixed OWF development (Fig. 2). Evidence of benthic habitat effects is predominantly available from OWFs in Europe and the USA. During the construction of fixed turbines, activities such as pile-driving, laying the foundations, anchoring cables and building offshore high-voltage direct current substations can disturb the seabed surrounding the OWFs, leading to changes in sediment composition and stability[84]. Benthic habitats and associated biodiversity can be entirely lost beneath the foundation, or become degraded by sediment plumes and smothering, displacing benthic organisms permanently or temporarily[85]. The total area lost by foundations is, however, small in relative terms of the overall OWF area, and evidence from one wind farm in the USA showed that recovery of the physical and biological conditions on the seafloor including its macrofauna occurred within approximately 3 years[86]. However, the kind of sediment, the installation technique, the local oceanographic processes and the species present are all likely to affect physical and biological recovery rates[86]. Because the OWF foundations also have potential to create habitat (discussed in 'Species abundance, biomass and diversity'), the loss of existing seabed habitat during installation might be offset by recruitment of species to these habitats over the years of operation[87].

Other than the muddy and sandy seafloor, more ecologically sensitive benthic habitats including seagrass meadows, coralligenous reefs, maerl beds, seamounts and deep-sea coral reefs could be damaged by improperly sited fixed-bottom turbines and subsea cables[6]. Further, impacts are not restricted to offshore environments but can also occur in coastal areas where infrastructure is built to connect turbines to the electricity grid. For example, installation of transmission cables and onshore high-voltage direct current substations can degrade sensitive coastal sites including wetlands, marshes, mangroves, mudflats and freshwater ponds that are home to birds and large numbers of other wildlife[88]. These habitats are often protected and host fragile biodiversity, making careful pre-construction planning and site selection essential.

Another potential, but under-explored, risk to benthic habitats during OWF operation is chemical pollution. Several methods to reduce corrosion, necessary to maintain operation of the turbines, can emit chemicals[89]; indeed, more than 200 different chemical compounds – including bisphenol A, phthalates, heavy metals (such as zinc, aluminium and indium) and other organic pollutants – could be released from OWFs into the marine environment[90]. The release of contaminants from turbine corrosion protection systems could pose ecotoxicological risks, especially in areas where aquaculture operations involving oysters, mussels or kelp are co-located near fixed or floating OWF installations[91]. However, impacts of OWF-related chemicals on biodiversity have not been tested in situ.

The decommissioning of OWFs can also disturb seabed sediments, potentially releasing chemicals that had settled during the operational phase (for example oils, heavy metals or microplastics). These impairments to water quality could affect benthic organisms and the wider food web. Decommissioning can either be complete or partial (leaving scour protection layers in place); an evaluation of the effects of these two strategies on benthic communities found that retaining scour protection preserved about 69% of associated benthic macrofauna species, whereas complete removal led to substantial biodiversity loss, suggesting that partial decommissioning supports benthic communities better than full decommissioning[37].

Indirect impacts of displacement of fisheries

During construction, fishery exclusion zones are often established around fixed and floating OWFs to prevent fishing vessel collisions or gear entanglement with the infrastructure. The exclusion zones tend to be larger around floating than fixed OWFs, because the former has dynamic cables and mooring lines that extend well beyond the turbine

Table 1 | Geographic and taxonomic gaps in available evidence on biodiversity effects

Taxonomic groups	Americas	Asia	Europe
Birds and bats	Positive: none Negative:[88] No effect:[125]	Positive: none Negative:[72] No effect: none	Positive:[126,127] Negative:[53,71,126,128,129] No effect:[130–132]
Fish	Positive:[133,134] Negative: none No effect:[33,135,136]	Positive: none Negative:[137] No effect:[138]	Positive:[19,30,96,139] Negative:[94,140] No effect:[31,141]
Marine mammals	Positive: none Negative: none No effect: none	Positive: none Negative: none No effect: none	Positive:[54,142,143] Negative:[46,144,145] No effect:[146]
Benthic invertebrates and habitats	Positive:[86] Negative:[59,147] No effect:[148]	Positive: none Negative:[149] No effect: none	Positive:[20,34,98,150,151] Negative:[85,152–154] No effect:[155,156]
Plankton and zooplankton	Positive: none Negative: none No effect: none	Positive:[157,158] Negative:[158] No effect: none	Positive:[17,18] Negative:[17,76] No effect:[18]

For each major taxonomic group and region, the table lists example references that found either a positive, a negative or no effect of offshore wind farms (OWFs) on biodiversity. For each reference listed, a three-level classification scheme following published methodologies[4,159] was used to qualitatively score the direction of the OWF on biodiversity as positive, negative or no effect. The biodiversity effect can include any of the six categories discussed in this Review.

footprint, creating additional seabed obstacles. Importantly, these physical constraints persist throughout the operational phase as well. Because these cables lie on or just beneath the seabed, mobile fishing gear such as trawl nets and dredges cannot often safely navigate or deploy within these zones[92]. This displacement of fisheries effectively transforms these areas into de facto marine protected areas[93]. The resulting biodiversity benefits within OWF boundaries could include a reduction in physical disturbance to benthic habitats; protection of essential species habitat; increased size, biomass and diversity of species; and potential spillover effects[94]. Spillover effects entail the outward movement of adult or juvenile marine species from protected or undisturbed OWF areas into surrounding fishable waters. For example, catch increases of up to 7% in areas adjacent to OWFs have been projected from exploratory scenarios using Ecospace, a spatial food web model that simulates ecological responses to management measures such as fishery exclusion zones[95]. Increased catch rates of valuable commercial species such as Atlantic cod (*G. morhua*), pouting (*Trisopterus luscus*) and brown crab (*Cancer pagurus*) have also been empirically observed in areas adjacent to OWFs[96,97] Although trawling is prohibited, some fisheries with static gear types are permitted to operate within an OWF. These fisheries could see benefits in the form of increased abundance and catches of certain species, such as lobsters, which have been found in higher numbers around turbine foundations[98].

The potential impact of displacement of commercial fisheries on benthic habitat and fish communities will depend on the amount of effort that is displaced (including any increased fishing effort to compensate for lost catches) and how this effort is redistributed. For example, displacement of fisheries from OWFs in the German North Sea area led to a noteworthy loss in fishing opportunities for flatfish species such as dab (*Limanda limanda*), sole (*Solea solea*) and brill (*Scophthalmus rhombus*)[99] as these species typically inhabit areas where OWF exclusion zones were implemented. Displacement of fisheries could also negatively affect fish stocks in areas where the fishing effort increases as a result of relocation or increased intensity of fishing activity[100].

Decommissioning OWFs temporarily prolongs fishing exclusions; as exclusion zones shrink, displaced fishers might initially return to the former OWF footprint. However, until full clearance and re-surveying are complete, some areas remain off-limits, leading to a phased re-entry that can concentrate effort at the new exclusion boundaries – potentially recreating local hot spots of pressure on biodiversity and uneven impacts on commercial fish stocks. Owing to growing concerns around the loss of fishing ground for the fishing industry, some policies, frameworks and strategies are now seeking to encourage opportunities for coexistence between OWF development, fishing and other offshore activities, such as aquaculture[101].

Summary of evidence and knowledge gaps

Several literature reviews from the past decade have concluded that the impact of OWF construction on biodiversity is negative overall[4,14,102]. However, as is evident from the discussion of effects in this section, biodiversity responses to OWFs are complex and it is difficult to identify prevailing trends in the available body of evidence. Importantly, the effects of OWFs have been investigated more frequently in some taxa than others, and more frequently in some regions than others (Table 1).

Effects vary substantially across taxonomic groups (Table 1). For example, hard-substrate foundations can provide new attachment sites for sessile invertebrates and algae, whereas noise, increased turbidity and sediment plumes can disrupt feeding and breeding behaviours of mobile benthic fauna and fish larvae. However, even these general taxonomic trends show variation in the literature; for example, some case studies have indicated no short-term effects on benthic communities and bivalves following construction[103].

Most of the available literature comes from OWFs in Europe and the Americas, with very few published studies coming from Asia, and currently none from Africa or Oceania (Table 1). This geographic imbalance underscores the urgent need for international coordination and knowledge transfer.

Assessment, monitoring and mitigation of OWFs

The risk of negative biodiversity impact and associated uncertainties regarding effective mitigation is one of the most relevant non-technical barriers to the expansion of the OWF sector, challenging the achievement of global climate and energy targets[104]. Given the range of possible effects, and the rate of increase in the offshore wind energy sector, improved assessment, monitoring and mitigation of biodiversity impacts are urgently needed. Current and emerging approaches to improved assessment, monitoring and mitigation are discussed in this section.

Assessment

The main instruments to identify and measure pressures and make plans to manage them are environmental and social impact assessments (ESIAs), environmental impact assessments (EIAs) and strategic environmental assessments (Box 2). These assessments, conducted during the pre-construction stage, are essential to identify the avoidance, minimization, restoration and offsetting measures required to mitigate against potential damage to biodiversity. Without these assessments, and their resulting environmental statements in place, projects will not receive consent to proceed and construction can be delayed or halted.

In the absence of a global standard, different regions take different approaches to assessing the potential impacts of OWF development and granting consent to proceed at the pre-construction stage[1,105,106]. Germany, Denmark and Netherlands use a centralized approach whereby the government conducts surveys and ESIAs (Box 2), specifying site selection and design. The UK and Australia use a decentralized approach where the government uses marine spatial planning methods to identify areas for leasing rounds, and developers conduct surveys and ESIAs. The USA and Taiwan adopt a hybrid of the two above approaches. The governance arrangement also affects data collection[107]. Environmental assessments are typically conducted for an individual OWF, which results in a lack of industry standardization of monitoring indicators and minimal cross-developer data sharing. These limitations inhibit understanding of population-scale and cumulative impacts, and could lead to ineffective mitigation[108,109].

In contrast to site-specific assessments, cumulative impact assessments (CIAs)[8] (Box 2) provide the ability to pool resources among several OWF projects, helping to support developers who tend to focus on site-specific processes for certainty, and to reduce costs and secure investment. Robust CIAs are urgently needed; offshore wind developments, especially when clustered regionally or occurring sequentially over time, pose cumulative impacts – ecological, social, spatial and temporal – that might not be evident when projects are evaluated in isolation[8,108,109]. In some jurisdictions such as the UK, the North Sea basin and the US Atlantic Outer Continental Shelf, these analytical processes have informed the development of cumulative environmental impact statements (Box 2), which are formal regulatory documents that compile and summarize CIA findings from multiple developers, federal and state agencies, and stakeholder consultations across projects. In the USA, agencies such as the Bureau of Ocean Energy Management (BOEM) have taken a programmatic approach to evaluating multiple offshore wind projects within the same region[110]. This strategy supports the early identification of overlapping pressures on marine biodiversity. For example, it helps to reveal cumulative impacts on migratory species, benthic habitats, fisheries and culturally important species that are often overlooked in isolated, project-level assessments.

However, current CIA and cumulative environmental impact statement practices still face several challenges. These include data gaps, methodological inconsistencies, limited availability of baseline and long-term monitoring data, and fragmented regulatory coordination across national and regional levels. To address these limitations, there is a growing need for standardized, regionally integrated CIA frameworks, embedded within ESIAs or EIAs, which vary by country, as well as within marine spatial planning processes[108,109]. Such frameworks should incorporate dynamic modelling tools, ecosystem-based management principles and continuous feedback loops informed by post-construction monitoring. Emerging technologies also offer promising assessment pathways for more effective CIA frameworks. For example, remote sensing, acoustic telemetry[111], environmental DNA (eDNA)[112] and artificial intelligence (AI)-powered ecosystem modelling[113] are being explored to assess and predict changes in marine biodiversity, behaviour and habitat use. When integrated into adaptive management strategies, these tools can improve the responsiveness and precision of cumulative assessments. Given the long operational phase (>30 years) of OWFs, decommissioning protocols also require similar advancements in assessment and adaptive

Box 2 | Pre-construction assessment approaches for offshore wind farms

Prior to construction of new offshore wind farms (OWFs), various assessments are used to determine the likely impacts of OWFs. These approaches differ in how comprehensively they address environmental and social dimensions.

Environmental and social impact assessment

An environmental and social impact assessment (ESIA) evaluates both the environmental and the socio-economic impacts associated with OWFs. Although an ESIA is common in many global contexts, regions including Europe and the UK are not obligated under their respective planning or environmental frameworks (such as the EU Environmental Impact Assessment (EIA) Directive) to conduct social impact assessments. As a result, assessments in these regions typically involve only the following:

- EIAs: project-specific evaluations of direct environmental impacts, such as changes to biodiversity or water quality
- Strategic environmental assessments: higher-level, policy-based or plan-based evaluations intended to shape broader decision-making

Although EIAs and strategic environmental assessments primarily focus on ecological outcomes, they can incorporate limited socio-economic elements, but do not constitute full ESIAs.

ESIAs and EIAs both identify measures to avoid, minimize or compensate for potential environmental impacts[2]. Pre-construction surveys (typically of plankton, birds, fish, marine mammals and benthic organisms) are used to establish an ecological baseline and to identify sensitive areas and species present[173]. The findings are compiled into an environmental statement, which is a formal document that summarizes predicted impacts and proposed mitigation strategies.

Cumulative impact assessment

A cumulative impact assessment (CIA) is a related but distinct approach that examines the combined effects of multiple existing, planned or reasonably foreseeable developments and their impacts on the environment and biodiversity. CIAs are particularly important when multiple projects occur in ecologically sensitive areas, where their in-combination impacts (the aggregated or synergistic effects of multiple actions) might be more substantial than those of any one project alone[108].

Although often conducted under the broader ESIA framework, a CIA is technically a component of the EIA process[173]. However, its implementation varies between countries and is often subject to uncertainty owing to inconsistent application[174].

Cumulative environmental impact statements

Cumulative environmental impact statements are comprehensive planning and regulatory documents that formally present the findings of a CIA. These statements document the combined environmental effects of multiple projects or actions, past, present and, potentially, for the foreseeable future.

management to ensure sustainable and environmentally responsible removal strategies[114].

Mitigation

One aspect of the pre-construction assessment process is to determine harmful environmental impacts that might need to be mitigated at later stages. Two of the most evident negative impacts of OWFs on marine wildlife are collision mortality and displacement of mobile species due to noise pollution and other disturbances. These impacts can be mitigated in multiple ways, with most applications to date being focused on birds and marine mammals (Fig. 3). To our knowledge, mitigation measures have not been fully established to address impacts on benthic habitats. However, several measures such as pre-construction site characterization, cable burial techniques and artificial reefs have been proposed to minimize disturbances to benthic ecosystems[115,116].

The mitigation hierarchy is widely adopted globally to decide what measures could be used to avoid, minimize, restore or offset against environmental damage[10,117]. Avoidance measures are taken to anticipate and prevent adverse impacts on biodiversity before actions or decisions are taken that could lead to such impacts, for example, by avoiding developments in key biodiversity areas[10]. Minimization measures are taken to reduce the duration, intensity, significance and/or extent of impacts that cannot be completely avoided (Fig. 3). Restoration measures are taken to repair degradation or damage to specific biodiversity features and ecosystem services of concern following project impacts that cannot be completely avoided and/or minimized. Offsetting measures aim to compensate for adverse impacts of a project that cannot be avoided, minimized and/or restored; the goal of offsetting is to ensure 'no net less' of biodiversity.

The mitigation hierarchy for marine birds, specifically, entails the following actions[107]: locating new OWF developments strategically to avoid high-use areas for vulnerable populations; minimizing impacts through temporal or structural alterations to infrastructure and operation (such as using bird-friendly turbine designs, and installing visual deterrents or radar systems to reduce collision risks); and compensating for unavoidable impacts by funding conservation authorities, environmental non-governmental organizations or government agencies to implement habitat restoration, species recovery plans or other conservation measures (such as artificial nesting towers for sensitive bird species). Despite increasing use of these mitigation measures, their efficacy has rarely been tested; of 212 field-tested approaches, only 36% detailed evidence of their effectiveness[118]. To address the uncertainty in effectiveness, compensatory measures are recommended in addition to avoidance and minimization strategies[107]. Compensatory measures should consider on-site and off-site approaches to strive for 'no net loss' or even a 'net gain' of bird species biodiversity[11].

Several European countries have applied methods to mitigate the impact of underwater noise on marine mammals[9]. These measures (Fig. 3) include using marine observers and acoustic deterrent devices to ensure that no marine mammals are present within the potential piling impact zone; introducing temporal and spatial restrictions on piling to protect marine mammals during sensitive times; and setting noise thresholds and using abatement technology such as bubble curtains to restrict the amount of noise energy emitted into the sea[119].

Monitoring

The potential impacts predicted during pre-construction assessments are monitored during construction and operational phases. Monitoring is typically focused on habitats, mammals and fish during construction, and on birds during operation (Fig. 3). Monitoring frequency, which is decided by national regulatory authorities (such as environment permitting agencies) and conducted by project developers or third-party environmental consultants, varies across projects and regions. Typical monitoring intervals are monthly for at least the first 3 years of operations, then phased down and resumed prior to decommissioning[108].

Specific challenges apply when monitoring for evidence of seabird collision with turbines. Human observation is not practical because the carcasses are carried away or sink; instead, collision risk models estimate risk by combining bird flight patterns, altitudes and turbine specifications to predict the probability of collisions[107]. To better validate these collision risk models, sensor-based technologies are being developed to detect collisions visually or via vibrations in the turbine blades, providing immediate data on collision avoidance and events[107].

Monitoring for marine mammal noise disturbance typically entails detecting mammal presence via onboard observers or passive acoustic monitoring operators; these methods are costly and can risk the health and safety of observers. Emerging technologies with less cost and lower risk to humans include surveys by unmanned aerial vehicles (UAVs), underwater vehicles or passive acoustic monitoring on moorings and towed arrays[120]. Traditionally, developers collect data on their area of operation; however, the large-scale movements of marine mammals requires regional information to best understand the impacts of OWFs. There are now multiple examples of data sharing and collaborative research agreements and partnerships with research institutions to provide regional datasets on the status, distribution and behaviour of marine mammals[120]. This regional approach could enable improved evaluation of the effectiveness of assessment and mitigation measures.

Other innovative monitoring technologies are now being used to monitor biodiversity other than birds and marine mammals (Table 2). These methods include eDNA techniques for assessing species diversity and relative abundance, baited remote underwater video, light traps for benthic invertebrates, acoustic soundscapes for fish and mammals, and the systematic monitoring of ship hulls for non-native species[108]. As the spatial extent of OWFs increases, so do the benefits of embracing strategic monitoring and technologies. For example, with floating OWFs further from shore, the use of digital twin simulations and sensors could have a key future role in their effective monitoring[114].

Summary and future directions

OWFs can both enhance marine habitats and introduce disturbances that harm marine species. This dual nature of OWF impacts emphasizes the importance of taking a nuanced, evidence-based approach to ensure OWFs are located in the right places to simultaneously meet climate goals and safeguard marine biodiversity. By understanding these positive and negative effects along with the key species affected, researchers and policymakers can develop planning and mitigation strategies that promote a nature-positive approach in the renewable energy sector[106].

Much of the current understanding of biodiversity effects comes from indirect observations, modelling or opportunistic observations rather than systematic, long-term field data (Box 1). For example, a 2024 systematic review concluded that there is currently insufficient direct evidence to confidently determine the impacts of OWF on commercial fisheries species[121]. This highlights the need for targeted research and monitoring to understand these effects. The limited spatial and temporal scope of current research hampers

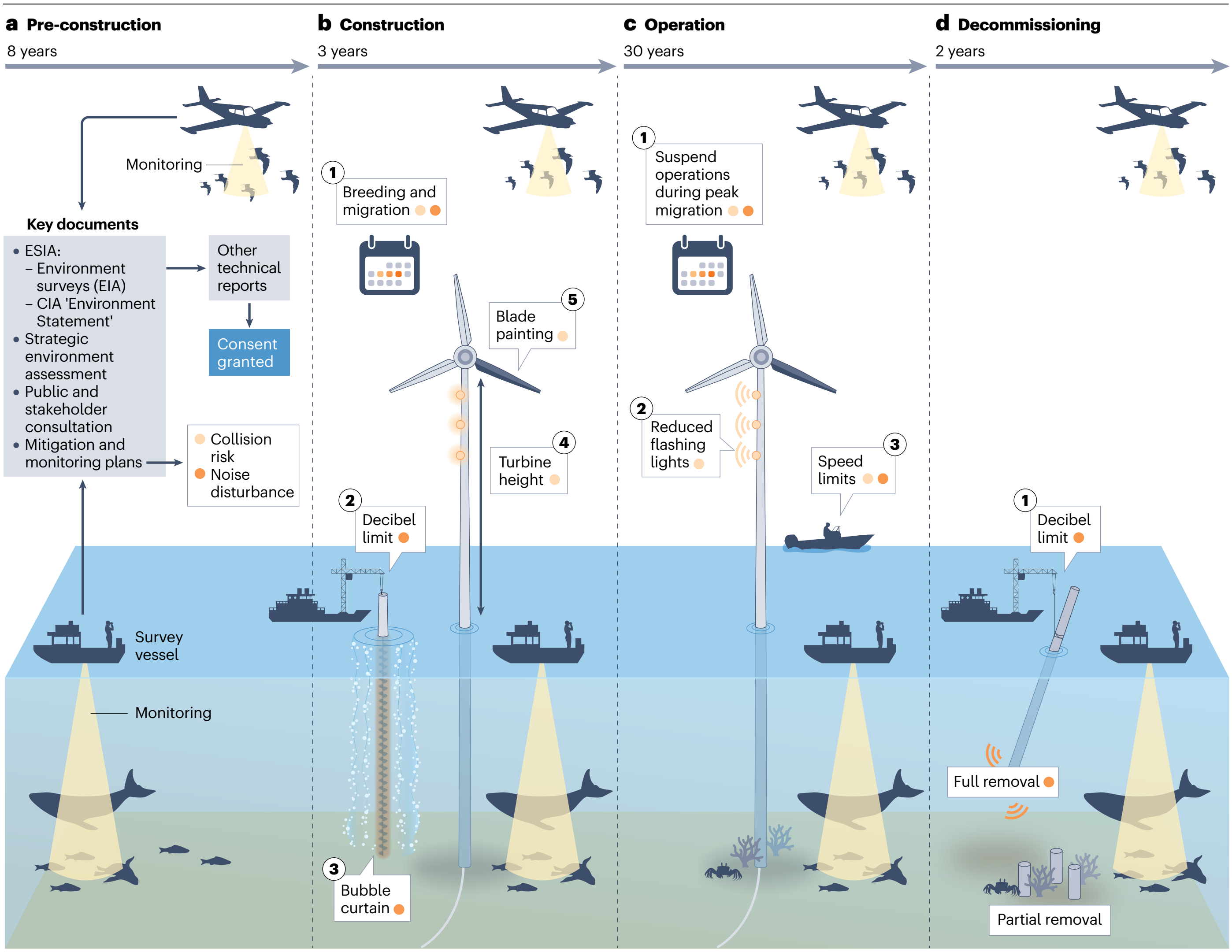


Fig. 3 | The assessment, mitigation and monitoring of collision risk and noise disturbance. Collision risk (yellow) and noise disturbance (orange) are two dominant negative effects of offshore wind farms (OWFs) that are assessed during the pre-construction stage, and monitored and/or mitigated during construction, operation and decommissioning stages. **a**, Consent to initiate a project requires pre-construction ecological surveys to establish the baseline (including species abundance, distribution and habitat use in the area), impact assessments, consultation with stakeholders and other technical reports. **b**, During construction, noise disturbance can be mitigated by avoiding construction during sensitive periods such as marine mammal breeding, calving or migration seasons, when species are most vulnerable to acoustic impacts (1); by applying a noise threshold (2); and by abating noise using bubble curtains (a ring of compressed air bubbles released around the noise source to form an acoustic barrier that reduces underwater sound transmission) (3). Potential collision risk can be mitigated by avoiding construction in sensitive areas (such as migratory flyways) and during sensitive periods (such as breeding seasons) (1); by installing shorter turbines (4); and by painting one turbine blade black to reduce visual blurring (5). **c**, During operation, collision risk can be mitigated by shutting down operations during peak migration periods (1); using flashing rather than steady white lights to reduce bird attraction (2); and imposing vessel speed restrictions (3). The presence of marine mammals is monitored in the operational stage, but no mitigation measures exist. **d**, During decommissioning, updated assessments (environmental and social impact assessments (ESIAs) or environmental impact assessments (EIAs)) are sometimes required. Mitigation of noise during decommissioning includes decibel limits (1) but not bubble curtains. CIA, cumulative impact assessment.

the ability to make confident generalizations or inform policy decisions. Expanding empirical studies with consistent sampling designs, such as the implementation of robust before–after–control–impact (BACI) or before–after–gradient frameworks across multiple sites and throughout different phases of OWF development, is essential to address existing knowledge gaps. Standardized biodiversity indicators and longer monitoring periods are also essential to address these gaps and ensure a robust understanding of OWF impacts on marine ecosystems over time and space.

Important research gaps include the relative impacts of floating OWFs (relative to fixed OWFs) and impacts of the decommissioning stage. Currently, the volume of literature on fixed OWFs strongly

Table 2 | Summary of traditional and innovative biodiversity monitoring approaches for fixed and floating offshore wind farms across project phases

Monitoring approach and definition	Application phase(s)	Benefits	Limitations	Example implementations
Vessel-based surveys: observers count birds, mammals and turtles from ships along transects	C, O, D	Extensive area coverage; established methodology	Weather-dependent; daytime only; high operational cost	North Sea surveys for seabird and marine mammal monitoring[108]
Aerial surveys: observers count seabirds and marine mammals from aircraft along transects	C, O, D	Rapid assessment over large areas; good for surface-active fauna	Expensive; weather/visibility limitations; cannot see submerged organisms	Environmental impact assessments (EIAs) in the North Sea and US East Coast[108]
SCUBA diver surveys: divers visually inspect benthic habitats and turbine foundations in situ	O	High-resolution data on sessile and reef organisms	Depth and sea-state limits; small spatial coverage; safety concerns	Surveys at European fixed-bottom turbines[151]
Underwater video: cameras on remotely operated vehicles (ROVs), or fixed, baited or unbaited stations, record benthic fauna and habitats	C, O, D	Non-invasive; detailed imagery; extended depth range	Limited field of view; requires retrieval; observer effort for analysis	ROV surveys at North Sea OWFs[20]
Passive acoustic monitoring: hydrophones record underwater soundscapes to detect vocalizing species (whales, fish) and anthropogenic noise	C, O, D	Continuous monitoring; effective for whales and dolphins; can be attached to moorings and towed arrays	Detects only vocal species; large data volume; range limited	National Oceanic and Atmospheric Administration (NOAA) and The Bureau of Ocean Energy Management (BOEM) recommendations[160]
Active acoustic (echosounders): sonar pulses (from single or multibeam echosounders) map seabed habitats and fish aggregations	C, O, D	Quantitative habitat and/or fish data; operates day and night	High cost; complex analysis; potential acoustic disturbance	Broadly used in fisheries and habitat mapping at OWFs[140]
Grab/net sampling: benthic grabs or trawl nets physically collect organisms for species identification and counts	C, O, D	Provides species-level identification; quantitative catch data	Destructive; gear bias; limited depth/scope	Beam trawl and grabs in North Sea OWF baseline studies[103]
Light traps: traps used to collect aquatic organisms, typically benthic invertebrates or small fish, by utilizing their attraction to light	O	Low cost; low environmental impact; can be used in complex, fragile and difficult-to-sample habitats	Catch rates affected by environmental factors (water movement and turbidity) and trap design and method of deployment	Sampling benthic and planktonic animals[161] but not yet used in OWF settings
Satellite remote sensing: high-resolution imagery detects large fauna (whales, seals) or environmental proxies (such as chlorophyll, temperature)	C, O	Covers vast areas; no disturbance; monitors environmental variables	Resolution too low for small species; methods are experimental	Ocean condition monitoring[162]
Telemetry: attaching transmitters (radio, satellite) to birds, bats or marine mammals to track movements	O	Detailed movement and habitat-use data	Only monitors tagged individuals; labour-intensive	Used for migratory birds in European waters[128]
Collision risk models verified with cameras and/or impact sensors: a modelled estimate of collision risk tested via sensor-based technologies	O	Can operate over long periods and reduce labour and cost versus observer studies	Maintenance of system; quality of footage; background noise of operating turbine	Wind turbine sensor array for monitoring avian and bat collisions[163]
Autonomous underwater vehicles (AUVs): unmanned underwater robots equipped with sensors (cameras, sonar, infrared imagery) for automated surveys	C, O, D	Extensive spatial coverage; multi-parameter data collection	High cost; technical complexity; limited endurance	AUVs tested for use in offshore monitoring in China[164]
Autonomous surface vehicles (ASVs): unmanned surface vessels with sensors (hydrophones, sonar, cameras, infrared imagery) operating autonomously	C, O, D	Persistent monitoring; cost-efficient relative to crewed ships	Surface-limited sensors; weather limitations	Multi-domain inspection of OWFs using ASVs[165]
Unmanned aerial vehicle (UAV) surveys: drones with cameras or sensors survey wildlife and surface conditions	C, O, D	High-resolution imagery; flexible deployment; minimal disturbance	Limited flight time and range; weather constraints; regulations	Review of UAV applications at floating OWFs[166]
Artificial intelligence (AI) and machine learning: automated algorithms process imagery or acoustic data for species identification and pattern recognition	C, O, D	Processes large datasets; improves detection accuracy	Needs training datasets; possible misclassification; maturing technology	Fast recognition of birds using deep learning models[167]
Digital twins: virtual models that integrate real-time environmental and engineering data to simulate OWF performance and biodiversity risk under different scenarios.	C, O, D	Enables predictive risk assessment; simulates extreme weather and climate change impacts; supports adaptive management	Still emerging; lacks field validation; requires integration with empirical data	Proposed for scenario planning in extreme conditions[114]; not yet empirically applied to biodiversity monitoring

All monitoring methods can apply to both fixed and floating structures, with the exception of SCUBA diver surveys which are predominantly limited to fixed structures. C, construction; D, decommissioning; O, operation; OWF, offshore wind farm.

outweighs that on floating OWFs, making the relative effects of floating OWFs on biodiversity uncertain. Future research should assess aspects unique to floating installations such as the spatial extension into deeper waters (leading to conflicts with offshore fisheries), the lack of seabed intervention for foundations (reduced sediment disturbance) and potentially increased collision and entanglement in cables from many marine mammals[81]. Similarly, the limited number of published studies monitoring biodiversity at the decommissioning phase means that meaningful conclusions cannot be drawn about how decommissioning activities will affect marine ecosystems and biodiversity. Limited available evidence suggests that repurposing or leaving individual OWF structures in place might reduce harmful biodiversity effects relative to full decommissioning[122], but more dedicated monitoring is warranted to identify the impacts of different decommissioning approaches[74]. Future investment in innovative monitoring tools (such as digital twin simulations, advanced sensor technologies and unmanned vehicles; Table 2) are an essential way forward to track and analyse biodiversity impacts more effectively across all OWF life-cycle stages, including decommissioning. These technologies can provide high-resolution, real-time data that complement traditional monitoring methods.

To improve the ability to predict, manage and mitigate the environmental impacts of OWFs, it is essential to adopt both globally coordinated and regionally tailored approaches. At the international level, the transference of data between countries via a global repository for OWF biodiversity effects could enable more robust modelling and decision-support tools, and ultimately assist with nature-positive mitigation outcomes[108]. For example, an international database, established by an established intergovernmental body such as the International Energy Agency (IEA), the CBD or the International Council for the Exploration of the Sea (ICES), could store ESIAs, EIAs and strategic environmental assessments, monitoring data and research findings from OWF projects worldwide. Regional platforms such as the UK's Marine Data Exchange (MDE) and transboundary systems such as OSPAR's Data and Information Management System (ODIMS) and HELCOM's Map and Data Service demonstrate the feasibility of open-access environmental data sharing. These models could inform the structure, hosting and governance of an international repository to support evidence-based planning and cross-regional learning. Such a repository could serve as a reference for policymakers, developers and conservationists, enabling them to identify global trends and regional differences in biodiversity responses. This international data sharing could help regions with slower but growing offshore wind development to identify optimal monitoring intervals and suitable data collection techniques (for example, eDNA sampling, acoustic monitoring, remote sensing and traditional field surveys) from the outset.

Such global coordination should be supported by the implementation of regional ecosystem monitoring programmes (REMPs) that tailor monitoring strategies to local biodiversity baselines and ecological sensitivities[123]. REMPs, increasingly recommended for use in marine spatial planning, including in offshore wind contexts in areas such as the North Sea[109], can provide place-based, ecologically meaningful insights. These programmes should be embedded within national regulatory frameworks and designed to capture effects across all stages of an OWF's life cycle – from pre-construction through to decommissioning – ensuring that both immediate and long-term effects on biodiversity are captured. A REMP framework could also enable focused research on the indirect or secondary impacts on biodiversity (such as changes in water quality, hydrodynamic regime and seabed stability), which are harder to identify than the more immediate and tangible effects (artificial reefs, altered food webs, displacement and barriers, collision risk). Monitoring processes need to focus on these impacts on specific biodiversity elements for which higher uncertainty has been identified.

Monitoring technologies are inherently dynamic and rapidly evolving, so no single one-size-fits-all methodology will be effective in all regions. Instead, we recommend that governments, scientific bodies and offshore wind developers collaboratively work to establish a shared framework of guiding principles defining core biodiversity indicators, standardized data formats and minimum monitoring intervals – to support consistent and comparable environmental assessments. Identifying these best practices would support consistency while maintaining flexibility for technological innovation and region-specific application. Comparable frameworks have proven effective in other sectors; for example, the International Seabed Authority's REMP in deep-sea mining, and the Ocean Biodiversity Information System (OBIS) both demonstrate how regionally tailored yet globally interoperable systems can be implemented to support collaborative, large-scale environmental management[124]. Together, these approaches will allow for better use of existing data, support the development of robust models and decision-support tools, and enable knowledge transfer between regions. Implementing these recommendations will require close collaboration among governments, industry stakeholders, researchers and conservation organizations to harmonize practices and ensure biodiversity considerations are fully integrated into all stages of OWF planning and operations, both regionally and globally.

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Competing interests

B.W. is employed by the Department for the Environment, Food and Rural Affairs (Defra) UK but contributed to this Review as a visiting fellow to Plymouth Marine Laboratory. All views are her own and do not express the views or opinions of Defra as an organization. The remaining authors declare no competing interests.

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